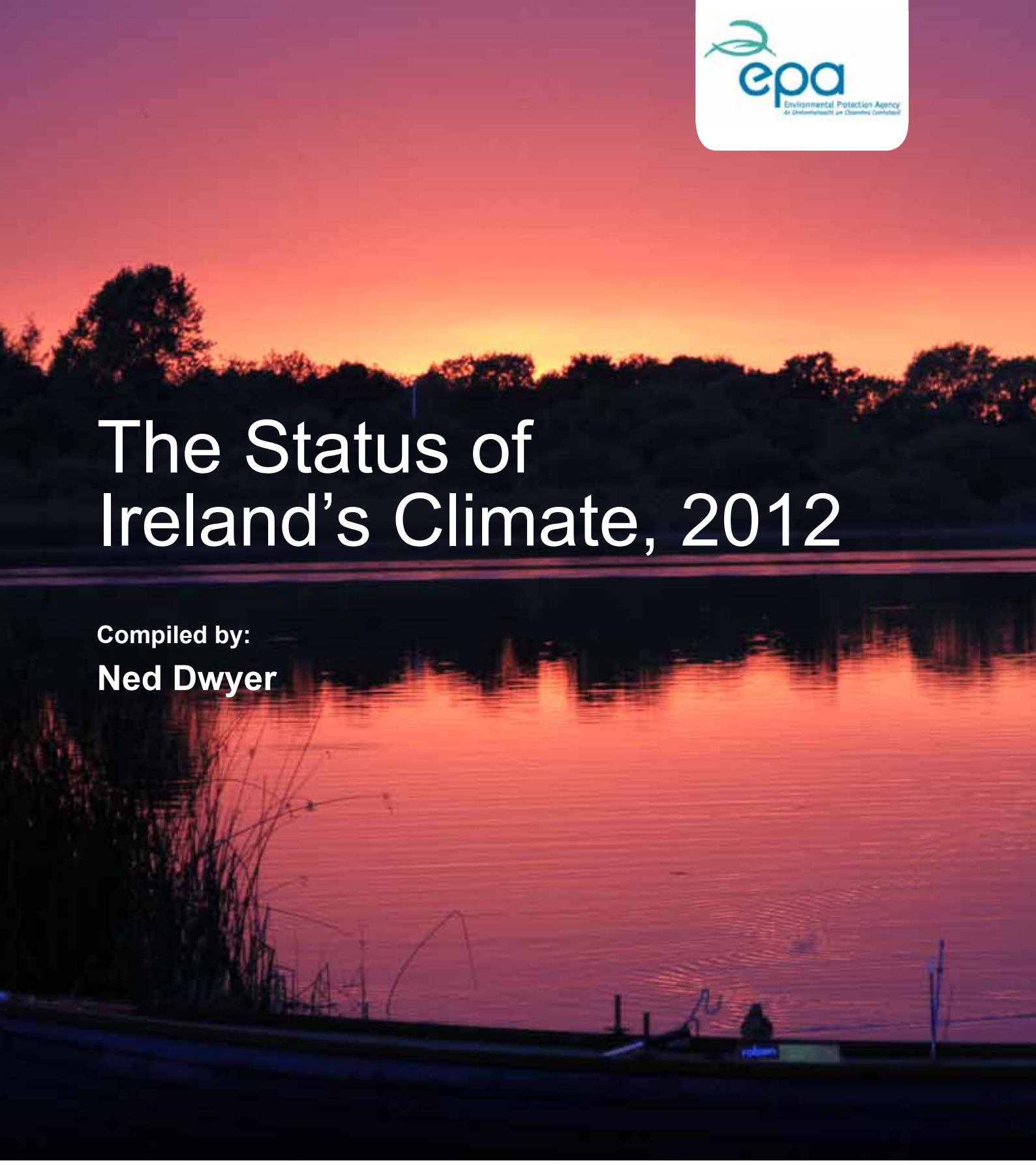
CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	The status of Ireland's climate, 2012
Authors	Dwyer, Ned
Publication date	2013
Original Citation	Dwyer, N. (2013) 'The status of Ireland's climate, 2012. Wexford, Ireland: Environmental Protection Agency.
Type of publication	Report
Link to publisher's version	http://www.epa.ie/pubs/reports/research/climate/ccrpreport26.html
Rights	© 2012, Environmental Protection Agency.
Download date	2026-11-14 16:30:57
Item downloaded from	https://hdl.handle.net/10468/2969

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh



The Status of Ireland's Climate, 2012

Compiled by:

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

© Environmental Protection Agency 2012

Acknowledgements

The author would like to thank staff at Met Éireann, the Marine Institute, Teagasc and the Environmental Protection Agency (EPA) for their collaboration and contributions to this report. In particular, the participation of Séamus Walsh (Met Éireann), Glenn Nolan (Marine Institute) Stuart Green (Teagasc), Phillip O'Brien and Frank McGovern (EPA) through the steering committee was extremely helpful in guiding the report compilation. Moreover, their direct contribution as authors and advisors on many of the chapters was instrumental in ensuring the quality of the work reported.

The contribution of all the authors, listed in Appendix 1, is gratefully acknowledged. They provided text, data, expert opinion and patiently reviewed and edited material during the writing of the report. Numerous others provided access to data and relevant publications and also gave valuable insights into many aspects of the Irish climate monitoring system. These include John Redmond (Forest Service), Paul Leahy, Brian Barrett (University College Cork), Kevin Delaney, Margaret Desmond, David Dodd, Anthony Mannix, Ahmed Nasr, Rebecca Quinn, Deirdre Tierney (EPA), Alison Donnelly (Trinity College Dublin), Denis Griffin, Rogier Schulte (Teagasc), Aditya Vaishya (National University of Ireland Galway), Phillip Woodworth (Proudman Oceanographic Laboratory), Peter Newport (Office of Public Works) and Denis Griffin (Department of Agriculture, Food and the Marine). We also acknowledge the SeaWIFS mission scientists and associated NASA personnel for the production of the data used in this report (ocean colour). The use of imagery and derived data from European Space Agency missions is also gratefully acknowledged.

Sincere thanks to all the photographers who allowed the reproduction of the many beautiful photographs used in illustrating the report. The help of Emily Gleeson of the Irish Meteorological Society is gratefully acknowledged for facilitating access to those photographs which were originally contributed to the Met Society's annual photographic competition.

Finally, I would like to thank my colleagues in the Coastal and Marine Research Centre at University College Cork for technical assistance, useful discussions, contributions to and review of some of the materials used in the report.

Disclaimer

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. Neither the Environmental Protection Agency nor the author(s) accept any responsibility whatsoever for loss or damage occasioned or claimed to have been occasioned, in part or in full, as a consequence of any person acting or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

ISBN: 978-1-84095-478-4 50/12/2012
Price: Free



Details of Project Partner

Dr Ned Dwyer
Coastal and Marine Research Centre
Environmental Research Institute
University College Cork
Naval Base
Haulbowline
Cobh
Co. Cork
Ireland

Tel.: +353 (0)21 4703104
Fax.: +353 (0) 21 4703132
Email: n.dwyer@ucc.ie
http://cmrc.ucc.ie



Photograph captions

Section	Photographer	Title
Title page	John Gale*	Ballykeeran Lake Sunset
Executive Summary	Triona McGrath	Preparing to launch
1	Mick Mackey	Reflection
2	Margaret O'Shea*	Autumn Sky, Rossbeigh Co. Kerry
2.1	Ned Dwyer	Bright Sky
2.2	Margaret O'Shea*	Autumn Sky, Rossbeigh Co. Kerry
2.3	Gerard Cunniam*	Curragh Convection, Co Kildare
2.4	Paddy Tubbritt*	Untitled
2.5	Valerie Robus*	Misty morning
2.6	Ned Dwyer	Winter sunset
2.7	Keith Lambkin	Weather Balloon
2.8	Marcus Austin*	Clouds on blue sky, Cratloe, Co. Clare
2.9	Catherine O' Callaghan	Aghada power station, Whitegate, Co. Cork
2.10	Ned Dwyer	Out to grass, Co. Kilkenny
2.11	Phillip O'Brien	Ploughed Fields
2.12	Karen Commane*	Untitled
2.13	Gavin Ó Sé*	Graignamanagh sunrise, Co. Kilkenny
3	Paddy Tubbritt*	Winter Sunset Kilfarrasy, Co. Waterford
3.1	Ned Dwyer	Co. Wexford Coast
3.2	Didac Perales	Cliffs of Moher, Co. Clare
3.3	IFREMER	Cold water corals, Atlantic ocean
3.4	Kathryn Smith	The Wild North Atlantic
3.5	Sean Kennedy*	Storm, Poolbeg Wall, Co. Dublin
3.6	Triona McGrath	Preparing to launch
3.7	Paddy Tubbritt*	Winter Sunset Kilfarrasy, Co. Waterford
3.8	Pauhla McGrane	Phytoplankton, *Emiliania huxleyi*
3.9	David Brannigan	Celtic Explorer at sea
3.10	Ned Dwyer	Near the Old Head of Kinsale, Co. Cork
4	Karl Jordan*	Untitled
4.1	Ned Dwyer	Countryside, Co. Waterford
4.2	Karl Jordan*	Untitled
4.3	Brian O' Connor	Maize crops, Currabinny, Co. Cork
4.4	Ned Dwyer	Summer colours, Co. Cork
4.5	Ned Dwyer	Bluebells, Co. Wicklow
4.6	Ned Dwyer	Saving the turf
4.7	Brian Barrett	Waterlogged, Great Island, Co. Cork
4.8	Peadar McMahon	Fire on Bragan mountain, Co. Monaghan
4.9	Margaret Gordon*	Salmon leap after the flood
4.10	Digby Lewis	Untitled
4.11	Ned Dwyer	The Shannon Pot, Co. Cavan
4.12	Brian Barrett	Potato crop, Great Island, Co. Cork
5	Liam Lysaght	Female Common Blue butterfly

*Courtesy of the Irish Meteorological Society

Table of Contents

Acknowledgements ii

Disclaimer ii

Details of Project Partner iii

Photograph Captions iv

Executive Summary vii

1. Introduction xi

1. Introduction 2

1.1 The Need for Climate Observations 2

1.2 Aims and Objectives 2

1.3 Observed Climate Change in Ireland 2

1.4 The Essential Climate Variables 3

1.5 Overview of Observations in Ireland 4

1.6 Use of Climate Data 8

2. Atmospheric Observations 9

2.1 Surface Air Temperature 10

2.2 Rainfall 14

2.3 Atmospheric Pressure 17

2.4 Surface Wind 19

2.5 Water Vapour 22

2.6 Surface Radiation Budget 25

2.7 Upper Air Temperature and Wind 28

Story Board 1: Met Éireann – Observing Climate for more than Seventy-five Years 31

2.8 Cloud Properties 33

2.9 Carbon Dioxide 36

2.10 Methane 40

2.11 Other Greenhouse Gases 43

2.12 Ozone 47

2.13 Aerosols 51

Story Board 2: Ireland – A Key Location for Global Atmospheric Observations 54

3. Oceanic Observations 57

3.1 Ocean Surface and Sub-surface Temperature 58
3.2 Ocean Surface and Sub-surface Salinity 62
3.3 Ocean Acidification and Carbon Dioxide Concentrations 65
3.4 Sea State 68
Story Board 3: Riding the Storm in the North Atlantic 71
3.5 Sea Level 73
3.6 Surface and Sub-surface Currents 77
3.7 Ocean Colour 79
3.8 Phytoplankton 82
3.9 Nutrients 84
3.10 Dissolved Oxygen 87
Story Board 4: Hidden Treasure – Ireland's Deep-water Corals 90

4. Terrestrial Observations 93

4.1 Land Cover 94
4.2 Albedo 98
4.3 Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) 101
4.4 Leaf Area Index 103
Story Board 5: Biodiversity and Habitats 106
4.5 Above-ground Biomass 109
4.6 Soil Carbon 112
4.7 Soil Moisture 115
4.8 Fire Disturbance 118
Story Board 6: Carbon Storehouses 121
4.9 River Discharge 124
4.10 Lake Levels and Areas 127
4.11 Groundwater 129
4.12 Water Use (Irrigation) 132
Story Board 7: Satellite Observations Provide a Global Picture 134

5. Discussion and Recommendations 137

References 140

Acronyms 144

Appendix 1: List of Authors 147



Executive Summary

Executive Summary

Ireland's climate is changing. This is consistent with regional and global trends which display rapid changes in many aspects of climate over the last century and the first decade of this century. The availability of high-quality climate observations is a critical starting point from which an understanding of past and emerging trends in the current climate can be developed. Such observations are vital for detecting change and providing the information needed to help manage and plan for the future in a wide range of socio-economic sectors.

Observations are also essential to help build robust projections of future climate, which can in turn inform policy formulation for appropriate mitigation and adaptation measures. Such measures should help us limit the negative socio-economic impacts and position us to take advantages of opportunities offered by a changing climate.

This report brings together observational information and data for over 40 climate variables and highlights changes and trends in aspects of Irish climate across the atmospheric, oceanic and terrestrial domains. The observations presented in this report contribute to the formulation of the Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS). The key findings in relation to Ireland's climate are:

Atmosphere

- Mean annual surface air temperature has increased by approximately 0.8°C over the last 110 years. The number of annual frost days has decreased whilst the number of warm days has increased.
- Average annual national rainfall has increased by approximately 60 mm or 5% in the period 1981 to 2010, compared to the 30-year period 1961 to 1990. However, clear changes in rainfall spatial patterns across the country cannot be determined with a high level of confidence.
- Current carbon dioxide (CO_2) concentrations of more than 390 ppm as measured at Mace Head, Co. Galway are in line with observations from around the globe and are higher than at any time over the last 400 thousand years.
- Concentrations of other greenhouse gases including methane (CH_4) and nitrous oxide (N_2O) are approximately 140% and 20% respectively above pre-industrial values and concentrations continue to increase.
- No long-term trend in wind speed can be determined with confidence.

Oceans

- Mean annual sea surface temperature, as measured at Malin Head, Co. Donegal, is now more than 1.0°C higher than the long-term average calculated for the period 1961–1990.
- Global surface ocean acidity has increased by over 30% since the Industrial Revolution. Observations in sub-surface and deep offshore waters around Ireland between 1991 and 2010 show significant increases in acidity.
- Historically, sea level has not been measured with the necessary accuracy to determine sea-level changes around Ireland. This represents a key gap in the Irish observation system. However, measurements from Newlyn, in southwest England, show a sea-level rise of 1.7 cm per decade since 1916. These measurements are considered to be representative of the situation to the south of Ireland.

- Since 2000, the occurrence of some potentially harmful ocean phytoplankton species during the winter months has increased.

Terrestrial

- One of the major land-use changes across Ireland since 1990 has been the conversion of grassland and peatland to forest. This expansion of forest area has seen the amount of carbon stored or sequestered in forest increase by 40%.
- It is estimated that Ireland's soil carbon stock has decreased by 27 million tonnes between 1990 and 2000. This is mainly due to changes in the management of peatland, including drainage and peat extraction and to a lesser extent to changes in patterns of agricultural land use and urban development.
- Observations of the timing of bud-burst for a number of tree species at the phenological gardens indicate that the beginning of the growing season (BGS) is now occurring more than a week earlier than in the 1970s, leading to an extension of the growing season. Such changes have been linked to a rise in average spring air temperature.
- Analysis of long-term river flows from over 40 measurement sites around the country shows a tendency for increasing annual mean flows. Moreover, seasonal analysis indicates that summer mean flows are dominated by increasing trends while there is a tendency also for increases in winter mean flows.

Observational Infrastructure

Many elements of Ireland's climate observation infrastructure are robust – however, there are a number of gaps and areas where improvements are necessary. The network of synoptic, climatological and rainfall stations operated by Met Éireann needs to be maintained and further developed to ensure the future of long-term, representative measurements. The Mace Head Research station, operated by the National University of Ireland Galway, has become a global reference site for the observation of a number of atmospheric composition variables. Nonetheless, 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.

There has been a significant growth and consolidation of ocean-observing systems since 2000, which is proving invaluable in improving understanding of ocean climate. It is vital that these systems are maintained and where possible enhanced to increase the number and quality of the measurements made. Only with long time-series will it be possible to detect trends in the ocean-climate variables and assist in making appropriate adaptation decisions. Ocean acidification is of growing international concern. There is a need for a long-term national commitment to monitoring the ocean carbonate system and ocean acidity in order to improve understanding of its potential impact on the Irish marine environment and economy.

A number of the land surface and hydrological variables have been monitored by various organisations for many years in support of policy and management objectives (e.g. water supply, land use). There is a need to ensure that these observations also contribute to long-term monitoring for climate purposes.

At least a dozen organisations have a role to play in monitoring aspects of Ireland's climate. It is vital that long-term monitoring is coordinated between these different bodies to avoid duplication and to maximise possibilities for synergy.

Systematic collection and management of climate data are essential. However, regular analyses and the reporting of status, trends and projections are also required. Long time-series, many in excess of 50 years, exist for a number of the meteorological and hydrological variables, yet only partial analyses have been carried out. Furthermore, observations of many of the land-surface variables have been made by satellite for a number of decades, but limited analyses of these have been completed for Ireland.

Opportunities and Recommendations

As an island on the western margins of Europe facing the Atlantic Ocean, Ireland is in a unique location for climate monitoring. It is recognised internationally as an ideal site for baseline atmospheric and oceanic observations. Ireland can capitalise on this and

contribute to developing improved environmental sensors, data transmission, storage, management and analysis solutions. These can be prototyped, tested and refined in the living laboratory offered by the Irish environment. Such developments would also contribute to the enhancement of the GCOS to which Ireland contributes as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC).

This report demonstrates that many elements of a climate observation, analysis and reporting system are in place, nonetheless there are a number of issues that need to be addressed in order to make it 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:

1. A structure or body is required to enhance coordination between organisations carrying out atmospheric, oceanic and terrestrial climate observations to ensure an integrated national approach and efficient utilisation of resources.
2. Observation programmes for some of the ECVs are well established (e.g. meteorological). Other ECV observations are carried out on a project or ad hoc basis (e.g. atmospheric composition, oceanic). It is vital that adequate resources are provided to: (i) maintain existing, established climate-observation programmes and (ii) guarantee the long-term continuity of project-based monitoring to international standards.
3. No long-term national observation programmes exist for a number of the ECVs (ocean acidification, pCO_2, ocean currents, phytoplankton, soil carbon, fire disturbance, water use). A prioritisation and costing exercise should be carried out with a view to implementing appropriate programmes over time.
4. Some variables are monitored under various operational and management programmes (e.g. river flows and lake levels as part of the Water Framework Directive; sea state for ocean weather forecasting) but not for climate purposes. Appropriate long-term climate observation sites should be identified and designated from among current observation sites.
5. Ensure data from the Irish National Tide Gauge Network established over the last decade by the Marine Institute and a number of public and private sector organisations can be used for the calculation of sea-level change. Provide analyses of these data with historical records from established, reliable tide gauges and link these to regional satellite-derived information on sea-level change.
6. Safeguard all existing and historical ECV data, complete digitisation of paper records (e.g. air temperature, precipitation and wind) and carry out quality checks and homogenisation of these data to ensure their adequacy for climate monitoring.
7. Comprehensive analysis has been carried out for the atmospheric composition and some of the meteorological and oceanic ECVs. However, only partial analyses have been completed for the majority of the other ECVs. Complete and regular detailed analysis should be carried out and reported on all ECV observations, including satellite data records where appropriate.

Conclusions

This analysis of Ireland's ECVs demonstrates that Ireland's climate is changing. These changes are consistent with regional and global trends, but local patterns of change are evident. It is essential that Ireland's climate observation system is maintained and enhanced in order to have the information required to understand these changes to enable planning for appropriate adaptation. This report makes a number of recommendations as to how Ireland's climate observation system can be improved in order to meet these needs.



1. Introduction

1. Introduction

1.1 The Need for Climate Observations

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

- Characterise the state of the climate system and its variability;
- Monitor the forcing of the climate system, including both natural and human contributions;
- Determine the causes of climate change;
- Provide a basis on which to assess future and predicted changes in climate;
- Help plan for and adapt 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 report (IPCC, 2007) provides a comprehensive picture of global changes and potential impacts. The report states that warming of the climate system, based on observations of air and ocean temperatures, is unequivocal and that it is very likely that increased temperatures observed since the mid-twentieth century are due to greenhouse gas emissions caused by human activities. The report also notes that many natural and human systems are affected by regional climate changes, and it highlights the need for adaptation to reduce vulnerability to climate change.

1.2 Aims and Objectives

The aim of this report is to highlight the state of Ireland's climate based on the collation and analysis of over 40 different variables observed in the atmospheric, oceanic and terrestrial environments. It follows on work carried out to document the state of Ireland's climate-observing system (Dwyer, 2008) and an action plan to assist the development of a comprehensive, reliable and sufficient national climate observing system (Dwyer, 2010). Where appropriate data exist, illustrative time-series are presented and trends reported. In other cases where the time period of observation is short, no specific monitoring programme is in place or the appropriate analysis has not been carried out, example products are presented and the gaps in observations and analysis highlighted. The organisations responsible for monitoring each of the variables are identified and finally guidance on where data and additional information can be accessed is provided. The information contained here comes from a large number of national and international sources.

This report is the first to bring together such a breadth of information on climate monitoring in Ireland. It is planned to provide updates on a regular basis in order to improve understanding of Ireland's changing climate and assist with taking the actions required to adapt appropriately.

1.3 Observed Climate Change in Ireland

As an island on the western margins of Europe facing the Atlantic Ocean, Ireland is in a unique location to monitor the climate. It is recognised internationally as an ideal site for conducting baseline atmospheric and oceanic measurements. Background concentrations of greenhouse gases and other constituents of the atmosphere, transported in predominantly unpolluted air masses by westerly winds, can be measured. Moreover, Ireland has sovereign rights and jurisdiction over a seabed area of 900,000 km^2, including deep-sea areas of over 3,000 m depth. Monitoring of Atlantic Ocean climate parameters is vital given its predominant role in determining the temperate climate conditions experienced in northwest Europe. Monitoring of the land surface and hydrological regimes is important given their environmental importance and their direct

influence on the socio-economic activities. While Ireland still has extensive areas of peatland (which play a key role in carbon and water storage), their health is very sensitive to changes in climate.

Monitoring of its various aspects helps in improving understanding of the climate and supports comparisons of observed change with projections. It can also give early warning of any changes, therefore allowing appropriate actions to be taken to adapt to and reduce the most deleterious impacts or indeed to take advantage of a changing climate.

Similar to the findings of the IPCC, evidence of climatic change has been reported for Ireland. McElwain and Sweeney (2007) highlighted that mean air temperature is increasing at a rate of 0.42°C per decade based on observations in the period 1980 to 2004. Changes in annual rainfall amounts were also noted, with an increase of over 300 mm in the period 1890 to 2003 observed at Malin Head, Co. Donegal. In general, increases in annual rainfall amounts decrease from west to east across the country, although much uncertainty about changes in rainfall patterns remains. Predictions of future rainfall suggest wetter autumns and winters and drier summers (Dunne et al., 2008). A detailed report on Ireland's ocean climate (Nolan et al., 2010) documented changes in a large number of ocean parameters. Sea surface temperature records exhibit a mean warming trend of 0.3°C between 1850 and 2008. Significant wave heights (the mean height of the highest 1/3 of waves), as determined from satellite altimeter records in the northeast Atlantic show an increasing trend of 14 cm per decade; and some phytoplankton species are now found in winter months compared with 20 years ago when they were absent.

1.4 The Essential Climate Variables

In 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was agreed and the GCOS secretariat was established to support the systematic observation of climate. An important task of GCOS was to define a set of variables that are considered a minimum to be monitored in order to have a comprehensive understanding of climate and its changes. These so-called Essential Climate Variables (ECVs), first defined in 2004, have been subsequently updated in 2010 (GCOS, 2010). They include observations of the physical, chemical and biological properties of the atmosphere, the ocean and the land surface. In defining ECVs, GCOS aims for global coverage and compatibility with regard to how measurements are made, therefore facilitating their inter-comparison. Observations are made by a combination of *in situ* measurement systems and, since the 1970s, satellite sensors. Satellites can take measurements over large areas, allowing 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 presented in Table 1.1.

Table 1.1. The Global Climate Observing System (GCOS) Essential Climate Variables (ECVs).[1]

Domain		Essential Climate Variables
Atmospheric	Surface	Air temperature, Precipitation, Air pressure, Surface radiation budget, Water vapour, Wind speed and direction.
	Upper air	*Earth radiation budget (including solar irradiance)*, Upper-air temperature, Wind speed and direction, Water vapour, Cloud properties.
	Composition	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases, Aerosol properties
Oceanic	Surface	Temperature, Salinity, Ocean acidity, Carbon dioxide partial pressure, Sea state, Sea level, *Sea ice*, Current, Ocean colour, Phytoplankton.
	Sub-surface	Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, *Ocean tracers*, Oxygen.
Terrestrial	Land surface	Land cover (including vegetation type), Albedo, Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass, Soil carbon, Soil moisture, Fire disturbance, *Permafrost*.
	Hydrology	River discharge, Lakes, *Snow cover, Glaciers and ice caps, Ice sheets*, Groundwater, Water use (irrigation).

1 Those ECVs denoted in *italics* are not discussed in this report.

1.5 Overview of Observations in Ireland

No single authority is charged with making the full range of observations of ECVs for Ireland. The monitoring networks and measurement systems that do exist are managed by a range of different bodies, including state agencies, regional authorities and third-level institutions. In many instances the observations made are not strictly for climate monitoring purposes but for operational requirements or research. For example, groundwater levels are monitored in relation to abstraction, tide levels for sea-traffic management, and vegetation biomass for forest management. Using such observations for long-term climate monitoring is not ideal, as measurement sites close or move, research programmes cease, and equipment is not calibrated to climate measurement standards, etc.

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 air temperature have been made since 1858, thereby allowing long-term variability to be tracked.

The Mace Head Atmospheric Research Station in 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 Galway although measurement programmes are funded, on a project basis, by a number of national and international organisations.

Regarding oceanographic observations, the longest continuous and reliable time-series include sea surface temperature (SST) and sea level, both of which have been measured at Malin Head, Co. Donegal since 1958. The establishment of the Marine Institute in the 1990s gave an impetus to the collection of oceanographic data. The establishment of the Irish Marine Buoy Network and the regular measurements made on cruises by the two national research vessels has helped to consolidate measurements of a range of variables, although the long-term investment to sustain many ocean observation programmes is uncertain.

A number of organisations carry out measurements of land-based and hydrological variables. The most important of these are the EPA, which oversees land-cover mapping, and coordinates certain hydrological measurements such as groundwater and lake levels and the Office of Public Works, which has an extensive river-flow monitoring network. Additional effort is required to put long-term monitoring of terrestrial variables for climate purposes on a sustainable footing.

Table 1.2 summarises the current monitoring status for all ECVs of relevance to Ireland. It shows the length of the observation period, the key organisations carrying out the measurements, the level of analysis to date and the security of the measurement programme. More complete details can be found in the relevant sections pertaining to the variables.

Observations of key surface and upper-air meteorological variables have been carried out by Met Éireann for many decades (some records date back to the late 1800s). While these measurement programmes are secure, resources are required to maintain and update equipment and enhance aspects of the observation networks. A number of reports detailing analysis of temperature and rainfall records are available (Sweeney et al., 2002; McElwain and Sweeney, 2007). However, only partial analysis of the other meteorological variables has been carried out. In a number of cases historical paper records need to be digitised and issues with inhomogeneities 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 greenhouse gases and other atmospheric composition variables have been monitored for approximately 30 years by a number of national and overseas bodies. Many of these programmes are funded on an ad hoc basis and long-term monitoring programmes are not completely secure. Nonetheless, detailed analyses of the data records collected have been carried out and the results have contributed to numerous 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 started only more recently. One of the most important initiatives has been the establishment of the Irish Marine Weather Buoy Network with instrumentation to record key surface and sub-surface information (e.g. water temperature, salinity, sea state) on a regular basis. The majority of the ocean-observation programmes are only partially secure: funding must be negotiated on an annual basis. There is no long-term, systematic programme of measurements in Irish waters with regard to the carbonate system (ocean acidity, CO_2 partial pressure), and observations of surface and sub-surface currents are made on an irregular basis.

Detailed analyses of much of the data collected has been carried out, and a significant report on the status of the ocean climate and ecosystem was published recently (Nolan et al., 2010). Although sea-level data have been collected at Malin Head since 1958, and

Table 1.2. Overview of Essential Climate Variables (ECVs) including length of observation period, key organisations carrying out the measurements, level of analysis carried out, and if the future of the observation programme is secure.

(Key: ● = yes; ● = partial; ● = no)

Essential Climate Variable	Length of period	Measurement organisations	Analysis	Programme secure
Atmosphere				
Air temperature	1881–2012	Met Éireann	●	●
Precipitation	1881–2012	Met Éireann	●	●
Air pressure	>100 yrs	Met Éireann	●	●
Surface radiation budget	1955–2012	Met Éireann	●	●
Wind	>100 yrs	Met Éireann	●	●
Water vapour	>50 yrs	Met Éireann	●	●
Upper-air temperature	1943–2012	Met Éireann	●	●
Upper-air wind	1943–2012	Met Éireann	●	●
Upper-air water vapour	1943–2012	Met Éireann	●	●
Cloud properties	>50 yrs	Met Éireann, NUI-G	●	●
Carbon dioxide	1992–2012	LSCE, France; NASA, USA	●	●
Methane	1987–2012	DECC, UK; NASA, USA.	●	●
Ozone	1993–2012	Met Éireann; EPA; DECC, UK	●	●
Other greenhouse gases	1978–2012	EPA; DECC, UK; NASA, USA.	●	●
Aerosols	1986–2012	Met Éireann; NUI-G	●	●

Oceanic				
Sea surface temperature	1958–2012	Met Éireann; Marine Institute		
Sea surface salinity	2000–2012	Marine Institute; ICES		
Ocean acidity	2008–2010	Marine Institute		
Sea state	2002–2012	Marine Institute		
Sea level	1958–2012	OPW; Marine Institute		
Surface currents	Irregular	Marine Institute; NUI-G; BODC; others		
Ocean colour	1997–2012	Space agencies		
CO_2 partial pressure	2008–2010	Marine Institute, NUI-G		
Sub-surface temperature	2005–2012	Marine Institute		
Sub-surface salinity	2000–2012	Marine Institute; ICES		
Sub-surface currents	Irregular	Marine Institute;, NUI-G; BODC; others		
Phytoplankton	1990–2012	Marine Institute; SFPA; SAHFOS		
Nutrients	1991–2012	Marine Institute		
Oxygen	2001–2012	EPA; Marine Institute		
Land Surface				
Land cover	1990; 2000; 2006	EPA		
Albedo	1981–2012	Space agencies		
fAPAR	1998–2012	Space agencies		
LAI	1998–2012	Space agencies		
Above ground biomass	Modelled	EPA		
Fire disturbance	Annual estimates since 1990	Forest Service		
Soil carbon	Estimates	None		
Soil moisture	1980–2012	Met Éireann, University College Cork		
Hydrology				
River discharge	>50 years	EPA; OPW; ESB		
Lakes	>50 years	EPA; OPW; ESB		
Groundwater	>40 years	EPA		
Water use (irrigation)	Estimates	None		

DECC, UK=Department of Energy and Climate Change; FARPAR=Fraction of Absorbed Photosynthetically Active Radiation; ICES=International Council for Exploration of the Sea; LAI=Leaf Area Index; LSCE=Laboratoire des Sciences du Climat et l'Environnement; NUI-G=National University of Ireland Galway; OPW=Office of Public Works; SAHFOS= Sir Alister Hardy Foundation for Ocean Science; SFPA=Sea Fisheries Protection Authority.

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

Sector	Use of climate data
Agriculture	• Identify the most viable seeds/crops and times for planting and harvesting and plan for irrigation needs and chemical intervention. • Plan for supplemental feeding of livestock, changes in grazing patterns and rotational management on the farm.
Biodiversity	• Assess 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 & industry	• Plan for changing demand for goods and services. • Identify vulnerability of supply chain, utilities (water and energy in particular) and transport arrangements to withstand 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 to workforce, customers and changing lifestyles.
Coastal & 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. increased levels of energy may be required to pump water and 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 and wave). • 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 the increased downtime and maintenance of power plants and transmission network due to extreme weather events.
Fisheries	• Identify the most viable species and locations for fishing. • 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 sea-food production (e.g. nursery areas, traditional shellfish beds) due to changes in near-shore salinities, 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 and plan for risk of pest pathogen 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. • Forecast levels of food-, water- and vector-borne disease and other indirect effects of climate, 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 CO_2 emission 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 and plan for 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' 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.
Water management	• Plan and manage for a sustainable water supply, both surface and groundwater, by identifying how water will be harvested, managed and distributed. • Manage for competing demand e.g. agriculture, industrial, drinking, recreation. • Identify resources at risk from soil and peat erosion, landslides and the spread of agricultural pollutants.

other locations for a number of decades, changes in the organisations responsible, measurement systems, location of the sensors, data quality, etc. have made it extremely difficult to analyse the historical datasets and extract a reliable trend.

Information for a number of land surface variables is predominantly derived from satellite observations; others are inferred from models or proxy data that are not direct observations. No specific programmes exist for the monitoring of soil carbon or for the direct observation of fire-affected areas. Satellite observations should be available for the foreseeable future. However, *in situ* measurements are vital for their validation.

Analysis of changes in land cover is carried out on a regular basis. Other land-surface variables have been only partially analysed, as components of short-term research projects whilst analysis of some variables has never been carried out.

Monitoring of the main hydrological variables has been conducted by a variety of bodies over the last 40 to 50 years. However, this has generally been for water-management and water-quality purposes. The EPA is currently in the process of establishing a network of monitoring sites for climate purposes. Some analyses of hydrology data in a climate context have been carried out, including a recent analysis of long-term trends in river flows (Murphy et al., 2012).

1.6 Use of Climate Data

Table 1.3 shows where reliable, high-quality climate data are required to help plan and manage in a wide range of socio-economic sectors. There is a need to take current climate information and forecasts into account when planning the development of these sectors in order to avoid costly social and economic impacts. A robust climate-observation system is vital to provide the necessary data to underpin such decision-making.



2. Atmospheric Observations

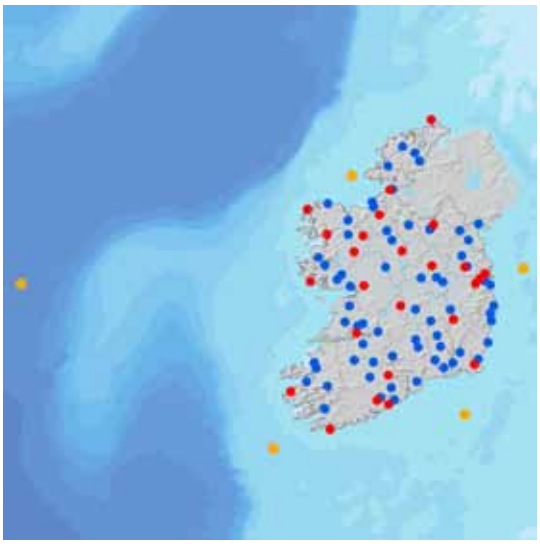
2.1 Surface Air Temperature

Séamus Walsh and Ned Dwyer

Surface air temperature is a key (and perhaps the most familiar) climate variable. More than 100 years of continuous instrumental observations exist in Ireland. The global mean surface temperature has increased by approximately 0.74°C over the last century, and most of this increase is very likely due to the observed increase in greenhouse gas emissions caused by human activities. Globally, over recent decades there has been a significant decrease in cold days and cold nights and a significant increase in warm days and nights and heat waves. Such changes are having severe impacts on the environment, biodiversity and human society.



Photo: © Ned Dwyer



Map 2.1. Location of surface air temperature observation stations.

Measurements

Surface air temperature in Ireland is measured at the 25 synoptic (red) and numerous climatological (blue) weather stations and also at the marine weather buoys (orange). Readings at automated synoptic stations are made every minute and at staffed stations 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 0900 UTC (Coordinated Universal Time). Data from synoptic and climatological stations are available in digital format from 1961. Surface air temperature is measured every hour on the marine weather buoys, the first of which was deployed in 2000.

'In Ireland the annual average surface air temperature has increased by approximately 0.8°C over the last 110 years.'

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[2] and the Phoenix Park. Figure 2.1 shows the mean annual observed temperatures (black dots) along with simple statistical fits to the data. The left-hand axis indicates anomalies (the difference between the mean annual temperature and the 1961 to 1990 normal or reference mean value) and the right-hand axis the mean annual temperatures for the period 1900 to 2011. Six of the top ten warmest years on record have occurred since 1990. The blue curve shows the 11-year moving averages. A simple linear trend line[3] (red) has been fitted to the annual anomaly values. This indicates that the annual average surface air temperature has increased by approximately 0.8°C over the last 110 years.

The temperature has varied over the period, with colder than normal episodes in the early part of the twentieth century and some cold years in the 1960s and '70s. Higher temperatures were recorded from the early 1930s to 1960 and from the late 1980s to the present. The overall trend is upwards and consistent with global patterns of change. It is interesting to note that although 2010 was a cold year by the standards of the previous two decades, it was not unprecedented in terms of the overall record, and indeed would have been typical of temperatures in the early part of the twentieth century.

An analysis of seasonal temperature difference, 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 20 years, although the anomalously cold winter of 2010 is evident.

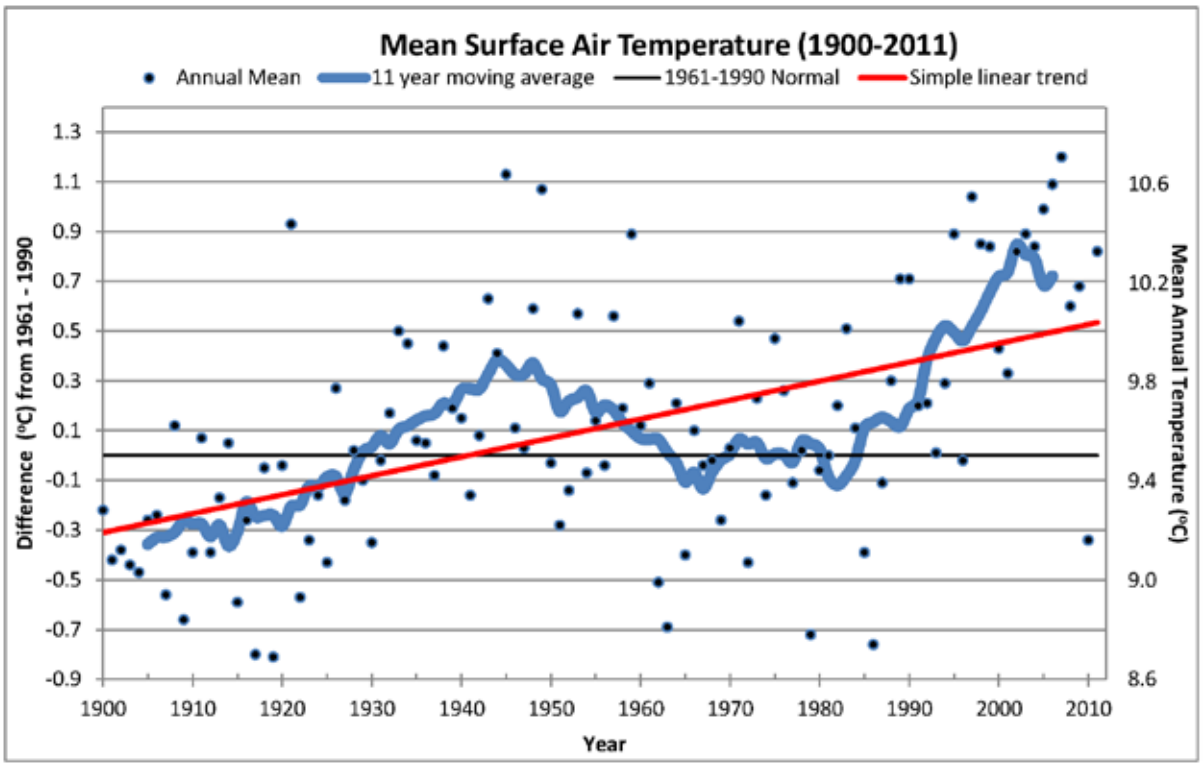


Figure 2.1. Annual mean surface air temperature (1900–2011).

2 The Station at Birr closed in October 2009; from late 2009 weighted data from the nearby TUSCON station at Gurteen were used.

3 A linear trend line is a basic but widely used statistical measure, however the length of the period used can change the trend.

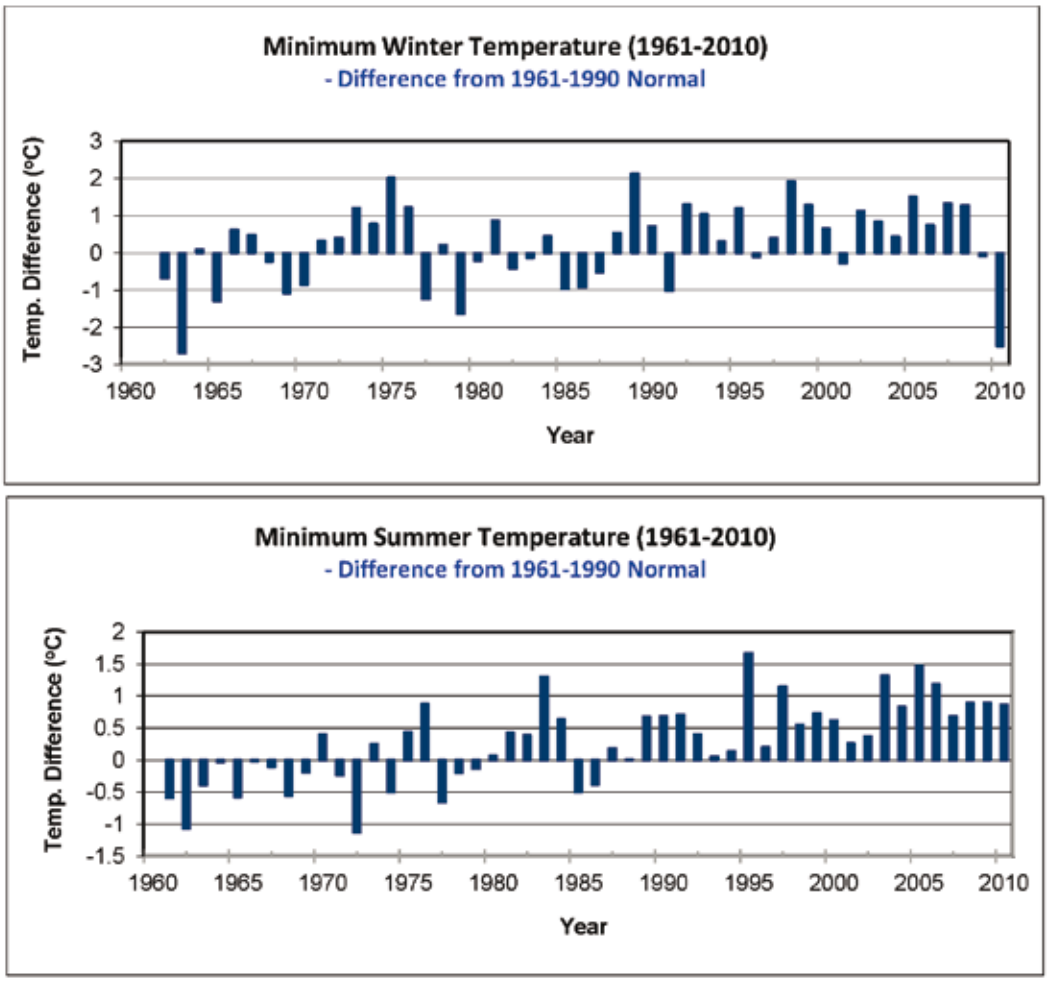


Figure 2.2. Winter (top) and summer (bottom) minimum surface temperature anomalies (1961–2010).

'The number of warm days has increased and the number of frost days has decreased over the last 50 years.'

Climate Change Indicators

The World Climate Research Programme has defined a range of climate change indicators to enable uniform comparison of these variables. In the case of temperature the indices include number of frost and ice days and days with temperatures above or below a certain threshold. Information on frost days, for example, is important to plan for road-gritting and heating requirements. Warm periods can have health implications, put pressure on water resources and increase tourism in certain areas. Trend maps have been calculated for the indicators from individual station records. Figure 2.3 shows that in the period 1961 to 2010 there has been an increase in the number of warm days (those with temperatures over 20°C), and a decrease in the number of frost days (those with temperatures below 0°C). This is in line with observations across Western Europe.

'Resources are required to produce homogenous temperature time-series and to collate and digitise paper records.'

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 Irish Marine Weather Buoy Network deployment is the result of collaboration between the Marine Institute, Met Éireann, the UK Met Office and the Irish Department of Transport. The Marine Institute maintains the

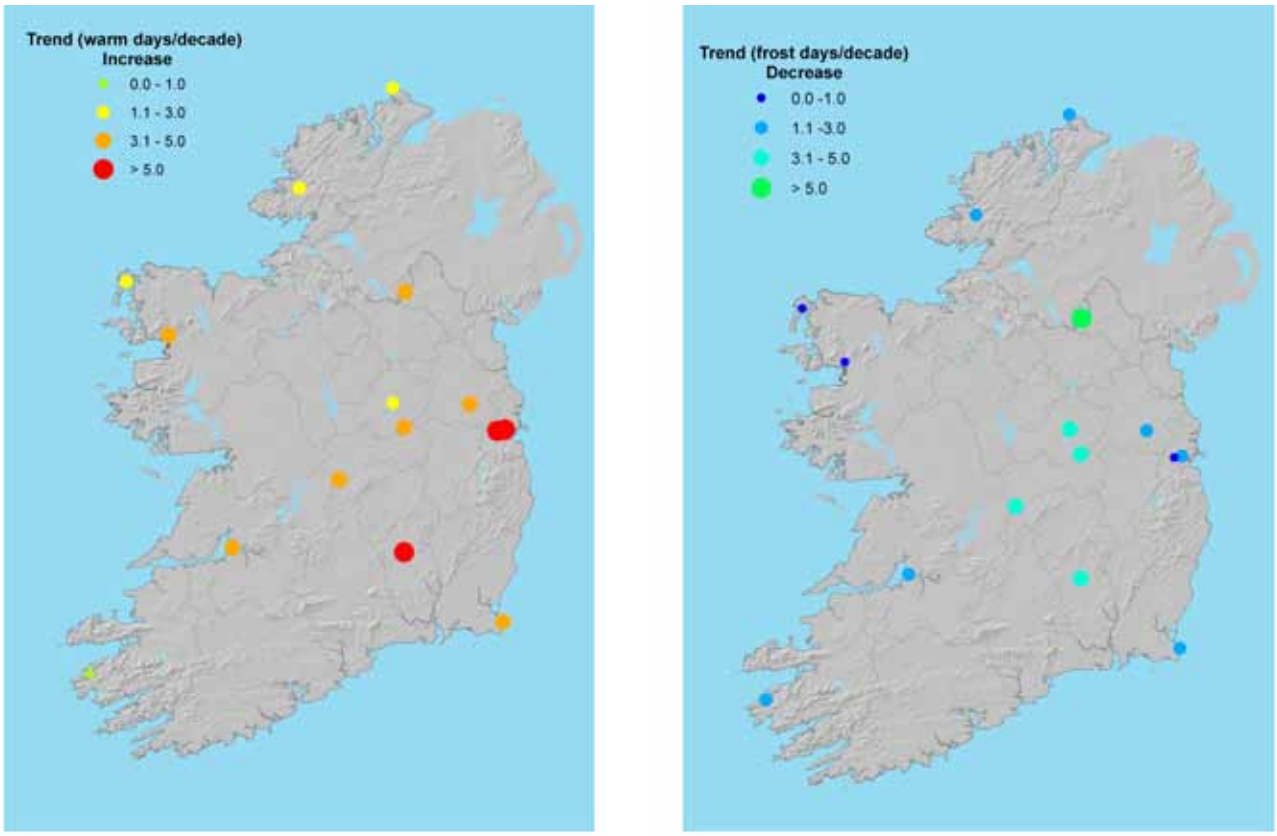


Figure 2.3. Trend in number of warm days per decade[4] (left) and number of frost days per decade[4] (right) (1961–2010).

Buoy Network hardware which is funded under a Memorandum of Understanding with the Irish Department of Transport 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 new building and tree growth in the vicinity of a station. Resources are required to produce homogenous temperature time-series and to collate and digitise paper records, including station metadata.

4 This represents the increase/decrease in number of days per year averaged over a decade.

Further Information and Data Sources

McElwain L. and Sweeney, J. (2007) *Key Meteorological Indicators of Climate Change in Ireland*. ERC Report 6, Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland, pp. 40: http://www.epa.ie/downloads/pubs/research/climate/name,23305,en.html

Information on air temperature in Ireland: http://www.met.ie/climate/temperature.asp

European project on climate data homogenisation methods: COST Action ES0601 Advances in homogenisation methods of climate series: http://www.homogenisation.org/v_02_15/

The World Climate Research Programme's expert team on climate change detection and indices: http://www.clivar.org/organization/etccdi/indices.php

Information on data availability: http://www.met.ie/climate/climate-data-information.asp

Long-term daily series of temperature and precipitation for a number of Irish stations are available from the European Climate Assessment & Dataset: http://eca.knmi.nl/

Information and observations from the Irish Marine Weather Buoy Network: http://www.met.ie/marine/marine_map.asp

Surface data from some Irish synoptic stations may be accessed at the US National Climate Data Centre: http://www7.ncdc.noaa.gov/CDO/cdo

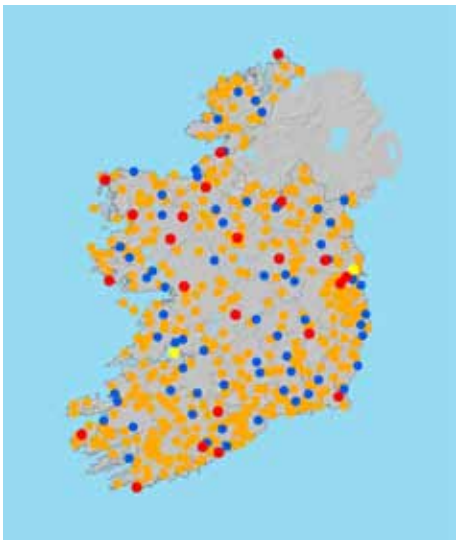
2.2 Rainfall

Séamus Walsh and Ned Dwyer

Rainfall (precipitation) plays a vital role in the water cycle and water balance and is essential for the maintenance of life. Because there can be a high variability in rainfall amounts over space and time, a dense network of ground measurement locations is required. Analysis indicates that globally rainfall amounts over land areas have increased by approximately 1% per decade over the twentieth century. In Europe the number of very wet days has increased over the last 50 years. The pattern, timing and intensity of such rainfall will have significant impacts on human society and the environment.



Photo: © Margaret O'Shea



Map 2.2. Location of rainfall observation stations.

Measurements

Rainfall has been measured in Ireland since the early nineteenth century with a peak of over 800 rainfall stations in the late 1950s. Currently rainfall is recorded at synoptic (red and yellow) and climatalogical (blue) weather stations; in addition, there is a wide network of voluntary rainfall observers (orange). At the 25 synoptic stations, readings are made every minute; at climate and rainfall stations a daily rainfall total is recorded. There are also a number of rain gauges in remote locations which are read once a month. Data from rainfall stations are available in digital format from January 1941. Rainfall radars at Dublin and Shannon airports (yellow) are used to infer up-to-the-minute precipitation extent and intensity across the country.

Precipitation can be inferred from measurements made by satellite sensors such as that on board the US Defense Meteorological Satellite Programme (DMSP) series. This is particularly important over oceans and in land areas with few ground-based sensors. An international collaborative programme will see the launch of a constellation of satellites from 2014 as part of the Global Precipitation Measurement (GPM) mission.

'There has been an increase in average annual national rainfall of approximately 60 mm or 5% in the period 1981 to 2010, compared to the 30-year period 1961 to 1990.'

Time-series and Trends

An analysis of annual rainfall totals, based on gridded data averaged over the area of Ireland shows a large year-to-year variability. The dark blue bars in Fig. 2.4 show the annual average rainfall totals (right axis) and the annual anomalies, or differences, from the 1961 to 1990 average (left axis). A moving average for periods of 11 years is also shown (red). Compared to an annual average rainfall of 1186 mm in the 30-year period 1961 to 1990 (bold black line), the period 1981 to 2010 (light blue dashed line) shows a 60 mm or 5% increase. In general, the larger increases in rainfall amount are recorded in the western half of the country.

An analysis of seasonal rainfall amounts over the same period shows small increases in all seasons over recent decades – however, the spatial distribution and intensity vary.

Climate Change Indicators

The World Climate Research Programme has defined a range of climate change indicators to enable uniform comparison of these variables. In the case of rainfall, these indices include number of wet days and heavy-rain days. Information on numbers of wet days can assist in water-supply management and knowledge of heavy-rain days can aid flood management. Trend maps have been calculated for the indicators for stations which have a near complete daily record for the 1961 to 2010 period. Figure 2.5 shows the trends for the number of wet days (days with rainfall greater than 0.2 mm) and the number of heavy rain days (days with rainfall greater than 10 mm).

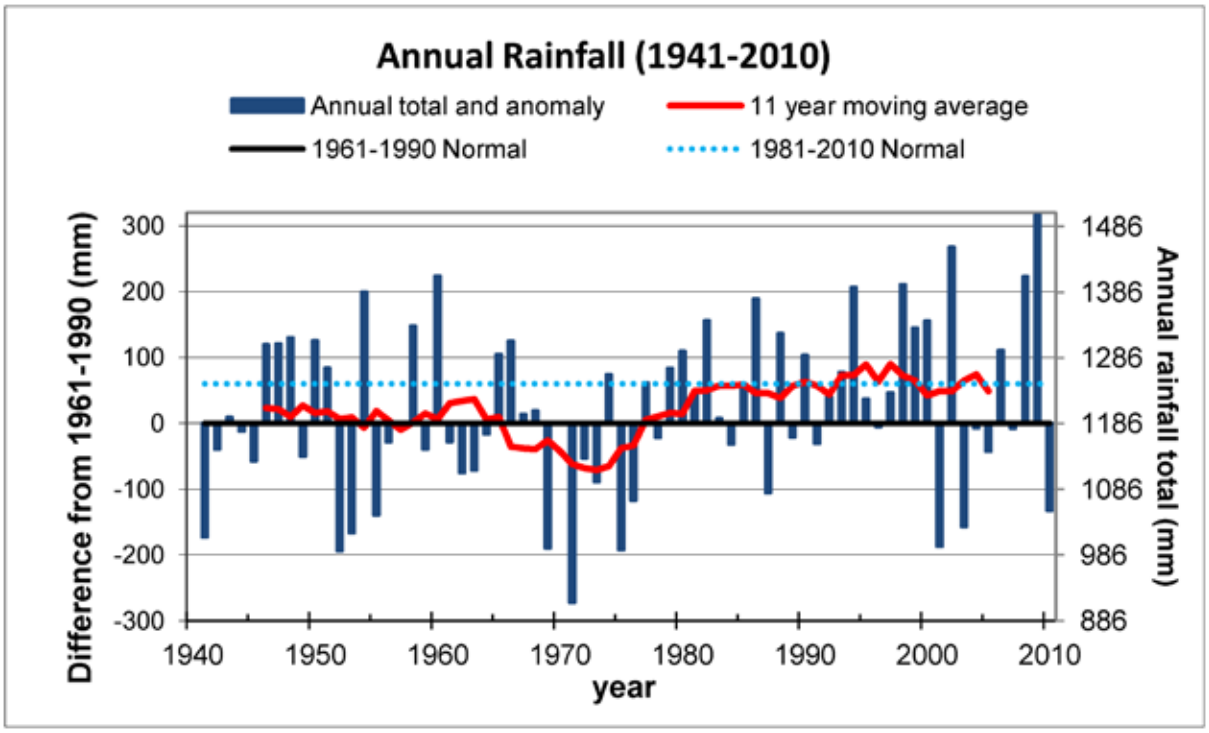


Figure 2.4. Annual rainfall totals and anomalies averaged over Ireland (1941–2010).

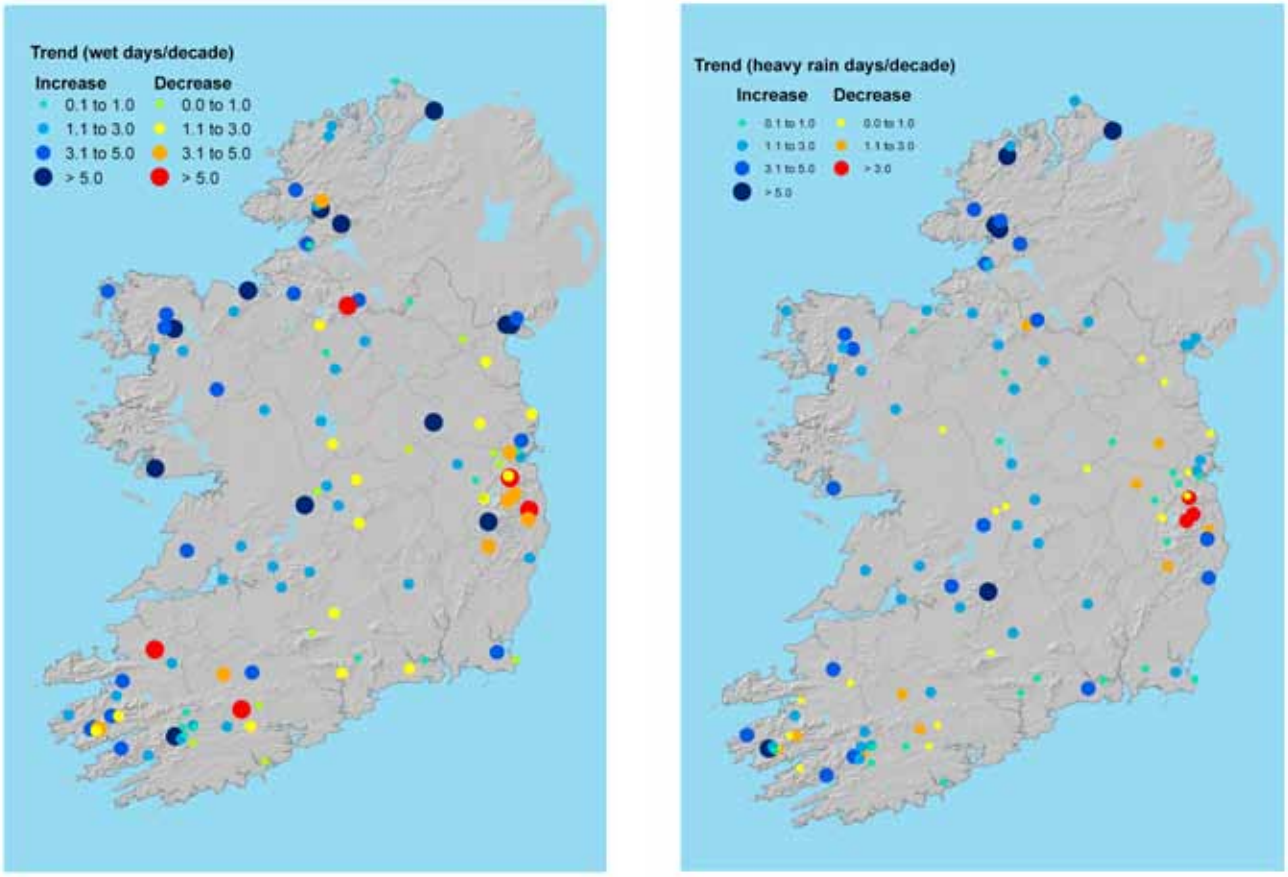


Figure 2.5. Trend in number of wet days per decade[5] (left) and number of heavy rain days per decade[5] (right) (1961–2010).

The trends for rainfall do not show the same level of confidence as those for temperature: they show greater regional variation and occasionally conflicting trends from stations that are geographically relatively close.

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

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. Further automation of the network is inevitable and will require financial investment as well as human resources. As with temperature, resources are required to produce homogenised datasets and to collate and digitise paper records, including station metadata.

5 This represents the increase/decrease in number of days per year averaged over a decade.

Further Information and Data Sources

McElwain, L. and Sweeney, J. (2007) *Key Meteorological Indicators of Climate Change in Ireland*. ERC Report 6, Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland, pp. 40: http://www.epa.ie/downloads/pubs/research/climate/name,23305,en.html

Information on rainfall in Ireland: http://www.met.ie/climate/rainfall.asp

The World Climate Research Programme's expert team on climate change detection and indices: http://www.clivar.org/organization/etccdi/indices.php

Information on the global precipitation measurement mission: http://gpm.gsfc.nasa.gov/

Near real time rainfall from radar: http://www.met.ie/latest/rainfall_radar.asp

Information on data availability: http://www.met.ie/climate/climate-data-information.asp

Long-term daily series of precipitation for a number of Irish stations are available from the European Climate Assessment & Dataset: http://eca.knmi.nl/

Surface data from some Irish synoptic stations may be accessed at the US National Climate Data Centre: http://www7.ncdc.noaa.gov/CDO/cdo

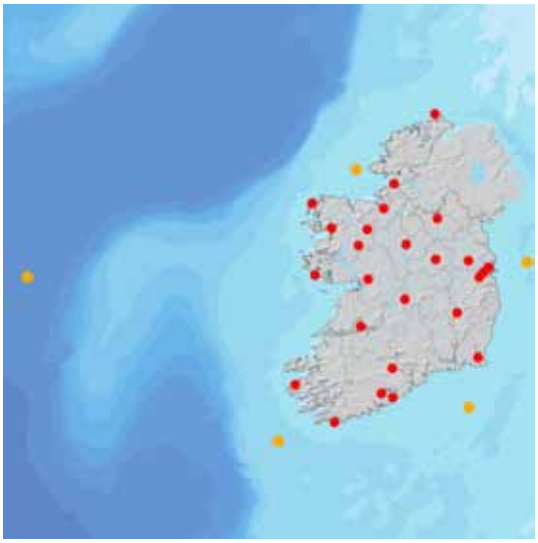
2.3 Atmospheric Pressure

Séamus Walsh and Ned Dwyer

Atmospheric pressure is an important parameter for monitoring the climate system, as the local and large-scale atmospheric circulation patterns are driven by differences in air pressure. Changes in global air pressure patterns can affect local and regional weather. An understanding of atmospheric pressure distributions and their variations is also fundamental to weather forecasting.



Photo: © Gerard Cunniam



Map 2.3. Location of atmospheric pressure observation stations.

Measurements

Atmospheric pressure is measured at the 25 synoptic weather stations operated by Met Éireann. Readings at automated stations (red) are made every minute. Pressure is also measured hourly at the marine weather buoys (orange), 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.'

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. The mean annual pressure series for Valentia Observatory Co. Kerry illustrated in Fig. 2.6 shows little variation; however, maximum and minimum series show greater variability, particularly the minimum values. These minima are due to mid-latitude cyclones or low-pressure systems which frequently pass over Ireland.

'Resources are required to digitise older pressure records and carry out comprehensive time-series analysis.'

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 if and how storm tracks are changing. The Irish Marine Weather Buoy Network deployment is the result of collaboration between the Marine Institute, Met Éireann, the UK Met Office and the Irish Department of Transport. The Marine Institute maintains the hardware which is funded under a Memorandum of Understanding with the Irish Department of Transport while Met Éireann monitors the quality of the observational data. Funding for this network is negotiated on an annual basis.

Further Information and Data Sources

Rohan, P.K. (1986) *The Climate of Ireland*, 2nd edn. Meteorological Service, Dublin.

Information on data availability: http://www.met.ie/climate/climate-data-information.asp

Information on air pressure in Ireland: http://www.met.ie/climate-ireland/pressure.asp

Information and observations from the Irish Marine Weather Buoy Network : http://www.met.ie/marine/marine_map.asp

Surface data from some Irish synoptic stations may be accessed at the US National Climate Data Centre: http://www7.ncdc.noaa.gov/CDO/cdo

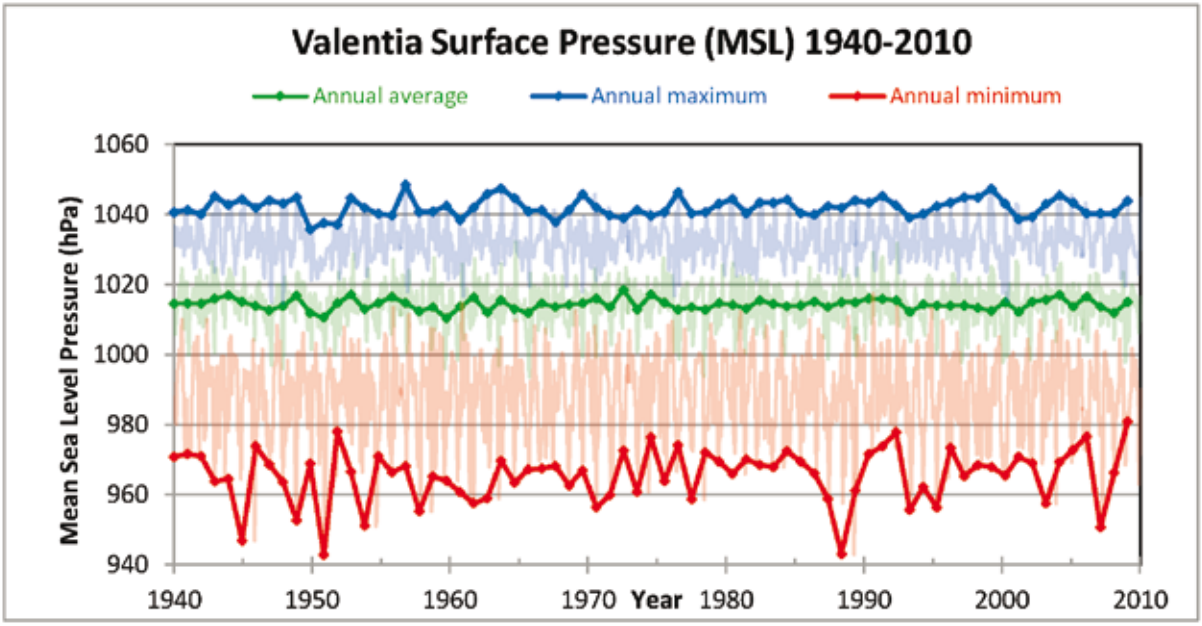


Figure 2.6. Monthly and annual minimum, average and maximum surface pressure at Valentia Observatory (1940–2010).

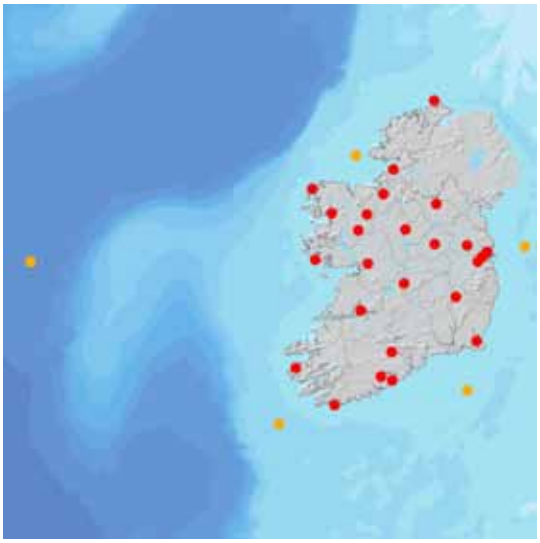
2.4 Surface Wind

Séamus Walsh and Ned Dwyer

Speed and direction are two of a range of measurements used to characterise wind and provide information on the strength and frequency of weather systems as they move across Ireland. Accurate information on wind is essential for planning in areas such as wind energy, forestry, and infrastructural development and it is also used in storm surge prediction. Globally, due to changes in measurement equipment, location and procedures at measurement masts, consistent wind speed data going back more than 15 to 20 years are not typically available – making it difficult to determine long-term trends.



Photo: © Paddy Tubbritt



Map 2.4. Location of surface wind-observation stations.

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

Measurements

Wind speed and direction are measured at the 25 synoptic weather stations (red) operated by Met Éireann and on the marine weather buoys (orange). Other parameters recorded include 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 in Ireland go back several decades at a number of 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.

Time-series and Trends

In Fig. 2.7 annual mean wind speeds (top) and the number of days per year with gale gusts (a wind speed of greater than 17.5 metres per second [m/s] or 34 knots [kt]) (bottom) are shown for Valentia Observatory Co. Kerry and Dublin Airport. Interannual variability is evident but no long-term trends can be determined with confidence. Weather patterns during the end of 2009 and 2010 brought very few storms and consequently lower than average wind speeds.

Figure 2.8 shows an average wind speed (colours) and direction (arrows) map for mid-February as derived from a 10-year (2000–2009) time-series of data from the QuickSCAT scatterometer.[6] This illustrates the prevailing westerlies with speeds in excess of 20 kt (10m/s) off the west coast of Ireland during that period.

'Resources are required to produce homogenous wind time-series and to collate and digitise paper records.'

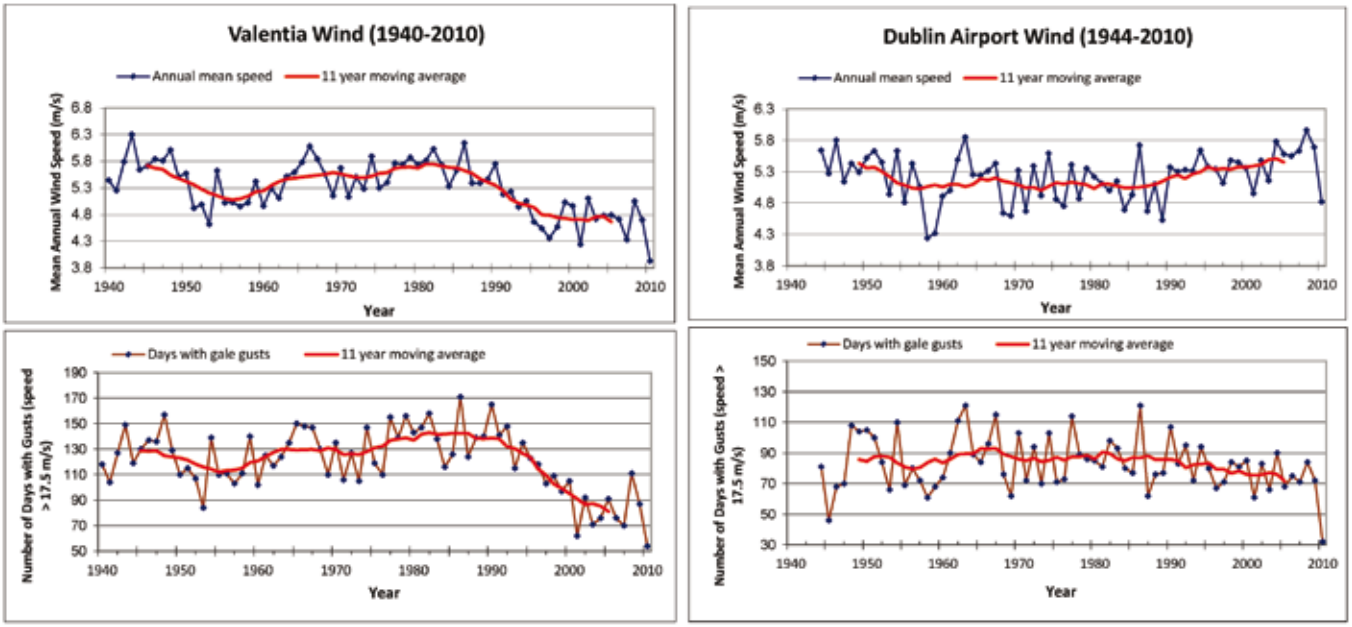


Figure 2.7. Annual mean wind speeds (top) and number of days per year with gale gusts (bottom) at Valentia Observatory (1940–2010) and Dublin Airport (1944–2010).

6 Data from the Climatology of Global Ocean Winds (COGOW) website (http://cioss.coas.oregonstate.edu/cogow), were provided courtesy of Oregon State University's Cooperative Institute for Oceanographic Satellite Studies (CIOSS).

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 Weather Buoy Network is the result of collaboration between the Marine Institute, Met Éireann, the UK Met Office and the Irish Department of Transport. The Marine Institute maintains the hardware which is funded under a Memorandum of Understanding with the Irish Department of Transport while Met Éireann monitors the quality of the observational data. Funding for this network is negotiated on an annual basis. Difficulties can arise with wind time-series because of inhomogeneities due to changes in instrumentation, and changes in station exposure due to new building and tree growth in the vicinity of a station. Comprehensive analysis of wind data should be carried out. Resources are required to produce homogenous time-series and to collate and digitise paper records, including station metadata.

Further Information and Data Sources

Risien, C. M. and Chelton, D.B. (2006) A satellite-derived climatology of global ocean winds, *Remote Sensing of Environment,* Vol. 105, No. 3, pp. 221–36.

Information on wind speed and direction in Ireland: http://www.met.ie/climate/wind.asp

Thomas, P., Cox, S. and Tindal, A. (2009) *Long-Term Wind Speed Trends In Northwestern Europe,* Garrad Hassan and Partners Ltd, Bristol, UK: http://www.gl-garradhassan.com/en/index.php

European project on climate data-homogenisation methods: COST Action ES0601 Advances in homogenisation methods of climate series: http://www.homogenisation.org/v_02_15/

Information on ASCAT, the scatterometer on board ESA's *MetOp* satellite: http://www.esa.int/esaLP/SEMBWEG23IE_LPmetop_0.html

Information on data availability: http://www.met.ie/climate/climate-data-information.asp

Surface data from some Irish synoptic stations may be accessed at the US National Climate Data Centre: http://www7.ncdc.noaa.gov/CDO/cdo

Information and observations from the Irish Marine Weather Buoy Network : http://www.met.ie/marine/marine_map.asp

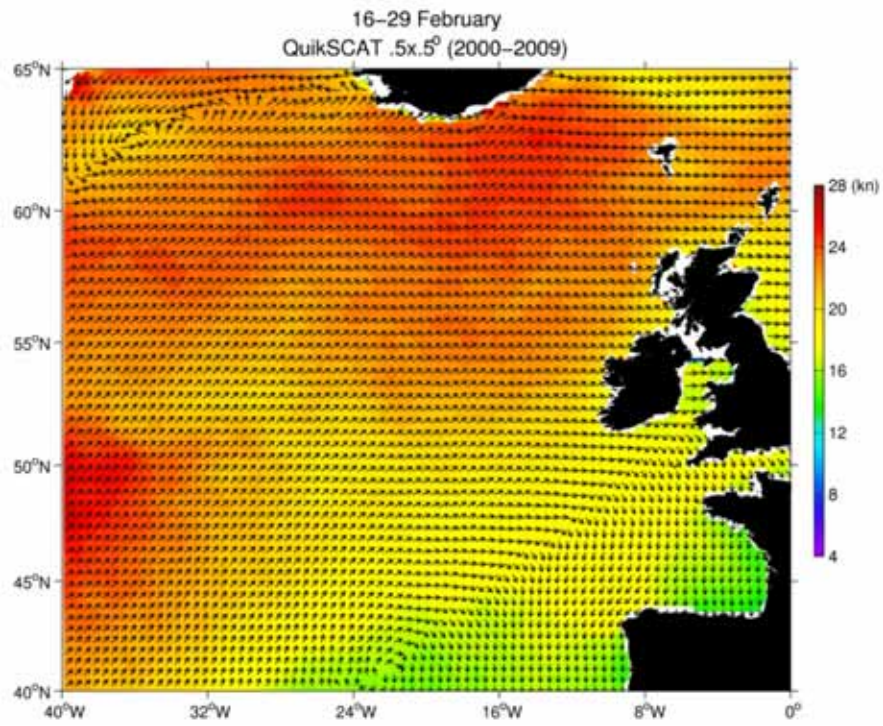


Figure 2.8. Example of a wind-speed and direction map derived from satellite-based scatterometer observations.

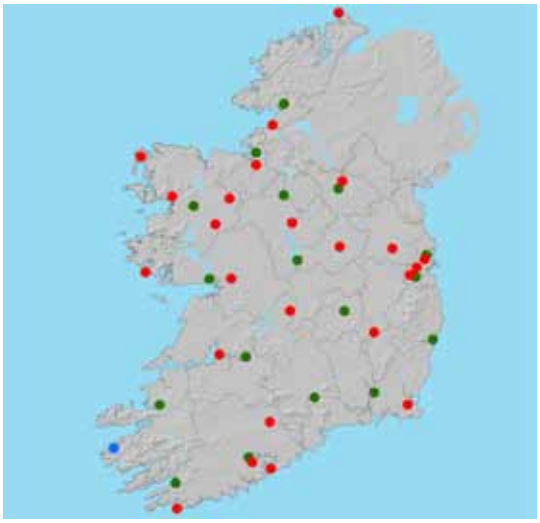
2.5 Water Vapour

Ned Dwyer and Séamus Walsh

Water vapour exists at all levels in the atmosphere. Near the surface it affects cloud formation and development and hence is a key driver of precipitation. It is the dominant greenhouse gas accounting for almost 60% of the natural greenhouse effect. Globally, higher air temperatures and warmer oceans have led to an increase in atmospheric water vapour which may be linked with more intense precipitation events and enhanced warming. The amount of water vapour in the atmosphere is highly variable in space and time. Knowledge of this variability in the upper atmosphere is still quite limited.



Photo: © Valerie Robus



Map 2.5. Location of humidity and water vapour observation stations.

'Water vapour is the dominant greenhouse gas, accounting for almost 60% of the natural greenhouse effect. Globally, higher air temperatures and warmer oceans have led to an increase in atmospheric water vapour.'

Measurements

Surface level water vapour and water vapour pressure are derived from humidity measurements taken at the 25 synoptic weather stations (red and blue) operated by Met Éireann. Since 1943, profiles of upper air humidity have been measured at Valentia Observatory in Co.

Kerry (blue) using radiosondes, which are released twice a day. Since 2009 column-integrated water vapour quantities are retrieved from a network of Global Positioning System (GPS) receivers (green) on an hourly basis.

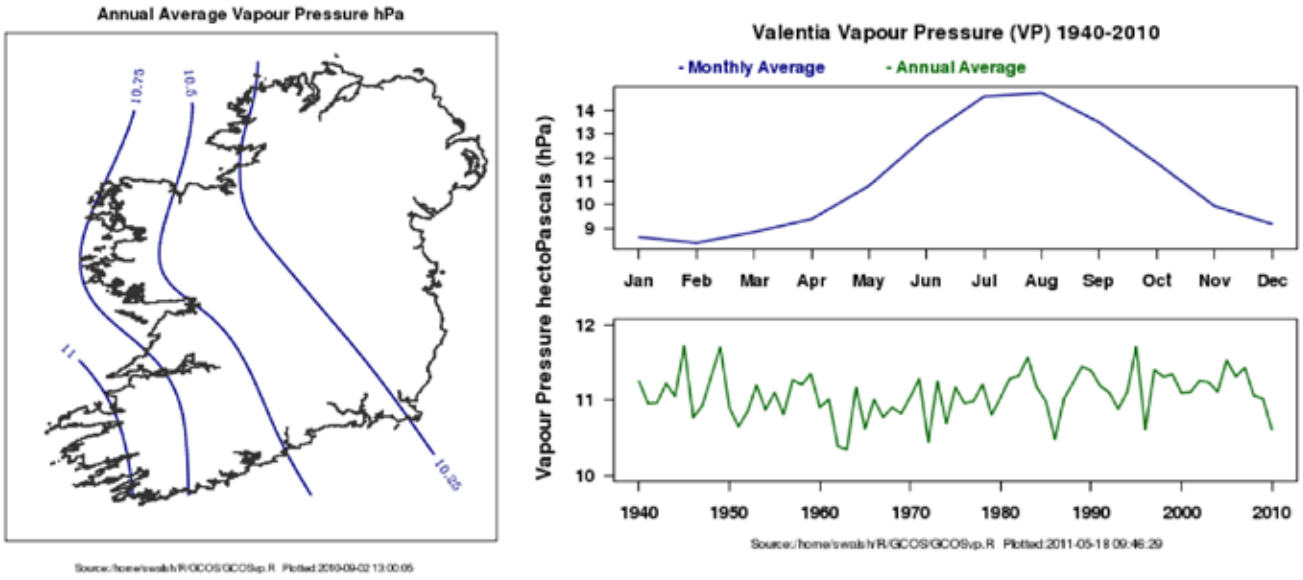
A number of sensors on different satellites measure water vapour. These include the SEVIRI instrument on the European Meteosat system.

> 'Insufficient analysis has been carried out to identify any trend in water vapour measurements over Ireland.'

Time-series and Trends

The water vapour pressure is related directly to the number of water vapour molecules in the air. The capacity of the atmosphere to hold water vapour increases with increasing temperature. Figure 2.9 (a) shows the annual average vapour pressure across the country derived from long-term synoptic weather station measurements, and Fig. 2.9 (b) how the monthly average vapour pressure at Valentia Observatory reaches a maximum in summer whilst the annual average vapour pressure can vary substantially from year to year. Due to the very limited analysis of these data to date, it is not possible to identify any trend in water vapour measurements over Ireland.

Analysis of the thermal infrared information collected by the *Meteosat-8* satellite is used to generate daily estimates of total water vapour content in the atmospheric column. In Fig. 2.10, which is an example product from 10 July 2005, the scale is in millimetres and represents how much rain would fall over each small area if the water vapour condensed into liquid.



(a) **(b)**

Figure 2.9. Annual average water vapour pressure across Ireland (a) and monthly and annual average water vapour pressure at Valentia Observatory (b) (1940–2010).

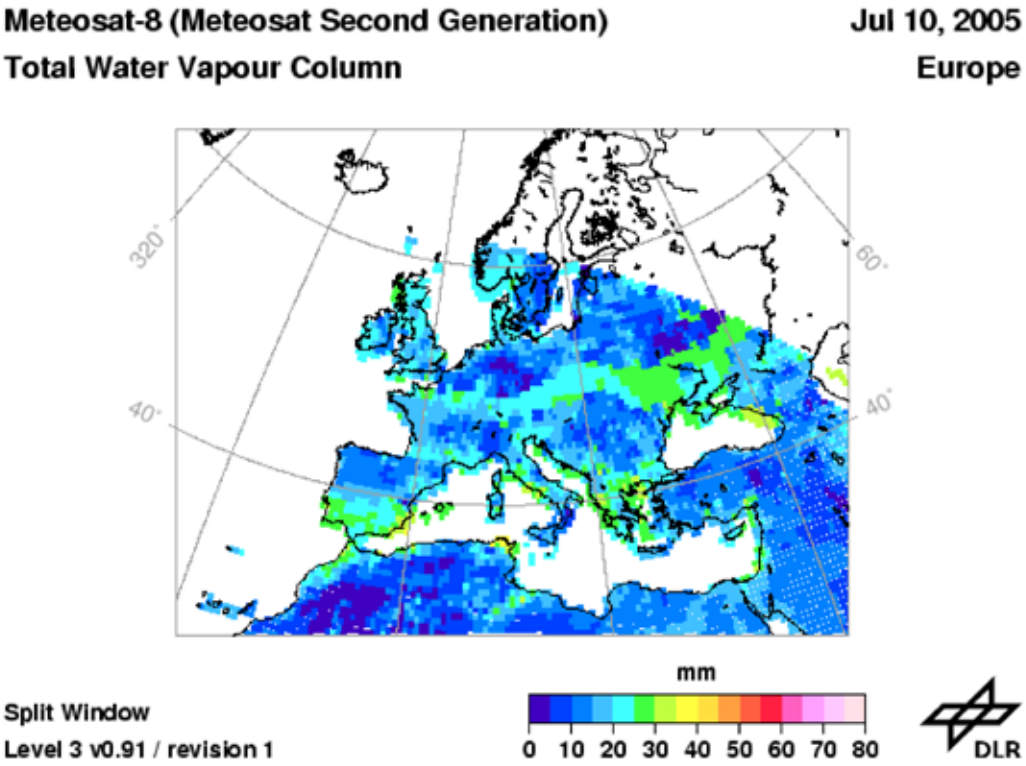


Figure 2.10. Example of total water vapour column content over Europe derived from *Meteosat*-8 satellite observations, 10 July 2005.

Maintaining the Observations

Ground and radiosonde measurements are carried out on an operational basis by Met Éireann. GPS receivers at Mace Head and Valentia Observatory have been operated as part of an EPA-funded research project; the remaining GPS receivers are operated and maintained by Ordnance Survey Ireland. Resources are required to digitise paper records and carry out systematic analysis of the long-term historical ground and upper air water vapour records.

Further Information and Data Sources

Schroedter-Homscheidt, M., Drews, A. and Heise, S. (2008) Total water vapor column retrieval from MSG-SEVIRI split window measurements exploiting the daily cycle of land surface temperatures, *Remote Sensing of Environment*, Vol. 112, pp. 249–58, doi: 10.1016/j.rse.2007.05.006

Hanafin, J.A., Jennings, S.G., O'Dowd, C.D. and McGrath, R. (in press) *Retrieval and analysis of atmospheric water vapour from GPS receivers*, EPA.

Information on radiosonde measurements at Valentia Observatory: http://www.met.ie/about/valentiaobservatory/radiosonde.asp

Information on data availability: http://www.met.ie/climate/climate-data-information.asp

Surface data from some Irish synoptic stations may be accessed at the US National Climate Data Centre: http://www7.ncdc.noaa.gov/CDO/cdo Note that humidity related measurements from Ireland have not been quality controlled.

European programme providing water vapour measurements derived from GPS: http://egvap.dmi.dk/

Water vapour column retrieval from the SEVERI instrument: http://wdc.dlr.de/data_products/TRACEGASES/seviri_twc/daily_twc_seviri.php

The atmospheric infrared sounder used for water vapour retrieval: http://airs.jpl.nasa.gov/

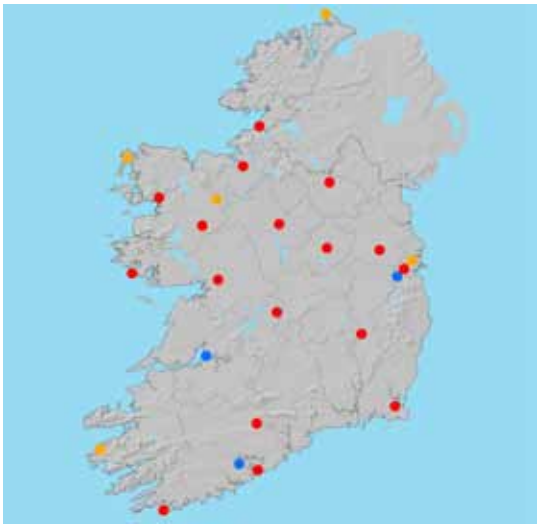
2.6 Surface Radiation Budget

Ned Dwyer, Kevin Black and Séamus Walsh

Energy reaches the Earth's surface directly from the sun 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. 'Net incoming radiation' is the quantity of radiation remaining at the Earth's surface. This includes visible light as well as infrared and ultraviolet radiation. Long-term changes in the amount of solar radiation reaching the Earth's surface can have a significant influence on climate, hydrological cycles and crop productivity.



Photo: © Ned Dwyer



Map 2.6. Location of sunshine duration and solar radiation observation stations.

Measurements

Historically, sunshine duration was the observed solar variable; more recently, there has been a shift to solar radiation (incoming radiation), also known as global radiation, which represents a more comprehensive measurement of solar energy. Both solar radiation and sunshine duration are observed at five Met Éireann synoptic stations (orange). Solar radiation is measured at an additional 17 automatic weather stations (red). Sunshine duration only is measured at three other staffed synoptic stations (blue). Further upgrades to the sunshine and radiation observation network are in progress.

'Annual average solar radiation declined approximately 19% over the period 1955 to 1984, with stabilisation and some evidence of an increase over subsequent years.'

Time-series and Trends

The most recent analysis of solar radiation data from seven synoptic stations has shown an approximately 19% drop in the annual average value over the period 1955 to 1984 after which it levelled off, with some evidence of an increase in more recent years. This is illustrated for Valentia Observatory in Fig. 2.11. The measurements from Valentia suggest that there was a greater decline over the summer months compared to winter; however, this is not consistent across all the stations. The stabilisation in and increase of solar radiation may, in part, be due to alterations in atmospheric optical properties. It may also be due to cleaner air caused by reductions in atmospheric pollutants, such as black particles, sulphate particles and/or sulphate cloud-forming nuclei, the presence of which lead to the sun's energy being reflected back into space before reaching the Earth's surface.

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

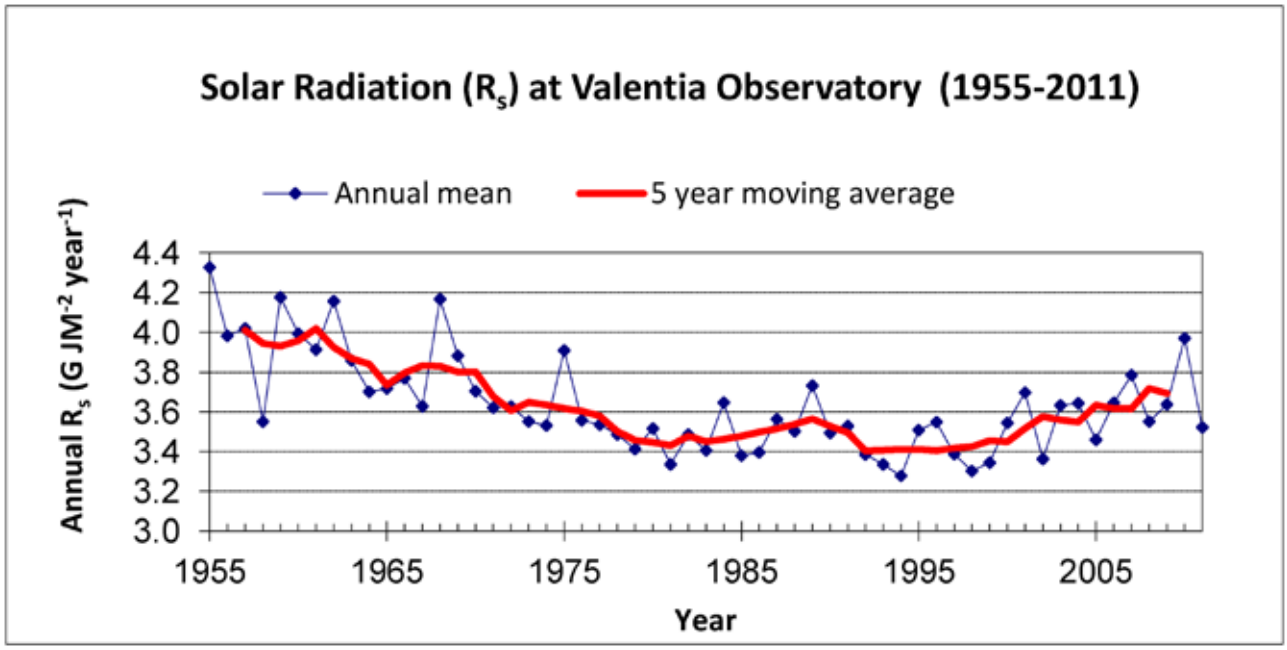


Figure 2.11. Annual solar radiation at Valentia Observatory (1955–2011). Units are in per metre squared GigaJoules (G JM^{-2}) per year.

Maintaining the Observations

A comprehensive suite of solar and terrestrial radiation measurement instrumentation is maintained by Met Éireann at Valentia Observatory. Solar radiation measurement instrumentation has been installed at all of the automatic TUCSON (The Unified Climate and Synoptic Observation Network) locations: therefore, the ongoing collection of data is ensured. Regular analysis of national trends in the net surface radiation balance needs to be carried out given its role in plant growth, the hydrological cycle and the larger climate system. The National University of Ireland Galway is carrying out a research project at the Mace Head Atmospheric Research Station, Carna, Co. Galway investigating the relationship between atmospheric constituents and solar radiation.

Further Information and Data Sources

Black, K., Davis, P., Lynch, P., Jones, M., McGettigan, M. and Osborne, B. (2006) Long-term trends in solar irradiance in Ireland and their potential effects on gross primary productivity, *Agricultural and Forest Meteorology,* Vol. 141, pp. 118–32.

Stanhill, G. (1998) Long-term trends in, and spatial variation of, solar irradiances in Ireland, *International Journal of Climatology*, Vol. 18, pp. 1030–50.

Information on sunshine and solar radiation from Met Éireann: http://www.met.ie/climate-ireland/sunshine.asp

Information on solar and terrestrial radiation observations at Valentia Observatory: http://www.met.ie/about/valentiaobservatory/solarradiation.asp

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

Baseline Surface Radiation Network: http://www.gewex.org/bsrn.html

2.7 Upper Air Temperature and Wind

Séamus Walsh and Ned Dwyer

Knowledge of the vertical profiles of temperature and wind in the atmosphere is vital for a better understanding of the weather and climate system. Globally, cooling of the upper atmosphere ('stratosphere') and warming of the lower atmosphere ('troposphere') has been observed over recent decades. This is one of the tell-tale indicators of greenhouse gas-enhanced climate change. Globally, measurements of upper air parameters are sparse. Because of its key location in the northeast Atlantic, Ireland makes a significant contribution to such measurements.



Photo: © Keith Lambkin



Map 2.7. Location of upper air observation station.

Measurements

Upper-air measurements have been taken by Met Éireann at Valentia Observatory, Co. Kerry since 1943 by means of a radiosonde – a helium-filled balloon with instruments attached. The balloon is released twice a day 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 temperature, humidity, wind speed and direction and pressure with a vertical resolution of up to 10 m. This enables the production of tephigrams or 'snapshots' of the vertical structure of the atmosphere.

'A slight decrease in upper air temperature has been observed at Valentia Observatory in recent decades; however, the time-series is too short to determine a long-term trend.'

Since the late 1970s satellite-borne microwave sounders have made measurements from which temperature has been derived at different levels in the atmosphere. Although they provide excellent spatial coverage, compared with the sparse coverage of radiosondes, there have been difficulties in integrating measurements from different sensors and ensuring their accuracy and comparability over time. Wind speed and direction can be derived by tracking cloud motion from successive satellite observations.

Time-series and Trends

Figure 2.12 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 over recent decades. This is consistent with global observations. Interannual variability is apparent in the upper air wind speed; however, as with the upper air temperature the time-series is too short to determine a long-term trend.

'Staff and resources need to be maintained at Valentia Observatory to ensure the continuation of upper air measurements.'

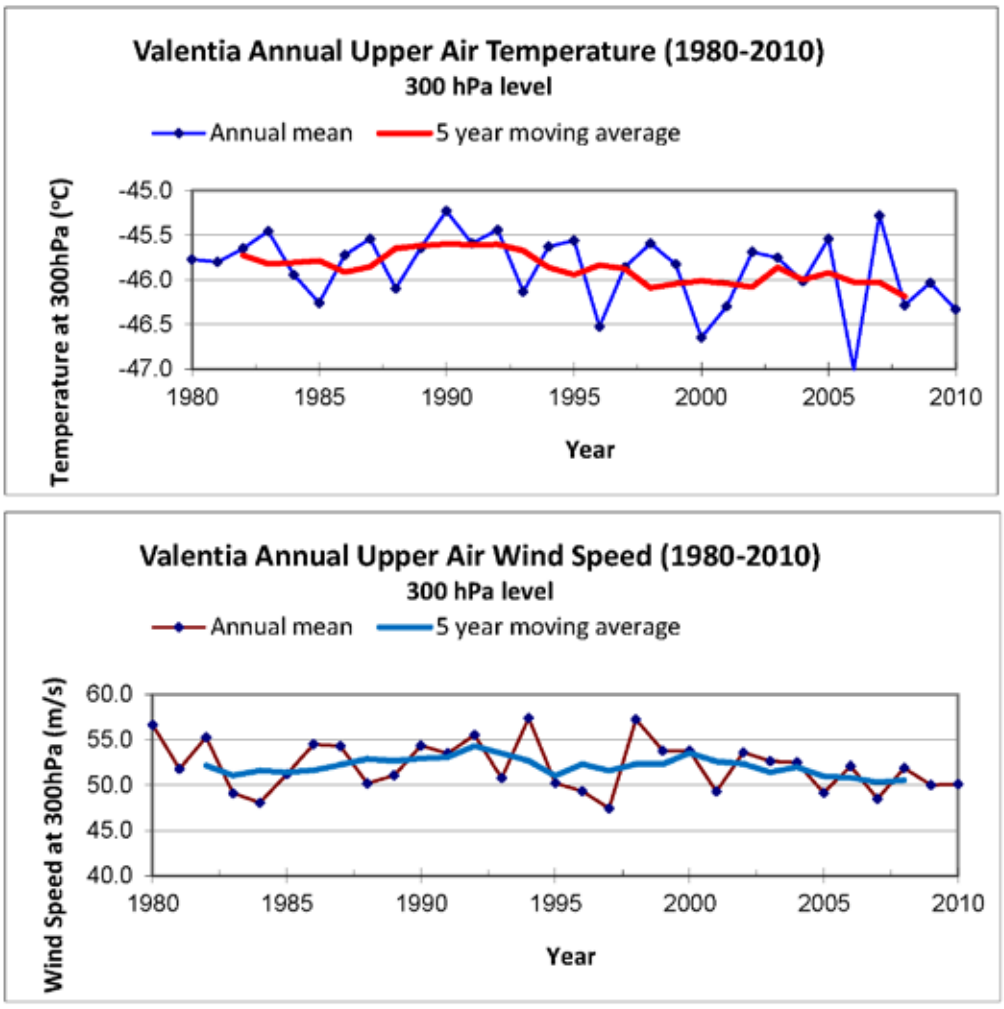


Figure 2.12. Example of annual mean temperature (top) and annual mean wind speed (bottom) at Valentia Observatory from one level in the atmosphere (1980–2010).

Maintaining the Observations

Staff and resources need to be maintained at Valentia Observatory to ensure the continuation of upper-air measurements. Resources are required to retrieve and digitise historical paper upper-air measurements. An advanced technology wind-profile sensor will be part of the European Space Agency's (ESA) Atmospheric Dynamics Mission-Aeolus due for launch in 2014. This will significantly increase the number and density of observations, in particular over ocean areas.

Further Information and Data Sources

Information on radiosonde measurements at Valentia Observatory: http://www.met.ie/about/valentiaobservatory/radiosonde.asp

Information on data availability from Met Éireann: http://www.met.ie/climate/climate-data-information.asp

Data, including those from Valentia are available from the Integrated Global Radiosonde Archive: http://www.ncdc.noaa.gov/oa/climate/igra/index.php

Information on the advanced microwave sounding unit on the European MetOp satellite: http://www.eumetsat.int/Home/Main/Satellites/Metop/Instruments/SP_2010053152718207?l=en

Information on ESA's ADM-Aeolus mission: http://www.esa.int/esaLP/LPadmaeolus.html

Story Board 1: Met Éireann – Observing Climate for more than Seventy-five Years

Ned Dwyer and Séamus Walsh



Figure SB1.1. Met Éireann's headquarters located in Glasnevin, Dublin.

Some of the first operational meteorology observations in Ireland were made on Valentia Island in 1860. The observatory on the island was part of a network established by the Royal Navy around Britain and Ireland to improve safety at sea. In subsequent years the British Meteorological Office expanded the network of weather stations around Ireland and operated them until 1936, when the Irish Meteorological Service was established.

The late 1940s and 1950s saw a rapid expansion in the observation network, with the setting-up of a balanced nationwide network of stations. Met Éireann has continued to adopt new technologies over the years, moving from mechanical to digital recording and, more recently, automating its synoptic network to the new generation of stations, known as TUCSON.

The observation network is made up of three types of station (Fig. SB1.2). The most advanced are the 25 *synoptic* or real-time automatic weather stations (red & yellow) many of which make observations of key variables every minute, including temperature, rainfall amount, wind speed and direction. *Climatological* stations (blue), of which there are over 70, make less frequent observations of temperature and rainfall. There are more than 500 *rainfall* stations (orange) most of which make one measurement daily of accumulated rainfall amount. The synoptic weather stations at Valentia Observatory and Malin Head are part of the World Meteorological Organisation's Global Surface Network (GSN) and have been submitting data to world data centres since October 1939 and May 1955 respectively. Observations from rainfall radars in operation at Dublin and Shannon airports (yellow) are used to infer up-to-the-minute precipitation extent and intensity across the country.

In addition to these surface meteorological measurements, surface ozone and a range of upper air measurements are made at Valentia Observatory.



Figure SB1.2. Met Eireann's observation network.



Photo: © Kilian Harford

Figure SB1.3. A typical TUSCON weather station.

Although the network is extensive, an assessment of its adequacy should be carried out and recommendations made for any changes necessary in order to meet current and future climate observation needs. Moreover, protection of existing observation sites from encroachment by new developments is vital for the integrity of the network. The longer a record from a particular site, the more valuable it is in terms of monitoring and quantifying climate change. The service also requires additional resources to collate and digitise historical paper records and to carry out more in-depth analysis of the wealth of observational data collected over the last 75 years.

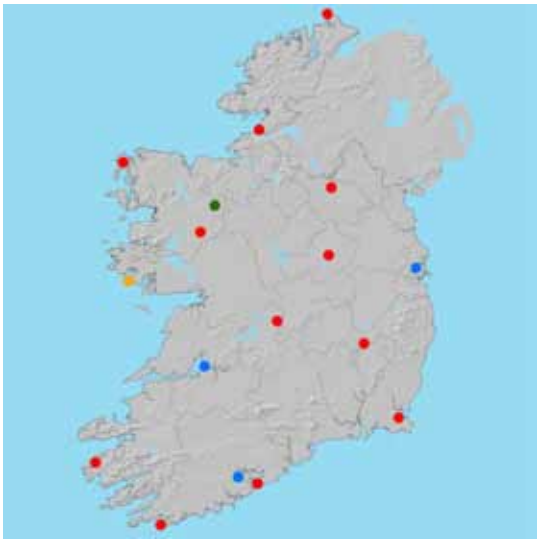
2.8 Cloud Properties

Ned Dwyer, Colin O'Dowd and Séamus Walsh

Clouds play an important role in maintaining the radiation balance and hydrological cycle of the Earth. 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. The combination of liquid water content, droplet size and number influences the amount of incoming solar radiation and outgoing infrared radiation reflected and absorbed. Significant uncertainties remain in the details of the relationship between aerosols, cloud properties and solar radiation.



Photo: © Marcus Austin



Map 2.8. Location of cloud-observation stations.

'Significant uncertainties remain in the details of the relationship between aerosols, cloud properties and solar radiation.'

Measurements

A range of cloud properties are observed at the Mace Head Atmospheric Research Station, Carna, Co. Galway (orange). These include vertical extent (cloud base and cloud top), cloud particle phase (liquid, ice), degree of adiabaticity,[7] liquid water path and liquid water content, microphysical

7 An adiabatic process is one in which no heat is gained or lost by the system.

properties such as effective radius, 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 (blue and green). Observations of cloud height and estimated total cloud cover are made at a number of automated synoptic stations (red, orange and green).

Satellite sensors are used to collect information on cloud coverage, cloud top temperatures and a number of microphysical properties. These represent one of the longest and most robust time-series of satellite observations for any of the ECVs.

Time-series and Trends

Figure 2.13 represents an example of the microphysical properties observed at Mace Head. The coloured lines show the varying number of cloud droplets in a cubic centimetre of water (Cloud Droplet Number Concentration, right colour bar), in clean air. These measurements were made over a five-hour period and show that the clouds extended from approximately 0.6 km to 1.02 km above the ground (left axis). The solid black line is the height averaged concentration (right axis) while the red line is a 7.5-minute running mean of the height average.

Figure 2.14 shows the mean global cloud fraction or cover for April 2010 determined using satellite data from the MODIS sensor on board the *Terra* satellite.[8] An analysis of such satellite-derived products for Ireland would be useful to determine if there is any trend or pattern in cloud cover.

'The Mace Head cloud observation programmes lack long-term and sustainable operational support.'

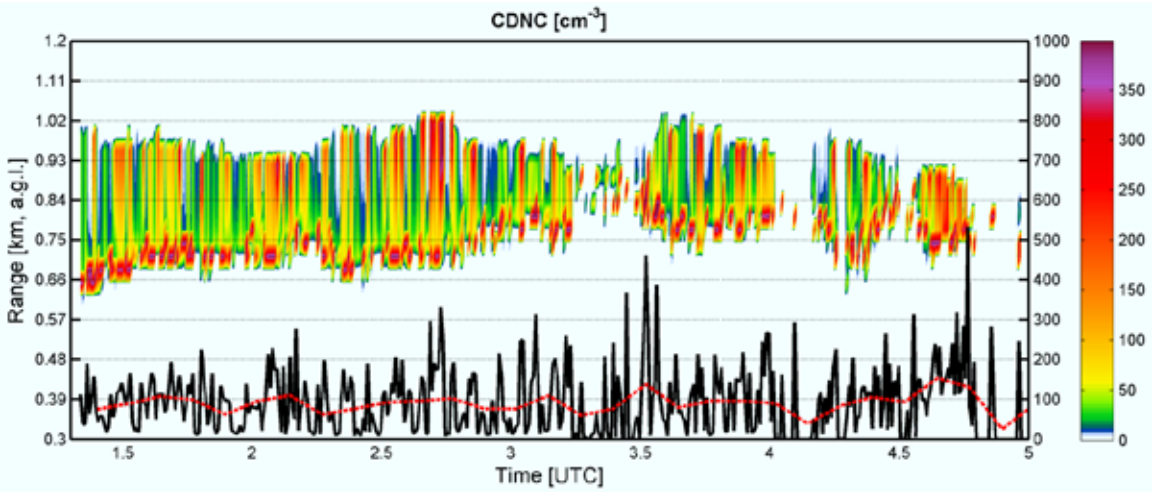


Figure 2.13. Example of one of the microphysical properties (Cloud Droplet Number Concentration) observed at Mace Head research station.

8 Analyses and visualisations used in this section of the report were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

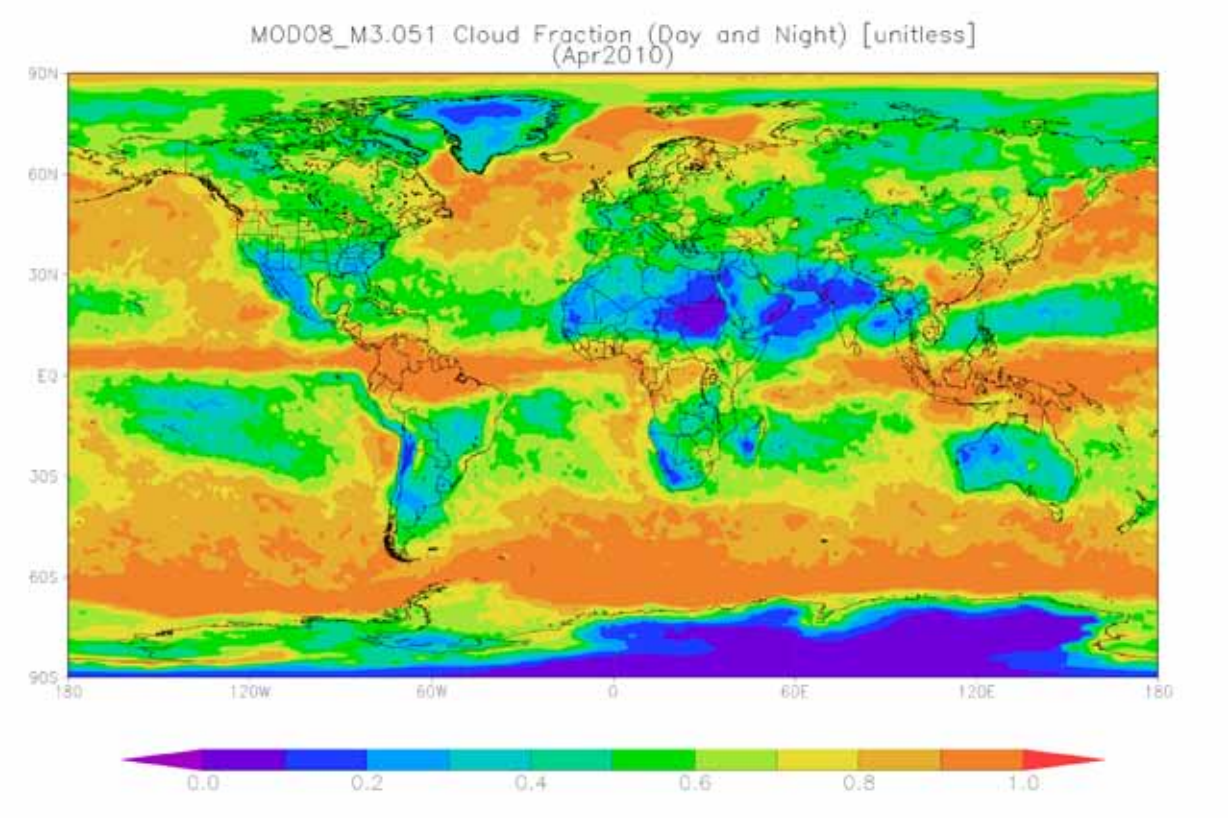


Figure 2.14. Example of a satellite-derived global cloud cover product, April 2010.

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. The Mace Head cloud observation programmes are funded on an ad hoc basis from a range of projects by the Centre for Climate and Air Pollution Studies [C-CAPS], School of Physics at the National University of Ireland Galway, but lack long-term and sustainable operational support. There is a need for ongoing research on the link between aerosols and cloud properties.

Further Information and Data Sources

Norris, J.R. and Slingo, A. (2009) Trends in observed cloudiness and Earth's radiation budget in Strüngmann Forum Report, *Clouds in the Perturbed Climate System: Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation*. Heintzenberg, J. and Charlson, R.J. (eds.) MIT Press.

Information on data availability from Met Éireann: http://www.met.ie/climate/climate-data-information.asp

Information on the Mace Head Facility: http://www.macehead.org

Information and data from ESA's Climate Change Initiative cloud project: http://www.esa-cloud-cci.org/

The World Climate Research Programme's International Satellite Cloud Climatology Project: http://isccp.giss.nasa.gov

Data via Giovanni from the Goddard Earth Sciences and Information Services Center: http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html

2.9 Carbon Dioxide

Ned Dwyer and Michel Ramonet

Carbon dioxide (CO_2) is the most important human-emitted greenhouse gas in the atmosphere. Globally, the biggest sources of additional CO_2 emissions are fossil-fuel burning, deforestation, vegetation fires and land-use changes. In Ireland major sources include fossil-fuel burning caused by energy generation and road transport. Before the Industrial Revolution the concentration of CO_2 was approximately 270 ppm (parts per million). Since the late 1700s, this has increased by about 38% and today stands above 390 ppm. At the UN Climate Change talks in Durban in 2011 it was recognised that there is an urgent need to limit the rise in the Earth's average temperature to less than 2°C above the pre-industrial temperature. This will require a cut of 50% in emissions before 2050 compared to 1990.



Photo: © Catherine O'Callaghan



Map 2.9. Location of carbon dioxide observation stations.

'Current CO_2 concentrations of more than 390 ppm are higher than at any time over at least the last 400 thousand years.'

Measurements

Atmospheric CO_2 concentrations have been measured at the Mace Head Atmospheric Research Station, Carna, Co. Galway (red) since 1992. High-precision measurements are made on an hourly basis. This site is of global importance as the measurements are representative of the underlying concentration of atmospheric CO_2 in the northeast Atlantic region. CO_2

concentrations are also measured at Carnsore Point, Co. Wexford and Malin Head, Co. Donegal (blue) since 2009.

The amount of CO_2 in the atmosphere can be inferred from satellite observations, such as those from the Japanese GOSAT and previously from the European ENVISAT. Ground-based measurements are vital for the validation of these satellite observations.

Time-series and Trends

CO_2 concentrations in the atmosphere are currently higher than at any time over at least the last 400 thousand years. Before the industrial era atmospheric CO_2 concentration was approximately 270 ppm. Now it stands at above 390 ppm due to additional emissions from human activities.

Measurements in Hawaii since 1958 (illustrated in Fig. 2.15) show steadily increasing concentrations of atmospheric CO_2. This is replicated since measurements began in 1992 at Mace Head.[9] The signal at Mace Head is more variable due to 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.

Global maps of the average atmospheric CO_2 concentration for August 2009 and February 2010 (Fig. 2.16) illustrate seasonal variability. Concentrations are lower in the Northern hemisphere in summer due to absorption by growing vegetation. CO_2 is released during the autumn and winter when part of the vegetation dies and decays. This seasonal variability is also evident in the *in situ* observations from Mace

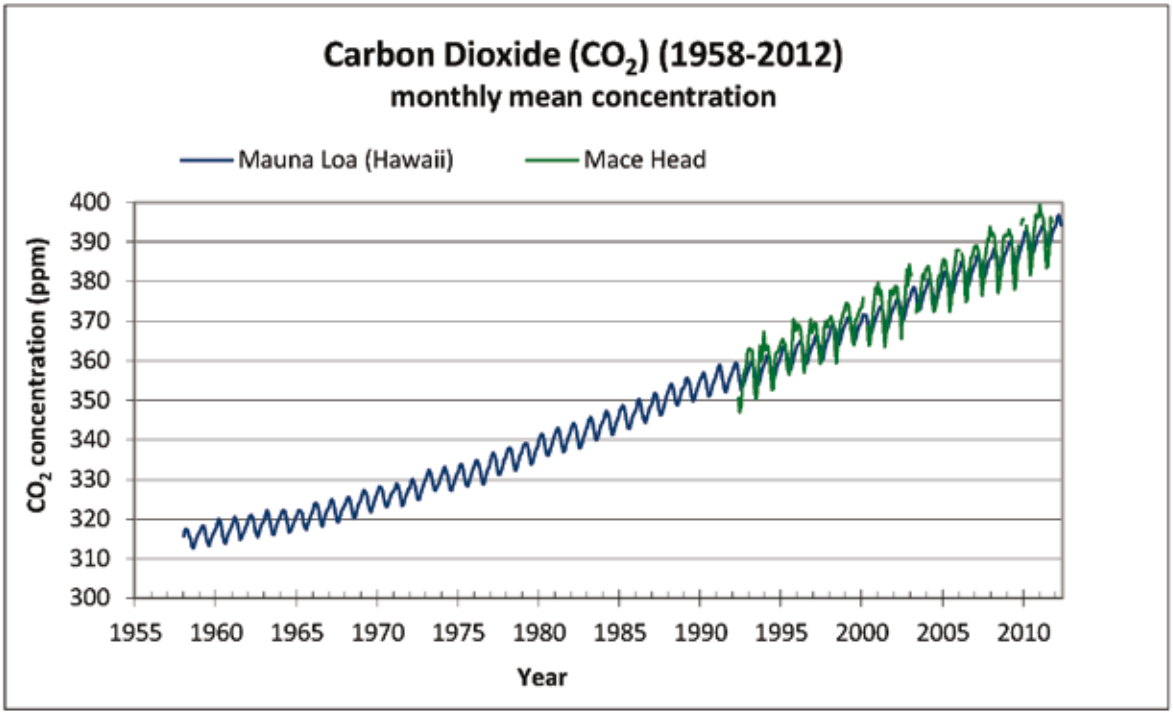


Figure 2.15. Monthly mean concentration of carbon dioxide at Mauna Loa, Hawaii (1958–2012) and Mace Head Research Station, Ireland (1992–2011).

9 Figure prepared from information courtesy of Dr Pieter Tans, NOAA/ESRL (Hawaii), Michel Ramonet, LSCE (France), and Colin O'Dowd, National University of Ireland Galway (Mace Head).

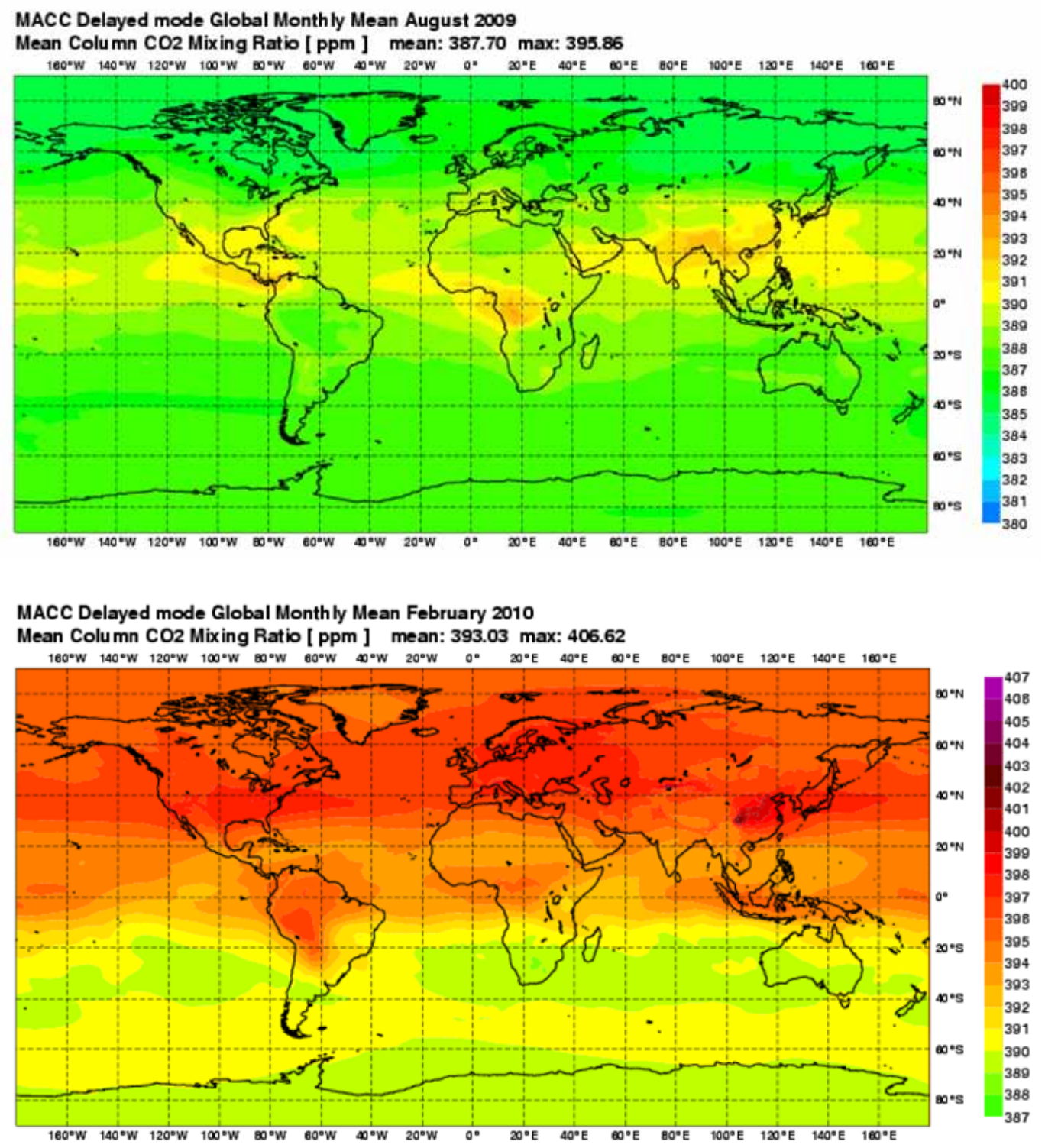


Figure 2.16. Example of global monthly mean carbon dioxide concentrations for August 2009 (top) and February 2010 (bottom) as derived from satellite observations.

Head (Fig. 2.15). These maps were generated by integrating satellite and ground-based observations as part of the Monitoring Atmospheric Composition and Climate (MACC) pre-operational atmospheric service of the European Global Monitoring for Environment and Security (GMES) programme.

'The Mace Head research station is of global importance as the CO_2 observations are representative of the underlying concentration in the northeast Atlantic region.'

Maintaining the Observations

Funding for CO_2 observations at Mace Head is from the Laboratoire des Sciences du Climat et de l'Environnement (LSCE – CEA/CNRS/UVSQ) in France. Equipment is maintained by the National University of Ireland Galway. The Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA) in the US has carried out weekly air sampling of CO_2 at Mace Head since 1991 as part of a long-term programme. This provides the possibility to compare the NOAA and the LSCE observations. CO_2 observations at Carnsore Point and Malin Head are funded under an EPA research programme as part of the European Integrated Carbon Observation System (ICOS).

Further Information and Data Sources

Ramonet, M., Ciais, P. Aalto, T., Aulagnier, C., Chevalier, F., Cipriano, D., Conway, T.J., Haszpra, L., Kazan, V. Meinhardt, F., Paris, J.-D., Schmidt, M., Simmonds, P., Xueref-Rémy, I. and Necki, J.N. (2010) A recent build-up of atmospheric CO_2 over Europe. Part 1: observed signals and possible explanations, *Tellus*, Vol. 62B, No. 1, pp. 1–13.

World Data Centre for Greenhouse Gases (including data from Mace Head): http://ds.data.jma.go.jp/gmd/wdcgg/

Data and Trends in Atmospheric Carbon Dioxide from Mauna Loa (Hawaii) http://www.esrl.noaa.gov/gmd/ccgg/trends/

Information on the Integrated Carbon Observation System (ICOS): http://www.icos-infrastructure.eu/

Information and data from ESA's Climate Change Initiative greenhouse gas project: http://www.esa-ghg-cci.org/

Data products from SCIAMACHY at the University of Bremen: http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/

Data products and information from GOSAT: http://www.gosat.nies.go.jp/index_e.html

Data and information on MACC: http://www.gmes-atmosphere.eu/

2.10 Methane

Ned Dwyer and Simon O'Doherty

Methane (CH_4) is the second most important greenhouse gas. It also influences concentrations of ozone and water vapour in the upper atmosphere. Approximately 40% of all CH_4 emitted globally is due to natural processes (e.g. wetlands, termites) while the remaining 60% is due to various human activities such as rice-growing, ruminant-raising, vegetation fires and fossil-fuel burning. In Ireland over 80% of reported CH_4 emissions are due to agricultural activities, with the remainder caused by waste disposal (e.g. landfill) and the energy sectors.



Photo: © Ned Dwyer



Map 2.10. Location of methane-observation stations.

'Current average global CH_4 concentrations of more than 1800 ppb are 140% higher than pre-industrial concentrations.'

Measurements

Atmospheric CH_4 concentrations have been measured at the Mace Head Atmospheric Research Station, Carna, Co. Galway (red) since 1987. High-precision measurements are made at 40-minute intervals. Given its location at the extreme west of Europe and because of prevailing westerly winds, the measurements are representative of the underlying concentrations of

atmospheric methane in the northeast Atlantic area. CH_4 concentrations have also been measured at Carnsore Point, Co. Wexford and Malin Head, Co. Donegal (blue) since 2009.

The amount of CH_4 in the atmosphere can be inferred from satellite observations, such as those which were made by the European *ENVISAT*. These can help fill in gaps in the global coverage of CH_4 observations. Ground-based measurements are vital for the validation of these satellite observations.

Time-series and Trends

Average global CH_4 concentrations in the atmosphere are now approximately 1800 ppb (parts per billion): this is a 140% increase on pre-industrial concentrations of approximately 750 ppb. Concentrations at Mace Head (Fig. 2.17) are higher because most sources of CH_4 are located in the northern hemisphere. Methane does not persist for more than a decade in the atmosphere, so these high concentrations are maintained due to human activities. Appropriate mitigation actions could reduce these concentrations quite quickly.

At Mace Head, increases in CH_4 have been observed from 1987 to 1998 (after which emissions level off). A further increase since 2007 can be observed. It is not clear what the source of this increase may be, although one hypothesis suggests that warmer than average summers in Siberia and increased precipitation in the tropics lead to more emissions from the vast wetlands in these regions.

A global map of atmospheric CH_4 concentrations for 2005[10] determined from the SCIAMACHY sensor on *ENVISAT* (Fig. 2.18) shows that the highest methane concentrations are in the northern hemisphere. Some of the major methane sources include wetlands in Siberia and tropical areas and rice fields in China and India.

> 'The Mace Head research station is of global importance as the CH_4 observations are representative of the underlying concentration in the northeast Atlantic region.'

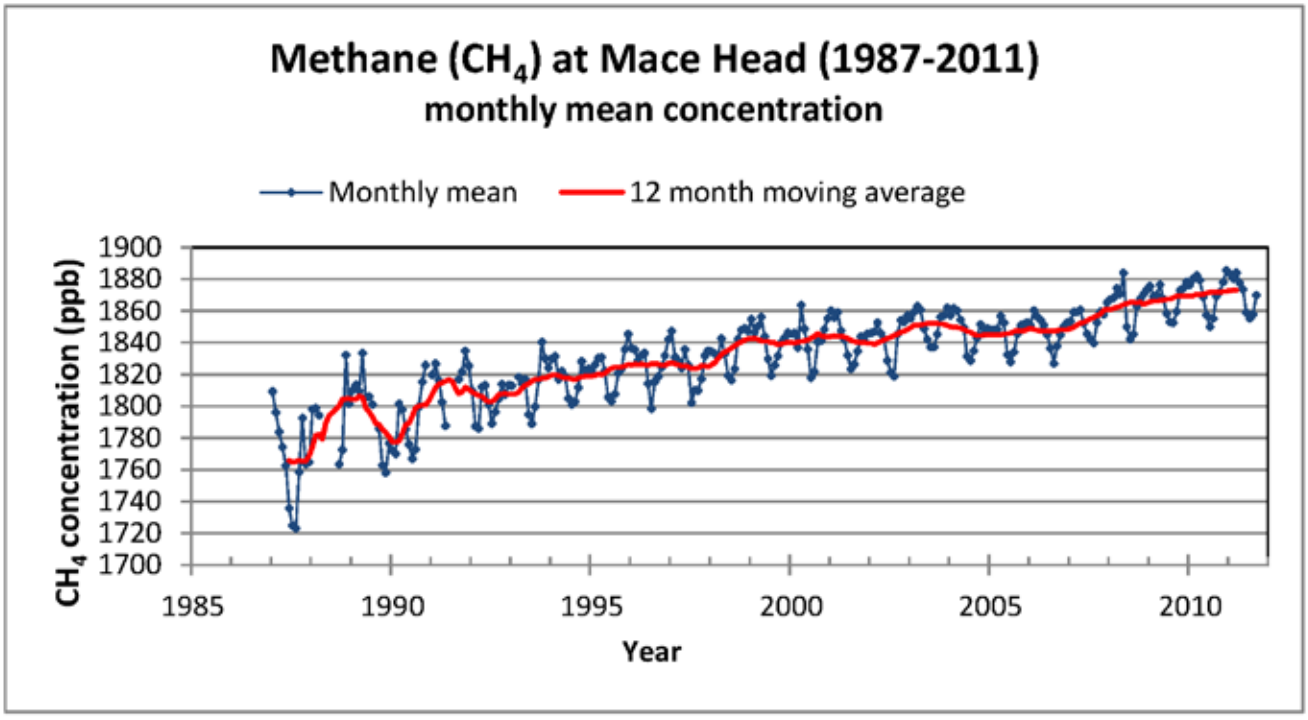


Figure 2.17. Monthly mean methane concentration observed at Mace Head Research Station (1987–2011).

10 from: http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/index.html

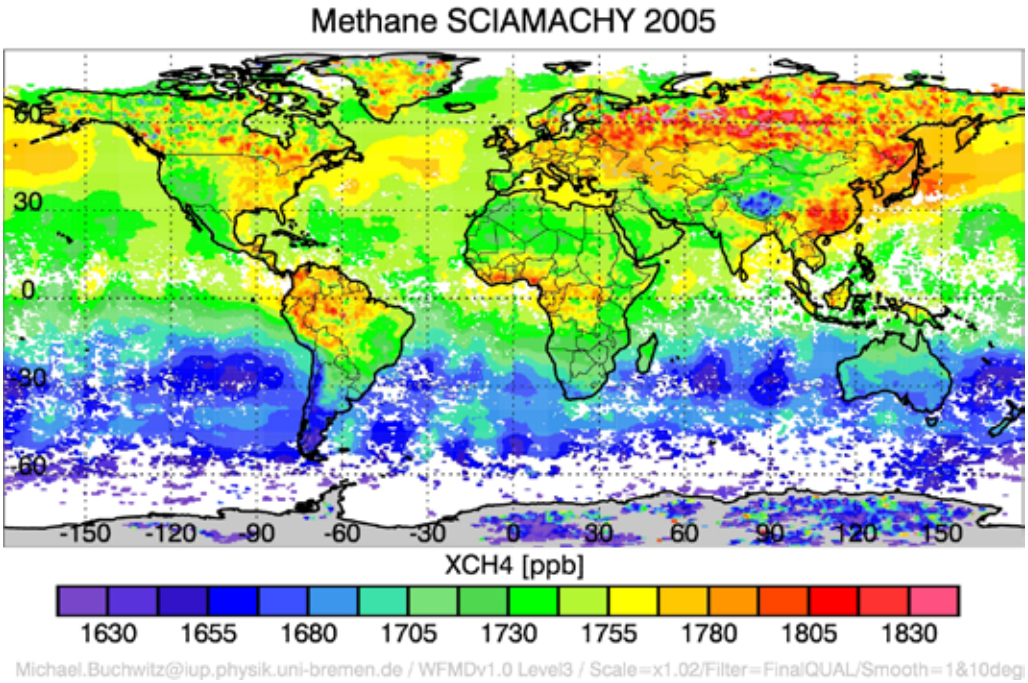


Figure 2.18. Example of annual global mean methane concentration for 2005 as derived from satellite observations.

Maintaining the Observations

Funding for CH_4 observations at Mace Head was originally from the UK's Department of Environment, Food and Rural Affairs (DEFRA) and since 2007 has been funded by the 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 the US National Aeronautics and Space Administration (NASA). AGAGE equipment is maintained by staff from the National University of Ireland Galway. CH_4 observations at Carnsore Point and Malin Head are funded under an EPA research programme as part of the European Integrated Carbon Observation System (ICOS).

Further Information and Data Sources

Dlugokencky, E.J., Bruhwiler L., White, J.W.C., Emmons, L.K., Novelli, P.C., Montzka, S.A., Masarie, K.A., Lang, P.M., Crotwell, A.M., Miller, J.B. and Gatti, L.V. (2009) Observational constraints on recent increases in the atmospheric CH_4 burden, *Geophysical Research Letters*, Vol. 36, L18803.

Rigby, M., Prinn, R.G., Fraser, P.J., Simmonds, P.G., Langenfelds, R.L., Huang, J., Cunnold, D.M., Steele, L.P., Krummel, P.B., Weiss, R.F., O'Doherty, S., Salameh, P.K., Wang, H.J., Harth, C.M., Mühle, J. and Porter, L.W. (2008) Renewed growth of atmospheric methane, *Geophysical Research Letters,* Vol. 35, L22805.

Methane observations from Mace Head and other AGAGE observatories: http://cdiac.esd.ornl.gov/ndps/alegage.html

Information about the AGAGE network: http://agage.eas.gatech.edu/

Information on the Integrated Carbon Observation System (ICOS): http://www.icos-infrastructure.eu/

Information and data from ESA's Climate Change Initiative greenhouse gas project: http://www.esa-ghg-cci.org/

Data products from SCIAMACHY at the University of Bremen: http://www.iup.uni-bremen.de/sciamachy/NIR_NADIR_WFM_DOAS/

2.11 Other Greenhouse Gases

Ned Dwyer and Simon O'Doherty

A number of other gases have been identified as contributing significantly to the enhanced greenhouse effect. The most important is nitrous oxide (N_2O), which is emitted from natural decay processes in the oceans and soils. It is also the result of human activities; in Ireland one of the main sources is the agricultural sector. Synthetic gases which are exclusively produced by human activity and which are very potent greenhouse gases include hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). These synthetic gases are controlled under the Montreal Protocol, due to their role in ozone depletion. However, their replacements are known to be also potent greenhouse gases.



Photo: © Phillip O'Brien



Map 2.11. Location of other greenhouse gas observation stations.

'Gases which replaced those which deplete ozone are increasing steadily and are contributing significantly to the enhanced greenhouse effect.'

Measurements

Many of these greenhouse gases are measured routinely at the Mace Head Atmospheric Research Station, Carna, Co. Galway, which is one of the five global stations forming the AGAGE network. Monitoring of a number of HFC and HCFC compounds started in 1994, and PFCs and SF_6 in 2004. N_2O and CFCs were measured at Adrigole, Co. Cork (blue) from 1978 to 1984.

N_2O in the stratosphere is inferred from measurements by sensors on board the US *AURA* and European *MetOp* satellite series. Sensors on the European *ENVISAT* satellite were used to measure the stratospheric distribution of some HCFCs.

Time-series and Trends

Before the industrial era atmospheric N_2O concentrations were approximately 270 ppb. Measurements at Adrigole and subsequently at Mace Head (Fig. 2.19) have shown a steady increase, with concentrations now above 320 ppb.

CFC-12 concentrations (Fig. 2.20) increased rapidly through the 1980s but after implementation of the Montreal Protocol in 2000 there was no further increase and levels have begun to drop since 2004. This is confirmation that the international agreement is working.

HFC-134a is an example of one of the refrigerant products that replaced ozone-depleting CFCs. It is also used in mobile air-conditioning and in foam-blowing applications. Its concentration, as well as a number of other synthetic gases, in the atmosphere is increasing steadily as shown in Fig. 2.21.

'The Mace Head research station is a key part of the global greenhouse gas observation network.'

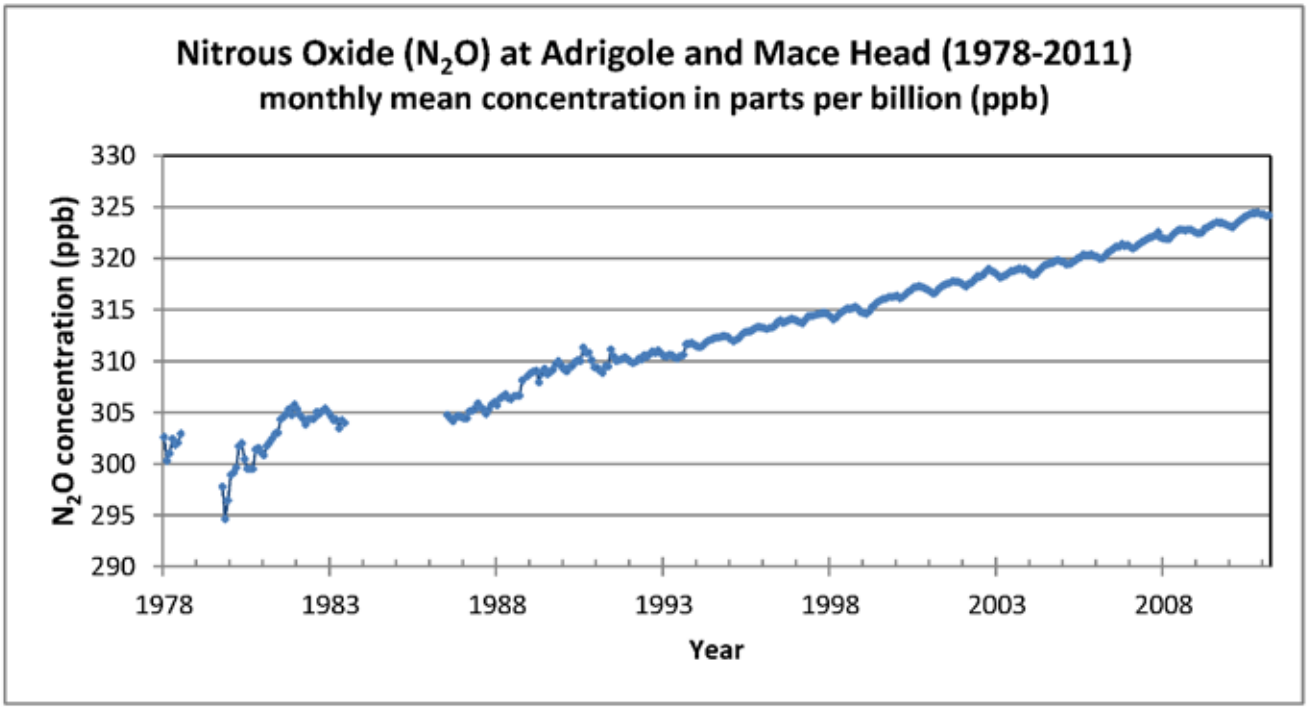


Figure 2.19. Monthly mean nitrous oxide concentration observed at Adrigole and Mace Head Research Station (1978–2011). There are some gaps in the data record.

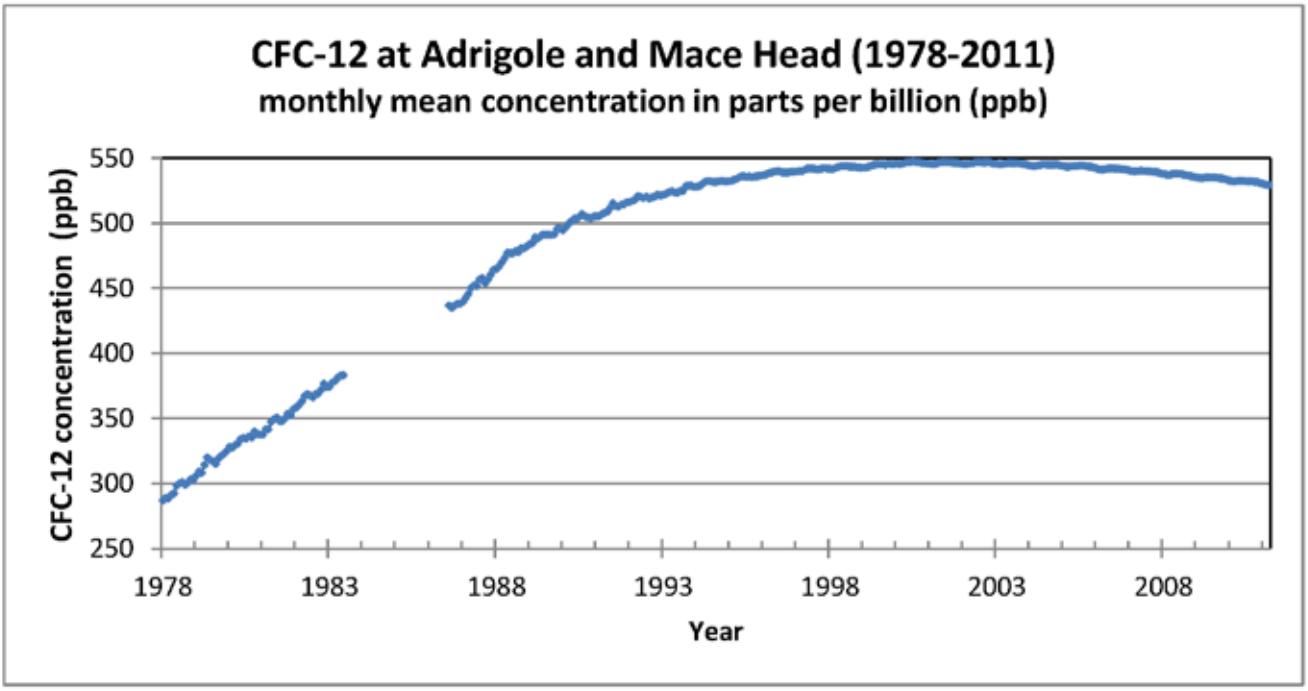


Figure 2.20. Monthly mean CFC-12 concentration observed at Adrigole and Mace Head Research Station (1978–2011). There are some gaps in the data record.

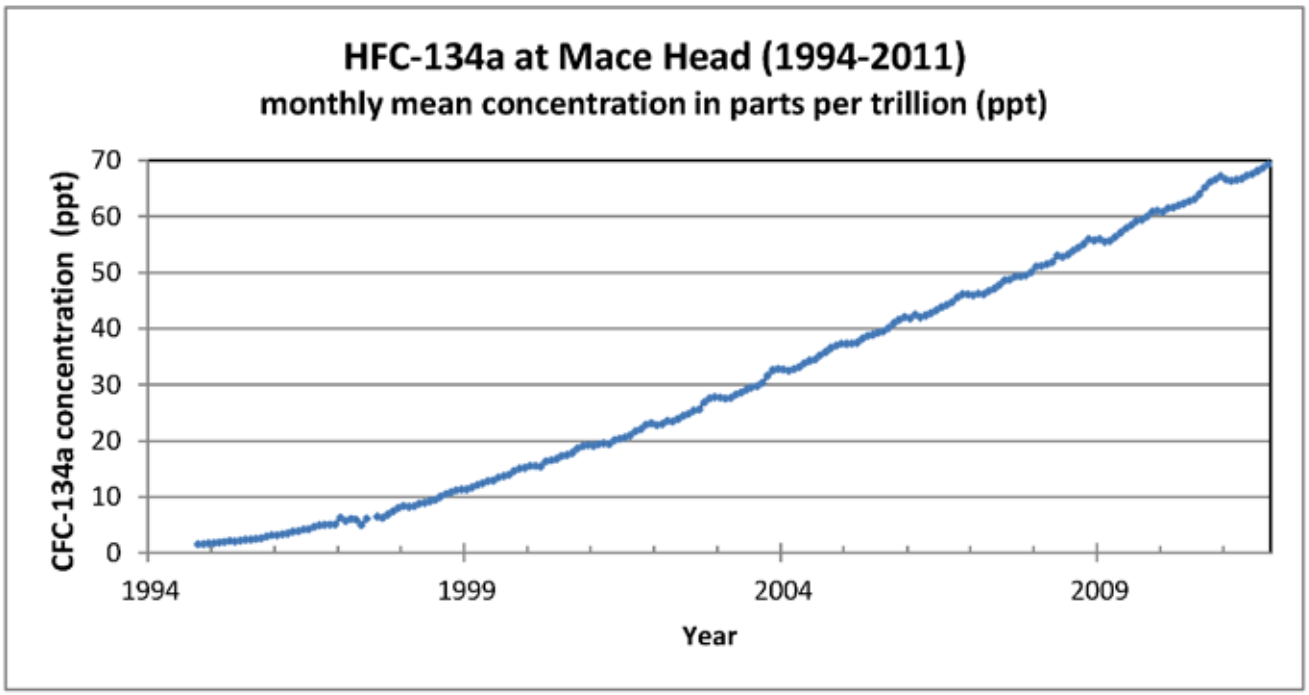


Figure 2.21. Monthly mean HFC-134a concentration observed at Mace Head Research Station (1994–2011).

Maintaining the Observations

Funding for greenhouse gas observations at Mace Head was originally from the UK's DEFRA and since 2007 the DECC, as part of its contribution to AGAGE. There is also funding from the US NASA. AGAGE equipment is maintained by staff from the National University of Ireland Galway.

Further Information and Data Sources

O'Doherty, S., Cunnold, D.M., Miller, B.R., Mühle, J., McCulloch, A., Simmonds, P.G., Manning, A.J., Reismann, S., Vollmer, K.K., Greally, B.R., Prinn, R.G., Fraser, P.J., Steele, L.P., Krummel, P.B., Dunse, B.L., Porter, L.W., Lunder, C.R., Schmidbauer, N., Hermansen, O., Salameh, P.K., Harth, Wang, R.H.J. and Weiss, R.F. (2009) Global and regional emissions of HFC-125 (CHF2CF3) from *in situ* and air archive atmospheric observations at AGAGE and SOGE observatories, *Journal of Geophysical Research,* Vol. 114, D23304.

O'Doherty, S., Cunnold, D.M., Manning, A., Miller, B.R., Wang, R.H.J., Krummel, P.B., Fraser, P.J., Simmonfd, P.G., McCulloch, A., Weiss, R.F., Salameh, P., Porter, L.W., Prinn, R.G., Huang, J., Sturrock, G., Ryal, D., Derwent, R.G. and Montzka, S.A. (2004) Rapid growth of hydrofluorocarbon 134a and hydrochlorofluorocarbons 141b, 142b, and 22 from Advanced Global Atmospheric Gases Experiment (AGAGE) observations at Cape Grim, Tasmania, and Mace Head, Ireland, *Journal of Geophysical Research,* Vol. 109, D06310.

Information on the Montreal Protocol: http://ozone.unep.org/new_site/en/montreal_protocol.php

GHG observations from Mace Head and other AGAGE observatories: http://cdiac.esd.ornl.gov/ndps/alegage.html

Information about the AGAGE network: http://agage.eas.gatech.edu/

Greenhouse Gas Online provides information and links to peer reviewed materials on the main greenhouse gases: http://www.ghgonline.org/index.htm

Information and data from the European *Infrared Atmospheric Sounding Interferometer* (IASI) instrument: http://smsc.cnes.fr/IASI/

Information and data from NASA's Microwave Limb Sounder (MLS) instrument: http://mls.jpl.nasa.gov/

2.12 Ozone

Ned Dwyer, Peter Simmonds, Gerard Jennings, Simon O'Doherty, Colin O'Dowd and Keith Lambkin

Ozone (O_3) is the third most important greenhouse gas in terms of radiative forcing. The influence of O_3 on climate is complex with different impacts in the upper and lower atmosphere. Although human activities do not emit ozone directly, atmospheric pollution, for example from industry, transport and the burning of vegetation, can create the conditions for enhanced ozone formation. As well as influencing the climate, surface O_3 can affect the human respiratory system and damage crops and other vegetation.



Photo: © Karen Commane



Map 2.12. Location of total column and ground ozone observation stations.

'The influence of O_3 on climate is complex with different impacts in the upper and lower atmosphere.'

Measurements

Total column O_3[11] has been measured at Valentia Observatory, Co. Kerry (red) since 1993 using ground-based optical equipment. Since 1994 vertical ozone profiles are routinely measured using equipment carried on weather balloons to heights greater than 30 km.

11 Represents the total amount of O_3 in a column from the surface of the Earth to the top of the atmosphere.

A ground-based O_3 observational network has been established with 11 sites around the country (blue), including Valentia Observatory (red).

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. *In situ* measurements are required to validate these satellite observations.

'Ozone levels in the upper atmosphere are observed to be slowly recovering since CFCs were banned in 1987.'

Time-series and Trends

Although a number of human activities lead to atmospheric O_3 formation, the emission of CFCs to the atmosphere causes O_3 reductions in the upper atmosphere (stratosphere) and has led to the formation of the 'ozone hole'. This 'hole' is biggest over the Antarctic where stratospheric ozone is severely depleted during the period August to October every year. This allows more harmful ultraviolet radiation to reach the Earth's surface. Since these chemicals were banned under the Montreal Protocol (1987), O_3 levels in the upper atmosphere are slowly recovering.

At Valentia Observatory measurements of total column O_3 vary throughout the year with a maximum reached in the Northern Hemisphere's spring season and a minimum in late autumn as illustrated in Fig. 2.22. Recent analysis of these data show trends of about 1.5% increase per decade at an average O_3 level of 325 Dobson Units (DU).

A recent analysis across the ground-level observation network notes a decrease in O_3 concentrations, in particular since 2000. This may be due to a decrease in the levels of regional-scale photochemical ozone production. However, analysis of ground level O_3 measurements at Mace Head Co. Galway (Fig. 2.23) shows that average annual O_3 amounts in the lower atmosphere increased over the period from 1987 to 1997 followed by a step change during 1997–1999 and relatively constant levels since. The red line shows a

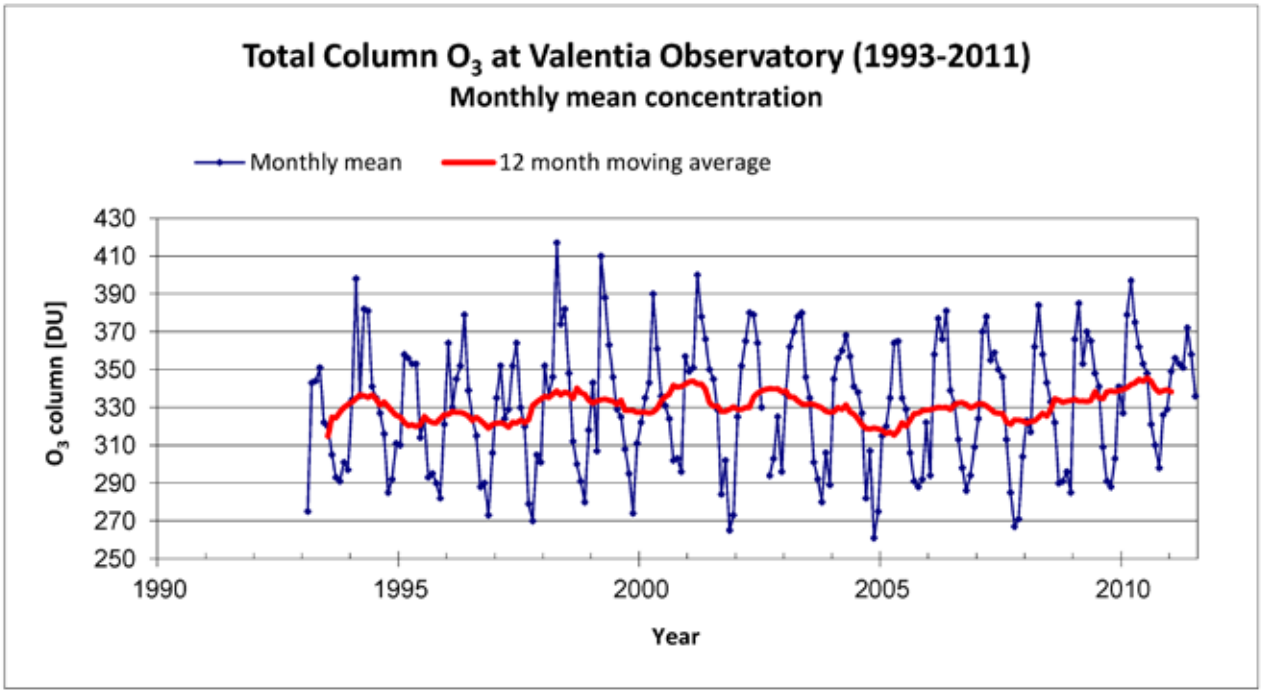


Figure 2.22. Monthly mean total column ozone concentration observed at Valentia Observatory (1993–2011).

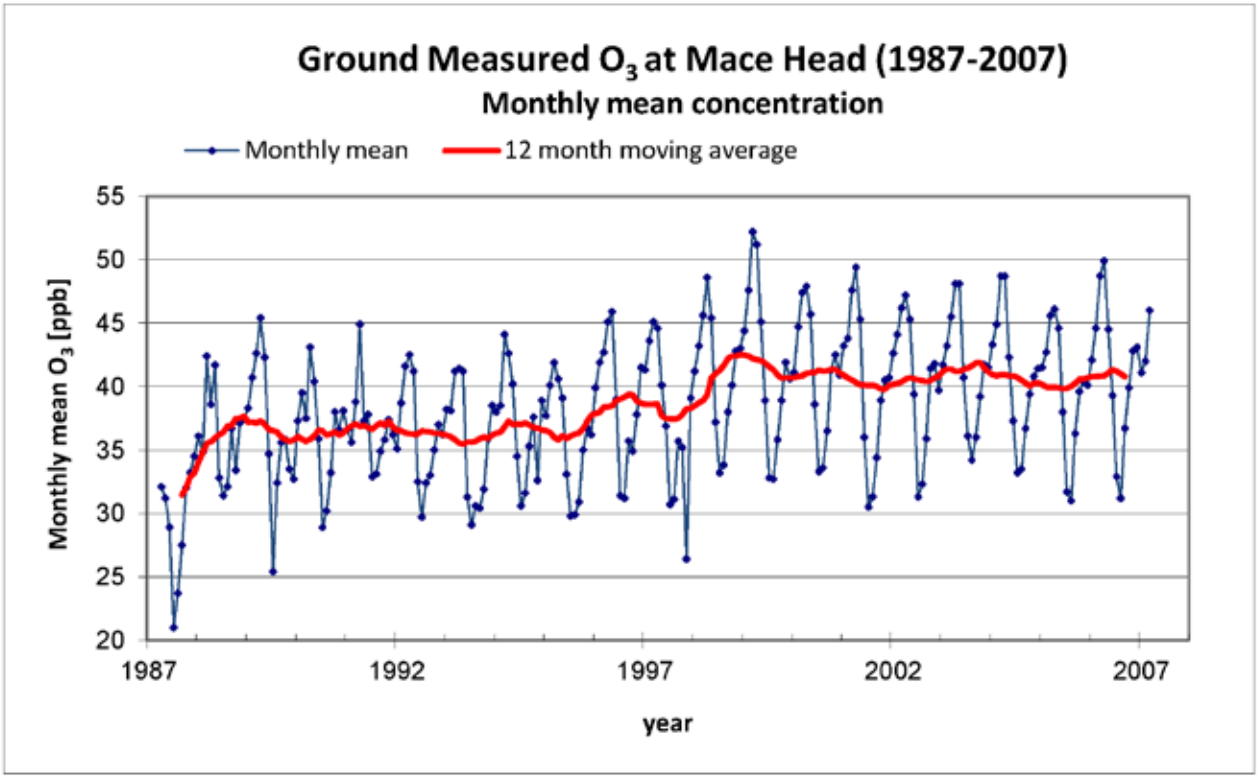


Figure 2.23. Monthly mean ground-level ozone concentration observed at Mace Head (1987–2007).

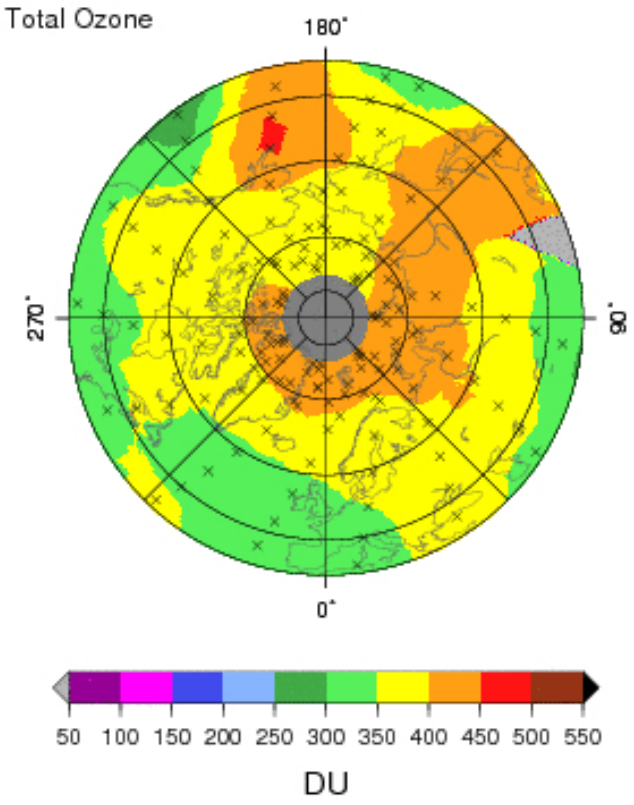


Figure 2.24. Polar view of total amount of ozone integrated from ground to top of the atmosphere, as determined by the SCIAMACHY instrument on board *ENVISAT*, 1 May 2010. Ireland can be seen toward bottom-centre of image, to the west of 0° longitude.

12-month running average over the period. The sharp increase in 1998/99 has been associated with large vegetation fires in the northern hemisphere during that period. Mace Head observations are strongly influenced by Atlantic marine air masses.

Maintaining the Observations

Funding for O_3 observations at Valentia Observatory is provided from Met Éireann's operational budget. However, the programme lacks long-term committed financing. Equipment maintenance and data handling is carried out by highly skilled on-site Met Éireann staff. Funding for observations at Mace Head was originally from the UK's DEFRA and since 2007 has been funded by the DECC. Equipment maintenance and data handling are carried out by highly skilled staff from the National University of Ireland Galway. The ground-based network is primarily for air quality monitoring and is maintained and funded by the EPA. Satellite-based sensors such as the Ozone Mapper Profiler Suite (OMPS) on board NASA's *Suomi* NPP satellite launched in January 2012 will ensure the continuity of stratospheric ozone observations.

Further Information and Data Sources

Derwent, R.G., Simmonds, P.G., Manning, A.J. and Spain, T.G. (2007) Trends over a 20-year period from 1987 to 2007 in surface ozone at the atmospheric research station, Mace Head, Ireland, *Atmospheric Environment*, Vol. 41, pp. 9091–8.

Keim, C., Eremenko, M., Orphal., J., Dufour, G., Flaud, J.-M., Höpfner, M., Boynard, A., Clerbaux, C., Payan, S., Coheur, P.–F., Hurtmans, D., Claude, H., Dier, H., Johnson, B., Kelder, H., Kivi, R., Koide, T., López Bartolomé, M., Lambkin, K., Moore, D., Schmidlin, F.J. and Stübi, R. (2009) Tropospheric ozone from IASI: comparison of different inversion algorithms and validation with ozone sondes, *Atmospheric Chemistry and Physics,* Vol. 9, pp. 9329–47.

Tripathi, O.P, Jennings, S.G., O'Dowd, C.D., Colman, L., Leinert, S., O'Leary, B., Moran, E., O'Doherty, S.J. and Spain, T.G. (2010) Statistical analysis of eight surface ozone measurement series for various sites in Ireland, *Journal of Geophysical Research,* Vol. 115, D19302, doi:io.1029/2010JD014040.

Tripathi, O.P., Jennings, S.G., O'Dowd, C.D., Lambkin, K. and Moran, E. (Submitted) Recent trends in stratospheric ozone at a mid-latitude observing station at Valentia, Ireland (51.94^0 N, 10.250 W) through ground-based and ozonesonde measurements from 1994 to 2009, *Journal of Atmospheric Science.*

Tripathi, O.P., Jennings, S.G., Colman, L., Lambkin, K., Moran, E. and O'Dowd, C.D. (2012) *Ozone Levels, Changes and Trends over Ireland – an integrated analysis*, EPA, pp. 137: http://www.epa.ie/downloads/pubs/research/air/name,33696,en.html

EPA Air Monitoring Programme: http://www.epa.ie/whatwedo/monitoring/air/

Global Atmosphere Watch (GAW) research at the World Meteorological Office on atmospheric ozone: http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html

University of Bremen, Institute of Environmental Physics, SCIAMACHY archive: http://www.iup.uni-bremen.de/scia-arc/

World Ozone and Ultraviolet Radiation Data Centre (WOUDC): http://www.woudc.org.

2.13 Aerosols

Ned Dwyer, Gerard Jennings and Colin O'Dowd

Atmospheric aerosols are small particles in the air that may be formed by natural or human activities. They include volcanic dust, wind-lifted dust, sea salt from spray, soot, industrial dust and sulphates. Industry, burning of fossil fuels and vegetation fires are some of the primary human activities that generate aerosols. They are relevant to climate in that they influence the global radiation balance directly by scattering and absorbing radiation and indirectly through influencing cloud albedo (reflectivity), cloud cover and lifetime. However, the magnitude of their effects on climate remains a significant source of uncertainty.



Photo: © Gavin Ó Sé



Map 2.13. Location of aerosol observation stations.

'The magnitude of the effects of aerosols on climate is a significant source of uncertainty.'

Measurements

Observations are made at the Mace Head Atmospheric Research Station, Carna, Co. Galway and Valentia Observatory, Co. Kerry. A range of aerosol parameters has been measured on a continual basis at Mace Head since 1986, although some measurements took place on an intermittent basis from 1958. Measurements made include the scattering, backscattering and absorption coefficient at various wavelengths; the total

particle number concentration, particle size and mass distribution; particulate matter (PM) mass (PM10 and PM2.5); black carbon mass concentration; 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 measurements 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 satellite sensors, such as MODIS on board the *NASA TERRA* and *AQUA* satellites make observations from which the aerosol optical depth can be inferred. *In situ* measurements are critical for validation of such observations.

'The suite of aerosol measurements at Mace Head is one of the most comprehensive in any remote location in the world.'

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 Fig. 2.25. This time-series of monthly geometric mean values of aerosol scattering coefficient for the period from 1999 to 2010 is an estimate of aerosol concentration. No trend is evident in the time-series.

Figure 2.26 shows a global map of aerosol optical depth as inferred from the MODIS sensor on the *AQUA* satellite, for the period August to October 2010. High aerosol optical depth over the Amazon region, parts of Siberia and south-western Africa is likely due to vegetation fires. Dust from the Sahara is carried out over the Atlantic Ocean and industrial aerosol is evident across southern Asia.

'The Mace Head aerosol observation programmes lack long-term and sustainable operational support.'

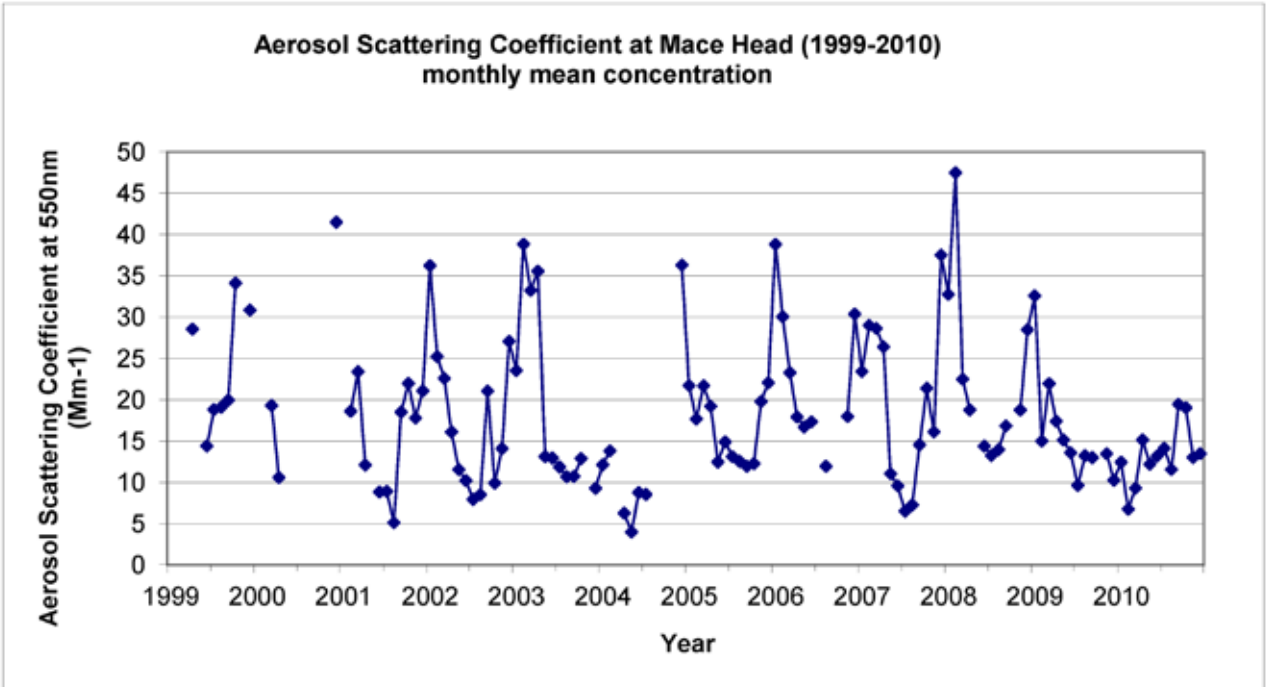


Figure 2.25. Monthly geometric mean values of aerosol scattering coefficient observed at Mace Head (1999–2010). There are some gaps in the data record.

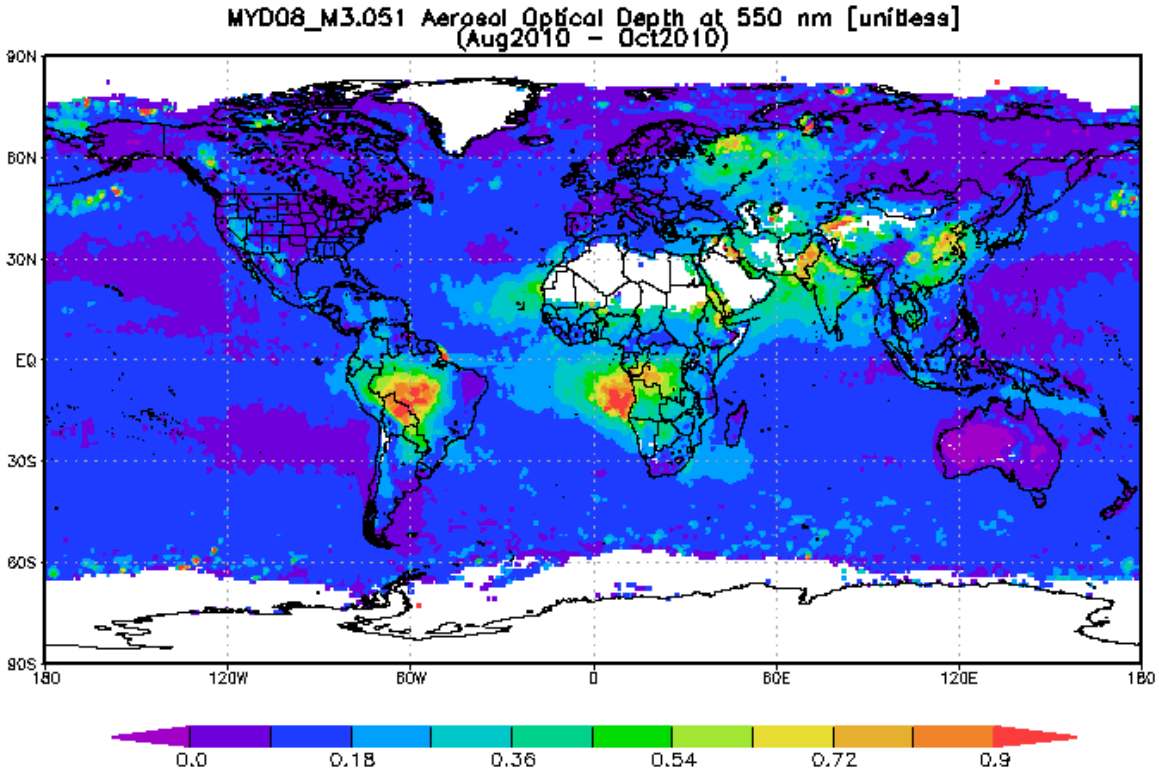


Figure 2.26. Example of global aerosol optical depth for the period August to October 2010 as derived from satellite observations.

Maintaining the Observations

Funding for aerosol observations at Valentia Observatory is provided from Met Éireann's operational budget. Equipment maintenance and data-handling are carried out by skilled on-site staff, in cooperation with the World Optical Depth Research and Calibration Centre. The Mace Head aerosol observation programmes are funded on an ad hoc basis from a range of projects by the Centre for Climate and Air Pollution Studies [C-CAPS], School of Physics at the National University of Ireland, Galway, but lack long-term and sustainable operational support.

Further Information and Data Sources

O'Connor, T.C., Jennings, S.G. and O'Dowd, C.D. (2008) Highlights from 50 years of aerosol measurements at Mace Head, *Atmospheric Research,* Vol. 90, pp. 338–55.

Information on the Mace Head Facility: http://www.macehead.org

A description of the Aerosol Optical Depth Measurement Programme at Valentia Observatory: http://www.met.ie/about/valentiaobservatory/aerosol.asp

World Data Centre for Aerosols: http://ebas.nilu.no/

Aerosol optical depth observations from Irish and international stations may be accessed at the World Optical Depth Research and Calibration Centre: http://www.pmodwrc.ch/worcc/

Information and data from ESA's Climate Change Initiative aerosol project: http://www.esa-aerosol-cci.org/

Aerosol optical depth as inferred from satellite sensors may be accessed at: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=aerosol_monthly

Story Board 2: Ireland – A Key Location for Global Atmospheric Observations

Ned Dwyer, Keith Lambkin and Colin O'Dowd



Figure SB2.1. A weather balloon being launched at Valentia Observatory, Co. Kerry (photo: © Met Éireann).

SB2

On the margins of western Europe facing the Atlantic Ocean, Ireland is in an ideal location to measure background levels of greenhouse gases and other constituents of the atmosphere, which are transported in predominantly unpolluted air masses by westerly winds. It is also appropriately situated to sample and study polluted air exiting Europe over the Atlantic. Valentia Meteorological and Geophysical Observatory, Co. Kerry and Mace Head Research Station, Co. Galway are recognised worldwide as key locations in the study of climate change, and their data and facilities are being used by dozens of institutions around the Globe. Both stations are part of the Global Atmosphere Watch (GAW) network, a programme of the World Meteorological Organisation involving 80 countries.

Valentia Observatory

Valentia Observatory was set up in 1868 as one of the first meteorological stations in Britain and Ireland and is now operated by Met Éireann. It is one of 25 synoptic weather stations making a full range of meteorological measurements at the surface, some at minute intervals. In addition, weather balloons (radiosondes) are launched twice a day to make measurements of pressure, temperature, humidity, wind speed and direction up through the atmosphere (Fig. SB2.1). The observatory is also Met Éireann's national solar and terrestrial radiation facility. By measuring solar radiation at different wavelengths, information on the chemical and physical makeup of the atmosphere can be determined.

Weather balloon ozonesondes and ground-based equipment are used to measure the amount of ozone throughout the atmosphere. Valentia is therefore a key site in monitoring the recovery of the ozone layer. Ground-level ozone which is a danger to humans as well as harmful to agricultural crops is also measured at the observatory.

Valentia also hosts one of the oldest International Phenological Gardens (IPG) in the country. More than 80 IPGs are located in 19 European countries. The idea of the IPGs is to carry out large-scale and standardised phenological observations, for the study of environmental change and climate impacts among others. The phenophases (annual timing of first leaves, first flowers, ripening,



Figure SB2.2. Laboratories and observational infrastructure at the Mace Head Atmospheric Research Station, Carna, Co Galway (photo: © National University of Ireland Galway).

leaf fall, etc.) of a number of specially cloned trees have been recorded at the Valentia IPG for over 40 years. These records, when compared to other similar cloned trees around Europe, provide a valuable climate change indicator.

Valentia participates in a number of background-air, precipitation-chemistry and radioactivity-monitoring programmes. Met Éireann's atmospheric chemistry laboratories analyse exposed air filters and collected rain water samples for numerous pollutants. Pollution monitoring on the site includes continuous measurements of nitrogen dioxide (NO_2) since 1989 and sulphur dioxide (SO_2 and SO_4) since 1981, representing the longest time-series of such measurements in Ireland.

Mace Head Atmospheric Research Station

The Mace Head Atmospheric Research Station (Fig. SB2.2) was established in 1958 and is operated by personnel from the Centre for Climate & Air Pollution Studies, Ryan Institute and School of Physics of the National University of Ireland Galway in collaboration with several international projects. Since 2002 it has been one of Met Éireann's synoptic weather stations, making surface-level measurements of a range of meteorological variables. However, it is best known internationally for its measurements of atmospheric gases and aerosols. Atmospheric methane (CH_4) and nitrous oxide (N_2O) concentrations have been measured since 1987, and carbon dioxide (CO_2) since 1992. Ground-level ozone (O_3) has been measured since 1983. Chlorofluorocarbons (CFCs) which contribute to ozone depletion have been measured since 1987, as part of the AGAGE programme. Their replacements, HCFCs, have been measured at Mace Head since 1995. A number of other important reactive gases are also observed (e.g. SO_2, OH, H_2SO_2, MSA, I_2).

A wide range of aerosol parameters, such as aerosol size, mass, optical characteristics, water activity and chemical composition are also measured at the site. Additional operational ground-based remote sensing and profiling equipment calculate aerosol optical depth and profiles, cloud properties, air temperature, humidity and water vapour profiles up to 15 km in altitude. Mace Head is one of the most advanced supersites in Europe, covering the most extensive range of greenhouse gases, reactive gases, aerosol properties and cloud properties. Data are webcast every 10 minutes and transmitted to the National University of Ireland Galway's data infrastructure.

Much of the data from these two observatories are made available to the appropriate international data centres, where they contribute to basic research knowledge, as well as improved understanding of climate change. It is vital that all the observation programmes carried out at Valentia and Mace Head are appropriately resourced as it is only with long-term observations that we can interpret how and why our climate is changing.

Further Information

A brief history of Valentia Observatory: http://www.met.ie/about/valentiaobservatory/default.asp

Information on and real time data from the Mace Head facility: http://www.macehead.org/



3. Oceanic Observations

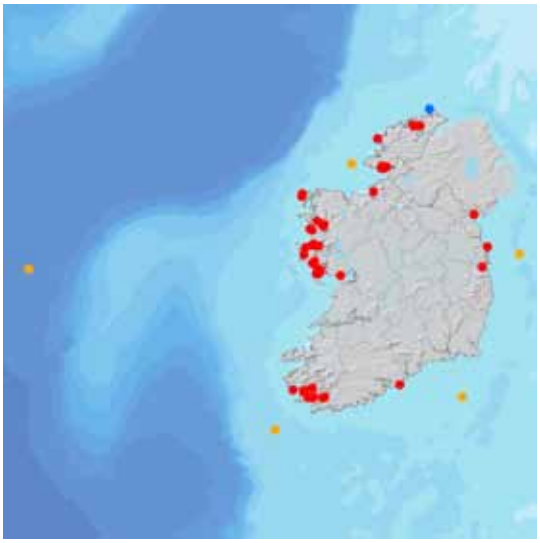
3.1 Ocean Surface and Sub-surface Temperature

Glenn Nolan and Ned Dwyer

The temperature of the oceans is influenced by a number of factors, including the amount of heat from the sun transferred to the water, surface and sub-surface circulation and current patterns. Global ocean surface temperatures have increased by approximately 0.7°C since the 1850s, with rapid warming since the 1960s. Monitoring of ocean temperature is important as thermal expansion due to warming, leading to sea-level rise. Temperature also determines both the plant and animal species present, thereby impacting biodiversity and fishing; it also influences the weather patterns and climate experienced on land.



Photo: © Ned Dwyer



Map 3.1. Location of sea surface temperature observation stations.

Measurements

Sea surface temperature (SST) measurements are made at several sites around the Irish coast (red) by the Marine Institute. Water temperature data have been collected at Malin Head Co. Donegal (blue) by Met Éireann since 1958. This is the longest SST record available for the Irish region, although records for parts of the northeast Atlantic go back to 1850. Since 2000, the marine weather buoy network (orange) routinely collects sea surface and sub-surface temperature data from five offshore locations.

Sea surface temperature can also be inferred from satellite observations with an accuracy of greater than ±0.3°C. For example, sensors on board the NASA *TERRA* satellite make daily measurements of SST.

'Sea surface temperature in Irish waters has increased at a rate of approximately 0.6°C per decade since 1994, which is unprecedented in the 150-year observational record.'

Time-series and Trends

Surface Temperature

Figure 3.1 shows the mean annual observed SST at Malin Head for the period 1961 to 2011[12] (right axis). The left-hand axis indicates anomalies (the difference between the mean annual temperature and the 1961 to 1990 reference mean value). This shows interannual variability from the 1960s to the 1980s and a progressive warming in the record from the early 1990s. This strongly ties in with the natural cycle of variability in 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.

The observations of SST from the offshore data buoys since 2000 are consistent with air-temperature observations made on land.

Figure 3.2 shows the SST around Ireland for May 2011 as determined from an average of a series of observations from the MODIS sensor on board the *NASA TERRA* platform. Temperatures around the island are in the approximate range of 10°C to 13°C.

Sub-surface Temperature

Over the last 50 years global ocean temperature has risen by 0.10°C approximately from the surface to a depth of 700 m. Since 2005 to the west of Ireland annual surveys have been carried out in the Rockall Trough to full depth. These are reported to the International Council for Exploration of the Sea (ICES) to summarise oceanic conditions in the Irish region.

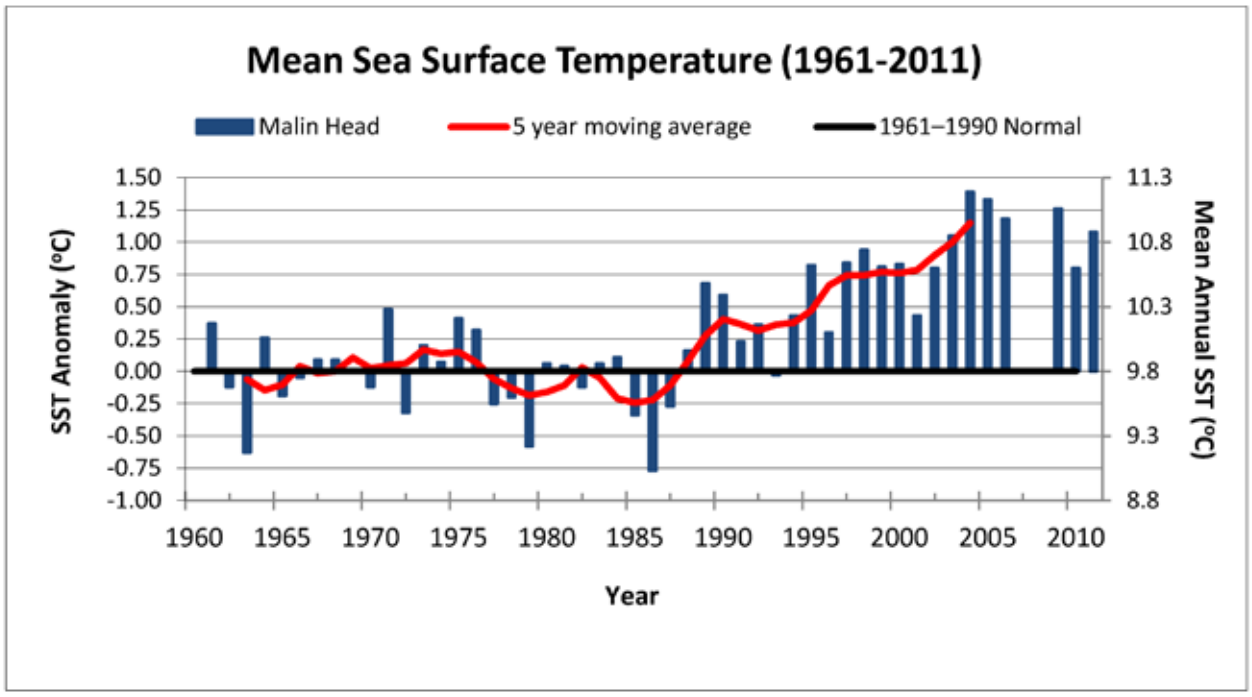


Figure 3.1. Mean annual sea surface temperature (SST) and anomalies measured at Malin Head (1961–2011).

12 Bucket measurements were made up to 2007; a moored electronic sensor has been used subsequently. Time-series data have been merged by adjusting the bucket to the electronic measurements.

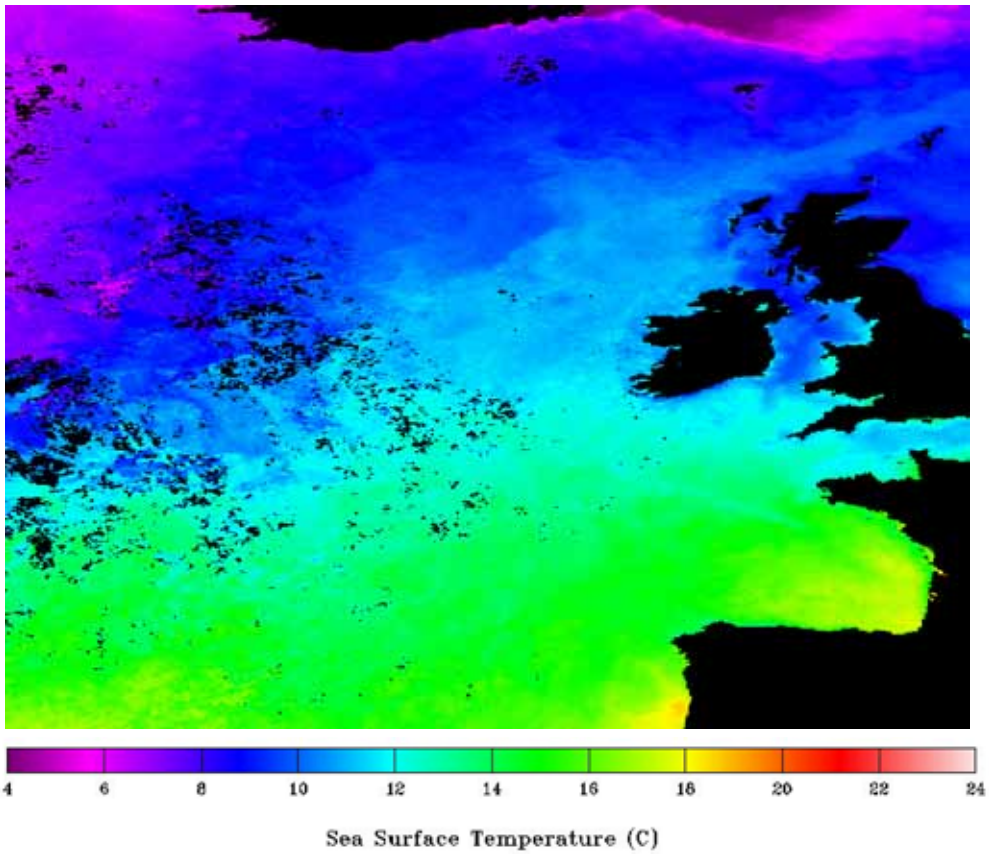


Figure 3.2. Example of sea surface temperature-distribution derived from satellite-based radiometer observations for May 2011.

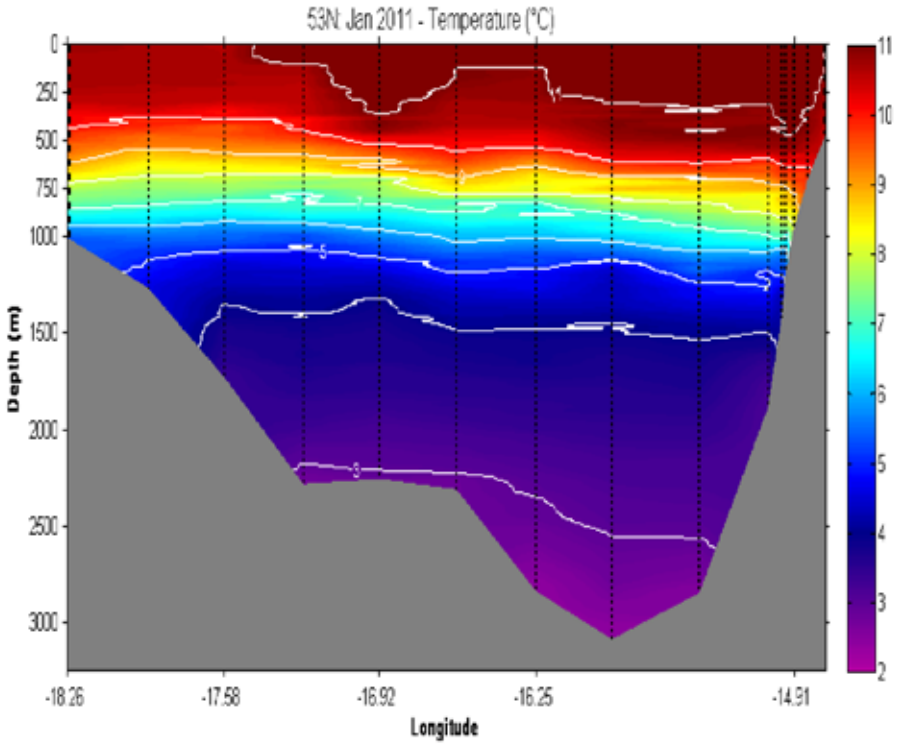


Figure 3.3. Deep-water temperature section for the Rockall Trough in January 2011 looking northward.

Figure 3.3 shows a typical deep water temperature section for the Rockall Trough in January 2011 looking northward. The near-surface water masses are evident in the 9°C–11°C range of the upper 750 m of the water column. The time-series of deep-water observations is too short to determine if any trend exists in the data.

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

Maintaining the Observations

The new temperature sensors at Malin Head are maintained by the Marine Institute on an annual basis. Data is now being recovered in real time. In 2011 a station was established to measure SST at Ballycotton, Co. Cork. Resources need to be allocated to ensure that this is maintained as a long-term reference station for the Celtic Sea. The Irish Marine Weather Buoy Network is funded under a Memorandum of Understanding with the Department of Transport. Funding for this network is negotiated on an annual basis. Deep sea sub-surface temperature observations are made annually and are funded under the National Development Plan Ship Time fund and through internal Marine Institute funding.

Further Information and Data Sources

Cannaby, H. and Hüsrevoğlu, Y.S. (2009) Low frequency variability and long-term trends in Irish SST records, *ICES Journal of Marine Science,* Vol. 66, No. 7, pp. 1480–9.

Cannaby, H. and Nolan, G. (2009) Physical oceanography. *Irish Ocean Climate and Ecosystem Status Report 2009*. Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, p. 100.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A. (2006) Global analysis of sea surface temperature, sea ice and night marine air temperature since the late nineteenth century, *Journal of Geophysical Research,* Vol. 108, pp. 4407–36, doi: 10. 1029/2002JD002670.

Malin Head Data (1958–2006) are archived by Met Éireann: http://www.met.ie/climate/climate-data-information.asp

Malin Head Data (since 2008) are archived by the Marine Institute and may be accessed on request: http://www.marine.ie/home/publicationsdata/

Information and observations from inshore SST measurement stations: http://www.marine.ie/home/publicationsdata/data/IMOS/

Information and observations from the Irish Marine Weather Buoy Network: http://www.met.ie/marine/marine_observations.asp

Information and data from the UK Met Office's Hadley Centre: http://www.metoffice.gov.uk/hadobs/

Physical oceanographic parameters including SST observations derived from satellite measurements are available from NASA's distributed data and archive centre: http://podaac.jpl.nasa.gov/

Physical oceanographic parameters including SST observations derived from satellite measurements are available from the GMES MyOcean portal: http://www.myocean.eu.org/

Information and data from ESA's Climate Change Initiative, SST project: http://www.esa-sst-cci.org/

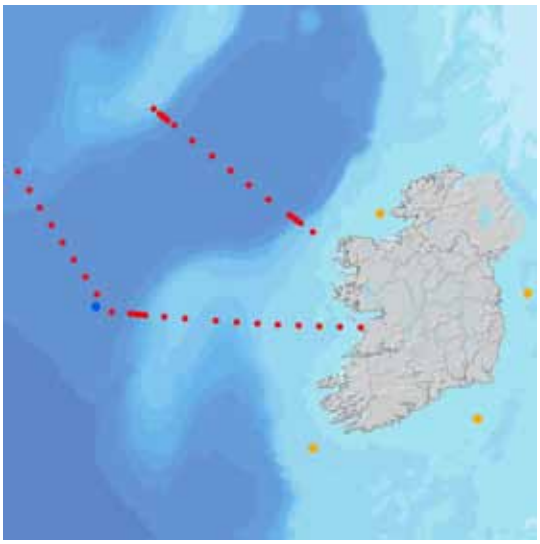
3.2 Ocean Surface and Sub-surface Salinity

Glenn Nolan and Ned Dwyer

Salinity is defined as the total amount of dissolved salts in water. These constitute approximately 3.5% of the ocean's mass, the remaining percentage being pure water. Although decadal changes have been observed, no long-term trend in salinity levels of the northeast Atlantic has been detected. Monitoring of ocean salinity changes is an indirect method of detecting changes in precipitation, evaporation, river runoff and ice melt and therefore helps in understanding changes in the Earth's hydrological cycle.



Photo: © Didac Perales



Map 3.2. Location of moored stations and cruise tracks for surface and sub-surface salinity observations.

'Surface and sub-surface salinity measurements around Ireland exhibit multi-annual variability but no distinct trend exists.'

Measurements

Since 2000, the Irish Marine Weather Buoy Network routinely collects sea surface and sub-surface salinity data from five offshore locations (orange and blue). Since 2008 salinity and temperature have been recorded hourly at five depths up to 1000 m on the M6 buoy mooring (blue). Salinity data have been collected by the ICES for many years but the dataset is

quite limited for the Irish region. Since 2004 standard oceanographic cruises (red) are also undertaken on an annual basis. The deep waters west of Ireland are monitored in winter, while the coastal shelf waters are monitored in May.

Sea-surface salinity can be monitored from space 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.

Time-series and Trends

Using the combined archive of salinity data from ICES, the Marine Institute and the World Ocean Database, Fig. 3.4 shows that annual mean salinity anomalies on the Irish shelf exhibit a multi-annual variability. This variability has been linked to variation in the North Atlantic Oscillation (NAO).[13] Salinity anomalies are calculated relative to the 1975–2007 climatology, and have been averaged over the region 48°–58°N, 3°–15°W. Surface salinity anomalies on the Irish shelf also show variability from year to year, with evidence of some freshening in coastal waters associated with increased winter rainfall.

Sub-surface Salinity

Figure 3.5 shows the key water masses and their salinity levels (psu) in the deep waters west of Ireland. Degrees longitude west of Greenwich are shown on the x-axis. Different situations pertain in the near-surface, intermediate and deep layers. In general, the deeper waters are less saline and the surface waters more saline.

Deep-water masses have been monitored since 2004 on standard oceanographic cruise sections. One highlight of this short time-series is the progressive freshening of the Labrador Sea Water (LSW) between 2006 and 2009 – representing the arrival in the Rockall Trough of waters that had formed in the Labrador Sea around 2000. The LSW has become more saline in 2010 and 2011. Near-surface and

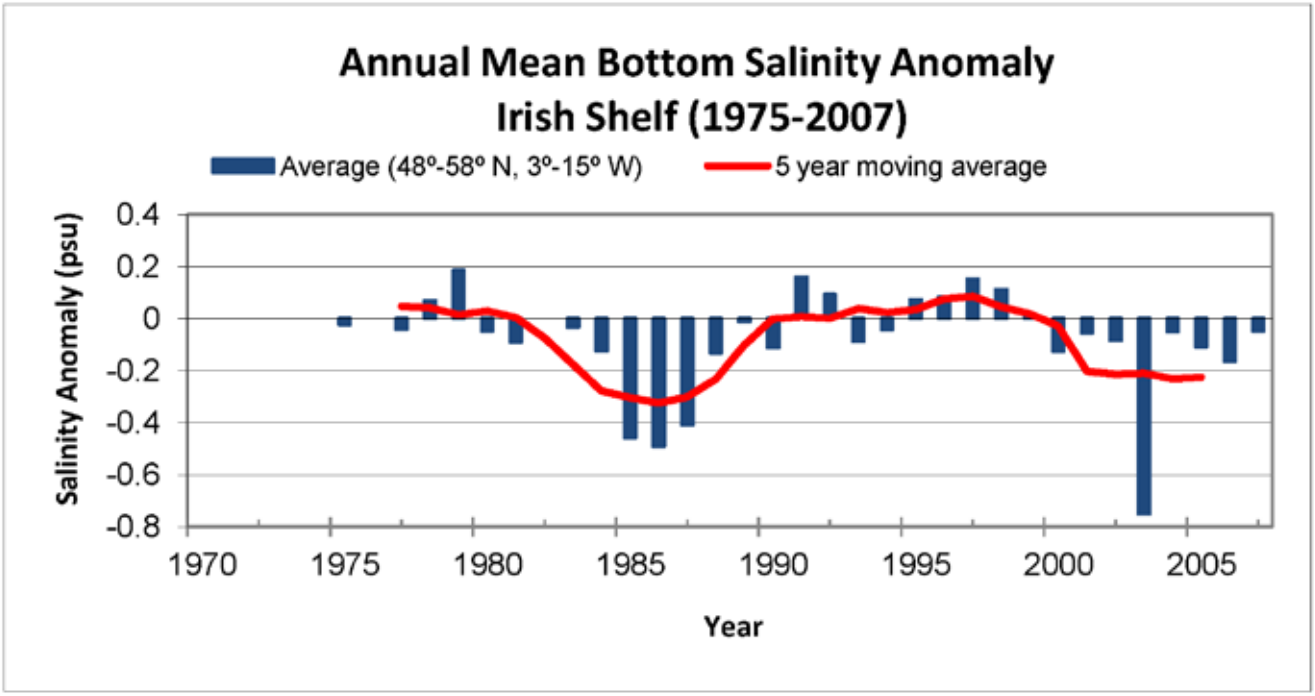


Figure 3.4. Annual mean salinity anomalies on Irish shelf (1975–2007).

13 The NAO describes a north south variation of atmospheric pressure centres between the Arctic low and subtropical Atlantic high mean sea-level pressure over the North Atlantic.

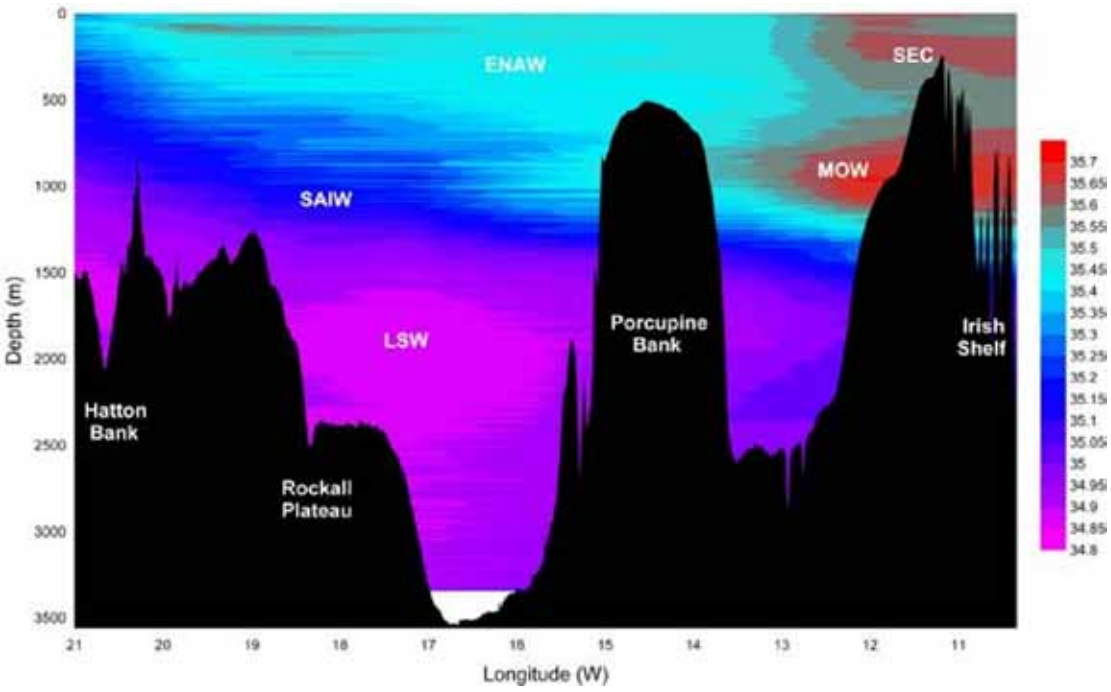


Figure 3.5. Key water masses and their salinity levels (psu) in the deep waters west of Ireland: SEC=Shelf Edge Current, MOW=Mediterranean Outflow Water, ENAW=Eastern North Atlantic Water, SAIW=Sub-Arctic Intermediate Water, LSW=Labrador Sea Water.

intermediate water masses are highly variable, with no obvious trend since these observations began.

'Annual measurements of deep-sea salinity need to be maintained to build on the existing time-series which is already revealing the complexity of sub-surface salinity.'

Maintaining the Observations

The National Weather Buoy Network is funded under a Memorandum of Understanding with the Department of Transport. Funding for this network is negotiated on an annual basis. Deep sea sub-surface salinity observations are made annually and are funded under the National Development Plan Ship Time fund and through internal Marine Institute funding.

Further Information and Data Sources

Cannaby, H. and Nolan, G. (2009) Physical oceanography. *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, 100 pp.

Fennell, S. (2007) A study of the behaviour and interannual variability of surface salinity and temperature at the M3 weather buoy off the southwest coast of Ireland. MSc, Marine Institute, Co. Galway, Ireland.

Information and observations from the Irish Marine Weather Buoy Network: http://www.met.ie/marine/marine_observations.asp

Oceanographic data from cruises are archived by the Marine Institute and may be accessed on request: http://www.marine.ie/home/publicationsdata/

Oceanographic data from cruises are archived by ICES on an annual basis: (www.ices.dk)

Information on the SMOS mission: http://www.esa.int/SPECIALS/smos/

Information on the AQUARIUS mission: http://aquarius.nasa.gov/index.html

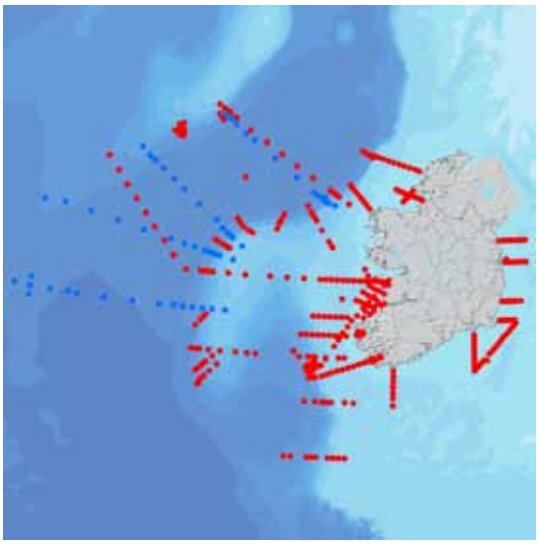
3.3 Ocean Acidification and Carbon Dioxide Concentrations

Triona McGrath, Evin McGovern, Glenn Nolan and Ned Dwyer

Atmospheric carbon dioxide (CO_2) caused by human activities is absorbed by seawater and leads to ocean acidification. It is estimated that levels of ocean acidity have increased by 30% over the last 200 years and projections by the IPCC are that it could increase by a further 120% by 2100, if emissions of CO_2 continue unabated. Although the ecological implications of ocean acidification are still unclear, there is mounting concern as to the potential effects of such rapid acidification on many marine species and in particular on calcifying species such as corals, shellfish and crustaceans. This has the potential for large knock-on effects on the whole ocean ecosystem and related socio-economic activities, including fishing and aquaculture.



Photo: © IFREMER



Map 3.3. Location of cruise tracks where observations of variables relating to the carbonate system have been carried out.

Measurements

Currently, there is no systematic ocean acidification monitoring programme in Irish waters. Between 2008 and 2010 as part of a joint project between the Marine Institute and the National University of Ireland Galway a series of measurements of carbonate and associated biochemical parameters were taken in coastal, shelf and deep waters (red), to establish the baseline state and variability of the carbonate system. These include dissolved inorganic carbon (DIC), total alkalinity (TA) and the partial pressure of carbon dioxide in the water (pCO_2).[14] pCO_2 measurements were also made in

14 Seawater pH can be calculated accurately from these parameters. Direct measurements of pH in seawater are insufficiently accurate for monitoring ocean acidification

coastal waters near the Mace Head Observatory, Co. Galway and on research surveys. Carbonate data measured across the Rockall Trough in some of the recent surveys were compared to data measured in the early 1990s by the World Ocean Circulation Experiment (WOCE) (blue).

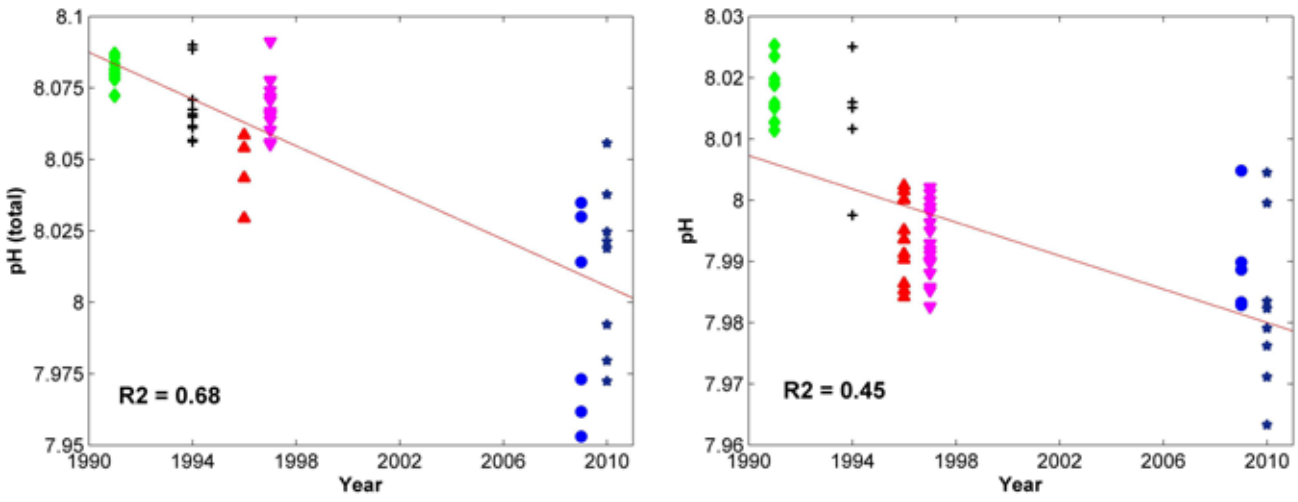
'Ocean acidity has increased significantly in sub-surface and deep offshore waters around Ireland between 1991 and 2010.'

Time-series and Trends

From measurements of DIC and TA, along with temperature, salinity and nutrients, calculations of acidity (pH) were made. In Fig. 3.6, the derived pH values are shown along the transects of the WOCE surveys (1990s) and the more recent 2008–2010 surveys in subsurface waters (a) and at depth (b) in the Rockall Trough. The different colours represent different transects. In sub-surface waters, after correcting the change in DIC for biological activity, there was a decrease of 0.043 pH units, representing an increase in acidity, between 1991 and 2010. This is in line with the IPCC's observed decline of 0.02 pH units per decade. In deeper waters (1500–2000 m) there was a decrease of 0.035 pH units, indicating an increase in acidity also at depth.

Figure 3.7 illustrates the seasonal variability in pCO_2, for a 12-month period from November 2008 to November 2009, as measured at a buoy near Mace Head. These are overlaid on the atmospheric CO_2 concentrations (green). Concentrations were generally lower in winter and higher in summer. A series of spikes recorded in summer 2009 may be associated with a large influx of freshwater into the bay area at these times. Concentrations of CO_2 measured during the open-ocean surveys generally displayed lower values over all seasons.

'Integrated monitoring of the carbonate system is vital but due to funding and resource restrictions there are no plans for continued observations at present.'



(a) (b)

Figure 3.6. Derived pH values from World Ocean Circulation Experiment (WOCE) (1990s) and more recent surveys in sub-surface waters (a) and at depth in the Rockall Trough (b).

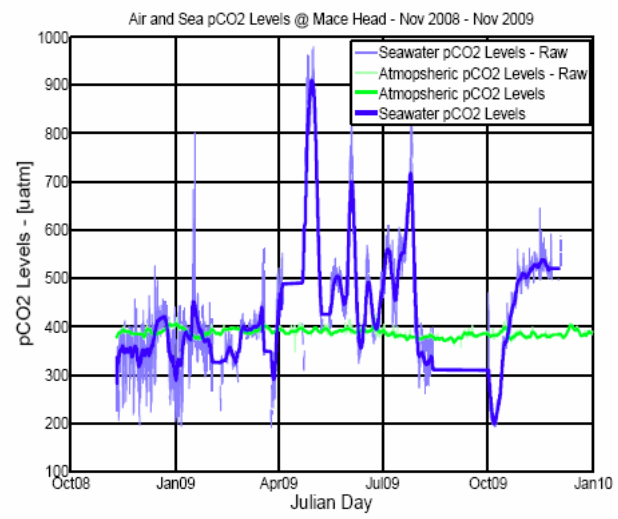


Figure 3.7. Variability in water CO_2 concentration (pCO_2), November 2008–November 2009, as measured at a buoy near Mace Head (blue). Atmospheric CO_2 concentration is also shown (green).

Maintaining the Observations

The results of this short-term project emphasise the importance of continued, integrated monitoring of the carbonate system alongside other oceanographic parameters in Irish coastal and deep waters, including vulnerable habitats such as cold water coral reefs on the Irish shelf slopes. This could be achieved cost effectively by including these parameters in current ship-based monitoring campaigns. Furthermore, the Mace Head atmospheric research station offers great potential for combined high-frequency monitoring of atmospheric-ocean processes. However, because of funding and resource restrictions, there are currently no plans for continued carbon observations.

Further Information and Data Sources

McGrath, T., Kivimae, C., Tanhua, T., Cave, R. and McGovern, E. (2012) Inorganic carbon and pH levels in the Rockall Trough 1991–2010, *Deep Sea Research-Part 1.*

Ní Longphuirt, S., Stengel, D., O'Dowd C. and McGovern, E. (2010) *Ocean Acidification: An Emerging Threat to our Marine Environment*. Marine Foresight Series No. 6, Marine Institute, Galway, p. 98.

O'Dowd, C., Cave, R., McGovern, E., Ward, B., Kivimae, C., McGrath, T., Stengel, D. and Westbrook, G. (2011) *Impacts of Increased Atmospheric CO_2 on Ocean Chemistry and Ecosystems.* Marine Institute, Galway.

Carbon data from cruises are archived by the Marine Institute and may be accessed on request: http://www.marine.ie/home/publicationsdata/

Carbon data are archived at the National University of Ireland Galway: http://www.nuigalway.ie/c-caps/

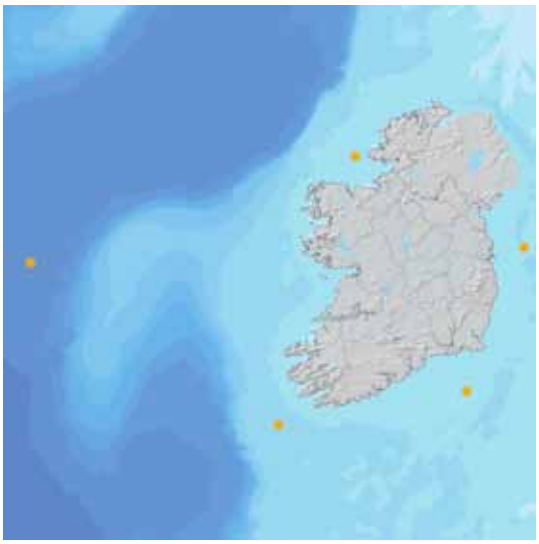
3.4 Sea State

Glenn Nolan, Ned Dwyer and Jeremy Gault

Observations of wave height, direction, length and frequency are relevant for monitoring changes in the marine environment, such as winds, storms and extreme events. Knowledge of sea state and how it is changing is also vital for the offshore oil industry, ocean energy development, shipping, coastal erosion and flooding among others. Increasing wave heights have been observed over the last 50 years in the northeast Atlantic, along with a northward displacement of storm tracks.



Photo: © Kathryn Smith



Map 3.4. Location of sea state observation stations.

Measurements

Non-directional measurements of waves have been made at the Marine Institute-operated offshore national weather buoys since 2002. Some of the buoys within the network now measure full-directional wave spectra, which provide complete information on wave frequencies and directions. By 2013 this enhanced information will become part of the standard suite of measurements on all buoys in the network.

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

'Analysis of data from satellite altimetry for the period 1988 to 2002 shows that there has been a general increase in wave height in the northeast Atlantic.'

Time-series and Trends

Analysis of data from satellite altimetry for the period 1988 to 2002 shows that there has been a general increase in wave height in the northeast Atlantic. Data from the Irish buoy network covers a relatively short

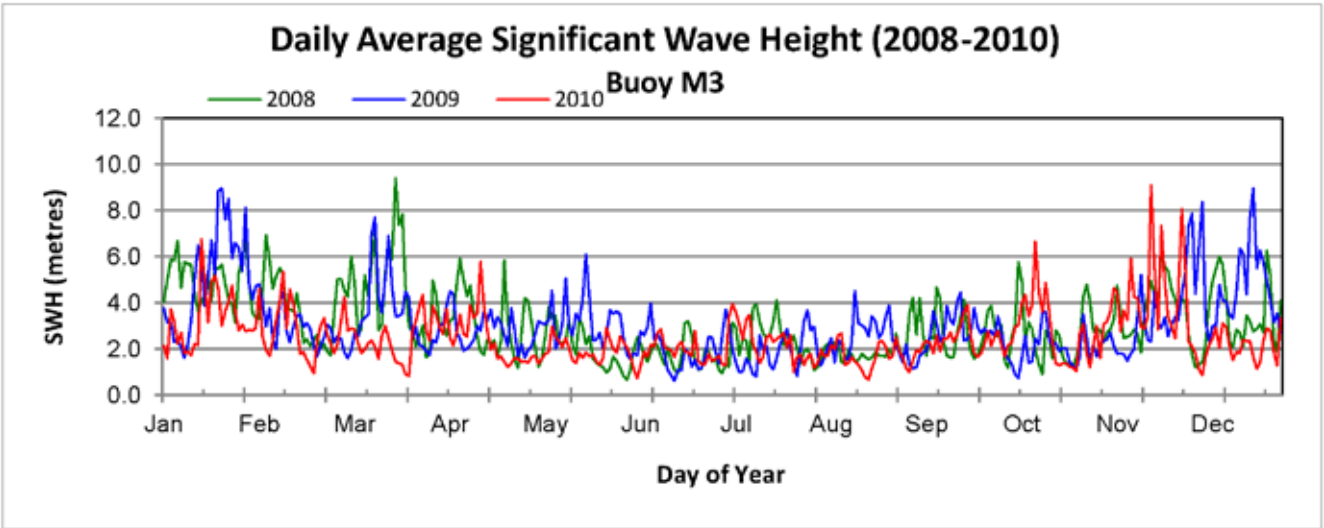


Figure 3.8. Daily averaged significant wave height at Buoy M3 (2008–2010).

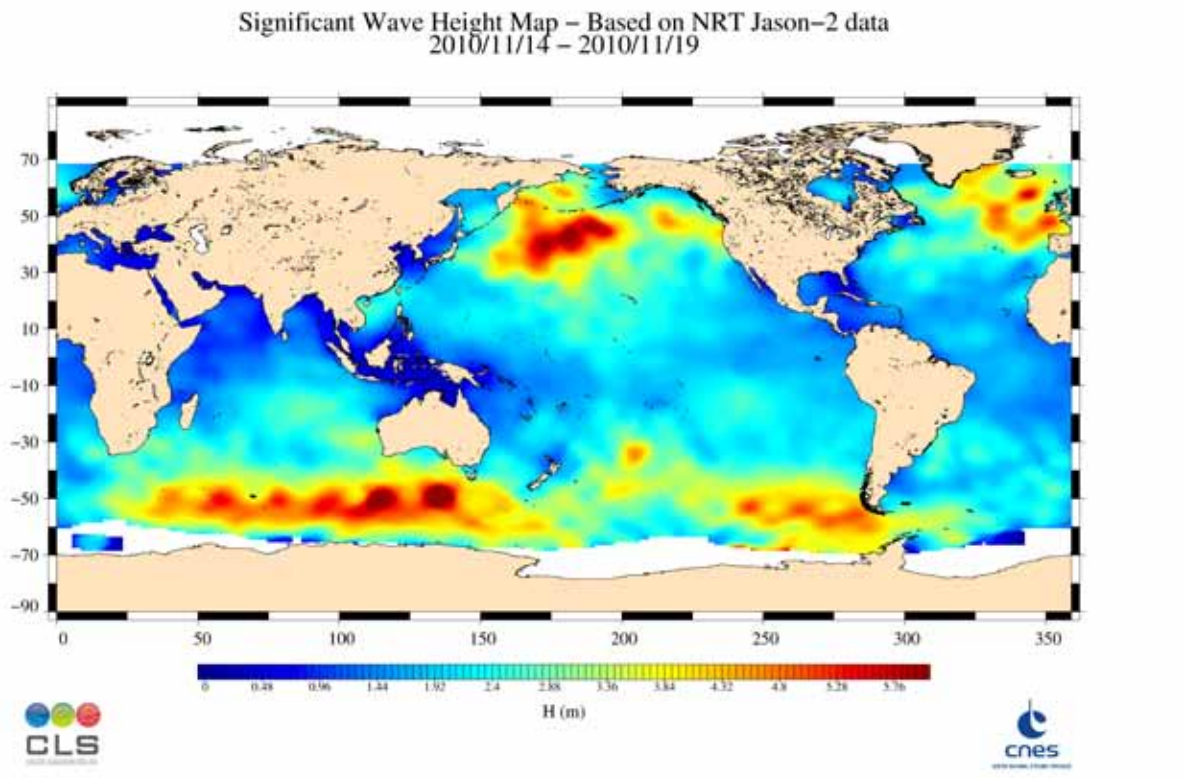


Figure 3.9. Significant wave heights as determined from measurements by the altimeter on board the *Jason-2* satellite for the period 14–19 November 2010.

period with the M3 buoy, located off the southwest coast, representing the longest available wave time-series (2002–2012) from the open ocean. Figure 3.8 shows averaged daily significant wave height (SWH)[15] for part of this time-series (2008–2010). Seasonal variations are evident: however, there is no obvious trend in the full-wave height dataset over the period 2002 to 2011.

Figure 3.9 shows the significant wave heights as determined from measurements by the altimeter on board the *Jason-2* satellite for the period 14–19 November 2010. Note the large waves observed in the northeast Atlantic, corresponding to a stormy period. These can also be seen in the M3 record above (red).

'The National Weather Buoy Network is a fundamental infrastructure for observing sea state and must be maintained.'

Maintaining Observations

The National Weather Buoy Network established in 2000 is a collaboration between the Marine Institute, Met Éireann, the UK Met Office and the Department of Transport. It is funded under a Memorandum of Understanding with the Department of Transport. Funding for this network is negotiated on an annual basis.

15 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.

Further Information and Data Sources

Woolf, D.K., Challenor, P.G. and Corron, P.D. (2002) The variability and predictability of North Atlantic wave climate, *Journal of Geophysical Research,* Vol. 107, p. 3145, doi:10.029/2001JC001124.

Information and observations from the Irish Marine Weather Buoy Network : http://www.marine.ie/home/publicationsdata/data/buoys/

Information and data on a range of wave products derived from satellite, in-situ and model data: http://www.globwave.org/

Altimeter-derived oceanographic products including sea state: www.aviso.oceanobs.com/

Story Board 3: Riding the Storm in the North Atlantic

Penny Holliday



Figure SB3.1. Location of ship during storm.

Surprisingly large wave heights were recorded in the northern Rockall Trough during a UK research cruise in February 2000. Individual wave heights of up to 29.01 m and significant wave heights (SWH)[16] of 18.5 m were observed by a ship-borne wave recorder on *RRS Discovery*. The measured SWH exceeds any previously recorded values, including those observed under hurricanes in the tropical North Atlantic. During a 12-hour period on 8–9 February, a total of 23 waves exceeded 20 m (peak-to-trough height), despite only severe storm force winds with speeds averaging 21 m/s. The extreme waves were generated by a long fetch and resonant conditions, during which the wave group travelled at the same speed as the storm itself across the North Atlantic.

SB3

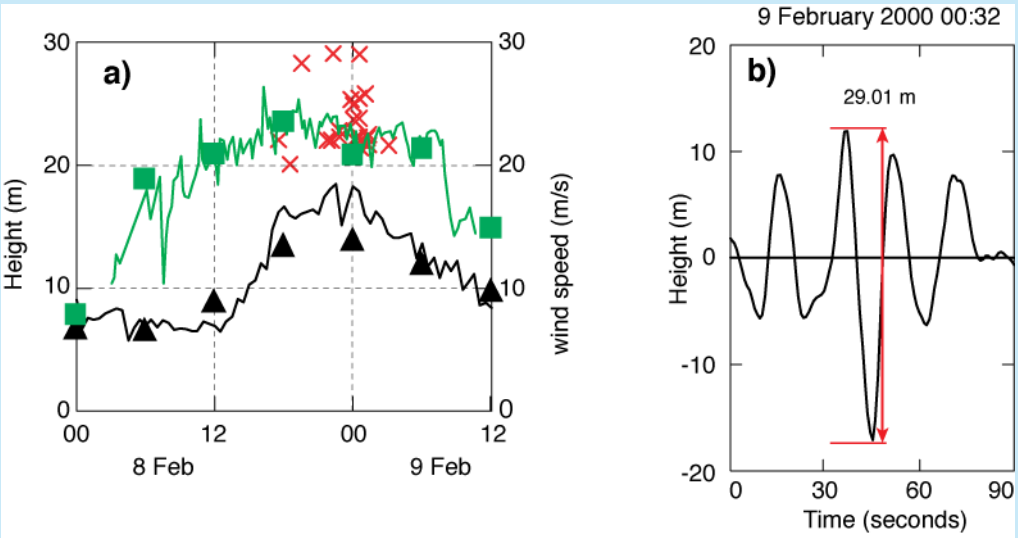


Figure SB3.2. Winds and extreme waves measured by *RRS Discovery* on 8–9 February 2000 at 57.5°N, 12.17°W (a). Black line is significant wave height, green line is wind speed (at 10 m above sea level), red crosses are individual wave heights that exceed 20 m. Wave hindcast model data shown as black triangles (significant wave height) and green squares (wind speed at 10m above sea level). The wave record showing the largest individual wave (b).

16 This is the average of the highest one-third of waves in a given period.

Wave-height climatologies developed largely from satellite data show that the sub-polar North Atlantic regularly experiences large wave heights. Particularly high waves develop under the storm track where winds are strong and the fetches can be very long. Yet the February 2000 measurements exceeded those expected according to the usual sources of wave-height information. Those subsequently predicted by a state-of-the-art wave hindcast model were lower because the resonating conditions were not replicated accurately (Fig. SB3.2). Simultaneous satellite records show only absent data at the time of the highest waves because data collected failed quality control limits during processing. The implication is that we would be unaware of the size of these waves if the ship had not been in this location at that time. This reinforces the need for *in situ* observations (on buoys and ships) to test wave models and improve climatologies.

Further Information

Holliday, N.P., Yelland, M.J., Pascal, R., Swail, V.R., Taylor, P.K., Griffiths, C.R., and Kent, E. (2006) Were extreme waves in the Rockall Trough the largest ever recorded? *Geophysical Research Letters,* Vol. 33, L05613, doi:10.1029/2005GL025238

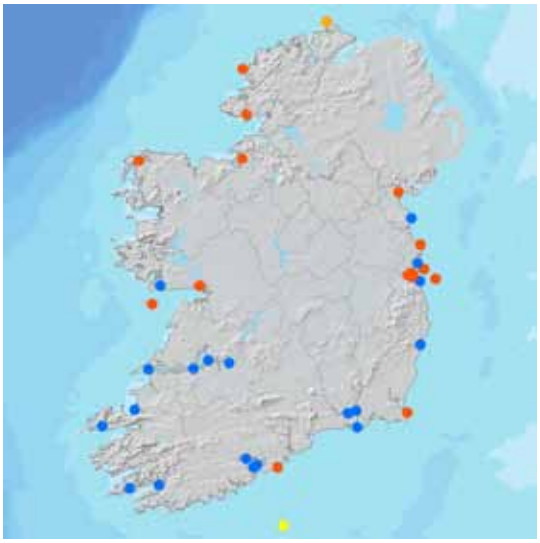
3.5 Sea Level

Ned Dwyer and Robert Devoy

All major cities in Ireland are in coastal locations subject to tides and any significant rise in sea levels could have major economic, social and environmental impacts. Estimates for the twentieth century show that the global average sea level rose at a rate of about 1.7 mm per year whilst estimates derived from satellite measurements for the period 1993 to 2012 indicate a rise of 3.18 mm per year. Sea levels are rising primarily because increasing global temperatures cause thermal expansion of the oceans as well as increasing freshwater input due to melting ice sources (e.g. glaciers and ice sheets, permafrost). An additional contributor to sea-level change, called 'isostatic glacial adjustment', has caused the north of Ireland to rise differentially as the land recovers from the loss of the huge mass of ice which covered it during the last Ice Age.



Photo: © Sean Kennedy



Map 3.5. Location of tide gauges for sea-level observation.

'Satellite observations indicate that the sea level around Ireland has risen by approximately 4–6 cm since the early 1990s.'

Measurements

Measurements of sea level rely on tide gauges which provide sea-level change relative to the land on which they lie. The longest and most reliable continuous records for Ireland are from Malin Head, Co. Donegal (orange) where a tide gauge has been in operation since 1958. A national tide gauge network (red), coordinated by the Marine Institute, is currently under development

with 17 gauges operational in 2012. Gauges are also operated by other organisations (blue) and include one deployed at the Marathon oil platform (yellow).

Sea level can also be retrieved with measurements from space-borne sensors. These sources indicate a sea-level rise around Ireland of approximately 2–3 mm per year since the early 1990s. However, satellite measurements need to be calibrated carefully, the most common method being the use of tide gauges.

Time-series and Trends

Tide gauge measurements have been made at Malin Head since 1958. However, it is difficult to access and compile a complete dataset as operation of the gauge has resided with a number of different organisations over the period. Since 2004 the Office of Public Works has been responsible for the operation of the gauge. Figure 3.10 shows the monthly mean sea level as

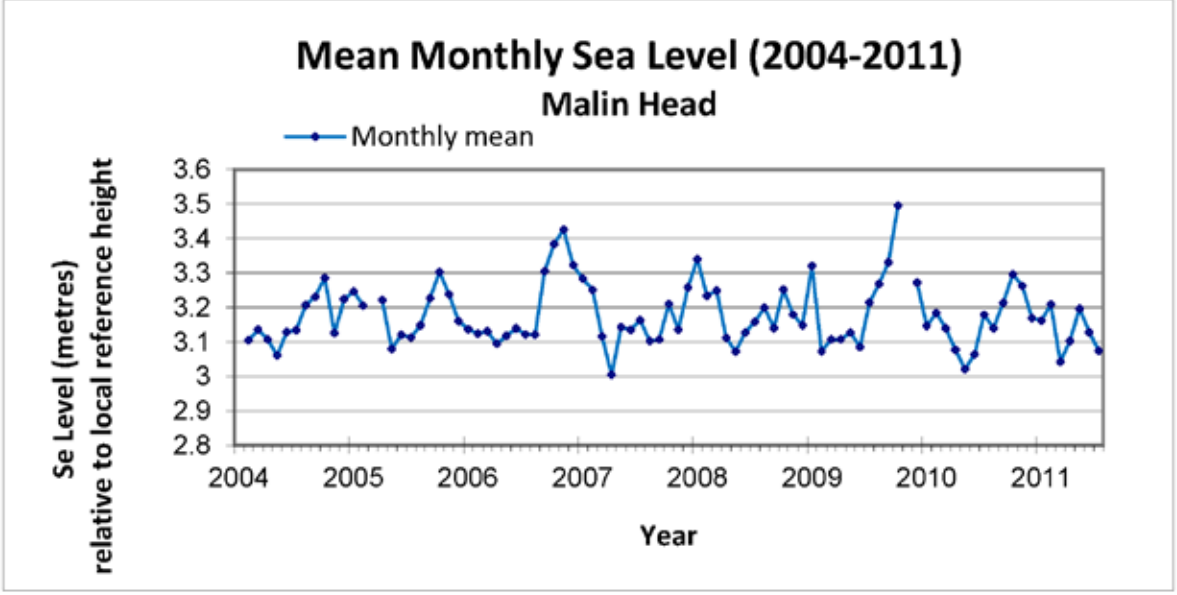


Figure 3.10. Mean monthly sea level observed at Malin Head (2004–2011).

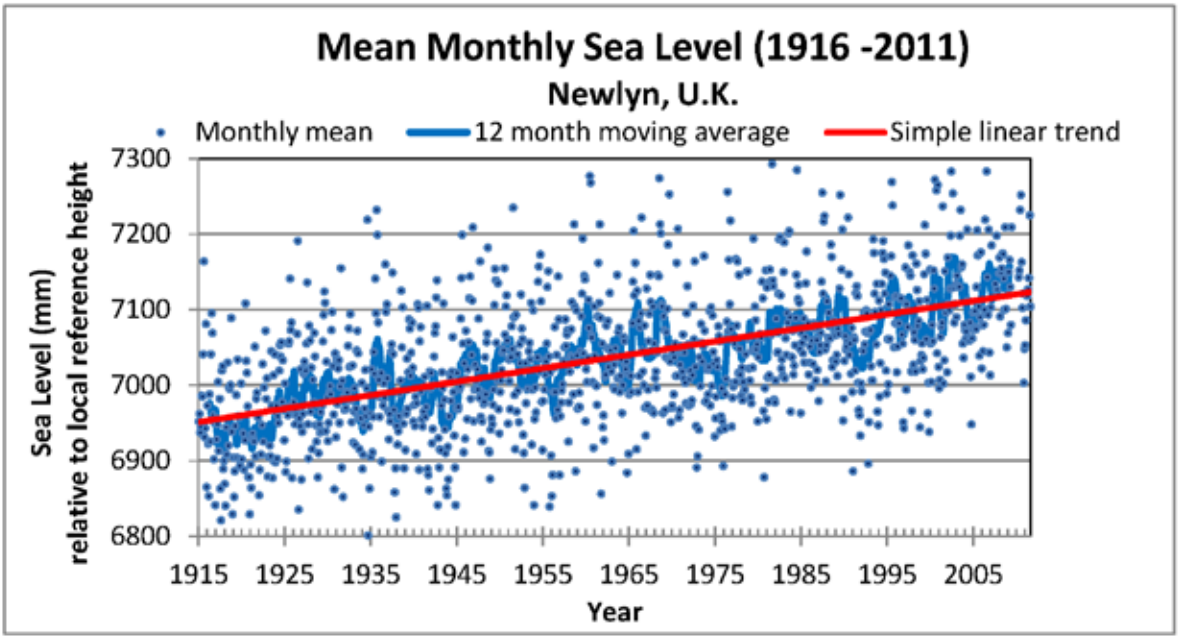


Figure 3.11. Mean monthly sea level observed at Newlyn, UK (1916–2011).

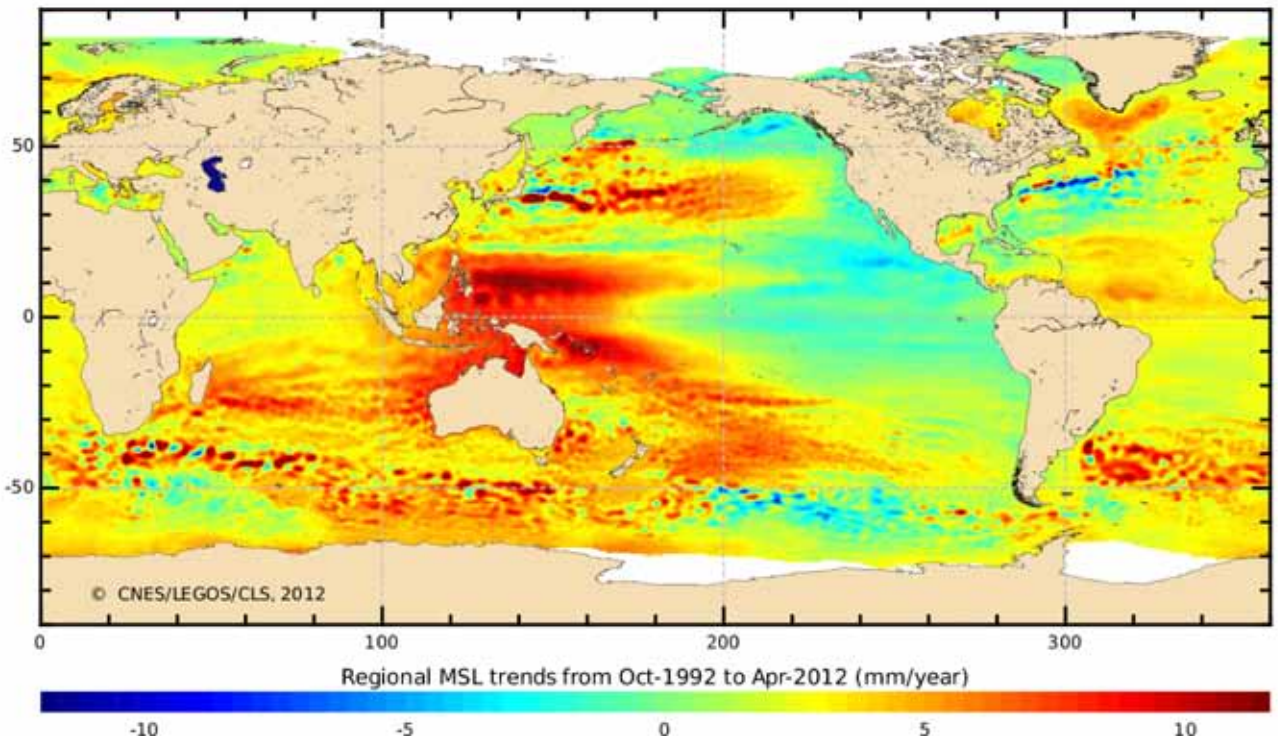


Figure 3.12. Global trends in sea level derived from satellite observations. © CLS/CNES/Legos.

derived from 15-minute measurements since 2004. As the data have not been corrected for glacial isostatic rebound, they cannot be readily used to make estimates of sea-level rise.

An extensive network of tide gauges has been in operation around the UK for many years. One of the longest time-series is available from the gauge at Newlyn in Cornwall (Fig. 3.11). Recent published analysis of these data indicates a rise in mean sea level of 1.7 (± 0.10) mm per year since 1916. This is consistent with measurements made using geological and geodetic approaches and has been attributed to climate-related change. These observations are indicative of the situation in the south of Ireland.

Figure 3.12 illustrates a global map of trends in sea level derived from data from a number of satellite altimeters, including *TOPEX/Poseidon* and the *Jason* series over the period 1992 to 2012. It reflects the impact of decadal scale climate variability on the regional distribution of sea-level rise.

'Long-term support of the Malin Head and Castletownshend tide gauge measurement sites must be guaranteed.'

Maintaining the Observations

The tide gauges installed around Ireland are owned by a number of organisations including the Office of Public Works, Met Éireann, the Marine Institute, Ordnance Survey Ireland and a number of local and port authorities. The Office of Public Work has operated the gauge at Malin Head since 2004 and is upgrading the site in 2012 to address some data-quality issues. It is also installing continuous GPS capability to assess the glacial isostatic rebound on an ongoing basis. Historical data from the Malin Head tide gauge should be collated and analysed to provide a consistent record of sea-level measurements. For climate change purposes it is vital that the Malin station and Castletownshend, Co. Cork adhere to the Global Sea Level Observing System (GLOSS) standards and are maintained for long-term monitoring. Institutional support is needed to guarantee the long-term integrity of such sites.

Further Information and Data Sources

Haigh, I., Nicholls, R. and Wells, N. (2009) Mean sea level trends around the English Channel over the 20th century and their wider context, *Continental Shelf Research*, Vol. 29, pp. 2083–98.

Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I. and Williams, S.D.P. (2009) Trends in UK mean sea level revisited, *Geophysical Journal International,* Vol. 176, pp. 19–30.

A special issue of *Oceanography* in July 2011 focused on sea level: http://www.tos.org/oceanography/archive/24-2.html

Royal Irish Academy, *3rd Scientific Statement, Climate and Sea Level Change, Irish Committee on Climate Change, Dublin,* http://ria.ie/About/Our-Work/Committees/Committees-for-Science/climate-change/statements-(1).aspx

Tide gauge data from around the world are available from: http://www.psmsl.org/data/obtaining/

Irish National Tide Gauge Network: http://www.irishtides.ie

Hydrometric data from the Office of Public Works is available from: http://www.opw.ie/hydro/

Maps and data from a range of satellite altimeter missions can be found at: http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/

Information and data from ESA's Climate Change Initiative, Sea Level project: http://www.esa-sealevel-cci.org/

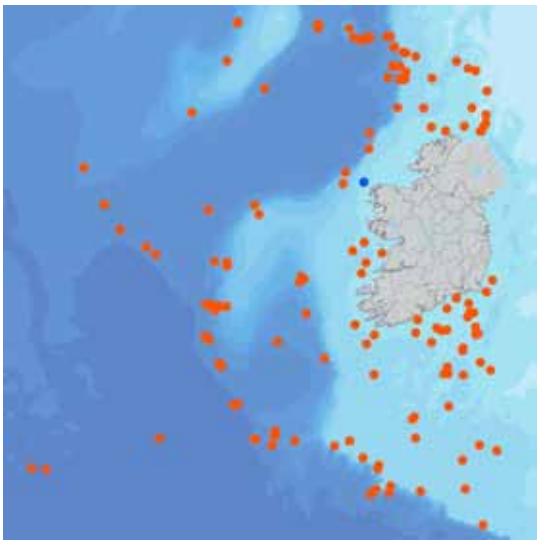
3.6 Surface and Sub-surface Currents

Glenn Nolan and Ned Dwyer

Ocean currents transport heat, freshwater and carbon from one part of the ocean to another and play a key role in determining climate conditions. The North Atlantic Current (NAC), an extension of the Gulf Stream draws relatively warm and saline subtropical waters northeastward across the Atlantic Ocean, helping to maintain the temperate climate conditions in northwestern Europe. Although multi-annual and decadal changes in the strength of the NAC have been recorded, there is no coherent evidence for a long-term trend.



Photo: ©Triona McGrath



Map 3.6. Location of current meters deployed in recent years.

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

Measurements

There are no permanently maintained current meter arrays in the ocean area adjacent to Ireland. There are a number of historical current meter and Acoustic Doppler Current Profiler (ADCP)[17]

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

records, which have been collected for research purposes. The map shows the location (red) of current meters deployed by a number of organisations in recent years. Near Belmullet, Co. Mayo (blue) current measurements have been made by the Marine Institute since 2010 in support of the evolving national ocean energy programme.

Recent research has shown that sea-surface height data from satellite altimeters and wind data from scatterometers can be combined to provide information on ocean surface currents. This work requires validation that can only be provided by *in situ* current meters.

Time-series and Trends

Figure 3.13 shows important current pathways in Irish waters.[18] Coastal currents (red) are associated with the boundaries between shallow areas where waters remain vertically mixed throughout the year and deeper regions where stratification occurs.

The Shelf Edge Current (green) is an important pathway for eggs and larvae of commercial fish species. Its strength and continuity fluctuates over seasonal and annual time scales in response to changes in the large-scale ocean atmospheric forcing.

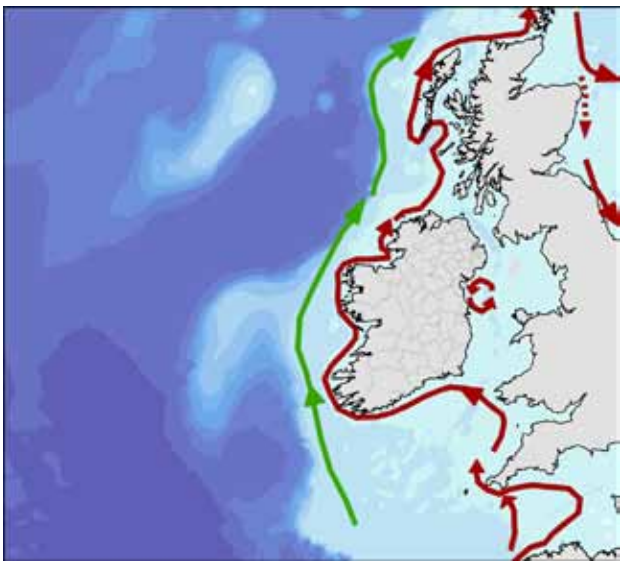


Figure 3.13. Main ocean current pathways around Ireland.

18 Adapted from Hill et al. (2008).

'The lack of a long-term current monitoring system in Irish waters represents a significant gap in the northeast Atlantic.'

Maintaining Observations

There is no long-term current monitoring system in place. Such a system would fill a significant gap in the northeast Atlantic and would be particularly useful in the Shelf Edge Current to monitor variability in a major source of Atlantic water input to the Nordic Seas. However, there are no plans or funding to advance this activity at present.

Further Information and Data Sources

Cannaby, H. and Nolan, G. (2009) Physical oceanography. *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, pp. 100.

Hill, A.E., Brown, J., Fernand, L., Holt, J., Horsburgh, K. J., Proctor, R., Raine, R. and Turrell, W.R. (2008) Thermohaline circulation of shallow tidal seas, *Geophysical Research Letters*, Vol. 35, L11605, doi:10.1029/2008GL033459.

Current meter data are archived and can be requested from the Marine Institute: http://www.marine.ie/home/publicationsdata/RequestForData.htm

Current meter data are archived and can be requested from the National University of Ireland, Galway's School of Earth and Ocean Science: http://www.nuigalway.ie/eos/

Current meter data are archived and can be requested from the British Oceanographic Data Centre: http://www.bodc.ac.uk/

Near-real time global ocean surface currents derived from satellite altimeter and scatterometer data: http://www.oscar.noaa.gov/

3.7 Ocean Colour

Ned Dwyer

Ocean colour refers to the sunlight reflected from the surface of the ocean. The particular characteristics of this reflected light are determined by the water constituents, primarily phytoplankton, suspended particles and dissolved organic compounds. Monitoring of ocean colour provides information on water quality and early warning of phytoplankton blooms and pollution events. Changes in colour patterns and characteristics can be related to and are indicative of climate changes.



Photo: © Paddy Tubbritt



Artist's impression of Envisat. Source: ESA

'No long-term trend is observed in chlorophyll concentrations derived from ocean colour observations around Ireland since 1997.'

Measurements

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

compounds. A continuous series of ocean colour datasets from a number of satellites exists since 1997.

Time-series and Trends

Chlorophyll concentration is the main parameter that is routinely derived from colour observations. Figure 3.14 shows the monthly average chlorophyll–a (Chl-a) concentration since 1997 in the northeast Atlantic around Ireland as determined from ocean colour observations by the *SeaWIFS* sensor.[19] A seasonal variation can be observed with maximum Chl-a levels reached in the summer months and a minimum in the winter. No trend is observed over the period of the measurements.

Observations of averaged Chl–a concentration for the periods January to March 2010 and June to August 2010 (Fig. 3.15) show that concentrations in the near coastal areas and the Irish Sea vary little from winter to summer.[19] However, concentrations increase significantly in the open ocean during the summer months. Note that white areas over the ocean represent cloud cover where no observations could be made.

'No systematic analysis of ocean colour observations for the northeast Atlantic has been carried out in Ireland.'

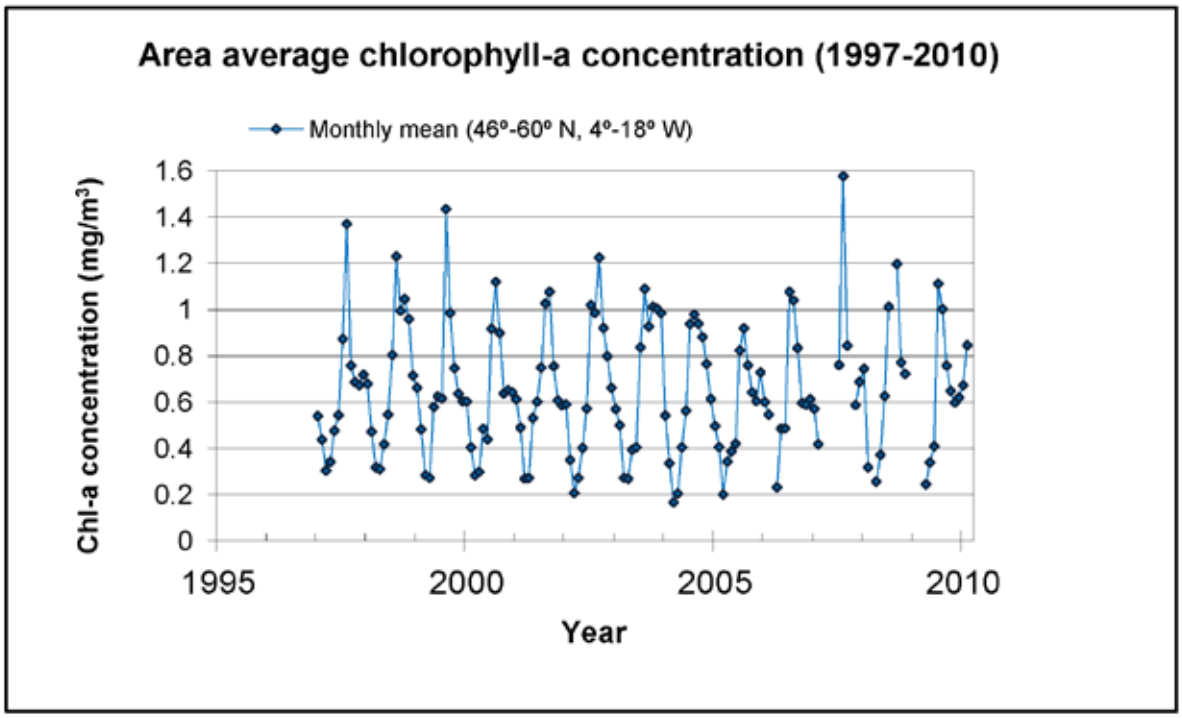
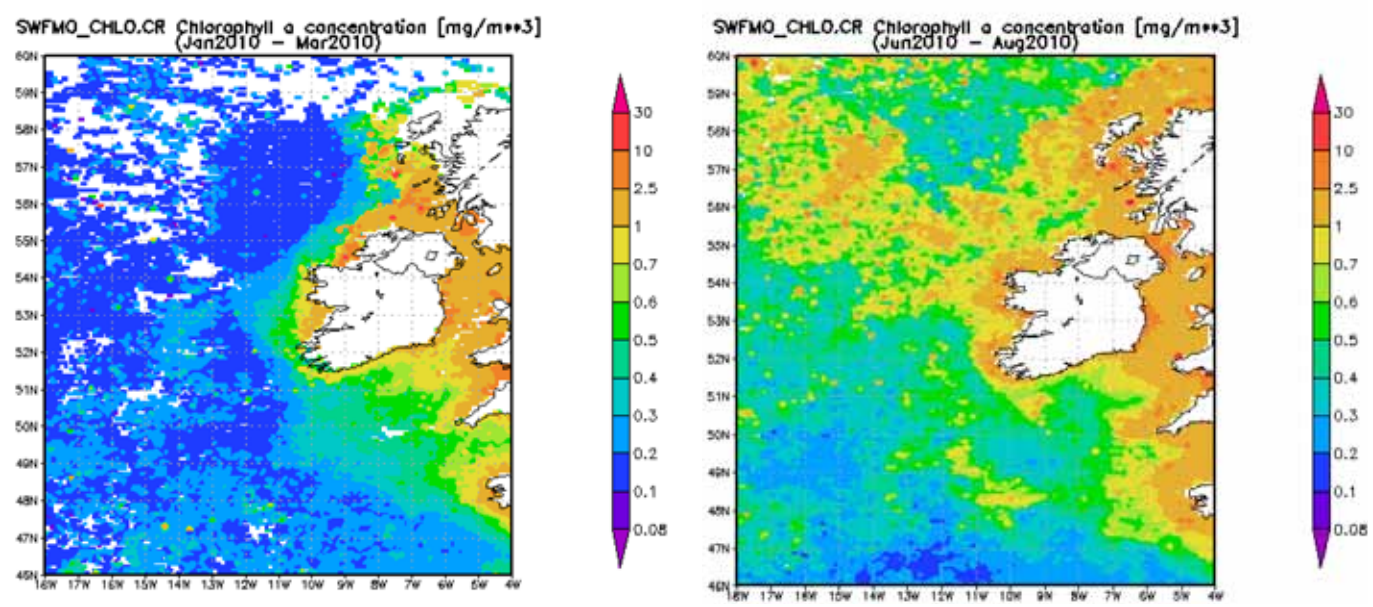


Figure 3.14. Monthly mean Chlorophyll-a concentration in the northeast Atlantic (1997–2010).

19 Analyses and visualisations used in this section of the report were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.



(a) (b)

Figure 3.15. Averaged Chlorophyll-a concentration for the periods January–March 2010 (a) and June–August 2010 (b).

Maintaining the Observations

A range of sensors from a number of space agencies makes observations of ocean colour. However, limited sensor lifetimes, inter-calibration and comparability of observations are key issues to be addressed. The reliability of satellite measurements in coastal areas needs to be improved. The existence of a 15-year time-series of colour observations for the seas around Ireland represents a valuable resource. A systematic analysis of these observations should be carried out.

Further Information and Data Sources

Acker, J.G. and Leptoukh, G. (2007) Online analysis enhances use of NASA earth science data, *Eos, Transactions*, *American Geophysical Union,* Vol. 88, No. 2, pp. 14 and 17.

International Ocean Colour coordinating group: http://www.ioccg.org/

Information and data from the ESA-funded Climate Change Initiative Ocean Colour project: http://www.esa-oceancolour-cci.org/

Information and data from the ESA-funded GlobColour project: http://www.globcolour.info/

Information and data from the ESA-funded CoastColour project: http://www.coastcolour.org/

Data from the GMES MyOcean Service: http://www.myocean.eu.org/

Information and data from NASA missions: http://oceancolor.gsfc.nasa.gov/

Data via Giovanni from the Goddard Earth Sciences and Information Services Center: http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html

3.8 Phytoplankton

Caroline Cusack, Joe Silke, Glenn Nolan and Ned Dwyer

Phytoplankton are minute organisms, mainly single-cell plants, that live in water. Like terrestrial plants they contain chlorophyll and require sunlight, nutrients, and appropriate physical water conditions to flourish. They are responsible for absorbing significant amounts of carbon dioxide (CO_2) from the atmosphere, although much of this is released when the plankton die. They are at the base of the marine food chain. Although not harvested directly by humans, phytoplankton are key to the health of marine ecosystems: therefore, any impact of climate change on phytoplankton will have significant knock-on effects.

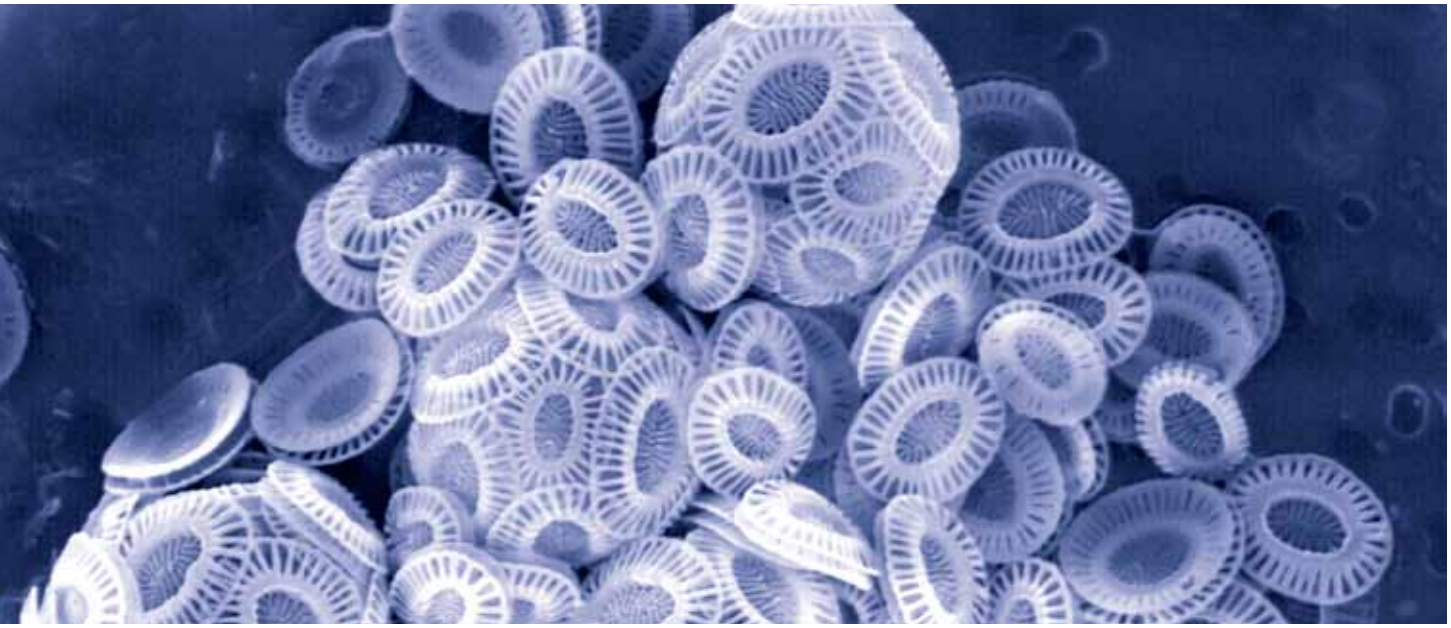
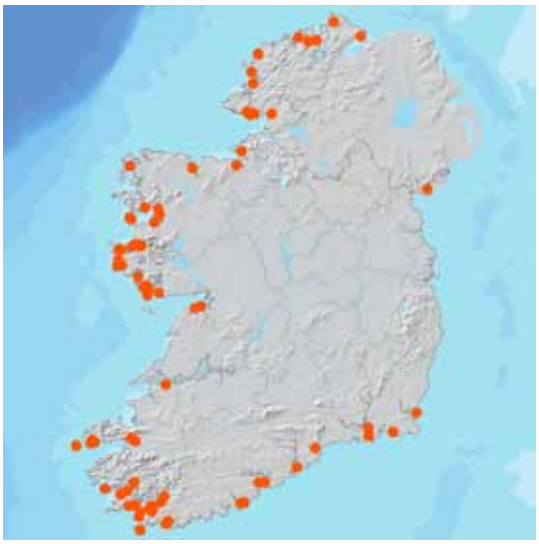


Photo: © Pauhla McGrane



Map 3.8. Location of phytoplankton observation stations.

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

Measurements

The Marine Institute analyses seawater samples for the presence of a wide variety of harmful and toxic phytoplankton from aquaculture sites around the Irish coast (red). The sampling programme is the responsibility of the Sea Fisheries Protection Authority (SFPA). At well-mixed shallow sites, surface seawater samples are collected while at deeper sites an integrated seawater sample from the water column is collected.

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. One of the longest continuous global satellite records is from the NASA *SeaWIFS* sensor which has been in operation since 1997, whilst the European *ENVISAT* made measurements of ocean colour from 2002 to 2012.

Time-series and Trends

An analysis of data on the presence and abundance of a potentially harmful microalga, *Karenia mikimotoi*, for the period 1990 to 2010 indicates its presence in Irish waters with a large interannual variability. Figure 3.16 shows the percentage of coastal water samples in which *K. mikimotoi* was present for each month since 1990. The most notable change is an increase, especially since 2001, in the percentage of samples in which it is found throughout the year, including winter. Over the last decade a warming trend has been observed in SST throughout the year in Irish waters. The Atlantic Multidecadal Oscillation (AMO) accounts for at least half of this change. This is currently in its warm (positive) phase and may be one of the reasons *K. mikimotoi* has been observed in winter samples.

'There is no operational climate change programme in place to monitor changes in phytoplankton community assemblages in Irish waters.'

Maintaining the Observations

Currently, there is no operational climate change programme in place to monitor changes in phytoplankton community assemblages in Irish waters. The data presented in this report originates from the National Monitoring Programme for Biotoxins. Phytoplankton are used as one of the biological quality elements for assessing changes in the nutrient levels of water bodies as part of the EU Water Framework Directive, coordinated by the EPA.

Further Information and Data Sources

Cusack, C. (2009) Phytoplankton, in *Irish Ocean Climate and Ecosystem Status Report 2009*. Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, pp. 100.

Silke, J., O'Beirn, F. and Cronin, M. (2005) Karenia*: An Exceptional Dinoflagellate Bloom in Western Irish Waters, Summer 2005.* Marine Environment and Health Series 21. Marine Institute, Galway, Ireland, pp. 44.

The phytoplankton data presented here are archived by the Marine Institute and may be accessed on request: http://www.marine.ie/home/publicationsdata/RequestForData.htm

Data from plankton tows in the North Atlantic are available from the Sir Alister Hardy Foundation for Ocean Science (SAHFOS): http://www.sahfos.ac.uk/

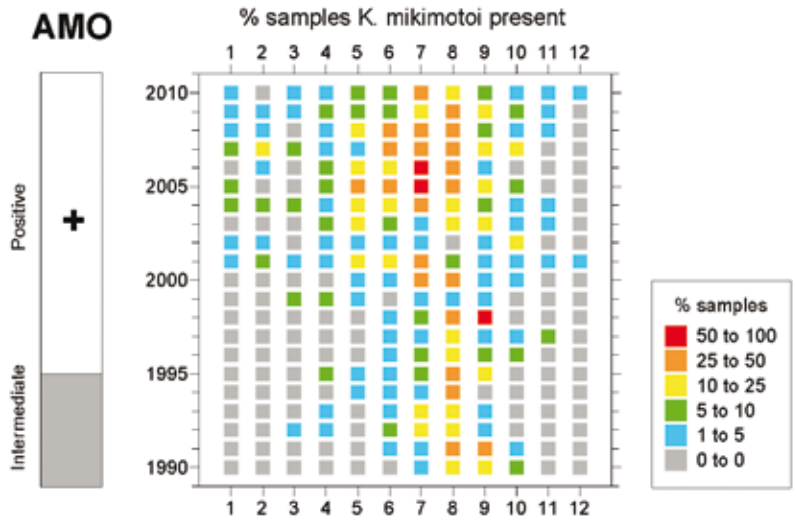


Figure 3.16. Percentage of coastal water samples in which *K. mikimotoi* was present for each month in the period 1990–2010. Also shown is the phase of the Atlantic Multidecadal Oscillation (AMO).

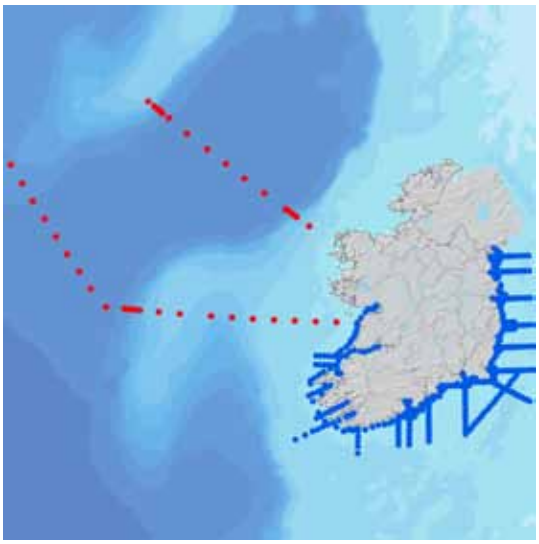
3.9 Nutrients

Triona McGrath, Evin McGovern, Glenn Nolan and Ned Dwyer

Nutrients such as phosphate, nitrate, silicate and iron control the growth of phytoplankton at the base of the marine food chain and hence play an important role in structuring marine ecosystems. Nutrient concentrations in Irish coastal waters are determined by concentrations in shelf seas and biogeochemical processes that may release or remove nutrients from the water column. Other important sources in coastal waters are associated with riverine inputs from both natural sources and 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.



Photo: © David Branigan



Map 3.9. Location of inshore points and offshore tracks where nutrient observations are made.

'As many of the factors determining nutrient concentration in coastal waters are likely to change with a changing climate (e.g. altered rainfall pattern and the effect on riverine discharges), it is critical that nutrient observations are maintained.'

Measurements

The best time to monitor nutrients is during the winter when uptake by phytoplankton is at a minimum. The Marine Institute has undertaken annual winter-nutrient monitoring surveys in the Irish Sea since 1991. This

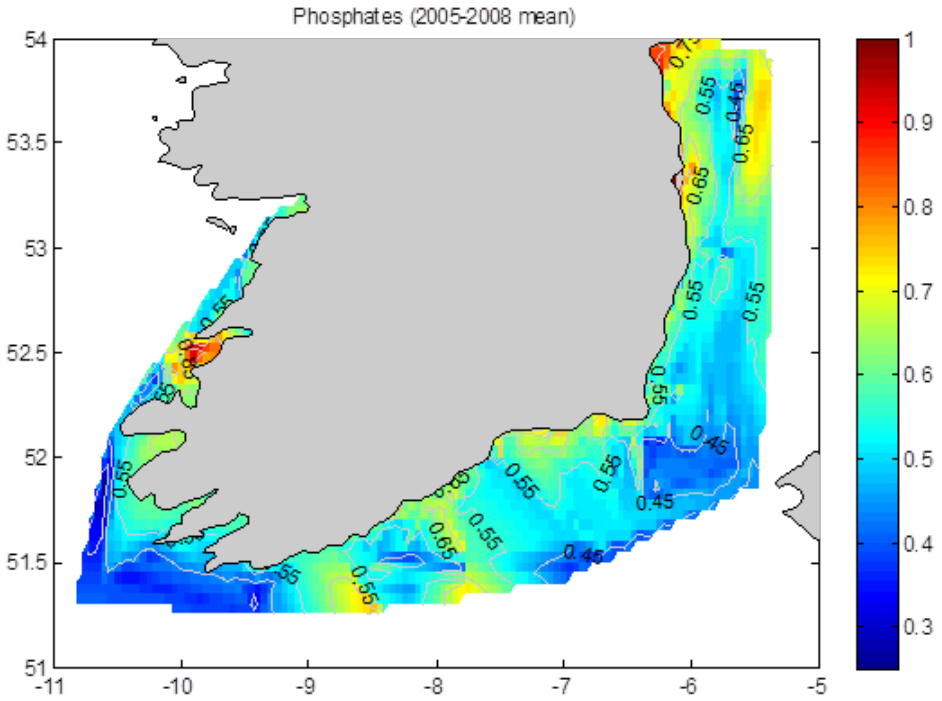


Figure 3.17. Mean surface phosphate concentrations (mμ), 2005–2008.

has been extended to the Celtic Sea and west coast waters over recent years, and includes both inshore point monitoring and transects (blue), although annual coverage is variable due to prevailing weather conditions during surveys. Nutrient data has been collected in the open ocean across the Rockall Trough (red) every winter since 2007.

Time-series and Trends

Nutrients in near-coastal areas

Trend analyses of data from 1990 to 2000, and also from 1996 to 2008, for the western Irish Sea, carried out by the Marine Institute, indicated a decrease in some nutrients. One example in Fig. 3.17 shows the mean surface phosphate concentrations in micro moles (mM) for the period 2005 to 2008 and highlights nutrient gradients from the coastline. Regions of elevated nutrients are associated with freshwater inputs and/or limited exchange of seawater.

Nutrients in the Rockall Trough

Nutrients at depth can be redistributed to the surface by mixing and water mass movements, whilst surface organic material such as plankton sinks and decomposes to release nutrients at depth. A full understanding of nutrient cycles requires sub-surface information. An example of such observations for nitrate is shown in Fig. 3.18. The vertical profiles and spatial distribution from a large number of samples for 2008 (red), 2009 (green) and 2010 (blue star) are compared with those from a similar WOCE transect in December 1996 (blue dot). This indicates relatively low nutrient concentrations in surface waters, with a sharp increase in nutrients below approximately 300 m. Lower nitrate in surface waters in 1996 relative to recent years is largely due to the earlier sampling period that year, where winter mixing had not replenished surface nutrients to their winter maximum concentrations. Below the surface layer, nutrient concentrations are similar through the water column in 1996 and 2008 to 2010.

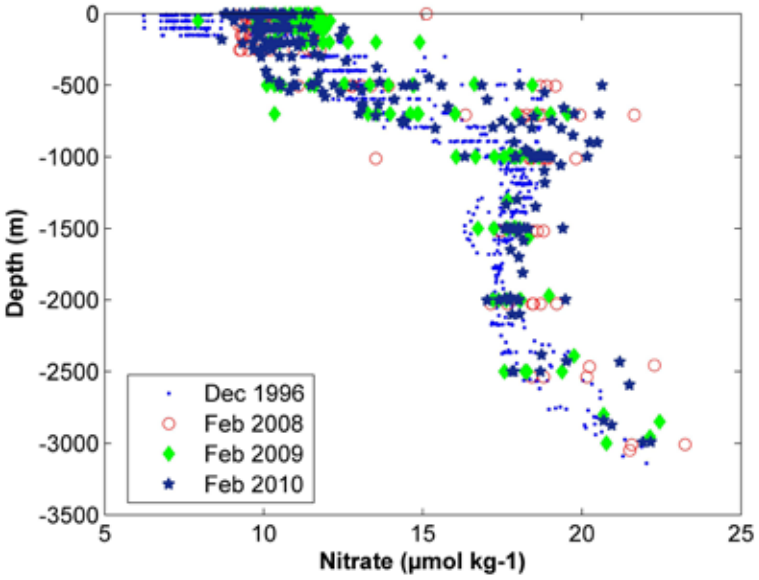


Figure 3.18. Sub-surface nitrate concentrations ((mM) from WOCE (1996) and more recent surveys in the Rockall Trough.

'Observations between 1996 and 2010 indicate that there is little change in sub-surface offshore nutrient concentration.'

Maintaining the Observations

The Marine Institute carries out an annual winter-nutrient monitoring programme in near-shore waters. Since 2007 this has been extended to include transects across the shelf in the deep sea Rockall Trough. In 2012 the inshore survey sampled northwest coastal waters for the first time. Surveys are funded under the National Development Plan Ship Time fund and through internal Marine Institute funding.

Further Information and Data Sources

McGovern, E., Monaghan, E., Bloxham, M., Rowe, A., Duffy, C., Quinn, Á., McHugh, B., McMahon, T., Smyth, M., Naughton, M., McManus, M. and Nixon, E. (2002) Winter nutrient monitoring of the western Irish Sea – 1990–2000, *Marine Environment and Health Series No. 4,* 2002, Marine Institute: Dublin.

McGrath, T., Nolan, G. and McGovern, E. (2012) Chemical characteristics of water masses in the Rockall Trough, *Deep Sea Research Part I: Oceanographic Research Papers*, Vol. 61, pp. 57–73.

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R.R. and McGovern, E. (2012) Inorganic carbon and pH levels in the Rockall Trough 1991–2010, *Deep Sea Research Part I: Oceanographic Research Papers,* Vol. 68, pp. 79–91, doi 10.1016/j.dsr.2012.05.011

Nardello, I., McGovern, E., Kiviame, C. and McGrath, T. (2009) Biogeochemical cycles in the Irish marine system, *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, pp. 100.

New, A.L., Smythe-Wright, D. (2001) Aspects of the circulation in the Rockall Trough, *Continental Shelf Research*, Vol. 21, Nos 8–10, pp. 777–810.

Nutrient data from cruises are archived by the Marine Institute and may be accessed on request: http://www.marine.ie/home/publicationsdata/

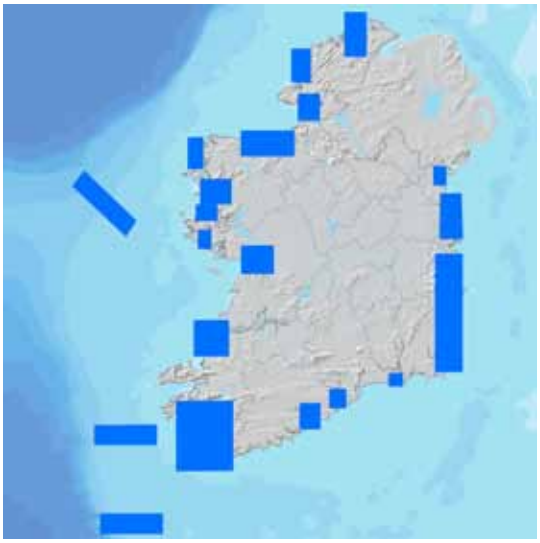
3.10 Dissolved Oxygen

Ned Dwyer, Shane O'Boyle and Glenn Nolan

There is an optimum range for dissolved oxygen concentration in oceanic water to avoid stress and potential death to ocean life. Projections indicate that concentrations could decrease by up to 20%, in part because of ocean warming and increased stratification in calm waters, leading to dead zones where no marine life is maintained. Other human-induced depletion is caused by excessive nutrient discharge into river and coastal systems. Observations are vital to give early warning of oxygen-depleted areas and to track the impact of climate change.



Photo: © Ned Dwyer



Map 3.10. Location of areas where dissolved oxygen observations are made.

Measurements

As part of the EPA's national estuarine and coastal waters-monitoring programme, dissolved oxygen measurements have been made in 20 coastal locations during the summer months since 2001. Additional measurements have been made off-shore by the *RV Celtic Explorer* and *RV Celtic Voyager* operated by the Marine Institute. All the measurements have been in areas of less than 200m depth.

'Modelled dissolved oxygen saturation shows healthy levels for the seas around Ireland.'

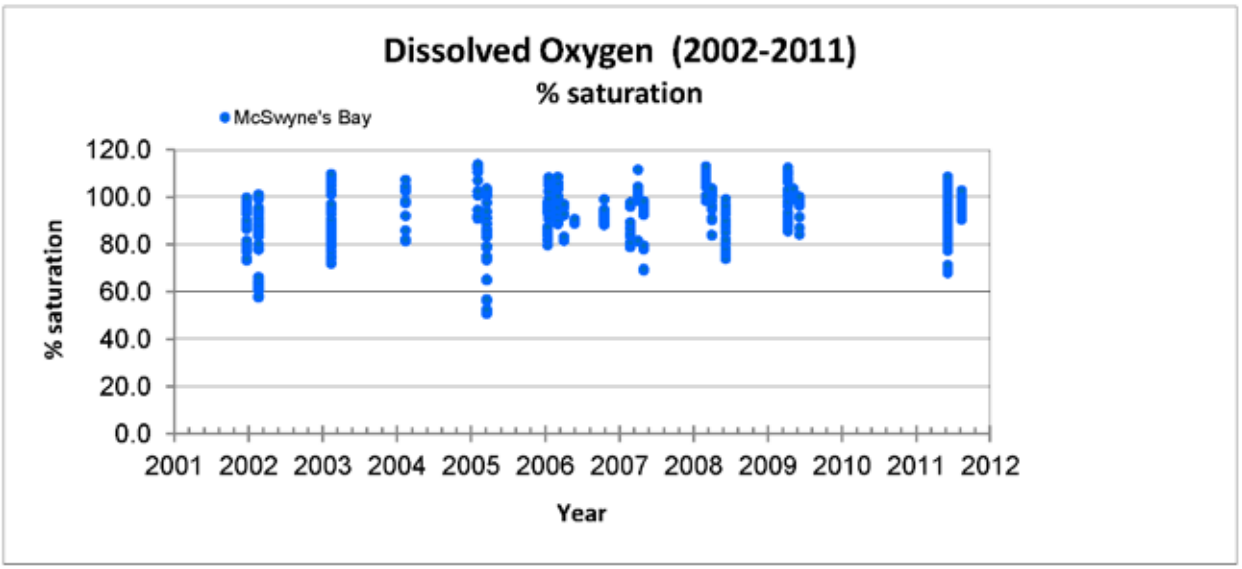


Figure 3.19. Percentage saturation of dissolved oxygen at McSwyne's Bay, Co. Donegal, 2002–2011.

3

Time-series and Trends

Figure 3.19 shows the percentage saturation of dissolved oxygen taken at sampling sites in McSwyne's Bay, Co. Donegal, mainly during summer months, from 2002 to 2011. Measurements were made at water depths ranging from just below the surface to 30 m. In general, the saturation levels were high over the period of the observations. Super-saturated values (>100%) usually occur in the well-mixed surface layer, while the lower saturation values are found in stratified sub-surface layers.

The distribution of bottom oxygen saturation levels is not measured directly but inferred from a robust model which uses the *in situ* data measurements. Figure 3.20 shows that highest bottom saturation values of 90% to 100% are associated with shallow bays and the mixed

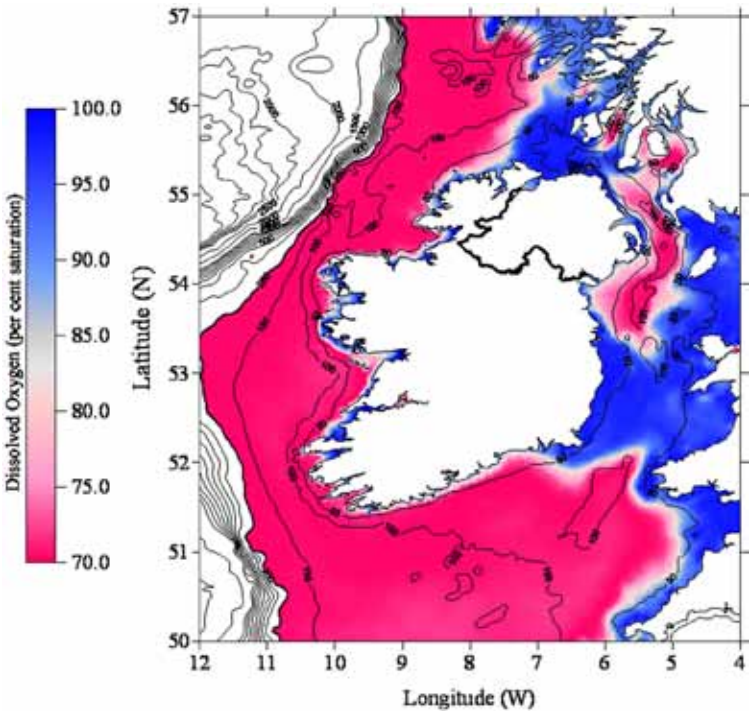


Figure 3.20. Distribution of modelled bottom dissolved oxygen saturation in Irish coastal and shallow shelf waters.

waters of the southern and eastern Irish Sea, and the southern Malin shelf between Ireland and Scotland. The lower values (approximately 70%) are associated with deep bays in southwest Ireland and offshore areas where the water is stratified. The sharp transition zone between higher and lower saturation levels reflects the distribution of thermal boundaries that separate mixed and stratified waters in the region. Saturation levels below 30% would be a cause for concern at the typical temperatures of the waters around Ireland.

A reduction in bottom dissolved oxygen levels due to enhanced stratification, while not sufficient in itself to cause oxygen depletion, increases the vulnerability of these stratified waters to impacts from the collapse of naturally occurring phytoplankton blooms and inputs from human activities such as discharges from wastewater treatment plants.

'Observations are vital to give early warning of oxygen-depleted areas and to track the impact of climate change.'

Maintaining the Observations

The EPA carries out annual measurements of dissolved oxygen content in coastal and estuarine waters as one of the measures under the Water Framework Directive. The Marine Institute measures dissolved oxygen during annual ship surveys carried out in offshore waters.

Further Information and Data Sources

O'Boyle, S., and Nolan, G. (2010) The influence of water column stratification on dissolved oxygen levels in coastal and shelf waters around Ireland, *Biology and Environment: Proceedings of the Royal Irish Academy,* Vol. 110B, No. 3, pp. 195–209.

O'Boyle, S., McDermott, G. and Wilkes, R. (2009) Dissolved oxygen in estuarine and coastal waters around Ireland, *Marine Pollution Bulletin,* Vol. 58, pp. 1657–663.

Vaquer-Sunyer, R and Duarte, C.M. (2008) Thresholds of hypoxia for marine biodiversity, *Proceedings of the National Academy of Sciences*. Vol. 105, p. 40.

Story Board 4: Hidden Treasure – Ireland's Deep-water Corals

Max Kozachenko

SB4

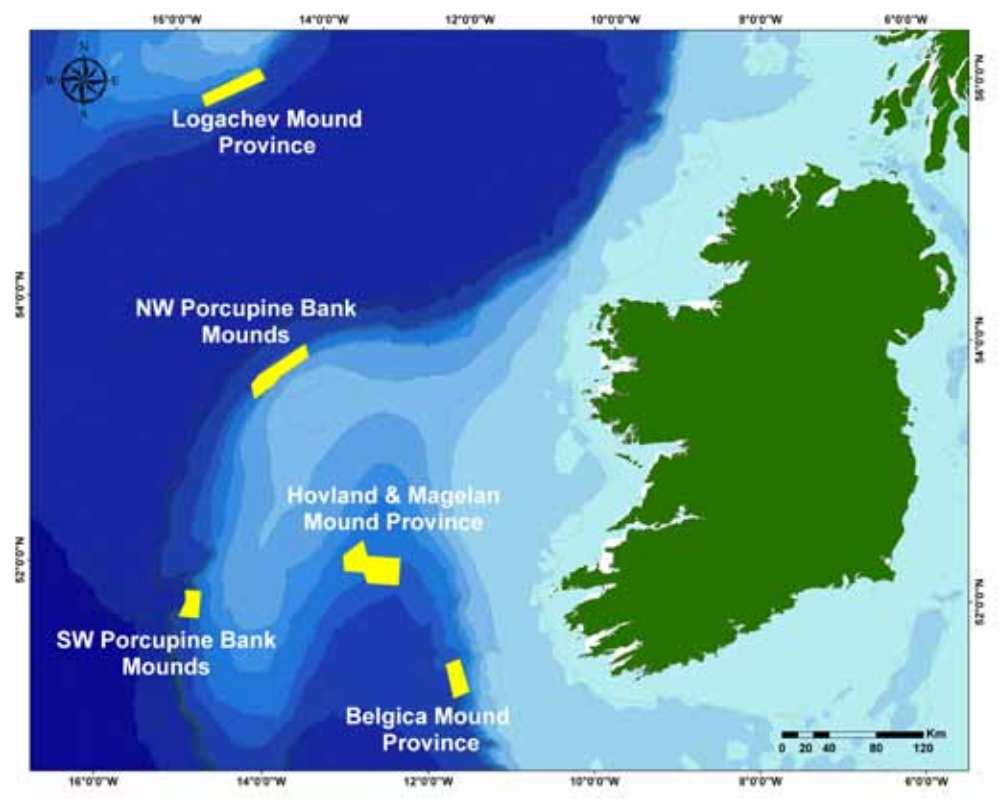


Figure SB4.1. Location of the main mound provinces in the Northeast Atlantic region.

Deep in the dark, cold waters of the Northeast Atlantic, the presence of corals has been known since the eighteenth century. However, the technologies to allow mapping of the full extent of these habitats has become available only in the last 20 years. These include multibeam and side-scan sonar as well as underwater video cameras which have revealed the spectacular shapes and colours of these underwater creatures.

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 and 1000 m and worldwide are found at depths of up to 2000 m. The main differences between these corals and their shallow water tropical counterparts are that they are able to survive in complete darkness below the light penetration depth and can tolerate water temperatures as low as 4°C. Warm-water reefs have a higher diversity of coral species in comparison to cold-water reefs (which are normally constructed with one or two main coral species), but the diversity of associated fauna is much higher among cold-water corals. The dominant reef-forming corals on the Northeast Atlantic margin are *Lophelia pertusa and Madrepora oculata.*

Corals normally grow in distinct localities (known as 'provinces') and may form small patches on the seabed,



Figure SB4.2. Photograph taken from a remotely operated vehicle (ROV) of deep-water corals at 800 m depth in the Porcupine Seabight, northeast Atlantic. The number of other creatures that can be seen in this photograph illustrates the high biodiversity of these corals. (Photo: © IFREMER).

small coral-topped mounds (25–100 m across and 5 m high) or giant carbonate mounds (1–5 km across and 50–300 m high). Live corals have been found in the Belgica, Logachev and the NW Porcupine Bank mound provinces. The Hovland and Magelan mounds are no longer active and have been completely covered with marine sediments (Fig. SB4.1).

For corals to begin to grow, a suitable hard substrate to which they can attach is needed. This can be made up of stones, shells or man-made objects such as ship-wrecks or oil industry installations. In addition, the corals need clean and fast-flowing water, and a sufficient food supply as they feed on particles (e.g. plankton) supplied by deep-sea currents in contrast to shallow water corals that get energy from symbiotic algae.

Why are Deep-water Corals Important?

Deep-water corals are associated with high biodiversity. Hence, fish are attracted to coral-populated areas because they provide enhanced feeding possibilities, a hiding place, and a nursery area (Fig. SB4.2). In recognition of their importance as habitats and their natural heritage significance, some of Ireland's deep-water coral settlements have been designated as the first marine Special Areas of Conservation (SAC).

Deep-water Corals and Climate Change

It is estimated that the carbonate mounds on which the corals are found initiated their growth *c.* 1.8 to 2 million years ago. Analyses of long sediment cores through these mounds suggest that the mound growth process was driven by changes in global climate. During warm interglacial periods, growth was driven by biological coral growth (average mound growth rate 10 cm per thousand years); during cold glacial periods biologically driven mound growth stopped, but mound elevation continued due to sediment deposition (average mound growth rate 5.8 cm per thousand years). Hence, deep-water coral carbonate mounds contain unique records of past climate change. Reconstructions of such past changes can potentially help to predict future trends.



Figure SB4.3. The fishing trawl track has badly damaged the coral in this video still from the Belgica mound province, eastern Porcupine Seabight, northeast Atlantic. © IFREMER.

Threats to Deep-water Corals

Commercial deep-sea fishing and the expanding offshore oil industry are the main threats to deep-water coral ecosystems and affect the corals' vitality through pollution, mechanical impact and increased sedimentation rates. Bottom trawling for deep-sea fish (e.g. Orange-Roughy) has been shown to destroy coral reefs completely beyond recovery (Fig. SB4.3). Oil-drilling operations are likely to increase the amount of suspended sediment that clogs coral polyps and together with oil pollution can harm corals.

Further Information

A comprehensive introduction to cold-water corals: http://www.lophelia.org/

The EU-funded Atlantic Coral Ecosystem Study: http://www.ecoserve.ie/projects/aces/

De Mol, B., Kozachenko, M., Wheeler, A., Hugo, A., Henriet, J.-P and Olu-Le-Roy, K. (2007) Thérèse Mound: a case study of coral bank development in the Belgica Mound Province, Porcupine Seabight, *International Journal of Earth Sciences,* Vol. 96, No. 1, pp. 103–20.

Wilson, J.B. (1979) The distribution of the coral Lophelia pertusa (L.) [L. prolifera (Pallas)] in the North East Atlantic, J. Mar. Biol. Assoc. UK, Vol. 59, pp. 149–64.

Wheeler, A.J., M. Kozachenko, L.-A. Henry, A. Foubert, H. de Haas, V.A.I. Huvenne, D.G. Masson, K. Olu-Le-Roy (2011) The Moira Mounds, small cold-water coral banks in the Porcupine Seabight, NE Atlantic: Part A—an early stage growth phase for future coral carbonate mounds? *Marine Geology,* Vol. 282, Nos 1–2, pp. 53–64.

Wheeler, A.J., Beyer, A., Freiwald, A., de Haas, H., Huvenne, V.A.I., Kozachenko, M., Olu-Le Roy, K. and Opderbecke, J. (2007) Morphology and Environment of Cold-water Coral Carbonate Mounds on the NW European Margin, *International Journal of Earth Science,* Vol. 96, 37–56, Series: 1.



4. Terrestrial Observations

4.1 Land Cover

Ned Dwyer

Land cover – the physical ground cover, such as grassland, forest, built environment, etc. – plays a key role in providing living space, food, water, energy and recreational opportunities. Land cover is the result of the complex interactions between climate and socio-economic factors. It affects and modifies climate in terms of water exchange from the ground to the atmosphere as well as contributing to the capture and release of greenhouse gases and aerosols. Information on land cover change is important in order to quantify these effects.



Photo: © Ned Dwyer

Measurements

Land cover is derived from analysis of a variety of data sources. At the local-scale ground surveys are the most effective tool whereas on regional and national scales aerial and satellite images are used. Aerial imagery from Ordnance Survey Ireland 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 programme.[20] A range of land-cover maps has been created for other purposes, such as the Teagasc Land Cover 1995, as part of a soils and sub-soils project and MOLAND which focuses on urban areas. LUCAS (Land Use and Cover Area frame Survey) is a European-scale collection of statistics on land-use change, where land-use observations are collected at points across the continent. Ireland was surveyed in 2009, with more than 4000 observations made.

Figure 4.1 shows the CORINE 2006 land-cover map for Ireland. Land cover is dominated by pastures, with complex and fragmented field patterns. Most arable land is found to the south and east and there is a small, fragmented forest area and a high proportion of wetland (peatland) cover types.

20 CORINE produces a land-cover map of the European environmental landscape based on interpretation of satellite images.

'In terms of land use there has been a significant net removal of carbon, in recent years, primarily due to an increase in forest area.'

Time-series and Trends

Figure 4.2 shows emissions (+) and removals (-) of carbon associated with the management and use of land from 1990 to 2010. In recent years, with an increase in forest, there has been a large increase in net removal of carbon.

The coloured polygons in Figure 4.3 represent areas that have changed from one land cover type to another around Dublin between 2000 and 2006. The colours represent the land cover in 2006. There has been an increase in urban development and infrastructure mainly on the periphery of the city, and a number of newly forested areas have been established in the Wicklow mountains area to the south. One of the major land-use changes across Ireland since 1990 has been the conversion of grassland and peatland to forest.

'A consolidated land assessment capability needs to be put in place with a view to developing a coherent and consistent set of land cover and land-use products.'

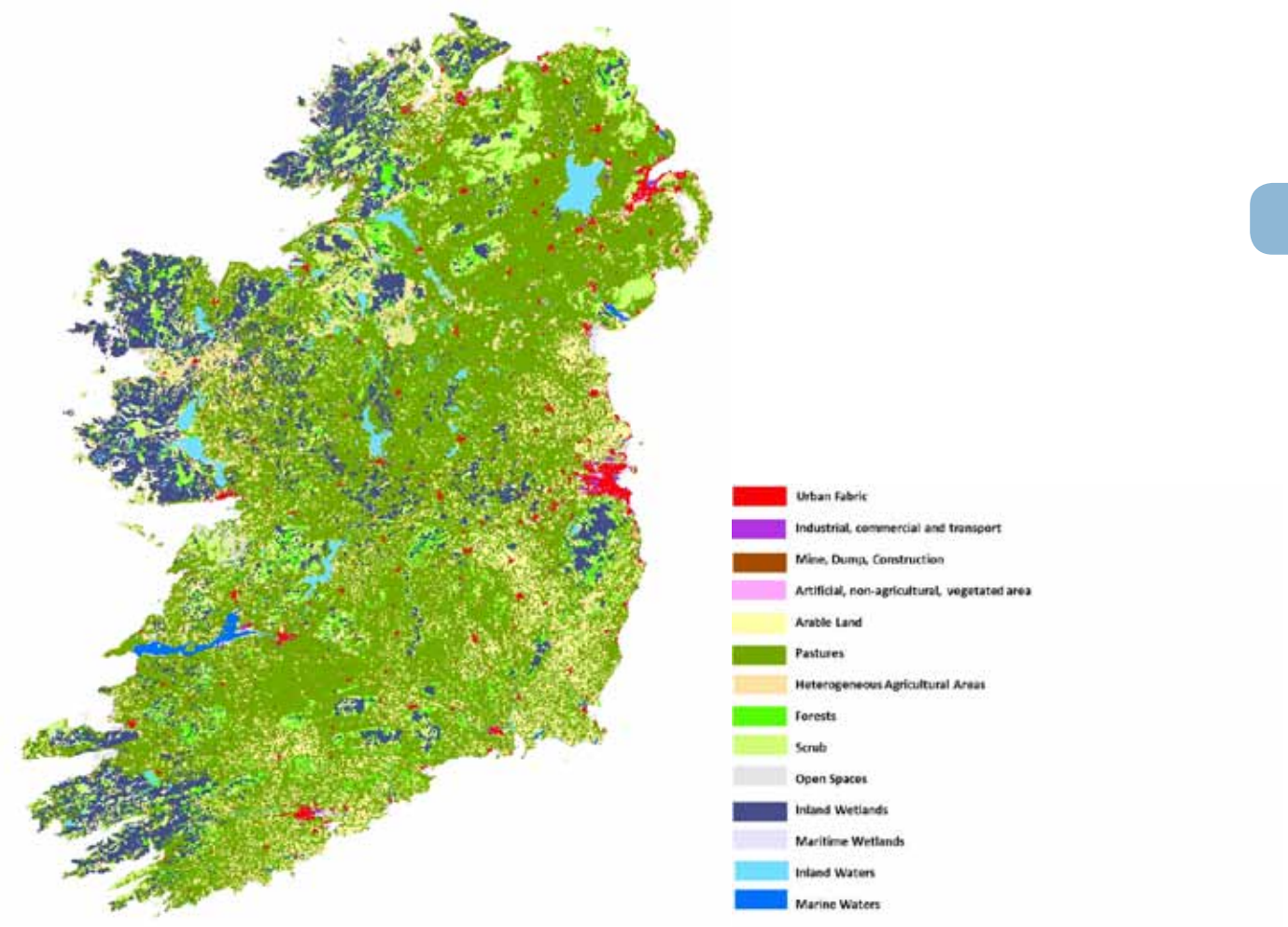


Figure 4.1. CORINE land cover map of Ireland (2006).

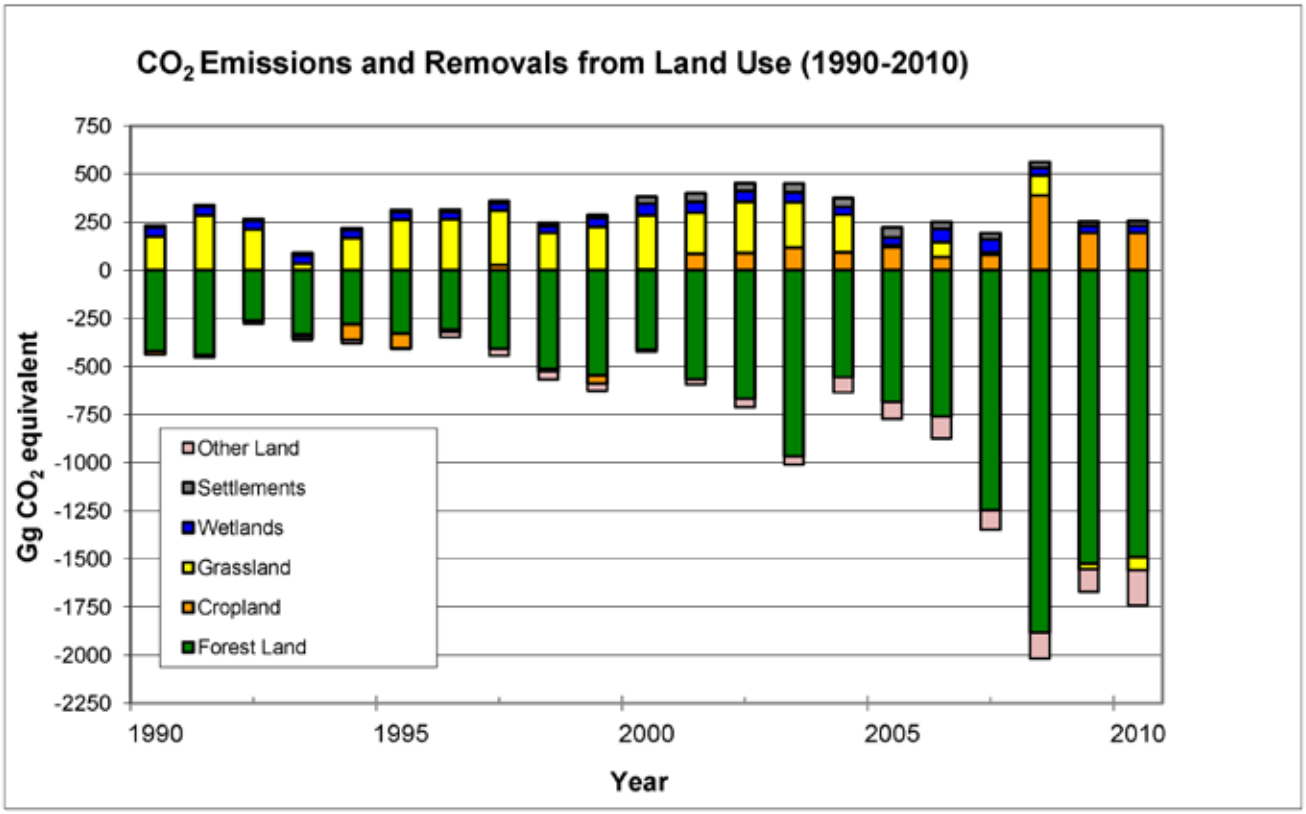


Figure 4.2. Emissions (+) and removals (-) of carbon associated with the management and use of land (1990–2010).

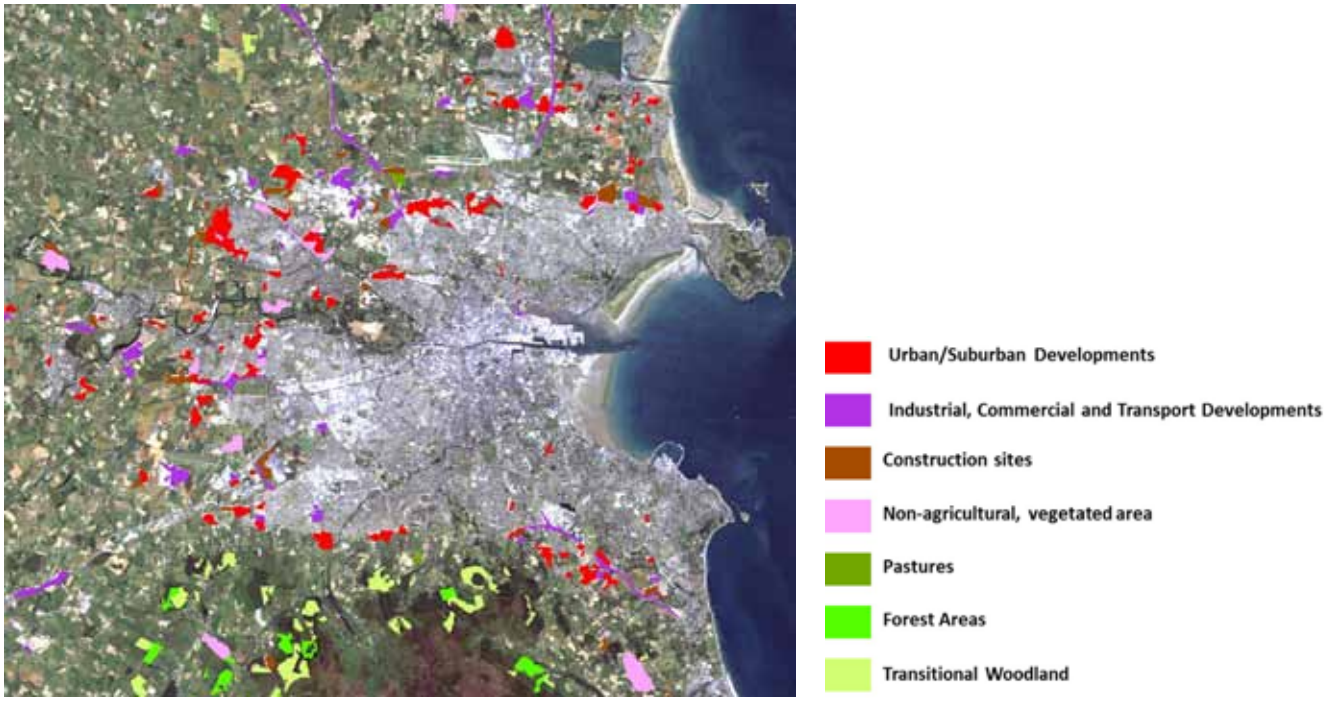


Figure 4.3. Land cover change in and around Dublin between 2000 and 2006 based on analysis of CORINE data.

Maintaining the Observations

The EPA oversees production of CORINE for the Republic of Ireland. The next CORINE land-cover map will be produced in 2013, based on 2012 data and will also encompass new high-spatial resolution maps of artificial surfaces, forest areas, agriculture areas, wetlands and water bodies. A number of other land-cover maps have been generated using differing methodologies and classification systems for individual institutional purposes or in response to European requirements. This makes integration very difficult. A consolidated land-assessment capability needs to be put in place with a view to developing a coherent and consistent set of land-cover/use products that takes the needs of the various land-cover communities into account.

Further Information and Data Sources

Duffy, P., Hanley, E., Hyde, B., O'Brien, P., Ponzi, J., Cotter, E. and Black, K. (2012) *National Inventory Report, 2012. Greenhouse Gas Emissions 1990–2010,* Reported to the UNFCCC, EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Information on Teagasc's land cover map can be found at: http://www.teagasc.ie/news/2010/201003-02.asp

Information on the MOLAND project of the Joint Research Centre of the European Commission is available at: http://moland.jrc.it/index.htm

The GEOLAND 2 project funded by the European Commission produces a range of land-mapping products: http://www.gmes-geoland.info/home.html

CORINE datasets are available from the EPA at: http://www.epa.ie/whatwedo/assessment/land/corine/datasets/

Forest Inventory data is available from the Forest Service at: http://www.agriculture.gov.ie/forestservice/forestservicegeneralinformation/abouttheforestservice/forestcoverdatasets/

Information and data for Ireland from the European Commission's LUCAS initiative may be found at: http://epp.eurostat.ec.europa.eu/portal/page/portal/lucas/data/lucas_primary_data_2009

4.2 Albedo

Ned Dwyer and Rory Scarrott

Albedo is the proportion of the total solar incident radiation that is reflected by the Earth's surface. Surfaces such as snow reflect most of the incident radiation and have a high albedo. Surfaces that absorb most of the incident radiation, such as dense forest and water bodies, have low albedo. The average Earth albedo is 0.3 on a scale from 0.0 to 1.0. However, this changes regionally and seasonally. Monitoring of albedo is important as changes of the Earth's surface due to natural and human causes influence the energy balance and hence climate. This is particularly important in polar, sub-arctic and glaciated regions.



Photo: © Karl Jordan



Artist's impression of Envisat. Source: ESA

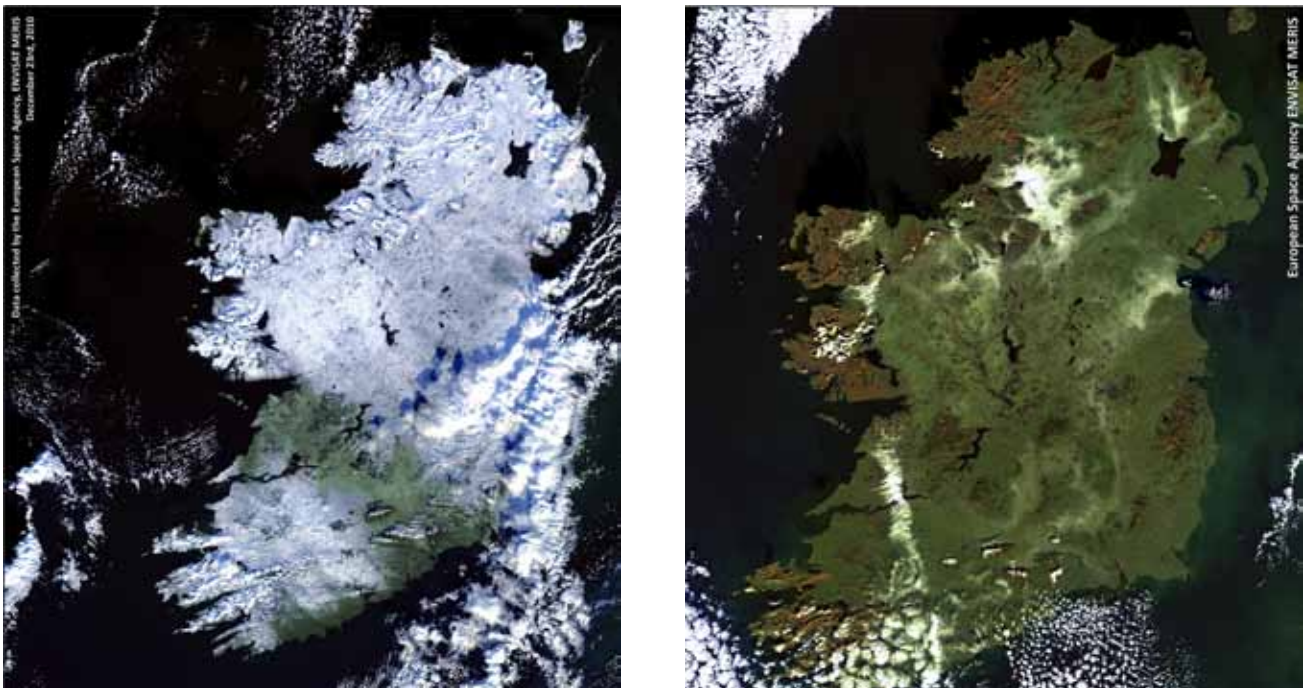
Measurements

Ground-based measurements are made at local scales and for research studies. 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 is very good continuity of satellite observations since the 1980s from which albedo estimates can be inferred.

'An analysis of global satellite data for the period 2000 to 2008 shows a slight increase in land surface albedo in the northern hemisphere and a slight decrease in the southern hemisphere.'

Time-series and Trends

An analysis of global satellite data for the period 2000 to 2008 found that in the northern hemisphere there was a small decrease in land-surface albedo of about 0.01 while in the southern hemisphere there was an increase of about 0.01 over the period. Hence, from a global perspective the land surface annual albedo appears quite stable. No specific analysis over Ireland has been carried out. Figure 4.4 shows two images of Ireland captured by the *ENVISAT* MERIS sensor in January (a) and February (b) 2011. In January, most of the country is covered in snow resulting in a high albedo whereas there is a much lower albedo from the vegetated surfaces in February. Note that clouds also have a high albedo.



(a) (b)

Figure 4.4. Satellite images of Ireland captured by the *ENVISAT* MERIS sensor, January (a), February (b) 2011. Images: © European Space Agency.

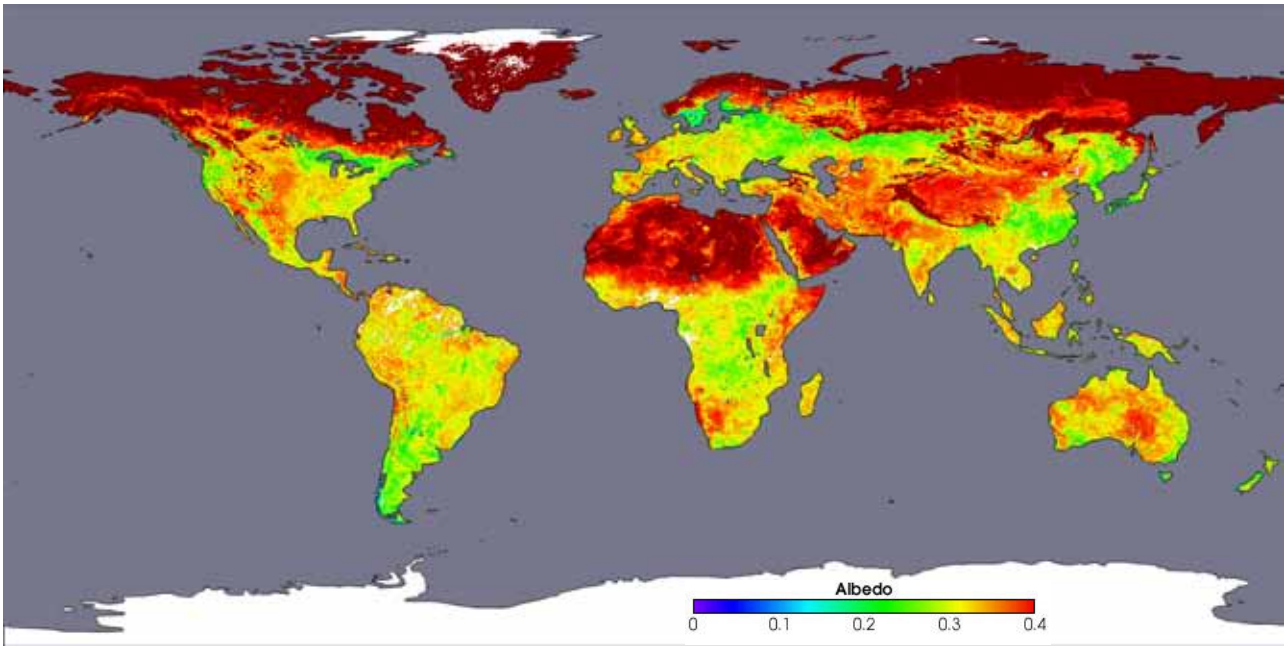


Figure 4.5 Global albedo inferred from measurements from the MODIS sensor (April 2002).

Figure 4.5 shows an example of a global albedo product for April 2002 inferred from measurements from the MODIS sensor. Albedo is high over deserts and snow-covered boreal regions. The albedo over Ireland is approximately 0.35.

'Ireland's requirements with regard to albedo analysis should be determined.'

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. Ireland's requirements with regard to albedo analysis should be determined. Regular cloud cover over Ireland could limit the use of *in situ* observations for validation of satellite data.

Further Information and Data Sources

Loeb, N.G. Wielicki, B.A., Su, W., Loukachine, K., Sun, W., Wong, T., Priestly, K.J., Matthews, G., Miller, W.F. and Davies, R. (2007) Multi-instrument comparison of top-of-atmosphere reflected solar radiation, *Journal of Climate,* Vol. 20, pp. 575–91, doi: http://dx.doi.org/10.1175/JCLI4018.1

Zhang, X., Liang, S., Wang, K., Li, L. and Gui, S. (2010) Analysis of global land surface shortwave broadband albedo from multiple data Sources, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* Vol. 3, No. 3, pp. 296–305.

General information on albedo:
http://www.eoearth.org/article/Albedo?topic=54300

Albedo products from the MODIS sensor:
http://modis-atmos.gsfc.nasa.gov/ALBEDO/

Albedo products can be accessed via the EU's GMES Geoland Service:
http://www.gmes-geoland.info/

4.3 Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)

Brian O'Connor and Ned Dwyer

Part of the radiation from the sun is absorbed by vegetation for growth. This is known as FAPAR or the Fraction of Absorbed Photosynthetically Active Radiation. Regular observations of FAPAR can help characterise the seasonal growth cycle of vegetation and monitor its inter-annual variability. It is useful for early warning of droughts and provides information on the efficiency of plants to absorb CO_2. A related concept, vegetation phenology, is used to describe the study of the timing of recurring events (e.g. bud-burst) and their causes.



Photo: © Brian O'Connor



Artist's impression of Envisat. Source: ESA

Measurements

FAPAR is not directly measurable, but is inferred from models describing the transfer of solar radiation in plant canopies. Ground-based reflectance measurements are made at local scales and for research studies and are very labour intensive. There is no long-term *in situ* monitoring programme in Ireland. Regional FAPAR estimates are generally based on observations from satellite sensors, which have the ability to measure the visible and infra-red radiation reflected by the Earth's surface on a regular basis.

'An analysis of FAPAR data for 2003 to 2009 has shown that it can be used to identify the start of spring in different land cover types.'

Time-series and Trends

The time-series of FAPAR images (Fig. 4.6), based on data from *ENVISAT* MERIS, over Ireland in 2010 for the periods (a) 1–10 January; (b) 1–10 May; (c) 1–10 July; (d) 1–10 September illustrates how photosynthetic activity varies during the year. The red regions correspond to high photosynthetic activity, and yellow to white areas, indicate vegetation with a low degree of photosynthetic activity. An analysis of FAPAR data over Ireland for 2003 to 2009 has shown that it can be used to identify the start of spring in different land-cover types.

'Work is required to analyse existing satellite datasets fully and explore the relationship of FAPAR with vegetation phenology and other climate parameters.'

Maintaining the Observations

Preliminary analysis of FAPAR data for Ireland for the period 2003 to 2009 has been carried out as part of a research project at University College Cork. Additional work is required to analyse existing satellite datasets fully and explore the relationships with vegetation phenology and other climate parameters: however, there are no programmes to carry this out at present.

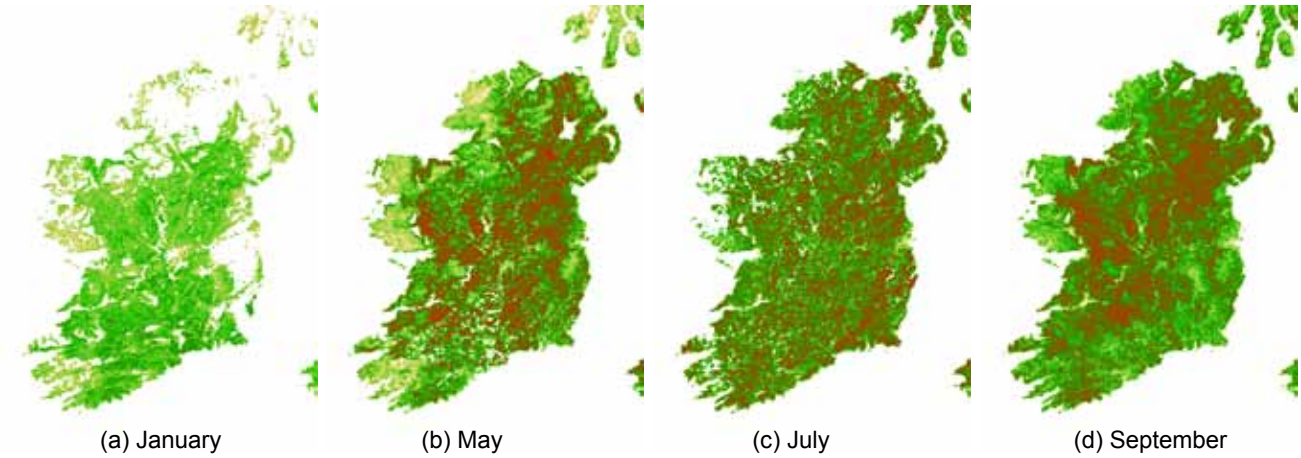
Further Information and Data Sources

O'Connor, B., Dwyer, E., Cawkwell, F. and Eklundh, L. (2012) Spatio-temporal patterns in vegetation start of season across the island of Ireland using the MERIS Global Vegetation Index, *ISPRS journal of Photogrammetry and Remote Sensing*, Vol. 68, pp. 79–84.

Information on the JRC FAPAR project:
http://fapar.jrc.ec.europa.eu/Home.php

Information on the NASA MODIS FAPAR project:
http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=15

Information on the CarboEurope IP project:
http://www.carboeurope.org/



(a) January (b) May (c) July (d) September

Figure 4.6. Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) derived from a series of *ENVISAT* MERIS images for four periods in 2010.

4.4 Leaf Area Index

Ned Dwyer and Matthew Saunders

Leaf Area Index (LAI) is a measure of the amount of plant leaf material in an ecosystem and is important for assessing the productivity or growth of vegetation. LAI is strongly related to the structure of a plant canopy and plays a key role in interactions between the atmosphere and the vegetation in processes such as water interception, evapotranspiration, photosynthesis, respiration, and leaf litter fall. LAI is also an important component in ecosystem process models designed to simulate biogeochemical cycles, hydrological budgets and carbon assimilation and sequestration.



Photo: © Ned Dwyer



Artist's impression of Envisat. Source: ESA

Measurements

LAI can be calculated directly by collecting leaf material over a certain area, or indirectly by measurements from hemispherical photography and other optical instruments. In Ireland ground-based measurements of LAI are being made as part of a number of research projects investigating ecosystem processes and carbon fluxes; however, no long-term, continuous measurement systems are in place.

LAI is calculated from satellite-sensor data using reflectance information from the visible and infrared part of the spectrum. Global maps of LAI have been generated on a regular basis using sensors such as MODIS and MERIS.

'An observed increase in the annual average LAI over Europe may be linked to increased average annual temperatures.'

Time-series and Trends

Measurements of LAI are being made at a grassland site in Co. Carlow. Figure 4.7 shows the observations between 2005 and 2008. Two silage cuts were made each year followed by cattle grazing. The impact of these land-use practices on the LAI is evident. Measurements made on a barley crop in Co. Carlow in 2005 and 2006 illustrate the increase in LAI during the crop growth phase and its steep decline after harvest, with some subsequent increases over autumn and winter due to the growth of barley volunteer seedlings and weeds. Measurements since 2002 made over a Sitka Spruce stand in Co. Laois planted in 1998 show a slight increase in LAI. The decreases in 2007 and 2009 are due to thinning of the stand in these years.

A recently published study, based on the analysis of a global set of satellite data for the period 1981 to 2006, indicates that there is a slight increase in the annual average LAI over Europe. At European latitudes, temperature is a controlling variable on plant growth,

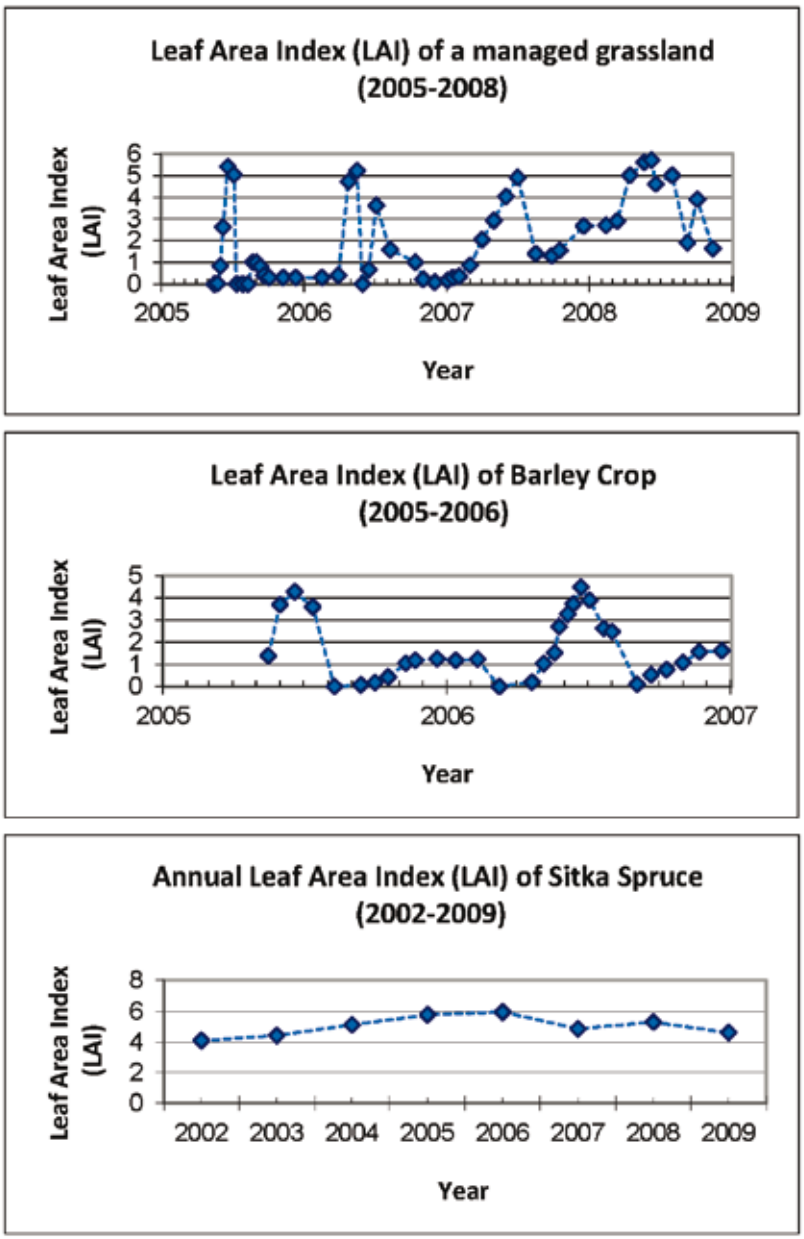


Figure 4.7. Leaf Area Index (LAI) measurements made at a grassland, crop and forest site respectively.

so this increase may be linked to increased average annual temperatures.

The example map[21] of LAI in Fig. 4.8 has been calculated with data from the *MERIS* sensor for 11 June 2005. Black indicates areas of no data (cloud or inland water). The areas of highest LAI (dark green) correspond to pasture, crops and forest whilst the areas of lowest LAI (yellow, red) correspond to upland, heath and urban cover types.



Figure 4.8. Leaf Area Index (LAI) derived from *ENVISAT MERIS* data for 11 June 2005.

21 Courtesy of Thomas Lankester, Infoterra.

'Long-term ground-based measurements of LAI over a number of different vegetation types are required to improve understanding of ecosystem processes and for the validation of satellite-derived measurements.'

Maintaining the Observations

Current ground-based measurements of LAI are funded as part of short-term projects. Long-term ground-based measurements over a number of different vegetation types are required to improve understanding of ecosystem processes and for the validation of satellite-derived measurements. The EPA and Teagasc are currently considering the designation of one or more sites to contribute to the ICOS as part of which measurements of LAI are required.

This would provide the opportunity to exploit the satellite datasets and validate them against ground-based measurements.

Further Information and Data Sources

Siliang, L., Ronggao, L. and Yang, L. (2010) Spatial and temporal variation of global LAI during 1981–2006, *Journal of Geographical Sciences*, Vol. 20, No. 3, pp. 323–32.

IMECC (Infrastructure for Measurements of the European Carbon Cycle): http://imecc.ipsl.jussieu.fr/

GHG Europe (Greenhouse gas management in European) land use systems: http://www.ghg-europe.eu/

The Integrated Carbon Observing System: http://www.icos-infrastructure.eu/

Story Board 5: Biodiversity and Habitats

Ned Dwyer, Eugenie Regan and John Coll

SB5







Photos: © E.W. Delaney; Butterfly and Hare: Liam Lysaght

Biodiversity and habitat properties are important for climate-impact studies, but they are not defined as ECVs as only aspects of these complex properties can be measured. Biodiversity refers to the range of flora and fauna supported in an area and habitats to the environment in which these plants and animals live. Ireland is home to over 30,000 species of animals, plants and fungi. Many of these are under threat as a result of changes in land use, intensive management of agricultural land and forested areas, fragmentation of natural habitats by infrastructure and urbanisation, the influence of mass tourism and pollution and the introduction of invasive species. Climate change is an additional factor influencing biodiversity. Many native species are poorly equipped to adapt to a rapid change in climate whilst some new and invasive species can take advantage of it. Biodiversity is estimated to have a national annual benefit of €2.6 billion, and supports a wide range of ecosystem services, providing everything from insect pollination of human food plants to absorption and filtering of pollutants.

Data and Information Collection

Data and information on biodiversity has been collected by a range of organisations and individuals, but are still incomplete. There are large amounts of data on terrestrial plants and vertebrates but little knowledge on others such as marine algae and invertebrates (e.g. worms, marine animals). Biodiversity data being collected in Ireland specifically in relation to monitoring the effects of climate change come from the Irish Butterfly Monitoring Scheme, insect surveys as part of the Rothamsted Light-trap Network, and monitoring of a range of trees in the Phenological Gardens. Since the 1960s observations of phenological events (such as bud-burst, leaf out, leaf fall) have been made at four gardens (blue) that form part of the International Phenological Garden Network (Fig. SB5.1). Recently, additional gardens have been added to the network (red) to provide better coverage of the country.



Figure SB5.1. International Phenological Gardens in Ireland.

Monitoring Flora and Fauna

Phenological events are observed on up to 20 different tree species in these gardens. One such species is Birch (*Betula pubescen).* Observations at the Valentia phenological garden, Co. Kerry (Fig. SB5.2), indicate that the beginning of the growing season (BGS) for this species occurs approximately 10 days earlier now compared to the early 1970s, which has led to an extension of the growing season. Similar changes have also been observed in other species at the garden and have been linked to a rise in average spring air temperature.

Regular monitoring of the numbers, and timing of life-cycle events, of insects such as butterflies and moths helps in understanding the impacts of climate change on invertebrates and the wider ecosystem. The Rothamsted Insect Survey National Light-trap Network was set up during the early 1960s and is coordinated

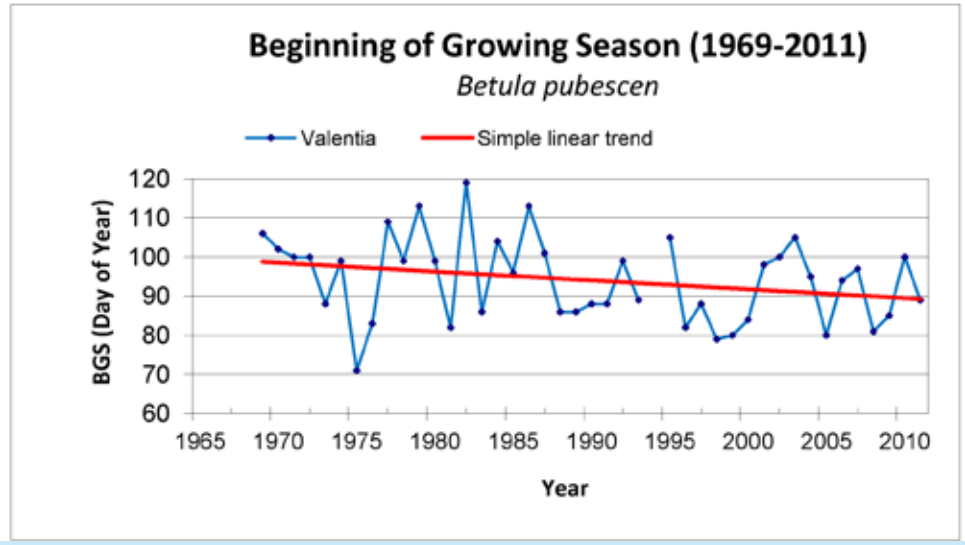


Figure SB5.2. Date of beginning of growing season for Birch as observed at Valentia phenological garden (1969–2011).

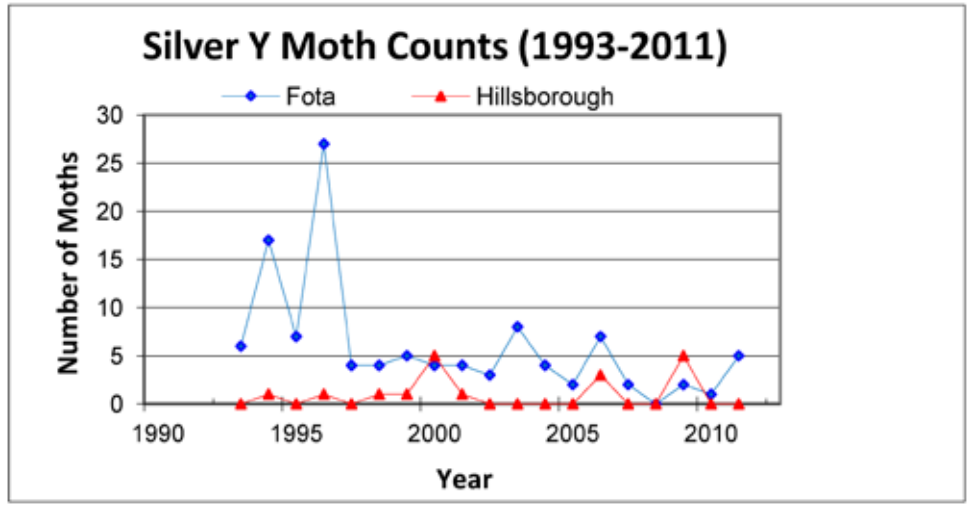


Figure SB5.3. Silver Y moth counts at Fota Wildlife Park, Co. Cork and Hillsborough, Co. Antrim (1993–2011).

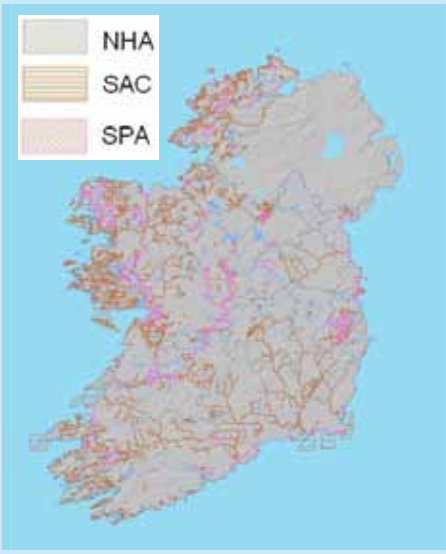


Figure SB5.4. Location of designated and proposed natural heritage areas (NHAs), special protection areas (SPAs), and special areas of conservation (SACs).

by Rothamsted Research at Harpenden, England. In Ireland, there are eight light-traps which monitor the number of macro-moths. These traps provide important standardised long-term data on Ireland's moth fauna. The traps at Fota Wildlife Park Co. Cork and Hillsborough in Co. Antrim are the longest-running traps in Ireland and were established in 1993 (Fig. SB5.3).

Habitat Protection

Designated conservation areas help to preserve habitats and biodiversity for the long-term and regular monitoring of their condition is carried out by the National Parks and Wildlife Service. Natural Heritage Areas (NHAs), SACs and Special Protection Areas (SPAs) are three of the most important designations (Fig. SB5.4). SACs and SPAs are also part of the much wider European Natura 2000 network of protected areas.

The Future of Biodiversity Observations

The National Biodiversity Data Centre (NBDC), currently funded by the Department of Arts, Heritage, and the Gaeltacht, is dedicated to the collation, management, analysis and dissemination of data and information on Ireland's biological diversity. The Centre coordinates the Irish Butterfly Monitoring Scheme. The Rothamsted Light-trap catches are operated by each site and processed and analysed by Rothamsted in the UK who share the data with the NBDC. The network of International Phenological Gardens has recently been upgraded and a number of new native species gardens established as part of the EPA-funded Climate Change Impacts on Phenology (CCIP) project at Trinity College Dublin. The data generated by each garden is shared with the International Phenological Gardens of Europe. There are plans to establish the NBDC as the portal for all Irish phenological data.

Further Information

The National Biodiversity Data Centre: www.biodiversityireland.ie

Ireland's Biodiversity in 2010 – *State of Knowledge*: http://biodiversity.biodiversityireland.ie

Carroll, E., Sparks, T., Donnelly, A. and Cooney, T. (2009) Irish phenological observations from the early 20th century reveal a strong response to temperature, *Biology and Environment: Proceedings of the Royal Irish Academy*, Vol. 109B, No. 2, pp. 115–26.

Coll, J., Maguire, C., Sweeney, J. (2009) *Biodiversity and Climate Change in Ireland – Briefing Paper*: http://www.comharsdc.ie/_files/Biodiversity_ClimateBriefing%20Paper_Final_6thJan_2009.doc.pdf

Information and maps of protected sites: http://www.npws.ie/protectedsites/

The impact of climate change on butterfly communities: http://www.bc-europe.org/upload/Impact_of_climate_change_on_butterfly_communities_1990-2009.pdf

Information on the Rothamsted insect survey: http://www.rothamsted.bbsrc.ac.uk/insect-survey/

Irish Phenology Network: http://www.tcd.ie/Botany/phenology/themes/plant/network.php

Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M. and Murphy, C. (2008) *Climate Change – Refining the Impacts for Ireland (2001-CD-C3-M1),* STRIVE Report 12. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. http://www.epa.ie/downloads/pubs/research/climate/name,26008,en.html

4.5 Above-ground Biomass

Ned Dwyer

Above-ground biomass refers to all living plant material above the soil and is one of the recognised stores of terrestrial carbon. Other stores include below-ground biomass, litter, dead wood and soils. Vegetation biomass contains a similar amount of carbon as the atmosphere and is therefore of great importance in understanding climate. Removal of vegetation, for example by fires, deforestation, and conversion of vegetated land to urban use, causes a net increase of carbon in the atmosphere, whereas an increase in forest leads to a reduction of atmospheric carbon as photosynthesis draws CO_2 from the atmosphere and stores it in biomass. In Ireland, most of the biomass is held in grassland and natural ecosystems. However, due to an ongoing policy of afforestation the greatest addition is in forest.



Photo: © Ned Dwyer

Measurements

Above-ground biomass is quantified in terms of the mass of plant material. In many instances, the mass is not measured directly but is inferred from volume. *In situ* measurement methods are used for small-scale studies but are labour intensive and time consuming. Although no direct estimates of forest biomass in Ireland are currently made, much work has been done on developing country-specific models to estimate biomass and hence carbon stocks in forests. These models take full advantage of the robust forest area data that are available. In general, an assessment of above-ground biomass is an adequate indicator of other carbon pools with the exception of soils.

'Models are used to estimate forest biomass using robust forest area data.'

Internationally, remote-sensing data from optical, radar and laser sensors have been used to estimate above-ground biomass as part of research studies. Robust, operational methods, however, are not yet in place.

'Forest carbon stock has increased by over 40% since 1990.'

Time-series and Trends

Figure 4.9 shows the modelled annual total forest carbon stock. This has increased steadily since 1990 as the area under forest increases and the trees mature: therefore, capturing more carbon. The biomass stored in other land cover types is essentially constant.

Forest area and type can be derived from analysis of satellite imagery, complemented with ground data. Figure 4.10 shows the location of forested areas from the CORINE land cover database for 2006. Forest products such as those produced under the GMES Fast Track initiative may also prove useful to verify biomass change at high spatial and temporal resolution.

Maintaining the Observations

As part of the national inventory reporting to the UNFCCC by the EPA every year, annual estimates of above-ground forest carbon stock are made. Estimates of above-ground biomass for other land covers are also carried out. A complete national forest inventory was last published in 2007 by the Department of Agriculture, Forestry and Food and the Forest Service. A repeat forest inventory was undertaken in 2012. The ESA is planning a mission currently entitled BIOMASS, based on radar technology, to take global measurements of forest biomass.

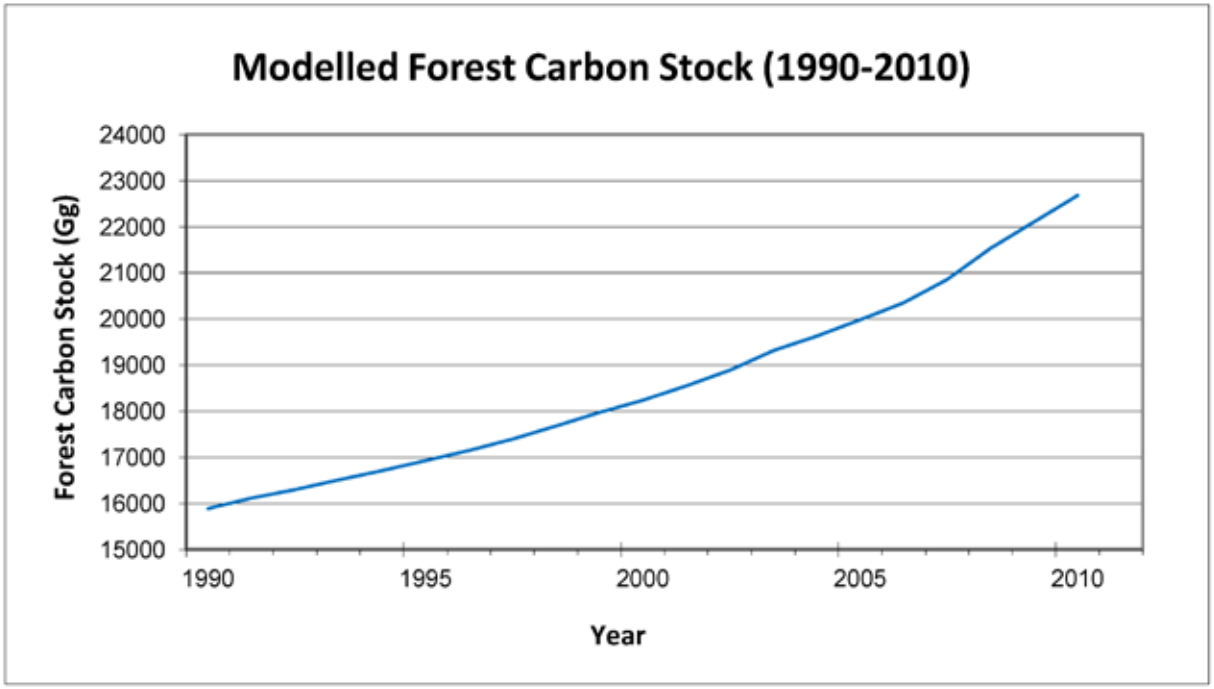


Figure 4.9. Modelled annual total forest carbon stock (1990–2010).

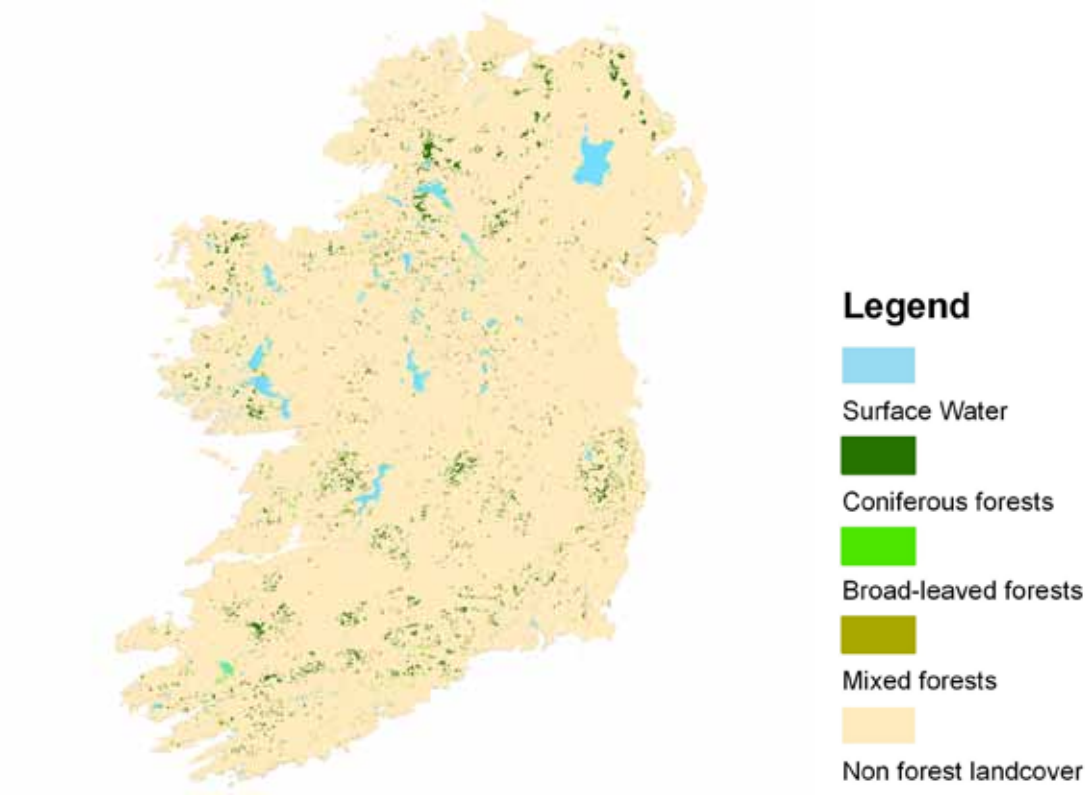


Figure 4.10. Location of forest areas, as derived from CORINE 2006.

Further Information and Data Sources

Duffy, P., Hanley, E., Hyde, B., O'Brien, P., Ponzi, J., Cotter, E. and Black, K. (2012) *National Inventory Report, 2012. Greenhouse Gas Emissions 1990–2010,* Reported to the UNFCCC, Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

Hendrick, E. and Black, K.G. (eds.) (2007) *Forest, Carbon and Climate Change, Local and International Perspectives, proceedings of the COFORD conference on 19/09/2007.*

European Space Agency, BIOMASS Mission: http://www.esa.int/esaLP/SEMFCJ9RR1F_index_0.html

Information on the GMES forest Fast Track products is available from: http://www.gmes-forest.info/

CORINE datasets are available from the EPA at: http://www.epa.ie/whatwedo/assessment/land/corine/datasets/

Forest Inventory data is available from the Forest Service at: http://www.agriculture.gov.ie/forestservice/forestservicegeneralinformation/abouttheforestservice/forestcoverdatasets/

4.6 Soil Carbon

Ned Dwyer and James Eaton

Carbon is incorporated into vegetation through the process of photosynthesis, whereby CO_2 is sequestered from the atmosphere. Following deposition of leaf litter and woody debris to the soil surface, decomposition of this plant matter along with root biomass transfers the carbon sequestered in vegetation to soil. Soil carbon is one of the largest carbon stocks in most terrestrial ecosystems. The amount of carbon present in the soil is determined by geology, soil type, climate and land use. In Ireland, peat soils dominate the terrestrial carbon budget. Changes in climate, in particular rainfall and temperature, impact on the carbon storage potential of soils. Peatlands are particularly vulnerable in this respect – particularly when the additional pressures on them caused by artificial drainage are taken into account.



Photo: © Ned Dwyer

Measurements

Changes in soil carbon are very slow and therefore difficult to detect and at a given site require observations over several decades. There is currently no long-term programme of this kind in Ireland. Estimations of country-wide carbon stock are currently made based on knowledge of soil type, carbon density, soil depth and land cover.

'It is estimated that Ireland's soil carbon stock has decreased by 27 million tonnes between 1990 and 2000 due mainly to drainage and extraction of peat.'

Time-series and Trends

Research based on historical records of land use estimates that soil carbon stocks have recovered/ increased throughout the second half of the twentieth century. However, reliable data on the absolute quantities of soil carbon in the past are not available. Two recent studies (Table 4.1) have made estimates of the soil carbon stock for 1990 and 2000 to 1 m depth and also for the complete soil profile. These indicate that there has been a decrease of 27 Tg (million tonnes) between 1990 and 2000. Estimates of carbon stock change in Ireland are dominated by changes to the management of peatland, including drainage and peat extraction and to a lesser extent by changes in patterns of agricultural land use and urban development.

Table 4.1. Estimated Soil Organic Carbon (SOC) stocks in Teragrams (Tg) in peatland only and all land covers including peat (from Eaton et al. 2008).

Description	Year	Peat SOC stock (Tg)	Total SOC stock (Tg)	Source
Stock to 1 m depth	1990	580	1,496	Eaton et al. (2008)
	2000	535	1469	
Complete soil profile	1990	1,089	2,048	Tomlinson (2005)
	2000	1,065	2,021	

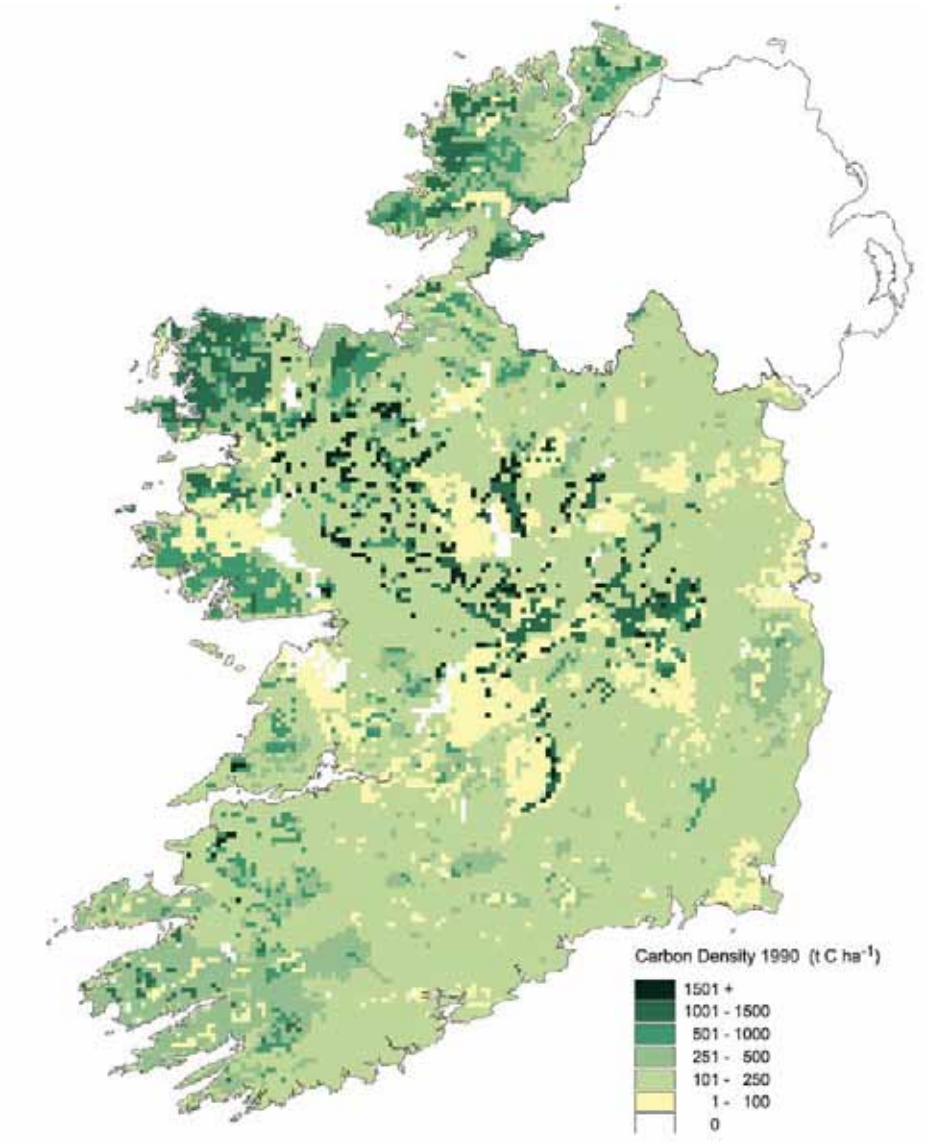


Figure 4.11. Estimated distribution of soil carbon density (1990). Reproduced from Tomlinson, 2005.

Soil carbon is highest in the west and northwest, where precipitation is highest; this encourages the formation of peat, and lowest in the east and southeast (where precipitation is lowest). This is reflected in Fig. 4.11 of soil carbon density (tonnes of carbon per hectare) where the highest densities, corresponding to raised bogs, stretch from the midlands towards the northwest. The lowest soil carbon densities are where shallow brown earths dominate.

'A network of permanent soil monitoring plots covering the main land uses for each soil type should be established.'

Maintaining the Observations

Reducing uncertainty of soil carbon dynamics in Ireland requires a better understanding of the variability and depth of peat soils, the role of erosion on soil carbon stocks, and the effect of afforestation on organic soils. Up to now the lack of a complete county level soil map has been a significant impediment. However, the EPA and Teagasc funded Irish Soils Information System project is under way, producing a 1:250,000 scale soil series map of Ireland to be completed by 2014. A network of permanent soil monitoring plots covering the main land uses for each soil type should be established.

Further Information and Data Sources

Daly, K. and Fealy, R. (2007) *Digital Soil Information System for Ireland – Scoping Study,* Final Report, EPA, Johnstown Castle Estate, Co. Wexford, Ireland: http://www.epa.ie/downloads/pubs/research/land/name,23747,en.html

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G. (2008) Land cover change and soil organic carbon stocks in the Republic of Ireland,1851–2000, *Climatic Change*, Vol. 91, Nos 3–4, pp. 317–34.

Tomlinson, R.W. (2005) Soil carbon stocks and changes in the Republic of Ireland, *Journal of Environmental Management,* Vol. 76, pp. 77–93.

MIDA, http://mida.ucc.ie to view the general soils map (1:575,000) of Ireland.

Irish Soil Information System: http://www.teagasc.ie/news/2009/200903-23.asp

4.7 Soil Moisture

Ned Dwyer and Séamus Walsh

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 regard to 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. 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.



Photo: © Brian Barrett



Map 4.1. Location of synoptic stations at which soil moisture deficits are calculated.

Measurements

Soil moisture can be determined using various *in situ* approaches. However, they are all labour intensive and only representative of local conditions. Met Éireann has estimated daily soil moisture deficits (SMD) at its synoptic stations since 1980. 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.

A number of satellite sensors make broad-scale measurements of soil moisture. Research continues on retrieval methods using data from high-resolution satellite radar sensors. Such satellite-derived values need to be carefully calibrated and validated with *in situ* measurements.

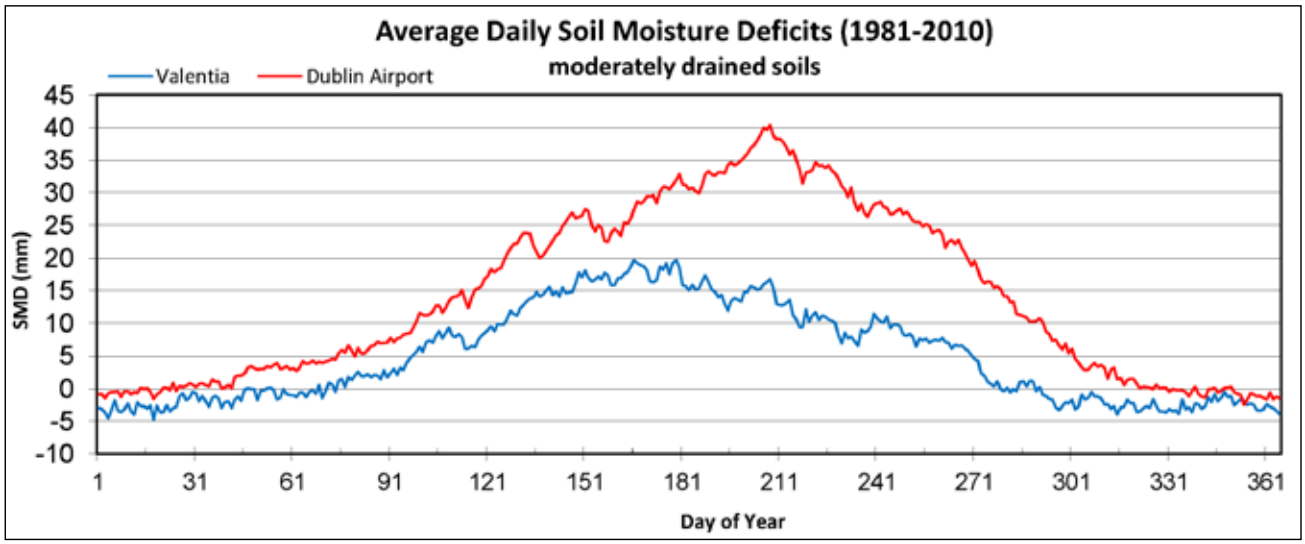


Figure 4.12. Average daily soil moisture deficits calculated at Valentia Observatory and Dublin airport (1981–2010).

'Met Éireann has estimated daily soil moisture deficits at its synoptic stations since 1980 but detailed analysis of trends needs to be carried out.'

4

Time-series and Trends

Figure 4.12 shows the average daily SMD for moderately drained soils based on data collected at Valentia Observatory and Dublin Airport synoptic stations from 1981 to 2010. 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 return quickly to non-saturated conditions. Greatest soil moisture deficits, which usually occur in the summer and when sustained can be indicative of droughts, generally occur in the east and southeast of the country.

Figure 4.13 shows the mean monthly surface soil moisture over Europe for August 2010 as determined from a combination of satellite microwave scatterometry and passive microwave radiometer data at a spatial resolution of 25 km.[22] Orange colours represent dry soils, whereas blues represents saturated soil.

22 Image courtesy of the Technical University of Vienna 's ESA funded WACMOS and Soil Moisture Climate Change Initiative projects

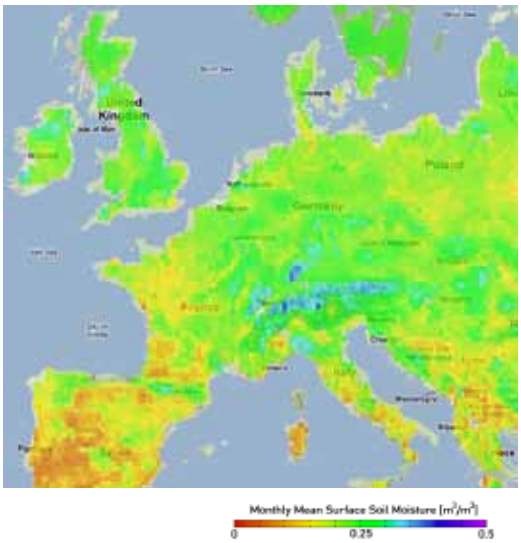


Figure 4.13. Mean monthly surface soil moisture over Europe for August 2010.

'A comprehensive needs analysis is required to secure and potentially enhance Ireland's limited evapotranspiration measurement network.'

Maintaining the Observations

The network of synoptic stations need to be maintained and further developed to ensure the future of long-term measurements. Evapotranspiration measurements are currently carried out at Valentia Observatory and Johnstown Castle. However, a comprehensive needs analysis is necessary to secure and potentially enhance this limited network. Further resources are required to conduct analysis of the historic record of SMD and perform research on alternative measurement techniques. The CMRC at University College Cork is a partner in an ESA-funded Climate Change Initiative project (2012–2014) to develop comprehensive and robust global soil moisture products using satellite data.

Further Information and Data Sources

Barrett, B.W., Dwyer, E. and Whelan, P. (2009) Soil moisture retrieval from active spaceborne microwave observations: an evaluation of current techniques, *Remote Sensing,* Vol. 1, pp. 210–42: http://www.mdpi.com/2072-4292/1/3/210/

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,* Vol. 44, pp. 95–110.

Schulte, R.P.O., Richards, K., Daly, K., Kurz, I., McDonald E.J. and Holden, N.M. (2006) Agriculture, meteorology and water quality in Ireland: a regional evaluation of pressures and pathways of nutrient loss to water, *Biology and Environment: Proceedings of the Royal Irish Academy,* Vol. 106B, No. 2, pp. 117–33.

Information on the SMOS mission: http://www.cesbio.ups-tlse.fr/us/indexsmos.html

ESA's Climate Change Initiative: Information and global time-series of soil moisture from satellites sensors: http://www.esa-soilmoisture-cci.org/

Soil moisture deficit maps from Met Éireann: http://www.met.ie/agmet/default.asp

Soil moisture deficit calculations: http://www.met.ie/climate/agri-meteo-data.asp

4.8 Fire Disturbance

Ned Dwyer, Séamus Walsh and Aidan O'Donoghue

Along with fossil-fuel burning and agriculture, vegetation fires are one of the largest contributors globally to human-caused greenhouse gas 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 are due to human causes, whether deliberate or unintentional. In Ireland fires are often set to clear gorse but can spread to adjacent forest areas. Occasional incidences of bog fires which release carbon from peat also occur.



Photo: © Peadar McMahon

Measurements

The area of vegetation burned each year in Ireland is not surveyed explicitly. Estimates of forest-burned area for reporting to the UNFCCC are based on replantation premiums provided to fire-affected landowners by the Forest Service. Data on other vegetation fires are not compiled centrally. Satellite data are used internationally to make regional and global estimates of fire disturbance and their impact on the atmosphere. Frequent cloud cover and the small size of the burnt area in Ireland limits the usefulness of satellite imagery. Daily fire risk is assessed by Met Éireann using meteorological variables.

'Using information on replantation premiums provided by the Forest Service, it is estimated that since 1990 on average 340 Ha of forest burns in Ireland each year.'

Time-series and Trends

Figure 4.14 shows forest burned area, based on the number of hectares of forest for which replantation grants were provided by the Forest Service. The amount of land under forest has been steadily increasing due to the government's afforestation policy and fires occur more frequently in younger rather than mature forest.

Met Éireann forecasts daily fire danger at some of its synoptic stations using a model which incorporates the most recent meteorological observations. Figure 4.15 shows the number of days per year since 1971, during the fire season, when danger of fire was considered very high or extreme based on Dublin and Shannon synoptic data. There is no long-term trend evident in this data.

Smoke plumes from a number of large fires can be seen on the image from 2 May, 2011 illustrated in Fig. 4.16. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's *TERRA* satellite acquired the image, and the fires the sensor detected are highlighted

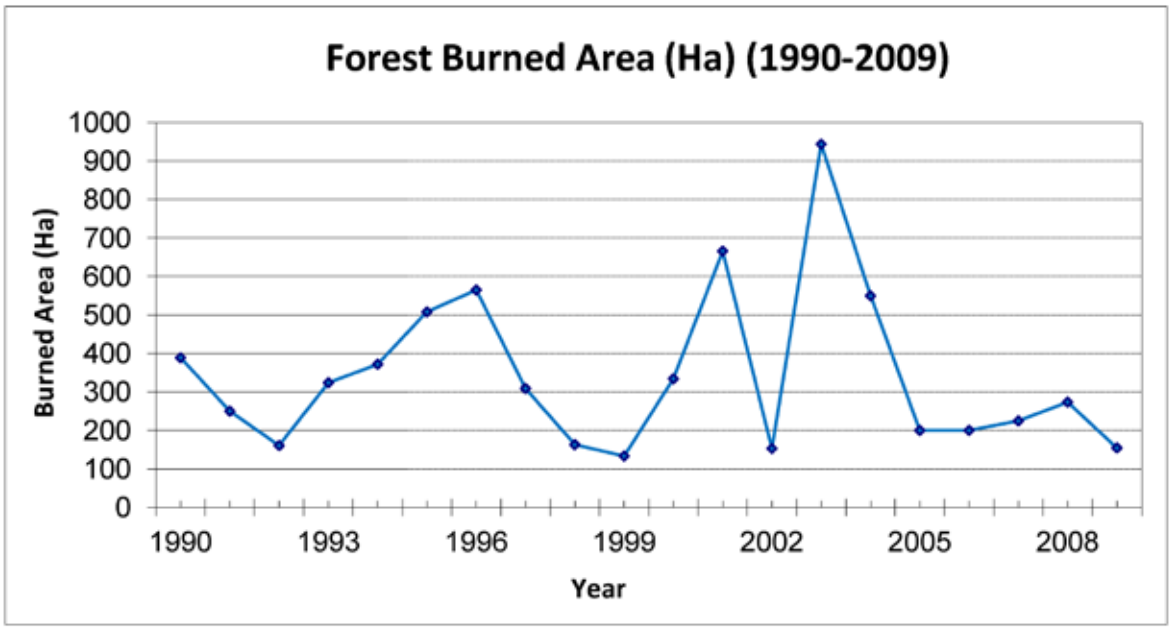


Figure 4.14. Forest burned area estimates based on hectares of forest for which replantation grants were provided by the Forest Service (1990–2009).

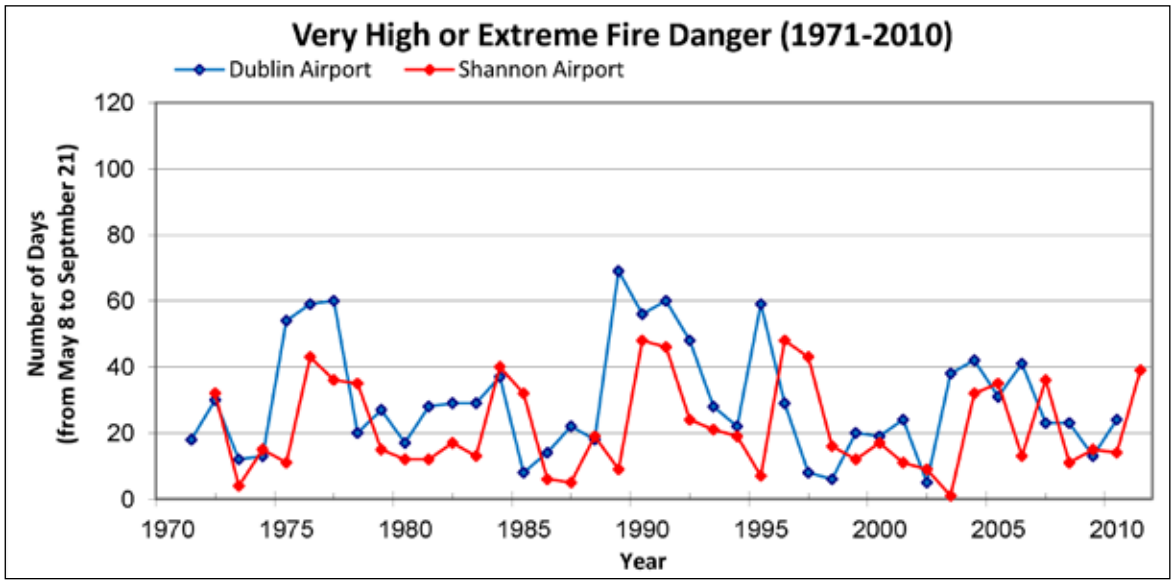


Figure 4.15. Number of days on which the fire index was very high or extreme as calculated using data from Dublin airport and Shannon airport synoptic stations (1971–2010).



Figure 4.16. A *MODIS TERRA* satellite image from 2 May 2011 shows smoke plumes from a number of vegetation fires. Fire locations are highlighted in red.

in red.[23] Dry, windy weather during early May allowed numerous fires, many of which had been set deliberately, probably with the intentions of burning gorse, to spread rapidly.

> 'It would be useful to record and collate the location and extent of forest fires and if possible other vegetation fires.'

Maintaining the Observations

Met Éireann calculates daily fire risk as part of its operational procedures. The Forest Service and Coillte maintain a record of area burned for replantation grants. It would be useful to record and collate the location and extent of forest fires and if possible other vegetation fires. Research into the potential of using remotely sensed imagery to map burned areas would be valuable. Further analysis of the historical fire risk data should be carried out.

23 NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC.

Further Information and Data Sources

Davies, D., Kumar, S. and Descloitres, J. (2004) Global fire monitoring using MODIS near-real-time satellite data, *GIM International,* Vol. 18, No. 4, pp. 41–3.

Giglio, L., Descloitres, J., Justice, C. O. and Kaufman, Y.J. (2003) An enhanced contextual fire detection algorithm for MODIS, *Remote Sensing of Environment,* Vol. 87, pp. 273–82.

Holden, N. M., Hochstrasser, T., Schulte, R. P. O., Walsh, S. (eds.) *2007 Making Science Work on the Farm. A Workshop on Decision Support Systems for Irish Agriculture,* Published by Joint Working Group in Applied Agricultural Meteorology: http://www.ucd.ie/agmet/Agment_workshop_online_version.pdf

MODIS Rapid Response System: http://rapidfire.sci.gsfc.nasa.gov/

MODIS images of fires in Ireland and Scotland in May 2011: http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=50468

ATSR World Fire Atlas: http://due.esrin.esa.int/wfa/

Ireland's Greenhouse Gas Inventory (including forest burned area as reported to the UNFCCC): http://erc.epa.ie/ghg/crfdownloads.jsp

Story Board 6: Carbon Storehouses

Fiona Cawkwell

Peatlands around the World

Peatlands are one of planet Earth's most important ecosystems, covering over 4 million km^2 and representing about a third of the estimated area of the world's wetlands. Peat is made up of the decaying remains of plant roots, leaves and even tree trunks, but it is also in a state of permanent saturation with typically 95% of its volume being water. Peatland formation and distribution is primarily a function of climate and topography, favouring wetter conditions with poorly drained soils, which encourages slow decomposition. Fens are often the precursor to peat bogs, forming in areas such as lake margins, where there is a good supply of mineral-rich ground water. Where there are moderate levels of rainfall, more material may accumulate in the fen, gradually building it up to a dome-shaped surface, or raised bog, which may be tens of metres deep. The living top layers of the bog are raised above the mineral-rich ground water source and depend on rainfall to extract nutrients. In some midland counties of Ireland these nutrient-poor raised bogs occupy former lake basins that drained away after the last Ice Age. Blanket bogs are much shallower, and typically extend over greater areas, often at higher elevation and where there is greater rainfall – for example, along the west coast of Ireland.



Figure SB6.1. Part of an IKONOS image of the Irish midlands from 18 March 2009.

Peatlands in Ireland

Peatlands are estimated to cover more than 17% of the land surface of the Republic of Ireland. From the air, it is possible to appreciate their extent across the country – only Finland, Canada and Indonesia have a greater percentage of their national landmass covered by peatlands! Satellite imagery is also useful for mapping the extent of different types of peatland. Figure SB6.1, part of an image acquired by the *IKONOS* satellite, shows an area of the Irish midlands where there has been considerable harvesting of peat for fuel (the dark browns and red browns), but also afforestation of previously stripped areas (the dark greens).

Partly as a consequence of the introduction of large-scale mechanised turf extraction, afforestation programmes and intensification of agriculture over the last 40 years, much of the original diversity of peatlands, and the habitats associated with them, have been lost.

Peatlands form over hundreds to thousands of years (indeed, the oldest bogs in Ireland pre-date human settlement in the country), and they react slowly to disturbance. In their natural state they are unique environments that support a wide variety of plants, some of which have adapted to a low nutrient, and frequently waterlogged soil. Bog cotton, with its white fluffy heads, is one of the most recognisable plants in the late spring and summer (Fig. SB6.2). Some plants, such as the Sundew and Butterwort, overcome the lack of ground nutrients by capturing and digesting insects, whereas mosses have the capacity to absorb up to 20 times their own weight of water. In their natural state, peatlands are less hospitable to birds and animals, due to limited food-bearing vegetation, waterlogged ground and lack of trees; however, this provides safe roosting and nesting sites for ground-loving birds such as the Meadow Pipit.



Figure SB6.2. Typical early summer vegetation of Irish peatland in its natural state (photo: © Fiona Cawkwell).

SB6

The Value of Peatlands

The low-nutrient water-logged environment of peatlands makes them unique in terms of biodiversity. They are also important in regulating the hydrological cycle as they retain and filter water. They act as an efficient terrestrial ecosystem for storing carbon, with twice as much carbon in global peatlands as in the global forest biomass. Significantly, they are also the most important long-term carbon store, locking it away for thousands of years and thereby playing an important role in global greenhouse gas balances. By sequestering atmospheric carbon, peatlands have contributed to cooling the Earth, but small changes in their ecology and hydrology can lead to very significant emissions of carbon dioxide (CO_2) and methane (CH_4). Peat extraction has an obvious and direct impact on the flora and fauna of peatlands, and clearing, draining and burning of peatlands globally is estimated to release more than 3 billion tonnes of CO_2 per annum into the atmosphere – equivalent to more than 10% of all global emissions from fossil fuels.

The Future of Peatlands

Peatland distribution has a strong relationship to climate, and with future climatic changes there will inevitably be impacts on peatland health and status. In particular, rising temperatures and changes in the amount, intensity and seasonal distribution of rainfall will affect the decay rates of vegetation, accumulation of peat, gas exchange and erosion. Ongoing draining, extraction, burning and afforestation are causing significant degradation of peatlands globally. Sustainable management of existing undrained peatlands demonstrate benefits for conservation of biodiversity and regulation of surface water flows as well as maintaining carbon storage and sequestration capabilities. Moreover, restoring peatlands and rewetting them can be a very cost-effective approach to mitigating greenhouse gas emissions due to human activities and sustaining the long-term health of not just the immediate peatland environment, but planet Earth.

Further Information

Black, K., O'Brien, P., Redmond, J., Barrett, F. and Twomey, M. (2009) The extent of peatland afforestation in Ireland, *Irish Forestry,* Vol. 65, pp. 61–71.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. and Stringer, L. (eds.) (2008) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report,* Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

Bord na Móna, a semi-state company that owns over 80,000 Ha of peatlands: http://www.bordnamona.ie/

Irish Peatland Conservation Council*:* http://www.ipcc.ie/

The EPA-funded Bogland project on sustainable peatland management: http://www.ucd.ie/bogland/

4.9 River Discharge

Ned Dwyer and Conor Murphy

Rivers are impacted by changes in climate, most notably changes in rainfall patterns but also temperature. Conversely, rivers play an important role in regional and local climate. Changes in the climate can cause alterations in the volume of water rivers carry, leading to droughts and floods which can have several social, economic and environmental impacts. Long-term, high-quality observations of river flows are necessary in order to understand the hydrological regime and to plan for water resource and flood management under changing climate conditions.



Photo: © Margaret Gordon



Map 4.2. Location of river flow monitoring stations in the reference network.

Measurements

River discharge or flow is measured and data collected by a number of agencies, including the EPA, the Office of Public Works, local authorities and the Electricity Supply Board (ESB). There are over 900 active river-flow meter stations in the country. Capitalising on this network, the EPA is completing the selection of high-quality reference hydrometric gauges that can be used for monitoring and detecting climate change signals. The stations identified include 35 from the Republic, and a further 8 in Northern Ireland from the UK Benchmark Network. The average record length of these stations is 40 years with a minimum of 28 and a maximum of 63 years.

'Summer mean river flows are dominated by increasing trends while there is a tendency for increases in winter mean flows for longer record stations.'

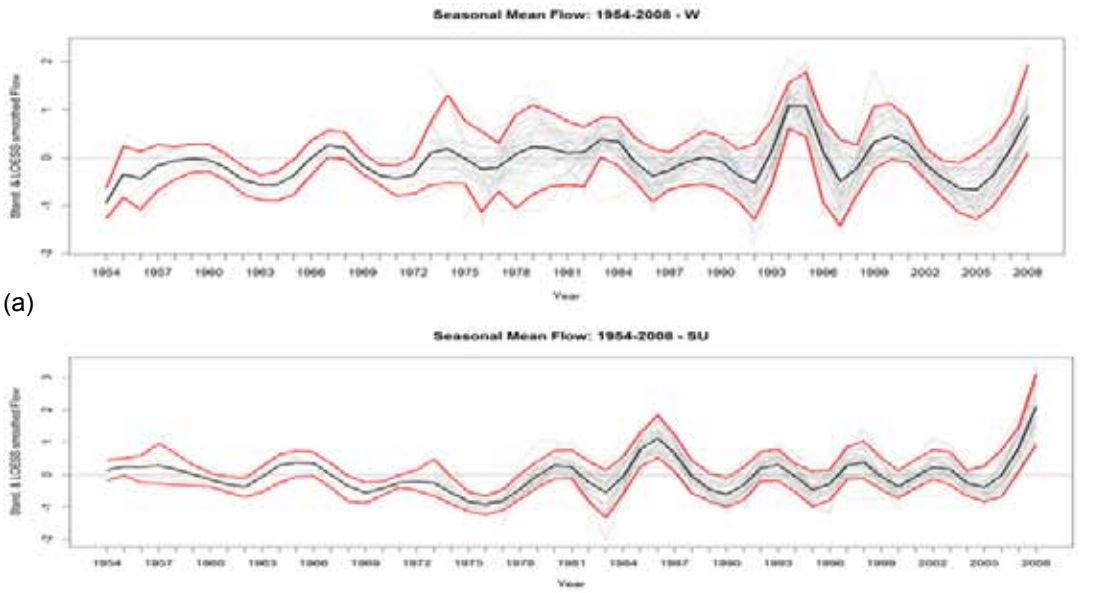
Time-series and Trends

Recent analysis of flows from the reference network, carried out for the EPA, indicates that trends in mean flows are highly complex and subject to large variability, with trends derived highly dependent on the time period analysed – making it difficult to extract climate change signals. Nonetheless, analysis of longer records of annual mean flows shows a tendency for increasing flows. In Fig. 4.17 the black line represents the standardised seasonal mean flow for winter (a) and summer (b) for the period 1954 to 2008. The zero line represents the average flow for the total period. The light grey lines show the flows at each of the reference stations while the red lines represent the envelope encompassing 95% of the values. This seasonal analysis indicates that summer mean flows are dominated by increasing trends while there is a tendency for increases in winter mean flow for longer record stations. Annual and winter high flows are also dominated by increasing trends.

Maintaining the Observations

Formal recognition of the reference river-flow monitoring network has been given as part of the recent review of hydrometric stations where climate change monitoring is seen as a primary purpose for the sites identified. It is crucial that the maintenance of river flow stations and the collection and processing of data are ensured through continued investment in the reference sites. This will enable basic information needs for water resource and flood management and environmental reporting in addition to climate change monitoring to be met. A long-term strategy should be developed for the maintenance and upgrade of the reference network as well as regular analyses of the data collected.

'It is crucial that the maintenance of river flow stations and the collection and processing of data is ensured via continued investment in the reference sites.'



(a)

(b)

Figure 4.17. Seasonal mean flows for winter (a) and summer (b) from river flow meters in the reference network (1954–2008).

Further Information and Data Sources

EPA (Environmental Protection Agency) (2011) *Review of the EPA Hydrometric Programme*. EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Murphy, C., Hall, J., Harrigan, S. and Wilby, R.L. (2012a) *HydroDetect: the identification and assessment of climate change indicators from an Irish Reference Network of River Flow stations.* Environmental Research Centre Report, EPA, Wexford, Ireland. (Submitted)

Murphy, C., Hall, J. ,Harrigan, S. and Wilby, R.L. (2012b) Evaluating long-term trends in mean- and high- river flows using a network of reference stations in Ireland, *Hydrological Sciences* (Submitted).

Nasr, A.E. and Bruen, M. (Under preparation) *Climate Change Indicators in the 7-day Sustained Low Flow (7SLF) series of Irish Rivers*. Environmental Research Centre Report, EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Register of hydrometric stations: http://www.epa.ie/whatwedo/monitoring/water/hydrometrics/network/

EPA's Hydronet website to access a range of hydrometric data: http://hydronet.epa.ie/

Information on flows at stations operated by the Office of Public Works may be accessed at: http://www.opw.ie/hydro/home.asp.

Flood hazard maps and reports can be downloaded from the Office of Public Works: http://www.floodmaps.ie/

Retrieval of river and lake levels from satellite altimetry: http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main

The Global Runoff Data Centre, a repository for the world's river discharge data and associated metadata: http://www.bafg.de/GRDC/

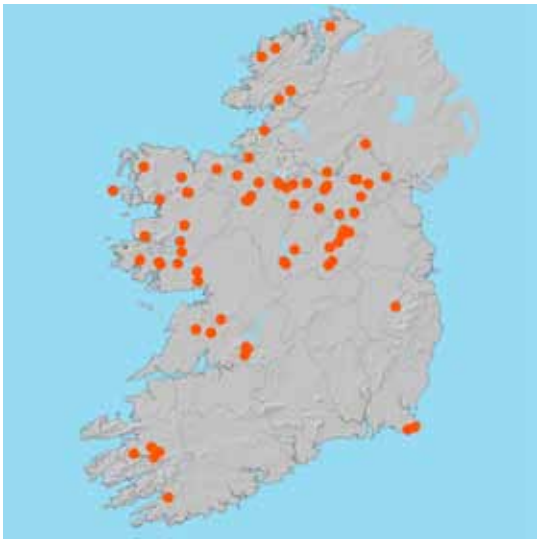
4.10 Lake Levels and Area

Ned Dwyer

Lakes affect climate primarily due to evaporation of water. In turn the level, area and temperature of lakes are impacted by regional climate. Lakes provide a range of services including drinking water, supply to industry and agriculture, recreational opportunities and ecosystem maintenance among others. In Ireland there are over 12,000 lakes, many quite small and shallow, mainly in the midlands and west. Measurement of levels, area and volume is important in order to monitor climate change effects and also for water management purposes.



Photo: © Digby Lewis



Map 4.3. Location of lake level monitoring stations.

Measurements

Lake levels are currently measured at 73 locations by the EPA, the Office of Public Works and the ESB. Some of the EPA measurements are carried out as part of Water Framework Directive requirements. In addition, the water temperature on over 220 lakes is being measured and an EPA coordinated programme to carry out a bathymetric survey of 820 lakes is under way, with over 300 lakes surveyed so far.

Satellite altimetry is used internationally to determine water levels in large lakes, with typical vertical accuracy of 20 cm. This provides useful data in the absence of *in situ* measurements.

'No systematic analysis of lake levels has been carried out to date.'

Time-series and Trends

No systematic analysis of lake levels has been carried out to date. Figure 4.18 shows an example of measurements of the monthly mean level for Lough Oughter in Co. Cavan from 1977 to 2011. This is a good example of an unimpacted lake with no water extraction and limited development in the lake surrounds. Levels change on a seasonal basis with a minimum during the summer months and a maximum during winter, but long-term trends in the data are not immediately evident.

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

Maintaining the Observations

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

Further Information and Data Sources

Information on the EPA's lake monitoring programme: http://www.epa.ie/whatwedo/monitoring/water/lakes/

Register of hydrometric stations: http://www.epa.ie/whatwedo/monitoring/water/hydrometrics/network/

Online hydrometric data for the local authority and EPA hydrometric network: http://hydronet.epa.ie/conditions.htm

Online hydrometric data for the Office of Public Works hydrometric network: http://www.opw.ie/hydro/index.asp?mpg=main.asp

Information and data on lake levels retrieved using satellite altimeters: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/

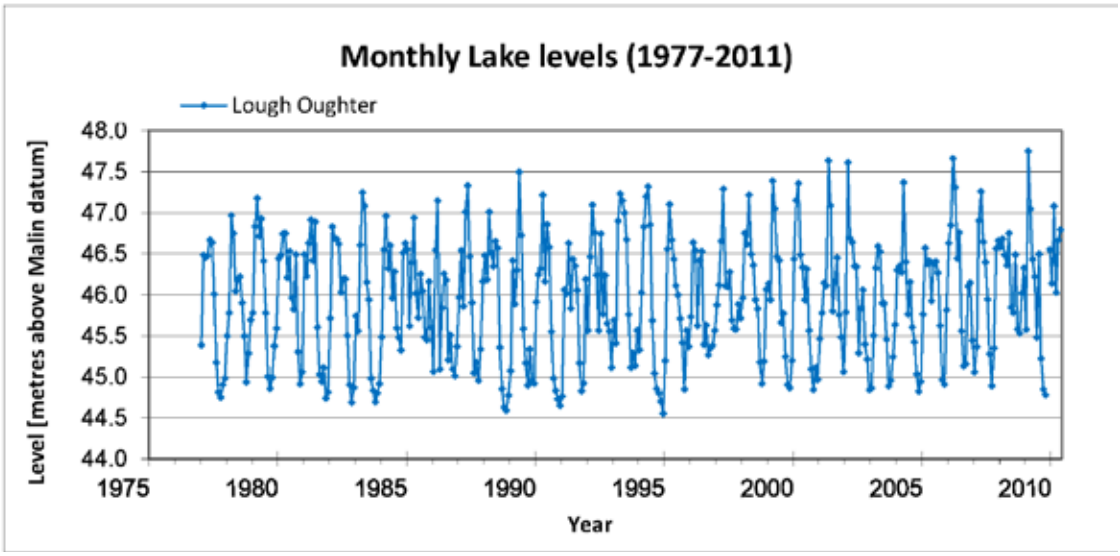


Figure 4.18. Monthly mean levels on Lake Oughter, Co. Cavan (1977–2011).

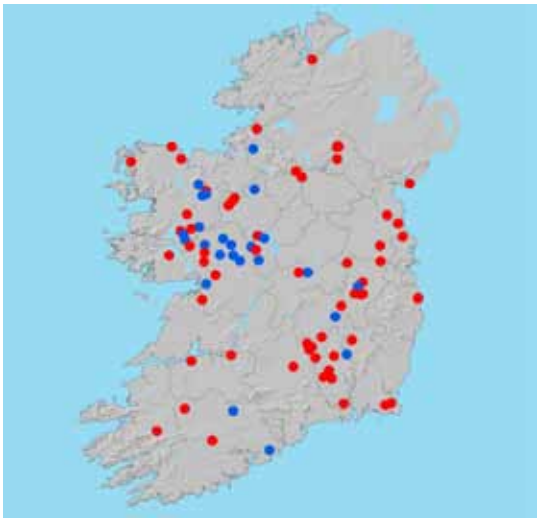
4.11 Groundwater

Ned Dwyer

Groundwater is located beneath the ground surface in pore spaces and fractures of geologic formations. If the geologic 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 freshwater 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 26% of drinking water is from groundwater sources. Groundwater recharge is influenced by not only rainfall and dry periods but also by human use. Risks to groundwater quality and quantity that may be exacerbated under a changing climate include depletion, pollution and salinisation.



Photo: © Ned Dwyer



Map 4.4. Location of groundwater monitoring stations.

Measurements

Groundwater level data have been collected in Ireland since the late 1960s. In the 1990s the EPA took responsibility for its monitoring and maintains a groundwater level monitoring network of approximately 70 sites. The data collected include groundwater level (red); overflow and abstraction at springs; well head elevation and aquifer unit/type. For some monitoring locations the specific yield, storage and the transmissivity of the aquifer have been calculated. Flow discharge at springs is also measured at 25 locations (blue).

Satellites which form part of the collaborative US and German Gravity Recovery and Climate Experiment

(GRACE) are being used for the monitoring of groundwater over large areas. Large pockets of water exert a greater gravitational pull on the satellites than areas without water. Over time the satellites can measure groundwater fluctuations.

'No systematic analysis of national groundwater levels has been carried out to date.'

Time-series and Trends

No systematic analysis of national groundwater levels has been carried out to date. Figure 4.19 shows an example of measurements of the daily mean level for a well in Knocktopher, Co. Kilkenny from 1980 to 2011. There are many data gaps in the early part of the series prior to 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. There is no evident long-term trend in the data.

'Selection of groundwater sites for climate monitoring purposes is under way.'

Maintaining the Observations

The EPA is responsible for groundwater monitoring and in 2006 the network was reviewed and updated in accordance with EU legislation. The selection of the subset of stations for climate monitoring purposes is underway. There have been significant upgrades to the groundwater level monitoring network in recent years and time will be required to collect and evaluate data from this. The network will be refined and data gaps filled as analysis of these data improves understanding of the hydrogeological systems.

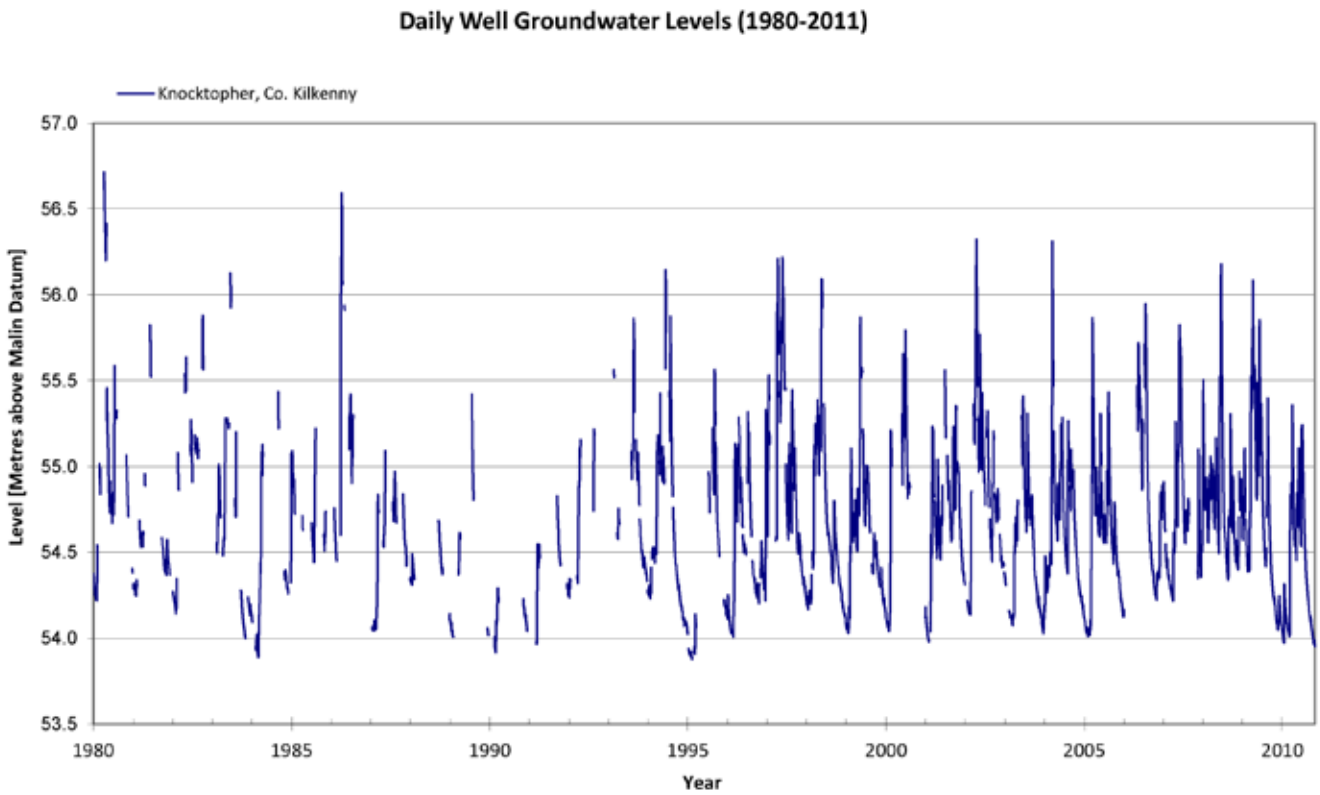


Figure 4.19. Daily mean groundwater level at a well in Knocktopher, Co. Kilkenny (1980–2011).

Further Information and Data Sources

Lucey, J. (comp.) (2009) *Water Quality in Ireland 2007–2008: Key Indicators of the Aquatic Environment.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland. p. 52.

McGarrigle, M., Lucey, J., and Ó Cinnéide, M. (2010) *Water Quality in Ireland 2007–2009,* EPA, Johnstown Castle Estate, Co. Wexford, Ireland. pp. 148: http://www.epa.ie/downloads/pubs/water/waterqua/name,30640,en.html

Tedd, K., Misstear, B., Coxon, C., Daly, D., Hunter-Williams, T., Craig, M. and Mannix, A. (2010) *Review of Groundwater Level Data in the South Eastern River Basin District.* STRIVE Report Prepared for the EPA and the GSI by Trinity College, Dublin.

The EPA's website on groundwater monitoring: http://www.epa.ie/whatwedo/monitoring/water/groundwater/programme/

Information on the GRACE mission: http://www.csr.utexas.edu/grace/

Groundwater aquifer maps, well locations, groundwater vulnerability maps and other relevant data may be downloaded from the Department of Communications, Energy and Natural Resources, DCENR: http://www.dcenr.gov.ie/Spatial+Data/Geological+Survey+of+Ireland/GSI+Spatial+Data+Downloads.htm

Groundwater relevant data may be viewed on the GSI's web-mapping service: http://www.gsi.ie/Programmes/Groundwater/Groundwater+web+mapping.htm

4.12 Water Use (Irrigation)

Ned Dwyer

Fresh water is used for agriculture, industrial and household activities. Globally, agriculture, and in particular irrigation, is the largest water-use sector, accounting for approximately 70% of all water withdrawn from rivers, lakes and the ground. Water use for agriculture in Ireland is limited to some early crop potatoes and vegetables grown under cover, mainly in the east and southeast. Monitoring of water use for agricultural purposes is important for appropriate water management and for understanding the effects of climate change on food production.



Photo: © Brian Barrett

Measurements

No measurements of water use for irrigation are made in Ireland. The Food and Agriculture Organization of the United Nations (FAO) has made an estimate of possible usage based on land-cover maps and on reports by the Central Statistics Office of potato crop acreage in 2000.

Time-series and Trends

The FAO estimates of the maximum possible irrigated area are based on Central Statistics Office reports of potato crop acreage and crops grown in plastic tunnels for 2000. It is estimated that an area of approximately 1100 ha, representing less than 1% of the total cultivated area of the country, is irrigated.

'It is estimated that less than 1% of the total cultivated area of the country is irrigated.'

Maintaining the Observations

Irrigation needs may change in the future with changes in precipitation patterns. However monitoring of water usage in all sectors should be carried out and coordinated given its impact on the hydrological cycle.

Further Information and Data Sources

FAO's Information System on Water and Agriculture:
http://www.fao.org/nr/water/aquastat/main/index.stm

Story Board 7: Satellite Observations Provide a Global Picture

Ned Dwyer

Images from satellites are familiar nowadays – ranging from cloud distributions on weather forecasts to high-resolution images of your house in viewers such as Google Earth. For more than 40 years, data from a wide range of satellite sensors have been used to observe the Earth and have improved immensely knowledge of many aspects of the climate system. Some of the major benefits of satellite observation systems include their ability to monitor almost all of the Earth's surface and surrounding atmosphere on a regular basis and in a consistent manner, thereby complementing ground-based observational infrastructure which is relatively sparse, particularly in many oceanic areas, polar regions, high mountain zones, arid desert areas and some developing countries. Satellite observations are also invaluable in contributing time-series data which can be input to models of the global climate system in order to forecast future climate conditions.

Satellite sensor data can contribute to the determination of more than 30 of the ECVs. For some of these, such as cloud properties and upper air temperatures reliable and complete time-series extend back more than 20 years, whilst land-cover mapping from local to global scales has long been one of the major application areas of satellite imagery (Fig. SB7.1). In other cases, such as for soil moisture or biomass, observations exist and work is ongoing to generate long-term, reliable time-series.

Sea surface temperature has been observed systematically, on a global basis for over 15 years. Global observations at a horizontal resolution of 1 km and an accuracy of approximately ±0.3°C are currently possible. Such information has been crucial for monitoring and providing early warning of major oceanic phenomena such as the El Niño Southern Oscillation (ENSO) in the Pacific Ocean

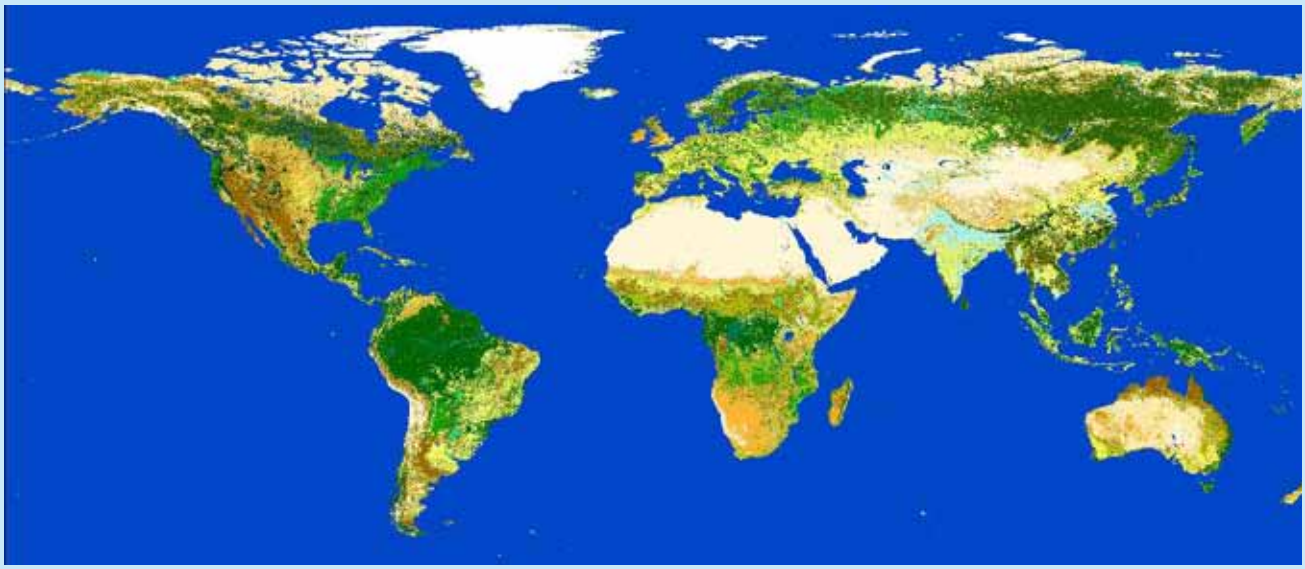


Figure SB7.1. Global land cover derived from data collected in 2009 from Envisat's Medium Resolution Imaging Spectrometer (MERIS) instrument. © ESA and UCLouvain.

(Fig. SB7.2). ENSO, which occurs on an irregular basis every five to eight years sees a significant warming of the ocean surface off the coast of South America and can have major impacts on the global climate, including flooding in parts of South America and severe droughts in parts of southeast Asia.

Although satellite observations are an invaluable source of information on the climate system there are significant challenges in working with the data. Data often comes from multiple satellite sensors; the sensors degrade over time; and satellites have a finite lifetime (5 to 10 years). In order to ensure high-quality and reliable observations the satellite data need to be carefully validated using *in situ* measurements and continuous calibration and quality control has to be carried out. It has taken some time for satellite-derived data products to become embedded in operational monitoring programmes. One of the most successful to date has been meteorology.

Recognising the valuable role that satellite data play in improving understanding of the climate the GCOS secretariat has published specific requirements with regard to the use of satellite-based products for climate observation. In support of this, the ESA conceived a Climate Change Initiative (CCI) which focuses on providing reliable, long-term satellite data sets for a number of the ECVs to assist climate change studies. Data from the many instruments on board ESA's flagship Earth-observation satellite *ENVISAT* have been used as part of the CCI. *ENVISAT* ceased operations in April 2012 and there is now pressure to launch the follow-up Sentinel series of satellites as soon as possible. Furthermore, the Global Monitoring for Environment and Security (GMES) programme, a joint initiative between the European Commission and the ESA contributes to the Global Earth Observing System of Systems (GEOSS) whose aim is to provide satellite-derived information on a range of key global issues including climate change. Figure SB7.3, which shows monthly mean CO_2 concentrations for August 2010, was generated as part of the GMES Monitoring Atmospheric Composition and Climate (MACC) project.

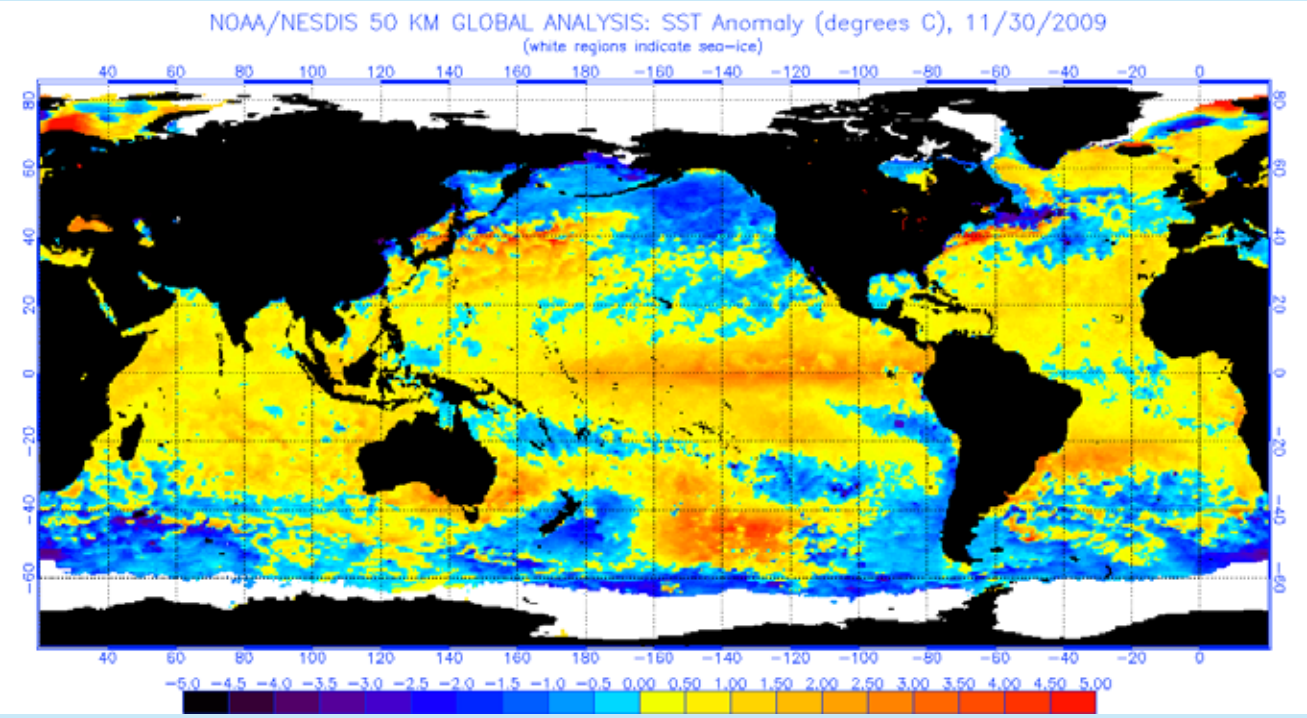


Figure SB7.2. Sea surface temperature anomalies based on satellite measurements for 30 November 2009 show that the El Niño event saw ocean temperatures more than 2°C above normal (orange) in the Eastern Pacific. Image © NOAA Satellite and Information Service.)

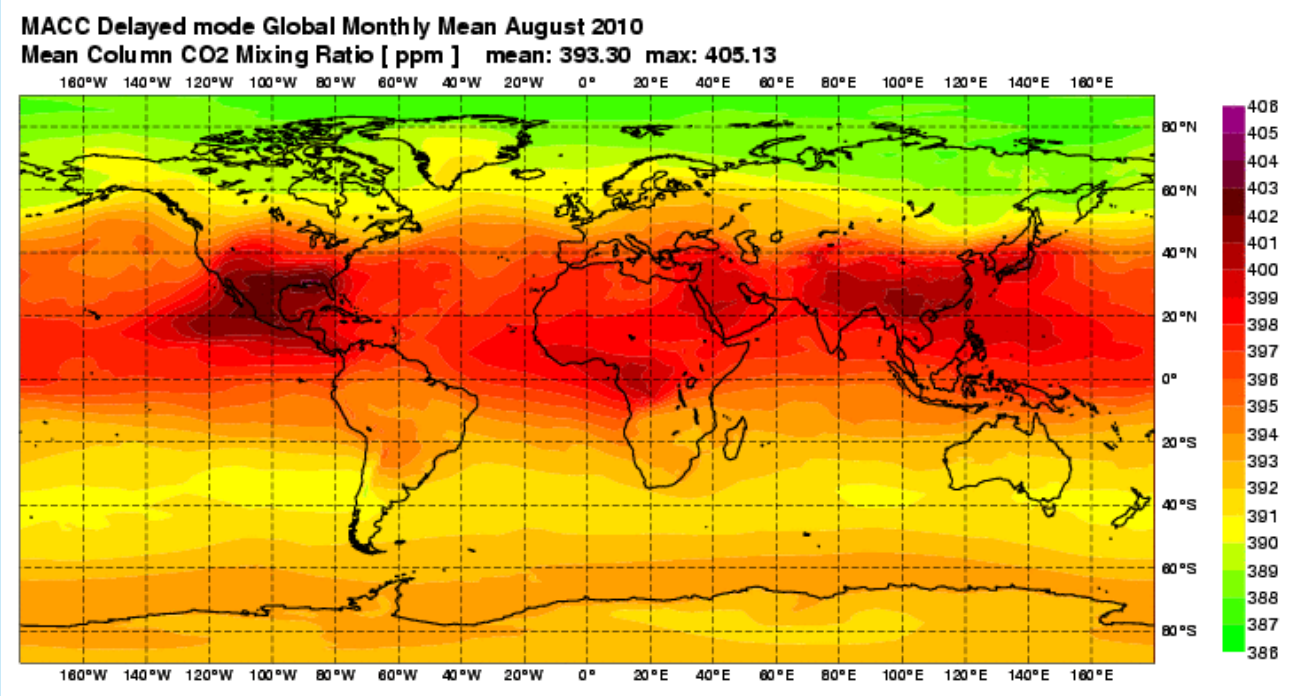


Figure SB7.3. Global mean monthly carbon dioxide concentration for August 2010 calculated from a combination of satellite and *in situ* measurements.

In Ireland there is limited use of satellite data for systematic monitoring of climate variables. The perception is that satellite data are expensive, difficult to interpret and more uncertain than ground-based systems. Nonetheless, some niche applications have developed. Imagery and data from the *Meteosat* satellites are used in weather forecasting by Met Éireann. The Marine Institute uses ocean colour data as part of its Harmful Algal Bloom service and high-resolution images from satellites including *Landsat* and *SPOT* are used in the production of land-cover maps such as CORINE. Ireland's participation in the EC/ESA GMES and ESA's Earth Observation programme offers the potential to increase expertise in remote-sensing data use and analysis along with the number of people working in the field. This will enhance use of remote-sensing products for climate studies.

Satellite remote sensing will never fully replace *in situ* observing systems, some of which have been in place for over 150 years. However, they offer a vital complement to these measurements and fill the gaps in areas where *in situ* sensors are not deployed or would be prohibitively expensive to install. New and improved satellite-based sensors are constantly being developed and deployed and will provide ever more detailed, frequent and reliable information regarding the state of our planet for decades to come.

Further Information

ESA's Climate Change Initiative*:* http://www.esa-cci.org/

ESA's GlobCover project: http://ionia1.esrin.esa.int/

Information on the GMES programme: http://www.gmes.info/

GCOS (2010) *Systematic Observation Requirements for Satellite-based Products for Climate. Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC – 2011 Update,* Report No. 154, http://www.wmo.int/pages/prog/gcos/index.php?name=Publications



5. Discussion and Recommendations

5. Discussion and Recommendations

The Earth's climate has always been changing. However, the rate of change over recent decades has been much higher than that for many tens of thousands of years. This rapid change is due to the enhanced greenhouse effect, caused by human activities which emit a range of greenhouse gases, including carbon dioxide and methane into the atmosphere. The ongoing increase in atmospheric concentrations of greenhouse gases is observed globally and also from monitoring stations in Ireland.

Climate change in Ireland mirrors many of the global trends. Mean annual surface air temperature has increased by approximately 0.8°C over the last 110 years. The number of annual frost days has been decreasing whilst the number of warm days has increased. Average annual national rainfall has increased by approximately 60 mm or 5% in the period 1981 to 2010, compared to the 30-year period 1961 to 1990: however, clear changes in rainfall patterns across the country cannot be determined with a high level of confidence.

Changes in the ocean climate are also evident. Sea surface temperature records from around Ireland exhibit a mean warming trend of 0.3°C between 1850 and 2008 with the warmest years in the record being 2005, 2006 and 2007. Sea level has not historically been measured with the necessary accuracy to determine sea-level changes around Ireland. Nonetheless, observations from southwest England show a sea-level rise of 1.7 cm per decade. These measurements are considered representative of the situation to the south of Ireland. Although there is no long-term national programme to monitor ocean acidification, a recent project conducted in Irish waters confirmed global trends of increasing acidification, which has severe implications for oceanic ecosystems and knock-on socio-economic impacts.

There has been a significant change in the distribution of land-cover type across Ireland in recent decades. The major changes have been an increase in urban areas and the conversion of grassland and peatland to forest. The expansion of forest area has seen the amount of carbon stored or sequestered in forest areas increase by 40% since 1990.

Analysis of long-term river flows from over 40 measurement sites around the country shows a tendency for increasing annual mean flows. Moreover, seasonal analysis indicates that summer mean flows are dominated by increasing trends while there is a tendency also for increases in winter mean flows.

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 needs to be maintained and further developed 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 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.

There has been a significant growth and consolidation of ocean-observing systems since 2000; this is proving to be invaluable in improving understanding of oceanic climate. It is essential that these systems are maintained and where possible enhanced to increase the number and quality of the measurements made. Only with long time-series data will it be possible to detect trends in the oceanic climate variables and therefore make appropriate adaptation decisions. Ocean acidification is of growing international concern. There is a need for a long-term national commitment to monitoring the ocean carbonate system and ocean acidity in order to improve

understanding of its potential threat to the Irish marine environment and economy.

A number of the land surface and hydrological variables have been monitored by various organisations for many years in support of policy and management objectives (e.g. water supply, land use). It is important to ensure that these observations also contribute to long-term monitoring for climate purposes.

At least a dozen different organisations have a role to play in monitoring aspects of Ireland's climate. It is vital that long-term monitoring is coordinated between these different bodies to avoid duplication and to maximise possibilities for synergy.

As important as the systematic collection and management of climate data is their regular analysis and the reporting of status, trends and projections. Many of the atmospheric composition variables monitored at the Mace Head Atmospheric Research Station have been reported on in a global context (Ramonet et al., 2010; Rigby et al., 2008; Derwent et al., 2007). An analysis of some meteorological variables was carried out in the last decade (Sweeny et al., 2002; McElwain and Sweeney, 2007). A comprehensive analysis of the ocean climate and ecosystem status was recently published by the Marine Institute (Nolan et al., 2010). Long time-series of data, some in excess of 50 years, exist for many of the meteorological and hydrological variables, yet only partial analyses have been carried out to date. Furthermore, regular observations of some of the land surface variables have been made by satellite since the 1980s, but limited analyses of these have been carried out for Ireland.

This report demonstrates that many elements of a climate observation, analysis and reporting system are in place: nonetheless, there are a number of issues that need to be addressed in order to make it 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:

1 A structure or body is required to enhance coordination between organisations carrying out atmospheric, oceanic and terrestrial climate observations to ensure an integrated national approach and efficient utilisation of resources.

2 Observation programmes for some of the ECVs are well established (e.g. meteorological). Other ECV observations are carried out on a project or ad hoc basis (e.g. atmospheric composition, oceanic). It is vital that adequate resources are provided to (i) maintain existing, established climate-observation programmes and to (ii) guarantee the long-term continuity of project-based monitoring to international standards.

3 No long-term national observation programmes exist for a number of the ECVs (ocean acidification, pCO_2, ocean currents, phytoplankton, soil carbon, fire disturbance, water use). A prioritisation and costing exercise should be carried out with a view to implementing appropriate programmes over time.

4 Some variables are monitored under various operational and management programmes (e.g. river flows and lake levels as part of the Water Framework Directive; sea state for ocean weather forecasting) but not for climate purposes. Appropriate long-term climate observation sites should be identified and designated from among current observation sites.

5 Ensure data from the Irish National Tide Gauge Network established over the last decade by the Marine Institute and a number of public and private sector organisations can be used for the calculation of sea-level change. Provide analyses of these data with historical records from established, reliable tide gauges and link these to regional satellite derived information on sea–level change.

6 *S*afeguard all existing and historical ECV data, complete digitisation of paper records (e.g. air temperature, precipitation, wind) and carry out quality checks and homogenisation of these data to ensure their adequacy for climate monitoring.

7 Comprehensive analysis has been carried out for the atmospheric composition and some of the meteorological and oceanic ECVs. However, only partial analyses have been completed for the majority of the other ECVs. Complete and regular detailed analysis should be carried out and reported on all ECV observations, including satellite data records where appropriate.

References

Acker J.G. and Leptoukh, G. (2007) Online analysis enhances use of NASA earth science data, *Eos, Transactions. American Geophysical Union,* Vol. 88, 2, pp. 14 and 17.

Black, K., Davis, P., Lynch, P., Jones, M., McGettigan, M. and Osborne, B. (2006) Long-term trends in solar irradiance in Ireland and their potential effects on gross primary productivity, *Agricultural and Forest Meteorology,* Vol. 141, pp. 118–32.

Black, K., O'Brien, P., Redmond, J., Barrett, F. and Twomey, M. (2009) The extent of peatland afforestation in Ireland, *Irish Forestry,* Vol. 65, pp. 61–71.

Cannaby, H. and Hüsrevoğlu, Y.S. (2009) Low frequency variability and long-term trends in Irish SST records, *ICES Journal of Marine Science,* Vol. 66, 7 pp. 1480–9.

Cannaby, H. and Nolan, G. (2009) Physical oceanography, in *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, 100 pp.

Carroll, E., Sparks, T., Donnelly, A. and Cooney, T. (2009) Irish phenological observations from the early 20th century reveal a strong response to temperature. *Biology and Environment: Proceedings of the Royal Irish Academy.* Vol. 109B, 2 pp. 115–26.

Coll, J., Maguire, C., Sweeney, J. (2009) *Biodiversity and Climate Change in Ireland – Briefing Paper*: http://www.comharsdc.ie/_files/Biodiversity_ClimateBriefing%20Paper_Final_6thJan_2009.doc.pdf

Cusack, C. (2009) Phytoplankton, in *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, pp. 100.

Daly, K. and Fealy, R. (2007) *Digital Soil Information System for Ireland – Scoping Study.* Environmental Protection Agency (EPA), Johnstown Castle Estate, Co. Wexford, Ireland: http://www.epa.ie/downloads/pubs/research/land/name,23747,en.html

Davies, D., Kumar, S. and Descloitres, J. (2004) Global fire monitoring using MODIS near-real-time satellite data*, GIM International,* Vol. 18 (4), pp. 41–3.

De Mol, B., Kozachenko, M., Wheeler, A., Hugo, A., Henriet, J.-P and Olu-Le-Roy, K. (2007) Thérèse Mound: a case study of coral bank development in the Belgica Mound Province, Porcupine Seabight, *International Journal of Earth Sciences,* Vol. 96, No. 1, pp. 103–20.

Derwent, R.G., Ryall, D.B., Manning, A.J., Simmonds, P.G., O'Doherty, S., Biraud, S., Ciais, P., Ramonet, M. and Jennings, S.G. (2002) Continuous observations of carbon dioxide at Mace Head, Ireland from 1995 to 1999 and its net European ecosystem exchange, *Atmospheric Environment*, Vol. 36, pp. 2799–807.

Derwent, R.G., Simmonds, P.G. Manning, A.J. and Spain, T.G. (2007) Trends over a 20-year period from 1987 to 2007 in surface ozone at the atmospheric research station, Mace Head, Ireland, *Atmospheric Environment,* Vol. 41, pp. 9091–8.

Dlugokencky, E.J., Bruhwiler L. White, J.W.C., Emmons, L.K., Novelli, P.C., Montzka, S.A., Masarie, K.A., Lang, P.M., Crotwell, A.M., Miller, J.B. and Gatti, L.V. (2009) Observational constraints on recent increases in the atmospheric CH_4 burden, *Geophysical Research* Letters, Vol. 36, L18803.

Duffy, P., Hanley, E., Hyde, B., O'Brien, P., Ponzi, J., Cotter, E. and Black, K. (2012) *National Inventory Report, 2012. Greenhouse Gas Emissions 1990–2010*, Reported to the UNFCCC, EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Dunne, S., Hanafin, J., Lynch,P., McGrath, R., Nishimura,E., Nolan, P., Ratnam, J.V., Semmler, T., Sweeney, C. and Wang, S. (2008) *Ireland in a Warmer World, Scientific Predictions of the Irish Climate in the Twenty-First Century*. (R. McGrath and P. Lynch, eds.), Community Climate Change Consortium for Ireland: www.c4i.ie/docs/IrelandinaWarmerWorld.pdf

Dwyer, N. (2008) *Climate Change – Implementation of the Global Climate Observing System in Ireland. Environmental Research Centre Report 8,* EPA, Johnstown Castle Estate, Co. Wexford, Ireland: http://www.epa.ie/downloads/pubs/research/climate/name,24240,en.html

Dwyer, N. (2010) *Current Status and Required Actions for National Climate Observing Systems.* Environmental Research Centre Report 14, EPA, Johnstown Castle Estate, Co. Wexford, Ireland: http://www.epa.ie/downloads/pubs/research/climate/name,27740,en.html

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G. (2008) Land cover change and soil organic carbon stocks in the Republic of Ireland,1851–2000, *Climatic Change*, Vol. 91, Nos 3–4, pp. 317–34.

EPA (Environmental Protection Agency) (2011) *Review of the EPA Hydrometric Programme.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Fennell, S. (2007) A study of the behaviour and interannual variability of surface salinity and temperature at the M3 weather buoy off the southwest coast of Ireland. MSc, Marine Institute, Co. Galway, Ireland.

Giglio, L., Descloitres, J., Justice, C. O. and Kaufman, Y.J. (2003) An enhanced contextual fire detection algorithm for MODIS, *Remote Sensing of Environment,* Vol. 87, pp. 273–82.

Global Climate Observing System GCOS (2010) *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (Update). GCOS Report 138. WMO/TD No 1523. World Meteorological Organization (WMO), Geneva, pp. 186: http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf

Haigh, I., Nicholls, R. and Wells, N. (2009) Mean sea level trends around the English Channel over the 20th century and their wider context, *Continental Shelf Research,* Vol. 29, pp. 2083–98.

Hanafin, J.A., Jennings, S.G., O'Dowd, C.D. and McGrath, R. (in print) *Retrieval and analysis of atmospheric water vapour from GPS receivers*, EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

Hendrick E. and Black K. G. (eds.) (2007) *Forest, carbon and climate change, local and international perspectives, proceedings of the COFORD conference on 19/09/2007.*

Hill, A.E., Brown, J., Fernand, L., Holt, J., Horsburgh, K. J., Proctor, R., Raine, R. and Turrell, W.R. (2008) Thermohaline circulation of shallow tidal seas, *Geophysical Research Letters,* Vol. 35, L11605, doi:10.1029/2008GL033459.

Holden, N.M. (2006) Agriculture, meteorology and water quality in Ireland: a regional evaluation of pressures and pathways of nutrient loss to water. *Biology and Environment: Proceedings of the Royal Irish Academy,* Vol. 106B, 2, pp. 117–33.

Holden, N. M., Hochstrasser, T., Schulte, R. P. O., Walsh, S. (eds.) (2007) *Making Science Work on the Farm. A Workshop on Decision Support Systems for Irish Agriculture.* Published by Joint Working Group in Applied Agricultural Meteorology: http://www.agmet.ie/Agment_workshop_online_version.pdf http://www.ucd.ie/agmet/Agment_workshop_online_version.pdf

IPCC (Intergovernmental Panel on Climate Change) (2007) *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.) IPCC, Geneva, Switzerland. pp. 104. http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Keim, C., Eremenko, M., Orphal., J., Dufour, G., Flaud, J.-M., Höpfner, M., Boynard, A., Clerbaux, C., Payan, S., Coheur, P.–F., Hurtmans, D., Claude, H., Dier, H., Johnson, B., Kelder, H., Kivi, R., Koide, T., López Bartolomé, M., Lambkin, K., Moore, D., Schmidlin, F.J. and Stübi, R (2009) Tropospheric ozone from IASI: comparison of different inversion algorithms and validation with ozone sondes, *Atmospheric Chemistry and Physics* , Vol. 9, pp. 9329–47

Loeb, N.G. Wielicki, B.A., Su, W., Loukachine, K., Sun, W., Wong, T., Priestly, K.J., Matthews, G., Miller, W.F. and Davies, R. (2007) *Multi-instrument comparison of top-of-atmosphere reflected solar radiation, Journal of Climate,* 20, pp. 575–91, doi: http://dx.doi.org/10.1175/JCLI4018.1

Lucey, J. (comp.) (2009) *Water Quality in Ireland 2007–2008: Key Indicators of the Aquatic Environment.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland. pp. 52.

McElwain, L. and Sweeney, J. (2007) *Key Meteorological Indicators of Climate Change in Ireland*. Environmental Research Centre Report 6, Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. http://www.epa.ie/downloads/pubs/research/climate/name,23305,en.html

McGarrigle, M., Lucey, J., and Ó Cinnéide, M. (2010) *Water Quality in Ireland 2007–2009,* EPA, Johnstown Castle Estate, Co. Wexford, Ireland. pp. 148: http://www.epa.ie/downloads/pubs/water/waterqua/name,30640,en.html

McGovern, E., Monaghan, E., Bloxham, M., Rowe, A., Duffy, C., Quinn, Á., McHugh, B., McMahon, T., Smyth, M., Naughton, M., McManus, M. and Nixon, E. (2002) *Winter Nutrient Monitoring of the Western Irish Sea – 1990–2000.* Marine Environment and Health Series No. 4. 2002, Marine Institute: Dublin.

McGrath, T., Nolan, G., McGovern, E. (2012) Chemical characteristics of water masses in the Rockall Trough. *Deep Sea Research Part I: Oceanographic Research Papers*, Vol. 61, pp. 57–73.

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R.R. and McGovern, E. (2012) Inorganic carbon and pH levels in the Rockall Trough 1991–2010, *Deep Sea Research Part I: Oceanographic Research Papers, Vol. 68, pp. 79–91. doi* 10.1016/j.dsr.2012.05.011

Metz, B. (2010) *Controlling Climate Change. Cambridge University Press,* pp. 359: http://www.controllingclimatechange.info/

Murphy, C., Hall, J. Harrigan, S and Wilby, R.L. (2012) Evaluating long-term trends in mean- and high- river flows using a network of reference stations in Ireland. *Hydrological Sciences Journal* (Submitted).

Murphy, C., Hall, J., Harrigan, S. and Wilby, R.L. (2012a) *HydroDetect: the identification and assessment of climate change indicators from an Irish Reference Network of River Flow stations.* Environmental Research Centre Report, EPA, Johnstown Castle Estate, Co. Wexford, Ireland. (Submitted).

Murphy, C., Hall, J. Harrigan, S and Wilby, R.L. (2012b) Evaluating long-term trends in mean- and high- river flows using a network of reference stations in Ireland, *Hydrological Sciences* (Submitted).

Nardello, I., McGovern, E., Kiviame, C. and McGrath, T. (2009) Biogeochemical cycles in the Irish marine system. *Irish Ocean Climate and Ecosystem Status Report 2009.* Nolan, G., Gillooly, M. and Whelan, K. (eds.) Marine Institute, Galway, Ireland, pp. 100.

Nasr, A.E. and Bruen, M. (Under preparation) *Climate Change Indicators in the 7-day Sustained Low Flow (7SLF) series of Irish Rivers.* Environmental Research Centre Report, EPA, Johnstown Castle Estate, Co. Wexford, Ireland.

New, A.L., Smythe-Wright, D. (2001) Aspects of the circulation in the Rockall Trough*, Continental Shelf Research*, Vol. 21, Nos 8–10, pp. 777–810.

Ní Longphuirt, S., Stengel, D., O'Dowd C., and McGovern, E. (2010) *Ocean Acidification: An Emerging Threat to our Marine Environment*. Marine Foresight Series No. 6, Marine Institute, Galway, pp. 98.

Nolan, G., Gillooly, M. and Whelan, K. (eds.) (2010) *Irish Ocean Climate and Ecosystem Status Report 2009*. Marine Institute, Co. Galway, pp 100 http://hdl.handle.net/10793/81

Norris, J.R. and Slingo, A. (2009) Trends in observed cloudiness and Earth's radiation budget in Strüngmann Forum Report. *Clouds in the Perturbed Climate System: Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation*. Heintzenberg, J. and Charlson, R.J. (eds.) MIT Press.

O'Boyle, S., McDermott, G. and Wilkes, R., (2009) Dissolved oxygen in estuarine and coastal waters around Ireland, *Marine Pollution Bulletin,* Vol. 58, pp. 1657–663.

O'Boyle, S., and Nolan, G. (2010) The influence of water column stratification on dissolved oxygen levels in coastal and shelf waters around Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy,* Vol. 110B, No. 3, pp. 195–209.

O'Connor, B., Dwyer, E., Cawkwell, F. and Eklundh, L. (2012) Spatio-temporal patterns in vegetation start of season across the island of Ireland using the MERIS Global Vegetation Index, *ISPRS journal of Photogrammetry and Remote Sensing*, Vol. 68, pp. 79–84.

O'Connor, T.C., S.G. Jennings and O'Dowd, C.D. (2008) Highlights from 50 years of Aerosol Measurements at Mace Head, *Atmospheric Research*, Vol. 90, pp. 338–55.

O'Doherty, S., Cunnold, D.M. Miller, B.R., Mühle, J., McCulloch, A., Simmonds, P.G., Manning, A.J., Reismann, S., Vollmer, K.K., Greally, B.R., Prinn, R.G., Fraser, P.J., Steele, L.P., Krummel, P.B., Dunse, B.L., Porter, L.W., Lunder, C.R., Schmidbauer, N., Hermansen, O., Salameh, P.K., Harth, Wang, R.H.J. and Weiss, R.F. (2009) Global and regional emissions of HFC-125 (CHF2CF3) from in situ and air archive atmospheric observations at AGAGE and SOGE observatories, *Journal of Geophysical Research,* Vol. 114, D23304.

O'Doherty, S., Cunnold, D.M . Manning, A., Miller, B.R., Wang, R.H.J., Krummel, P.B., Fraser, P.J., Simmonfd, P.G., McCulloch, A., Weiss, R.F., Salameh, P., Porter, L.W., Prinn, R.G., Huang, J., Sturrock, G., Ryal, D., Derwent, R.G. and Montzka, S.A. (2004) Rapid growth of hydrofluorocarbon 134a and hydrochlorofluorocarbons 141b, 142b, and 22 from Advanced Global Atmospheric Gases Experiment (AGAGE) observations at Cape Grim, Tasmania, and Mace Head, Ireland, *Journal of Geophysical Research,* Vol. 109, D06310.

O'Dowd, C., Cave, R., McGovern, E., Ward, B., Kivimae, C., McGrath, T., Stengel, D. & Westbrook, G. (2011) *Impacts of Increased Atmospheric CO_2* on Ocean Chemistry and Ecosystems. Marine Institute, Galway.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. and Stringer, L. (eds.) (2008) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report,* Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

Ramonet, M., Ciais, P. Aalto, T., Aulagnier, C., Chevalier, F., Cipriano, D., Conway, T.J., Haszpra, L., Kazan, V. Meinhardt, F., Paris, J.-D., Schmidt, M., Simmonds, P., Xueref-Rémy, I. and Necki, J.N. (2010) A recent build-up of atmospheric CO_2 over Europe. Part 1: observed signals and possible explanations, *Tellus B, Vol. 62, No. 1, pp. 1–13.*

Rayner N. A. Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, *A.* (2006) Global analysis of sea surface temperature, sea ice and night marine air temperature since the late nineteenth century, *Journal of Geophysical Research,* Vol. 108, pp. 4407, doi: 10. 1029/2002JD002670.

Risien, C. M. and Chelton, D.B. (2006) A satellite-derived climatology of global ocean winds, *Remote Sensing of Environment,* Vol. 105, 3, pp. 221–36.

Rigby, M., Prinn, R.G., Fraser, P.J., Simmonds, P.G., Langenfelds, R.L., Huang, J., Cunnold, D.M., Steele, l.P., Krummel, P.B., Weiss, R.F., O'Doherty, S., Salameh, P.K., Wang, H.J., Harth, C.M., Mühle, J. and Porter, L.W. (2008) Renewed *growth of atmospheric methane, Geophysical Research Letters,* Vol. 35, L22805.

Rohan, P.K. (1986) *The Climate of Ireland*, 2nd edn. Meteorological Service, Dublin.

Schroedter-Homscheidt, M., Drews, A. and Heise, S. (2008) Total water vapor column retrieval from MSG-SEVIRI split window measurements exploiting the daily cycle of land surface temperatures, *Remote Sensing of Environment,* Vol. 112, pp. 249–58.

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,* Vol. 44, pp. 95–110.

Seiz, G. and Foppa, N. (2007) *National Climate Observing System (GCOS Switzerland).* MeteoSwiss and ProClima, pp. 92 http://www.proclim.ch/4dcgi/proclim/en/Media?1022

Siliang, L., Ronggao, L. and Yang, L. (2010) Spatial and temporal variation of global LAI during 1981–2006, *Journal of Geographical Sciences*, Vol. 20, 3, pp. 323–32.

Silke, J., O'Beirn, F. and Cronin, M. (2005) Karenia: *An exceptional dinoflagellate bloom in western Irish waters, summer 2005.* Marine Environment and Health Series 21. Marine Institute, Galway, Ireland, pp. 44.

Stanhill, G. (1998) Long-term trends in, and spatial variation of, solar irradiances in Ireland, *International Journal of Climatology*, Vol. 18, No, 9, pp. 1030–50.

Sweeney, J., Donnelly, A., McElwain, L., and Jones, M. (2002) *Climate Change Indicators For Ireland, ERTDI* Report 2, Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland: http://www.epa.ie/downloads/pubs/research/climate/name,12157,en.html

Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M. and Murphy, C. (2008) *Climate Change – Refining the Impacts for Ireland.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland. http://www.epa.ie/downloads/pubs/research/climate/name,26008,en.html

Tedd, K., Misstear, B., Coxon, C., Daly, D., Hunter-Williams, T., Craig, M. and Mannix, A. (2010) *Review of Groundwater Level Data in the South Eastern River Basin District.* STRIVE Report Prepared for the EPA and the GSI by Trinity College, Dublin.

Thomas, P., Cox, S. and Tindal, A. (2009) *Long-Term Wind Speed Trends In Northwestern Europe.* Garrad Hassan and Partners Ltd, Bristol, UK: http://www.gl-garradhassan.com/en/index.php

Tomlinson, R.W. (2005) Soil carbon stocks and changes in the Republic of Ireland, *Journal of Environmental Management,* Vol. 76, pp. 77–93.

Tripathi, O.P, Jennings, S.G., O'Dowd, C.D., Colman, L., Leinert, S., O'Leary, B., Moran, E., O'Doherty, S.J. and Spain, T.G. (2010) Statistical analysis of eight surface ozone measurement series for various sites in Ireland, *Journal of Geophysical Research.,* Vol. 115, D19302, doi:io.1029/2010JD014040.

Tripathi, O.P., Jennings, S.G., Colman, L., Lambkin, K., Moran, E. and O'Dowd, C.D. (2012) *Ozone levels, changes and trends over Ireland – an integrated analysis.* EPA, pp. 137: http://www.epa.ie/downloads/pubs/research/air/name,33696,en.html

Tripathi, O.P., Jennings, S.G., O'Dowd, C.D., Lambkin, K. and Moran, E. (Submitted) Recent trends in stratospheric ozone at a mid-latitude observing station at Valentia, Ireland (51.940 N, 10.250 W) through ground-based and ozonesonde measurements from 1994 to 2009. *Journal of Atmospheric Science* (Submitted).

Vaquer-Sunyer, R and Duarte, C.M. (2008) Thresholds of hypoxia for marine biodiversity, *Proceedings of the National Academy of Sciences*, Vol. 105, No. 40.

Wheeler, A.J., Beyer, A., Freiwald, A., de Haas, H., Huvenne, V.A.I., Kozachenko, M., Olu-Le Roy, K. and Opderbecke, J. (2007) Morphology and environment of cold-water coral carbonate mounds on the NW European margin, *International Journal of Earth Science,* Vol. 96, 37–56, Series: 1.

Wheeler, A.J., M. Kozachenko, L.-A. Henry, A. Foubert, H. de Haas, V.A.I. Huvenne, D.G. Masson, K. Olu-Le-Roy (2011) The Moira Mounds, small cold-water coral banks in the Porcupine Seabight, NE Atlantic: Part A—an early stage growth phase for future coral carbonate mounds? *Marine Geology,* Vol. 282, Nos 1–2, pp. 53–64.

Wilson, J.B. (1979) The distribution of the coral Lophelia pertusa (L.) [L. prolifera (Pallas)] in the North East Atlantic, *Journal of the Marine Biological Association of the UK,* Vol. 59, pp. 149–64.

Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I. and Williams, S.D.P. (2009) Trends in UK mean sea level revisited, *Geophysical Journal International* Vol. 176, pp. 19–30.

Woolf, D.K., P.G. Challenor and Corron, P.D. (2002) The variability and predictability of North Atlantic wave climate, *Journal of Geophysical Research,* Vol. 107, p. 3145, doi:10.029/2001JC001124.

Zhang, X., Liang, S., Wang, K., Li, L. and Gui, S. (2010) Analysis of global land surface shortwave broadband albedo from multiple data Sources, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 3, No. 3, pp. 296–305.

Acronyms

AGAGE	Advanced Global Atmospheric Gases Experiment
AMO	Atlantic Multidecadal Oscillation
AVHRR	Advanced Very High Resolution Radiometer
BGS	Beginning of Growing Season
BODC	British Oceanographic Data Centre
C-CAPS	Centre for Climate and Air Pollution Studies
CCI	Climate Change Initiative
CCIP	Climate Change Impacts on Phenology
CDNC	Cloud Droplet Number Concentration
CEA	Atomic Energy Commission (France)
CFC	Chloroflourocarbon
Chl-a	Chlorophyll a
CLS	Collecte Localisation Satellites
CMRC	Coastal and Marine Research Centre
CNES	Centre National d'Etudes Spatiales
CNRS	Centre National de la Recherche Scientifique
CORINE	Coordinated Information on the European Environment
DAFM	Department of Agriculture Food and Marine
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DIC	dissolved inorganic carbon
DMSP	Defense Meteorological Satellite Programme
EC	European Commission
ECV	Essential Climate Variable
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
ESA	European Space Agency
ESB	Electricity Supply Board
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GHG	Green House Gases
GLOSS	Global Sea Level Observing System
GMES	Global Monitoring for Environment and Security
GPM	Global Precipitation Measurement

GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSN	Global Surface Network
HAB	Harmful Algal Bloom
HCFC	Hydrochlorofluorocarbons
hPa	hectoPascal
ICES	International Council for Exploration of the Sea
ICOS	International Carbon Observing System
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LSCE	Laboratoire des Sciences du Climat et l'Environnement
LSW	Labrador Sea Water
LUCAS	Land Use and Cover Area frame Survey
MACC	Monitoring Atmospheric Composition and Climate
MERIS	Medium Resolution Imaging Spectrometer
MI	Marine Institute
MODIS	Moderate Resolution Imaging Spectroradiometer
MOLAND	Monitoring Land Use/Cover Dynamics
MSL	Mean Sea Level
NAC	North Atlantic Current
NASA	National Aeronautics and Space Administration
NBDC	National Biodiversity Data Centre
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NUIG	National University Ireland Galway
OMPS	Ozone Mapper Profiler Suite
OPW	Office of Public Works
pCO_2	partial pressure of carbon dioxide
PFC	Perfluorocarbons
pH	measure of acidity in a solution
POL	Proudman Oceanographic Laboratory
Ppb	parts per billion
Ppm	parts per million
Psu	practical salinity unit
SAC	Special Area of Conservation
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SCIAMACHY	Scanning Imaging Absorption spectrometer for Atmospheric Chartography
SFPA	Sea Fisheries Protection Authority
SLR	Sea Level Rise
SMD	Soil Moisture Deficit
SMOS	Soil Moisture Ocean Salinity
SOC	Soil Organic Carbon
SPA	Special Protection Area
SPOT	Système Pour l'Observation de la Terre
SST	Sea Surface Temperature

SWH	Significant wave height
TA	Total alkalinity
TCD	Trinity College Dublin
Tg	Teragrams (equivalent to 1 tonne)
TM	Thematic Mapper
TUCSON	The Unified Climate and Synoptic Observation Network
UCC	University College Cork
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UTC	Coordinated Universal Time
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines
WOCE	World Ocean Circulation Experiment

Appendix 1: List of Authors

Black	Kevin	University College Dublin & Forest, Environmental Research and Services Ltd
Cawkwell	Fiona	University College Cork (UCC)
Coll	John	National University of Ireland Maynooth
Cusack	Caroline	Marine Institute
Devoy	Robert	Coastal and Marine Research Centre, UCC
Dwyer	Ned	Coastal and Marine Research Centre, UCC
Eaton	James	University College Cork (now at TerraCarbon LLC, USA)
Gault	Jeremy	Coastal and Marine Research Centre, UCC
Holliday	Penny	National Oceanography Centre, UK
Jennings	Gerard	National University of Ireland Galway
Kozachenko	Max	University College Cork
Lambkin	Keith	Met Éireann
McGovern	Evin	Marine Institute
McGrath	Triona	Marine Institute
Murphy	Conor	National University of Ireland Maynooth
Nolan	Glenn	Marine Institute
O'Boyle	Shane	Environmental Protection Agency (EPA)
O'Doherty	Simon	University of Bristol
O'Donoghue	Aidan	Coastal and Marine Research Centre, UCC (now at St Colman's College, Fermoy, Co. Cork)
O'Dowd	Colin	National University of Ireland Galway
O'Connor	Brian	Coastal and Marine Research Centre, UCC (now at Environmental Research & Assessment, UK)
Ramonet	Michel	Laboratoire des Sciences du Climat et de l'Environnement
Regan	Eugenie	National Biodiversity Data Centre
Saunders	Matthew	University College Dublin
Scarrott	Rory	Coastal and Marine Research Centre, UCC
Silke	Joe	Marine Institute
Simmonds	Peter	University of Bristol
Walsh	Séamus	Met Éireann