1. Introduction

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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

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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	yes	yes
Precipitation	1881–2012	Met Éireann	yes	yes
Air pressure	>100 yrs	Met Éireann	partial	yes
Surface radiation budget	1955–2012	Met Éireann	partial	yes
Wind	>100 yrs	Met Éireann	partial	yes
Water vapour	>50 yrs	Met Éireann	partial	yes
Upper-air temperature	1943–2012	Met Éireann	partial	yes
Upper-air wind	1943–2012	Met Éireann	partial	yes
Upper-air water vapour	1943–2012	Met Éireann	partial	yes
Cloud properties	>50 yrs	Met Éireann, NUI-G	partial	partial
Carbon dioxide	1992–2012	LSCE, France; NASA, USA	yes	partial
Methane	1987–2012	DECC, UK; NASA, USA.	yes	partial
Ozone	1993–2012	Met Éireann; EPA; DECC, UK	yes	yes
Other greenhouse gases	1978–2012	EPA; DECC, UK; NASA, USA.	yes	partial
Aerosols	1986–2012	Met Éireann; NUI-G	yes	partial

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.

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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.