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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Developing Ireland's Greenhouse Gas and Transboundary Air Pollution Monitoring Network

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

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

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

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

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

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We regulate the following activities so that they do not endanger human health or harm the environment:

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- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
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- Monitoring and reporting on Bathing Water Quality.

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- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

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The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Developing Ireland’s Greenhouse Gas and Transboundary Air Pollution Monitoring Network

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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DISCLAIMER

This report is based on research carried out/data from 2016 to 2019. More recent data may have become available since the research was completed.

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

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Executive Summary

The Atmospheric Composition and Climate Change (AC3) network is a system of observational sites across the country, which are used to characterise greenhouse gases (GHGs) and short-lived climate forcers. The research project here describes the development and operation of the associated instrumentation and infrastructure and gives an update on the current status of the network.

1. Station infrastructure, instrumentation, visualisation and information technology infrastructure have all been significantly improved.
2. Significant redevelopment of the Carnsore Point and Malin Head sites has been undertaken.
3. Multiyear inversion of GHGs is now being undertaken.
4. Data from a recent EMEP (European Evaluation and Monitoring Programme – the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe) campaign characterising the performance of the source apportionment algorithm of the AE33 aethalometer (black carbon) have been analysed and evaluated.
5. Given both the national and international importance of climate change, it is critical to maintain a level of investment in infrastructure, analytical systems and associated measurements to ensure that Ireland is at the forefront of this critical area.

1 Introduction

The Environmental Protection Agency (EPA) Climate Change and Atmospheric Composition network carries out measurements of the greenhouse gases (GHGs) methane (CH_4) and carbon dioxide (CO_2) under the preparatory phase of the ICOS (Integrated Carbon Observation System) programme, and short-lived climate forcers (SLCFs), as well as EMEP (European Evaluation and Monitoring Programme – the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe) monitoring at three Irish sites (Malin Head, Carnsore Point and Mace Head). A number of ancillary sites deal with EMEP monitoring only (Oak Park and Johnstown Castle). Characterisation of SLCFs includes black carbon (mass) measurement and aerosol characterisation [size distribution (scanning mobility particle sizer – SMPS), particle number (condensation particle counter – CPC), particle scattering (nephelometer), particle mass (tapered element oscillating microbalance – TEOM) and particle speciation (aerosol chemical speciation monitor – ACSM)]. The network will continue to operate under a framework funding agreement between the National University of Ireland Galway (NUIG) and the EPA.

The report on this research project follows on from a previous fellowship report (Martin and O'Dowd, 2020) outlining the operation of the Atmospheric Composition and Climate Change (AC3) network. The implementation and incremental improvement of the issues raised in the earlier report constitute a large part of the work undertaken in this project. In this regard, the executive summary of the earlier report identified the following points:

- The AC3 network is an established valuable national research and monitoring infrastructure that is being developed incrementally and monitors GHGs and SLCFs in line with best practice from both pan-European and global monitoring programmes.
- Station infrastructure, instrumentation, visualisation and information technology infrastructure have all been significantly improved.
- Ancillary measurements have now been well established at the sites (black carbon, particle number, aerosol composition, aerosol size distribution and ozone). These measurements allow GHG data to be extremely well characterised in terms of differences between regional and local pollution.
- Significant redevelopment of the Carnsore Point site is currently being undertaken. This involves a new laboratory facility and utilisation of a 60-metre tower for sampling. This will help to ensure more complete sampling of regional air masses.
- Data from the GHG component of the network have recently been used to infer high-resolution, bottom-up estimates of Irish CH_4 emissions for 2012 and the data from this network will facilitate multiyear estimates for both CH_4 and CO_2.
- A recent EMEP campaign characterising the performance of the source apportionment algorithm of the AE33 aethalometer (black carbon) has been undertaken and the data are currently under evaluation.
- Given both the national and international importance of climate change, it is critical to maintain a level of investment in infrastructure, analytical systems and associated measurements to ensure that Ireland is at the forefront of this critical area.

In addition to the continued operation of the network, a number of developments that took place during the course of the project are discussed in this report.

These developments related to:

- infrastructure upgrade at Carnsore Point and Malin Head;
- brown carbon source apportionment for AE33 instruments;
- an EMEP intensive campaign;
- inverse modelling;
- consolidation and expression of the ICOS Ireland position.

1.1 Network Definition

There have been discussions between NUIG and the EPA regarding the future definition of the network. We are working towards a long-term sustainable network with state-of-the-art instrumentation, adequate levels of staffing and appropriate site infrastructure. Table 1.1 defines the current configuration of the network.

Table 1.1. Instrumental status and performance, February 2020

	Measurement	Site	Instrument	Currently operational	Data capture rate, % (2019)	Transferred in real time to EPA	Submission to ICOS EMEP	Open data API
1	Ozone	MHD	Envirotechnology 400E	✓	> 95	✓	N/A	In progress
2	Ozone	CRP	Thermo 49I analyser	✓	> 95	✓	N/A	
3	Ozone	MLH	Envirotechnology 400E	✓	> 95	✓	N/A	
4	Black carbon	MHD	Magee Scientific AE33	✓	< 95[a]		Submitted for recent EMEP campaign – full submission being prepared – beginning of 2020	
5	Black carbon	CRP	Magee Scientific AE33	✓	> 95[b]			
6	Black carbon	MLH	Magee Scientific AE33	✓	> 95			
7	Black carbon	UCD	Magee Scientific AE16	X	< 95[c]			
8	CH_4 and CO_2	MHD[d]	PICARRO G2401	✓	> 95		Submitted to ICOS	
9	CH_4 and CO_2	CRP	PICARRO G1302	✓	> 95			
10	CH_4 and CO_2	MLH	PICARRO G1302	✓	> 95			
11	Particulate mass	MLH	PALAS FIDAS	✓	> 95		Full submission being prepared – beginning of 2020	
12	Particulate mass (PM$_{10}$)	CRP	TEOM[e]	✓	> 95			
13	RT aerosol speciation	UCD	ACSM	✓	< 95			
14	RT aerosol speciation	MHD	HR-ToF_AMS	X[f]	> 95			
15	RT aerosol speciation	MLH	ACSM	✓	< 95[g]			
16	Particle number	MHD	TSI CPC	✓	> 95			
17	Particle number	CRP	TSI CPC	✓	> 95			
18	Particle number	MLH	TSI CPC	✓	> 95			
19	Particle size distribution	MHD	SMPS	✓	> 95			
20	Particle size distribution	MLH	U-2000 SMPS	✓	> 95			
21	Offline aerosol chemical composition	MLH	Digital DA 80 HTD	✓	> 95		Submitted by Met Éireann to EBAS	
22	Offline aerosol chemical composition	CRP[h]	Digital DA 80 HTD	✓	> 95			
23	ICOS compliant meteorology	MLH	Various ICOS-compliant sensors	✓	> 95		Submitted to ICOS	
24	ICOS compliant meteorology	CRP	Various ICOS-compliant sensors	✓	> 95			
25	Aerosol scattering (nephelometer)	CRP	TSI nephelometer	✓	> 95		Full submission being prepared – beginning 2020	
26	Ammonia sampling[i]	CRP MLH MHD	Passive samplers	✓	< 95[j]			

[a] Laboratory refurbishment resulted in instrumental downtime.

[b] There was a problem with this instrument in the first week of February 2020 owing to storm-related issues.

Table 1.1. Continued

[c] This instrument was the predecessor to AE33 and was taken from Carnsore Point when that instrument was upgraded. It worked periodically and is no longer in service and needs to be replaced.

[d] Problem with instrument (G1301) September 2019 – replaced with instrument (G2401) as part of staged replacement. G1301 is being tested at the moment.

[e] This instrument suffered a breakdown in December 2019 and is awaiting repair.

[f] Instrumental issue since April 2019 requires repair or replacement.

[g] There was an issue with a water removal device. This has been repaired and the instrument is now being tested for redeployment in the field.

[h] There have been a number of issues with this instrument and it needs replacement.

[i] Additional sampling undertaken at Johnstown Castle, Oak Park and EPA Monaghan office.

[j] Sample holder supplied not suitable for coastal sites at high tide and we need to fabricate something more suitable to the Irish environment – requested new design parts from the EPA in January 2020.

API, application programming interface; CRP, Carnsore Point; MHD, Mace Head; MLH, Malin Head; UCD, University College Dublin.

2 Infrastructure Upgrade

2.1 Status of Infrastructure Upgrade at Malin Head

We have developed the site at Malin Head over the past few years. The site is made up of two main buildings (see Figure 2.1). One of these buildings (upper-level building) is close to the main meteorological tower (shown on the right in Figure 2.1).

Historically, measurements were undertaken in the lower building, which is currently used for all measurements at this site. The laboratory in the lower building has been refurbished over the past 3 years. The refurbishment of the laboratory included resurfacing the floor and the installing benching, air conditioning and an aerosol inlet (Figure 2.2). Air conditioning was installed in the laboratory owing to the temperature fluctuations shown in Figure 2.3. This fluctuation is in part due to the construction of the laboratory and will adversely affect the performance of instruments on the network. Figure 2.4 shows the current lower building laboratory.

2.1.1 Relocation of greenhouse gas measurements to upper building

The GHG and ozone instrumentation is being relocated to a disused room in the upper building at the Malin Head site so that the sample inlets can be mounted at a higher elevation on the Met Éireann meteorological mast. This would greatly improve the quality of these measurements by minimising near surface local interference and measurement artefacts. This room has recently been refurbished (see Figures 2.5 and 2.6).

Air conditioning was installed at this building in January 2020.

Figure 2.1. Malin Head (lower building on left of picture).

2.2 Status of Infrastructure Upgrade at Carnsore Point

Carnsore Point is a headland located at what could be considered to be the extreme south-eastern tip of Ireland in County Wexford. This station is located at approximately 52° 10′ N, 6° 21′ W at an elevation of about 9 m above mean sea level and is on the site of the Carnsore Wind Farm operated by Hibernian Wind Power (see Figure 2.7). The GHG instruments and other instrumentation operated by the EPA are housed in a metal shipping container modified for laboratory use. The presence of the wind turbines in the path of easterly airflow is likely to have some effect on the measurements of certain aerosol parameters for wind directions within a generally easterly sector but this effect is expected to have much less impact on atmospheric gas measurements. The site has clear uninhibited exposure to a south-east to west–south-west marine sector and the dominant prevailing winds are south-westerly. The area is remote and there are no dwellings close to the site.

One of the ultimate objectives of the ICOS network is to use data to provide estimates of Irish GHG emissions through a technique called inverse modelling. The method relies on measurements of well-mixed regional air pollution compared with baseline conditions to assess regional contribution. To make this technique feasible, local pollution must be minimised. We had a major concern regarding the influence of local pollution at this site. This is due to the close proximity of the sampling point to livestock. These can come within 5 m of the sampling location and, given the large emissions of CH_4 associated with cattle (250–500 litres/day), there is a significant possibility of local pollution spikes

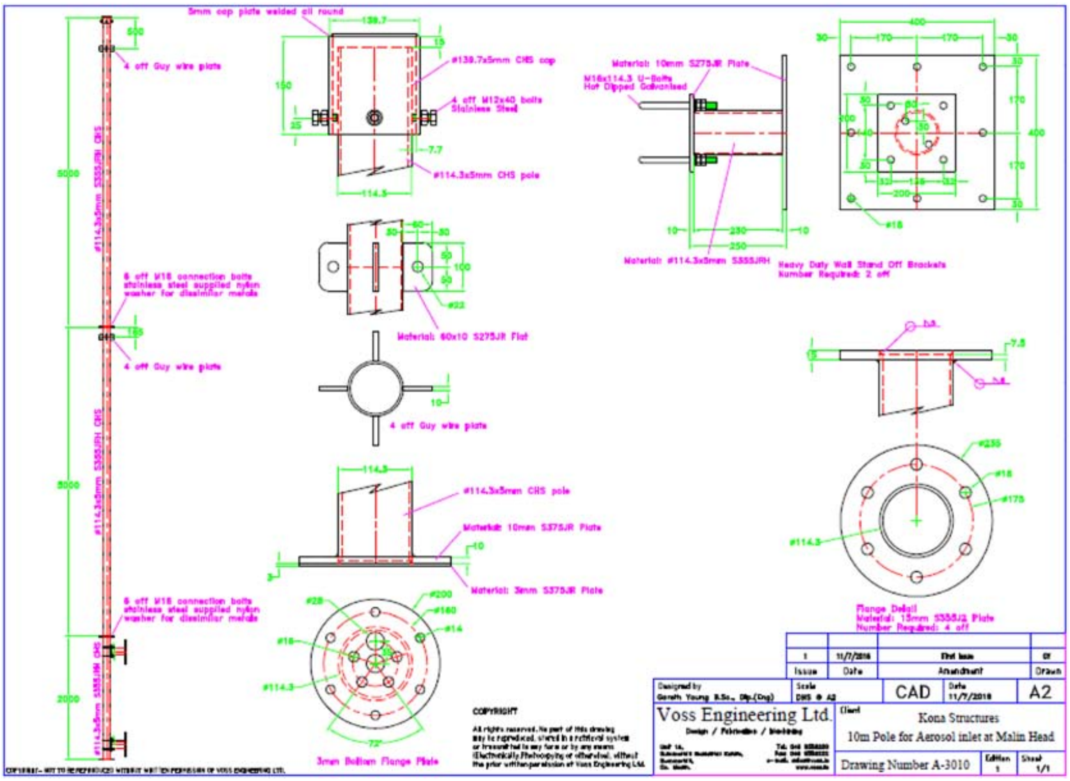


Figure 2.2. Aerosol inlet installed at Malin Head.

within the ambient record. The level of this interference will depend on a large number of factors, including (a) the number of livestock, (b) the location of livestock and (c) wind speed, wind direction and atmospheric stability. These effects can be negated by sampling at multiple heights and it was decided to construct a new compound with a larger footprint, with better facilities and access to the Electrical Supply Board (ESB)-owned tower (65 m elevation).

The EPA joined the ESB (which owns Hibernian Wind Farm) in an application for planning permission that facilitated access to the tall tower and the installation of a new container. Once this was approved there were a number of meetings with the ESB to finalise access to the tower. The tower also required some remedial work prior to its use as a sampling mast and this was undertaken by the ESB. The new container was installed in the first quarter of 2019

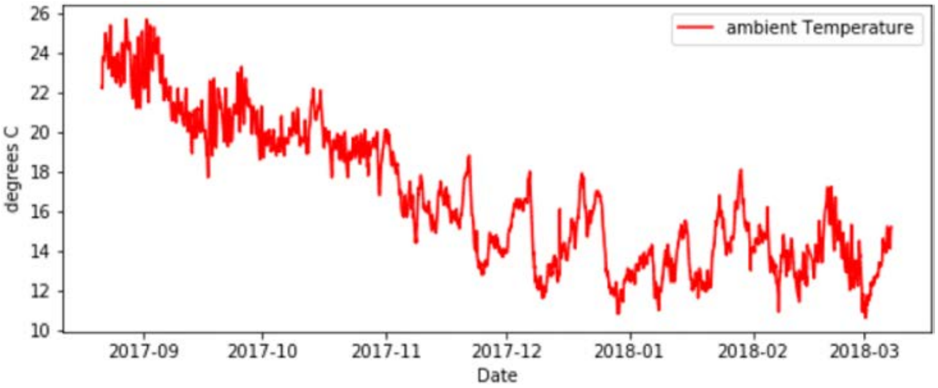


Figure 2.3. Temperature fluctuation at the Malin Head aerosol laboratory, which resulted in the installation of the air conditioning.

Figure 2.4. Current aerosol laboratory at Malin Head (lower building).

(see Figure 2.8). The current status of the infrastructure is as follows:

- new laboratory and toilet facilities installed;
- air conditioning installed;
- tower certified;
- temporary electrical connection installed.

The outstanding work is as follows:

- A permanent electrical connection is still to be installed (December 2019). The final phase of work needs to be completed. There has been a delay due to the COVID-19 pandemic. This is in part due to restrictions to site entry. Entry is allowed only for work that is deemed "essential for operations". Certification courses by the site owner have also been reduced in frequency since the pandemic restrictions began, which has also caused delays.
- Mast work still to be undertaken (line installation and anemometry installation due to be completed subject to agreement with the site manager on health and safety paperwork).
- Transfer of instrumentation from the existing facility needs to take place, as does the installation of inlets for monitoring.
- The installation of a fire alarm in the new facility is required.
- Some small site modifications are required to comply with requests from the site manager regarding the EPA compound.
- A new internet connection is still to be installed.

Figure 2.5. Disused room in top cottage before refurbishment.

Figure 2.6. Refurbished room (October 2019).

Figure 2.7. Carnsore Point location and site.

Figure 2.8. Carnsore Point location and site (November 2019).

3 Brown Carbon Source Apportionment

The network of aethalometers provides a unique opportunity to test the AE33's inbuilt algorithm (Sandradewi *et al*., 2008) to calculate the brown carbon or biomass burning (BB) percentage of the total measurement. The calculation formula relies on the fact that BB absorbs better in the lower (370 nm, 470 nm) wavelengths, while black carbon (BC) absorbs only at the higher wavelengths (880 nm, 950 nm). A key factor is a variable called the Ångström absorption exponent, commonly referred to as α (alpha). This is the dependence of the aerosol optical thickness on wavelength and varies, in this case, with the type of fuel being burnt and how it is being burnt to produce the BC. The instrument defaults are 1 for BC and 2 for BB, yet it has been shown in other papers that alpha values tend to be much higher for BB, in the range of 7–10 for example for turf (peat), a common heating fuel in Ireland.

The instruments are capable of showing trends in BB percentage over time. Figure 3.1 shows monthly averages of BB for Carnsore Point, Mace Head and Malin Head for the period January–December 2018, showing a decrease by nearly half between the winter and summer at the stations. Interestingly, when data where BC is > 100 ng/m^3 are filtered out, leaving essentially background levels of BC with their respective BB values, there is virtually no change between winter and summer BB. However, when BC values of < 1000 ng/m^3 are filtered out, the corresponding BB averages are higher in the winter and lower in the summer than they are in the complete data series, which confirms that there is a definite impact of home heating on BB in the winter time. Until more precise measurements of BB can be made, this approach at least allows for the basic analysis of trends in BB, as well as a comparison of the stations relative to each other. The fact that this trend in BB is not reflected in BB values of < 100 ng/m^3 may be caused by more uncertainty in the measurements at lower values.

In a recent study, Zotter *et al*. (2017) experimented with alpha values for traffic and wood burning at various locations throughout Switzerland and determined the "ideal" values to be 0.9 (α_{tr}) and 1.68 (α_{wb}). However, these numbers may not apply to other regions of the world where different fuel sources, i.e. peat [which has much higher alpha values (Garg *et al*., 2016)], are more commonly burned. Other studies have tried to obtain the BB contribution to total carbon (TC) using the ratio of organic carbon (OC)/elemental carbon (EC) (Pio *et al*., 2011), but this relies on several assumptions. In that study, OC is defined as the sum of secondary OC + fossil fuel OC (OC_{ff}) + biofuel OC + BB OC, and EC is equated to the sum of BB EC + fossil fuel EC (EC_{ff}), so that under certain conditions (an urban environment in winter), OC is approximately equal to OC_{ff} and EC is approximately equal to EC_{ff}. However, the authors found that this was not actually the case unless measured inside a heavily trafficked tunnel, and even less so in rural areas, where there was always some background level of OC. Using customised software developed by the Paul Scherrer Institute (PSI), it was possible to test different alpha values on the aethalometer data.

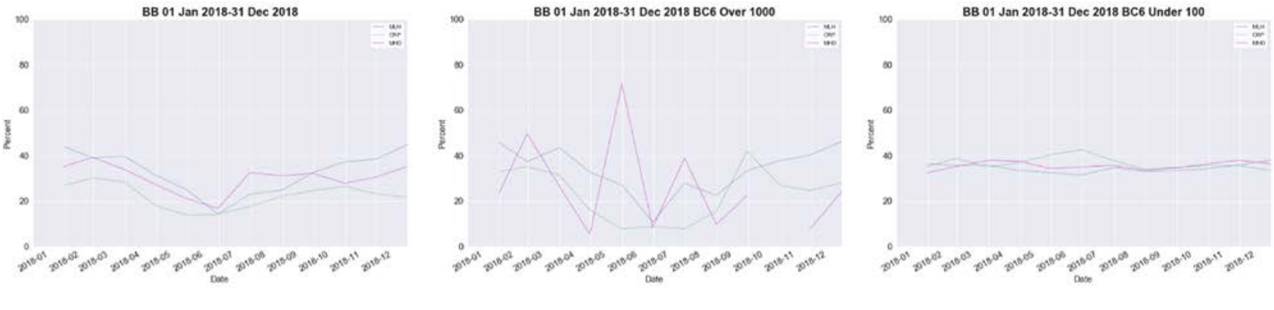


Figure 3.1. Monthly average BB percentage for Carnsore Point (green), Mace Head (purple) and Malin Head (blue). Left plot shows all BB data, centre plot shows BB only where BC is < 100 ng/m^3 and right plot shows where BC is > 1000 ng/m^3.

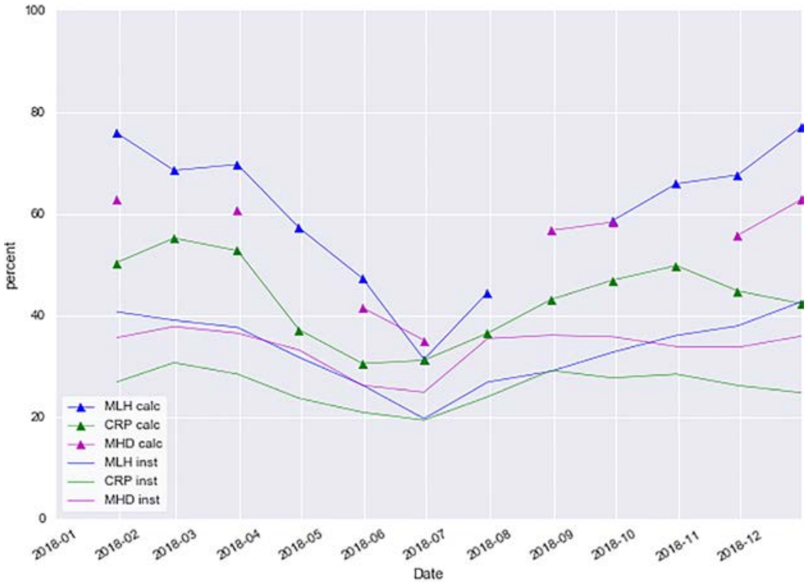


Figure 3.2. Monthly BB percentage using instrument and calculated alpha values with alpha values of 0.9 (traffic) and 1.86 (wood burning) from 1 January to 31 December 2018. CRP, Carnsore Point; MHD, Mace Head; MLH, Malin Head.

The formula used is the same as that programmed into the instrument and yields the same results as the instrument when the instrument default alpha and mass absorption cross-section values are used. This enables an understanding of uncertainties associated with the calculation of the seasonal cycle of BB.

The output from the PSI software gives the BCTR (black carbon traffic) and BCWB (black carbon wood burning) components in ng/m^3 as well as the percentage of BB (BC_WB_ratio). When applying the alpha values of 0.9 (α_{tr}) and 1.68 (α_{wb}) derived by Zotter *et al*. (2017) to the data from the three Irish stations, the BB percentage is nearly double that of the BB percentage reported with the instrument default settings of 1 (α_{tr}) and 2 (α_{wb}), and, in fact, seems unrealistically high at between 60% and 80% versus the 20–40% with the default alpha values. Figure 3.2 shows the difference in BB when using the instrument default values versus the values recommended by Zotter *et al*. (2017).

On the basis of Figure 3.2, it is hard to say which values are correct, without knowing what they should actually be. A study by Helin *et al*. (2018) on BC source apportionment in Finland found that the BB contribution varies greatly between urban and suburban areas, particularly in winter. Most of the air reaching the Irish stations contains regional pollution, which is more dispersed from its sources; however, at Malin Head in particular there can be local influences, resulting in higher concentrations of pollution.

4 EMEP Intensive Campaign

4.1 Background

In winter 2018, Ireland participated in an intensive measurement period (IMP), conducted by EMEP, along with several other European countries and including both rural and urban sites. This took place from December 2017 to March 2018, as part of an effort to establish a Europe-wide uniform system for the collection and monitoring of carbonaceous aerosols, which could be used for model validation. All data from the campaign are being uploaded to the EBAS online database (http://ebas.nilu.no/) to establish a long-term record (Aas *et al*., 2018). The EBAS database is an online resource hosting atmospheric chemical and physical composition data submitted by participants of various programs and networks such as EMEP, Global Atmospheric Watch (GAW) and Aerosols, Clouds, and Trace Gas Infrastructure (ACTRIS) for use in international monitoring and research projects. It is owned and operated by the Norwegian Institute for Air Research (NILU).

In addition to the overarching goal of data collection, the primary purpose of this campaign was to achieve more accurate alpha values to determine the BB contribution to aethalometer measurements, as well as to compare filter-sampled EC with the BC (or BC6 when specifically using the 880-nm wavelength data) collected using aethalometers. This was done through simultaneous measurements of aethalometer BC, and EC, OC and TC collected from a high-volume sampler. Measurements of the wood-burning tracer levoglucosan were used to validate the BB measurements of the aethalometer and assess the BB contribution to TC, as well as to establish site-specific alpha values for the aethalometers. The collection and processing of high-volume sampler data was performed by colleagues from University College Dublin (UCD) and submitted to NILU by our research group at NUIG along with data from the AE33. NILU will conduct further processing on the data, and it will be made publicly available through its EBAS database. For the purpose of this study, daily averages of BC, EC, OC, TC and levoglucosan from only the Irish stations of Carnsore Point, Mace Head and Malin Head were analysed, with the addition of measurements from UCD, a suburban site where an aethalometer was stationed for the duration of the campaign, and the initial results are presented here.

4.2 Evaluation of Elemental Carbon/Organic Carbon from the EMEP Intensive Monitoring Period

The source apportionment of BB clearly requires further study, and, for this purpose, EMEP/ACTRIS conducted an IMP in winter 2018. As mentioned previously, this involved the collection of daily averages of aethalometer BC, and EC, OC and TC collected from a high-volume sampler. As shown in Figure 4.1, the EC and BC measurements agree quite well at all stations, although they were slightly lower at Mace Head. This is most likely because Mace Head is the least polluted environment of the stations, and

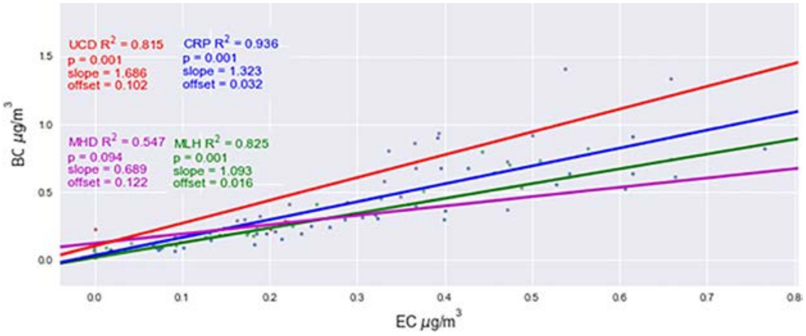


Figure 4.1. Elemental carbon from high-volume sampler vs aethalometer BC for the four Irish sites from 18 January to 6 March 2018. CRP, Carnsore Point; MHD Mace Head; MLH, Malin Head.

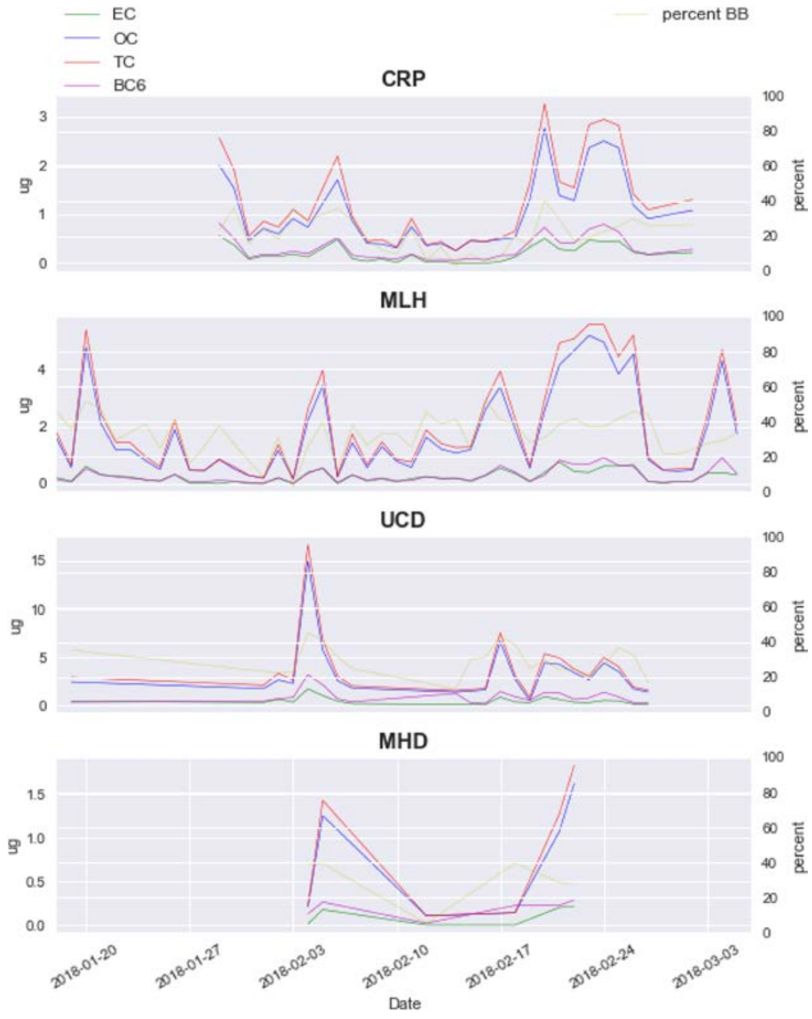


Figure 4.2. Total carbon, EC, OC and BC values (left axis) and BB percentage (right axis) from 18 January to 6 March 2018. CRP, Carnsore Point; MHD, Mace Head; MLH, Malin Head.

levels of BC are frequently below the detection limit of the instruments.

The following time series (Figure 4.2) also show good agreement between EC and BC, and the ratios of BC/EC are typical for rural areas according to a study by Salako *et al*. (2012), which looked at the variation in the ratios across various parts of the world and also determined that higher correlations were likely to be a result of similar sources. A large part of the TC comprises OC, which constitutes a large fraction of organics.

A breakdown of the OC/EC ratios and the OC/TC ratios (Tables 4.1 and 4.2, respectively) show that OC is in fact at least seven times higher than EC (ignoring Mace Head here due to a limited number of data points resulting from a large number of negative

Table 4.1. OC/EC ratios

Site	Count	Mean	Standard deviation
CRP	27	7.05	5.19
MHD	6	51.21	65.27
MLH	43	8.83	6.20
UCD	22	7.11	2.21

CRP, Carnsore Point; MHD, Mace Head; MLH, Malin Head; UCD, University College Dublin.

Table 4.2. OC/TC ratios

Site	Count	Mean	Standard deviation
CRP	27	0.85	0.05
MHD	6	0.92	0.06
MLH	43	0.88	0.04
UCD	22	0.86	0.06

CRP, Carnsore Point; MHD, Mace Head; MLH, Malin Head; UCD, University College Dublin.

Table 4.3. Literature OM/OC ratios

Type of site	OM/OC ratio	Location	Source
Urban	1.56	Phoenix, AZ	Ruthenburg *et al.*, 2014
	1.59	Average 14 Chinese cities (winter)	Xing *et al.*, 2013
	1.6	Los Angeles, CA	Turpin and Lim, 2001
		Denver, CO	
Rural	1.77	Olympic National Park, WA	Ruthenburg *et al.*, 2014
	1.78	Acadia National Park, ME	El-Zanan *et al.*, 2009
	1.9	K-puszta, rural Hungary	Kiss *et al.*, 2002
Coastal	1.91	Hong Kong, China	Chen and Yu, 2007
	2.1	Crete, Greece	Bougiatioti *et al.*, 2013
	2.16	Atlanta, GA	El-Zanan *et al.*, 2009

EC values). This is in accordance with previous studies (e.g. Pio *et al.*, 2011) that found similar results, particularly in rural and remote regions. OC/EC ratios greater than 2 are indicative of secondary organic aerosol (SOA) formation (Bougiatioti *et al.*, 2013). Another study demonstrated that significant amounts of both OC and EC (between 25% and 33%) fall into the $PM_{2.5}$ (particulate matter $\leq 2.5\,\mu m$) and larger category (Wang *et al.*, 2016).

As shown in Table 4.2, OC also constitutes more than 80% of the TC and thus may account for a large part of the organics measured at the stations.

Organics were measured with the aerosol mass sprectrometer (AMS) at Mace Head and ACSM at UCD during the EMEP campaign, albeit only particles in the PM_1 (particulate matter $< 1\,\mu m$) category. PM_1 OC has not been very thoroughly investigated, and so it is difficult to find relevant studies showing its contribution to the total PM_1 mass. It has been shown that the winter-time PM_1 OC in a suburban area of Zagreb, Croatia, constituted 19.88% of the total PM_1 measured, as well as an additional 23.76% of $PM_{2.5}$ and 24.15% of PM_{10} (particulate matter $\leq 10\,\mu m$) (Godec *et al.*, 2012). This demonstrates that OC contributes a large fraction to the total mass in each size category. Organic matter (OM), of which OC is a subset, must therefore be even larger in all size categories. Indeed, when plotting the PM_{10} OC against the PM_1 OM for Mace Head and UCD, the ratio was < 1, and the time series consistently showed the measured OM as less than the OC. Therefore, an attempt was made to find how much OM PM_{10} there should be based on OM/OC ratios found in previous studies (El-Zanan *et al.*, 2009) which found OM/OC ratios of, on average, 2.07 (ranging from 1.58 at Indian Gardens, Arizona, to 2.58 at Mount Rainier, Washington) for remote regions of the USA, which were higher than other results cited by that study, and the ratio of 1.4 (the estimated average molecular weight per carbon weight derived from theoretical and laboratory studies in the 1970s (Turpin and Lim, 2001) commonly used in mass reconstruction. Table 4.3 outlines values found in other studies for different types of environments. It is noteworthy that the "coastal" locations have the highest OM/OC ratios, even when they are urban environments.

Applying a simple formula, $OC_{PM10} \times x = OM_{PM10}$, where x is the OM/OC PM_{10} ratio, and solving this equation using a range of site-appropriate OM/OC ratios from previous studies, the calculated OM_{PM10} can be used to derive OM_{PM1} as a percentage of total OM. The results of this are shown in Table 4.4, and, while it is still uncertain exactly which OM/OC ratio is most appropriate for each station, it is evident that 1.4 is too low for both. For Mace Head it appears to be a minimum of 2, and for UCD 1.59 seems to be a reasonable ratio. This implies that nearly half of the OM is larger than PM_1. El-Zanan *et al.* (2009) note that the ratios increase as the OM is transported over long distances and the aerosols age and become more oxygenated and polar during SOA formation. Thus, it is likely, also based on the calculations below, that

Table 4.4. Mace Head and University College Dublin OM/OC ratio ranges and OM_{PM1} percentage

Site	OM/OC ratio	OM_{PM1} percentage of OM
MHD	1.91–2.16	56–63
UCD	1.56–1.6	42.8–44

MHD, Mace Head; UCD, University College Dublin.

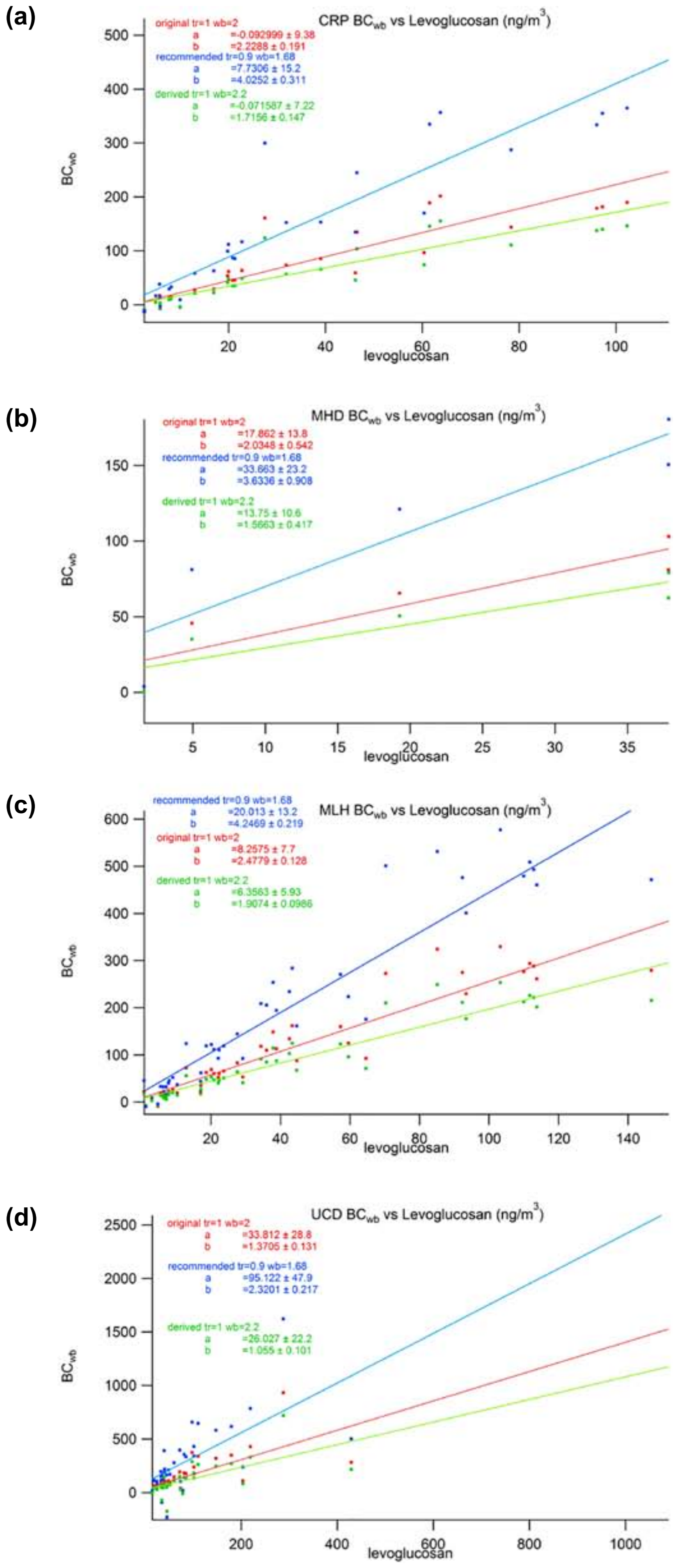


Figure 4.3. BC$_{wb}$ versus levoglucosan levels for all four locations during the EMEP campaign. CRP, Carnsore Point; MHD Mace Head; MLH, Malin Head.

the UCD ratio will be lower than that for Mace Head, as it is located in an urban area and Mace Head is a remote rural/coastal environment. The authors also note that ratios will tend to be lower during the winter months due to less photochemical activity.

Previous studies at Mace Head (Yttri *et al*., 2007) found that OM constituted 8.9% of PM$_{10}$ at that station, using a conversion factor of only 1.4, which, according to these latest measurements, could mean that a much larger percentage of OM falls into the coarse particle category.

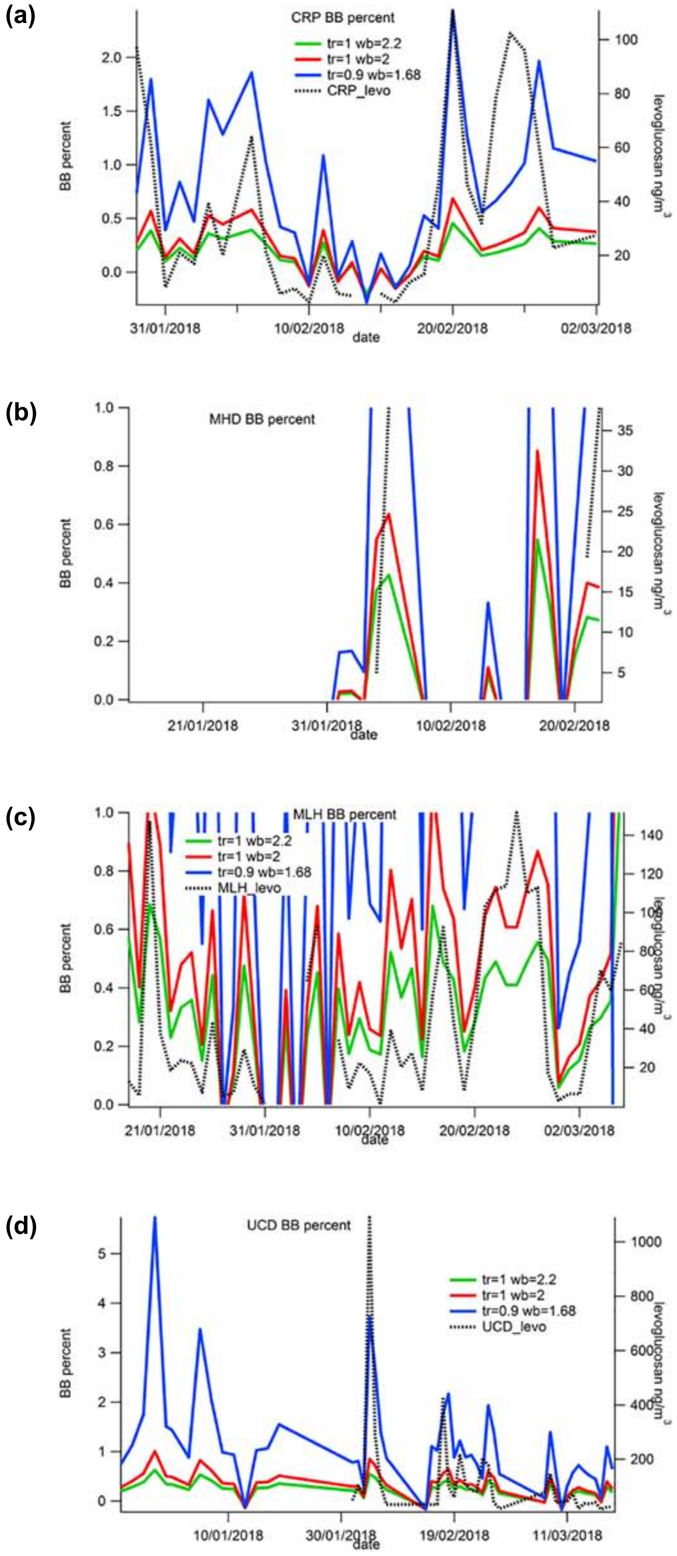


Figure 4.4. Time series of BB percentage and levoglucosan levels. CRP, Carnsore Point; MHD Mace Head; MLH, Malin Head.

Some studies have shown seasonal variations at all sites, and this suggests that a single estimate cannot be representative of the OM/OC ratio for any location (Ruthenburg *et al*., 2014). Factors such as plankton blooms, which occur near the coasts of Ireland in the spring and autumn, can add significant amounts of OM to the atmosphere, thus increasing the OM/OC ratio (Cavalli, 2004). Future measurements will be able to determine these numbers more accurately, but for now it is possible to provisionally estimate them.

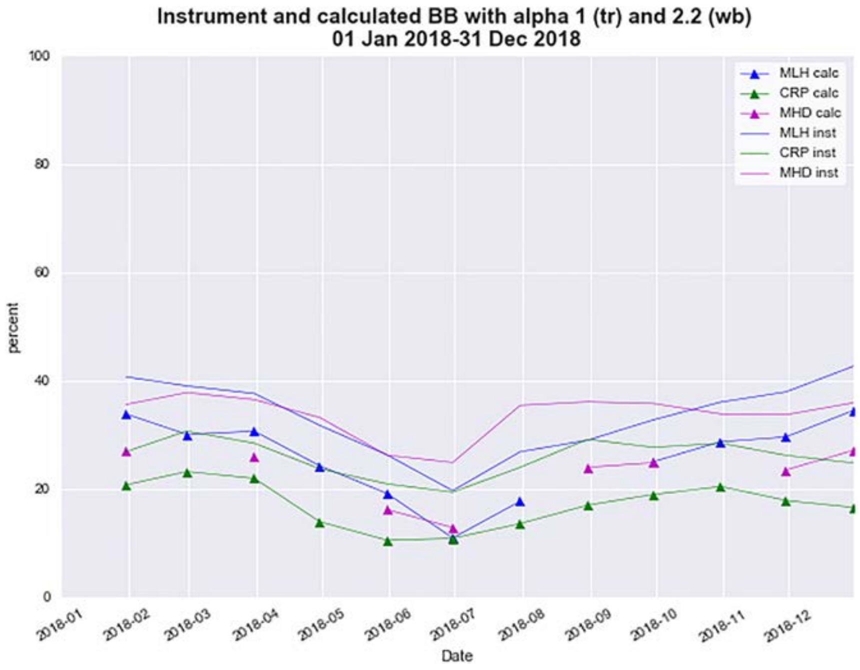


Figure 4.5. Seasonal cycle of BB using levoglucosan-derived alpha values.

An analysis of the levoglucosan results yielded higher alpha values than the literature recommended value (1.68) (Zotter *et al*., 2017) and the instrument default setting (2) for the BB component, but values were still not significantly higher than the instrument default. Shown here are the correlation plots of the "wood burning" contribution (BC_{wb}) to levoglucosan, keeping the α_{tr} set at 1 and changing the α_{wb} to obtain the lowest *y*-intercept, followed by the daily average BB percentage time series along with levoglucosan based on these values. For all four locations, the α_{wb} was around 2.2, which is reasonably close to the default setting of 2 (Figure 4.3). Increasing the α_{wb} resulted in the BB percentage almost disappearing completely, and decreasing α_{wb}, as demonstrated using the recommended value of 1.68, caused BB to exceed 100% in almost all cases, which is highly unlikely given that these are daily averages (Figure 4.4). Figure 4.5 shows the monthly averages for the year with seasonal cycle for the instrument default settings compared with the new levoglucosan-based alpha values. There are of course limitations to this method, as levoglucosan is removed from the atmosphere at a faster rate than BC (Helin *et al*., 2018), and it is mainly a wood-burning tracer in countries with significant levels of residential heating through BB. In Ireland, however, most solid fuel burning for residential heating is related to peat.

Nevertheless, there is a strong correlation ($r^2 = 0.83$) of BC_{wb} to levoglucosan, and, as can be seen in the time series, levoglucosan levels are frequently high, especially during winter, suggesting that as a first approximation the use of levogluosan as a proxy of BB is useful for these studies. Further work to improve these estimates is planned.

5 Inverse Modelling

One of the main endeavours that utilises the AC3 network data are EPA-funded projects to infer Irish GHG emissions. The primary objective of these projects is to improve the inversion modelling capabilities in Ireland applied to GHG emissions, in particular to CH_4, but with a longer term view of potentially expanding this to other pollutants of interest, e.g. nitrous oxide. In brief, the detailed objectives were:

- the implementation, development and optimisation of an inverse modelling system (Figure 5.1) (FLEXINVERT) for CH_4 emissions in the Irish domain;
- the independent verification of emissions and sinks of CH_4 in Ireland based on data from key boundary sites to produce estimates for 1 or 2 years (Figure 5.2)
- the provisional assessment of the relative contributions from individual sources using modelling and observational data analysis techniques;
- the expansion of expertise in Ireland on inverse modelling of emission estimates;
- the establishment of engagement with the community to ensure that the best practices are implemented and to provide the starting point for future project collaborations on modelling and assessment of GHG emissions in Europe.

In the main, these objectives have been met and Figure 5.2 shows the monthly CH_4 flux for 2012 (right-hand panels) along with differences between the inversion estimates and the a priori data used.

Further development of the inversion scheme using Irish network data will take place, incorporating data from the AC3 network (Figure 5.3). The main aim of these projects is to further quantify uncertainty associated with top-down Irish emissions.

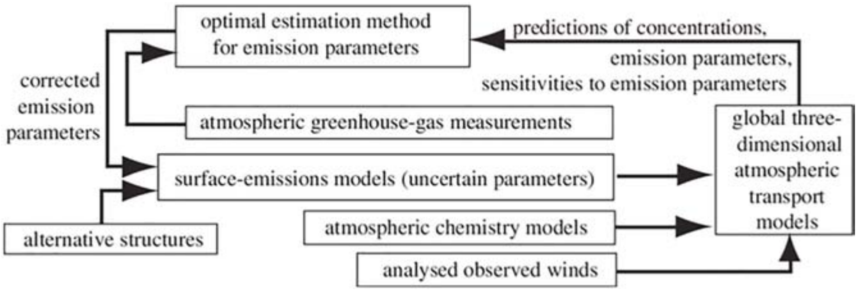


Figure 5.1. Schematic diagram of the FLEXINVERT system, which combines observations, a priori and background information and model sensitivities to provide CH_4 surface flux estimates. Using data from the Irish network, estimates of CH_4 emissions were performed for 2012.

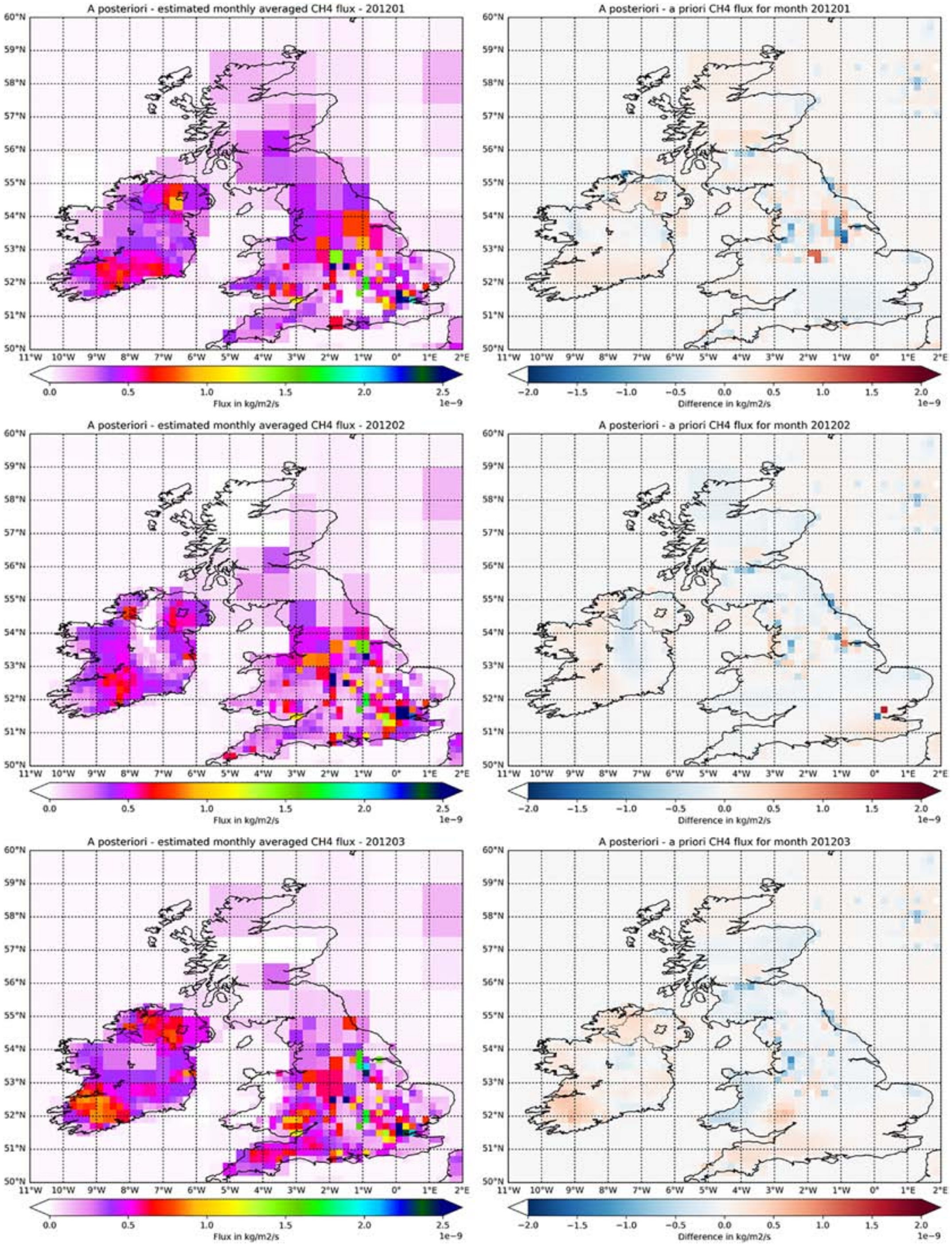


Figure 5.2. Monthly flux estimates (left) and the difference between the estimates (using the "all sites" specifications) and the a priori EDGAR_0.1 × 0.1_ANT (right).

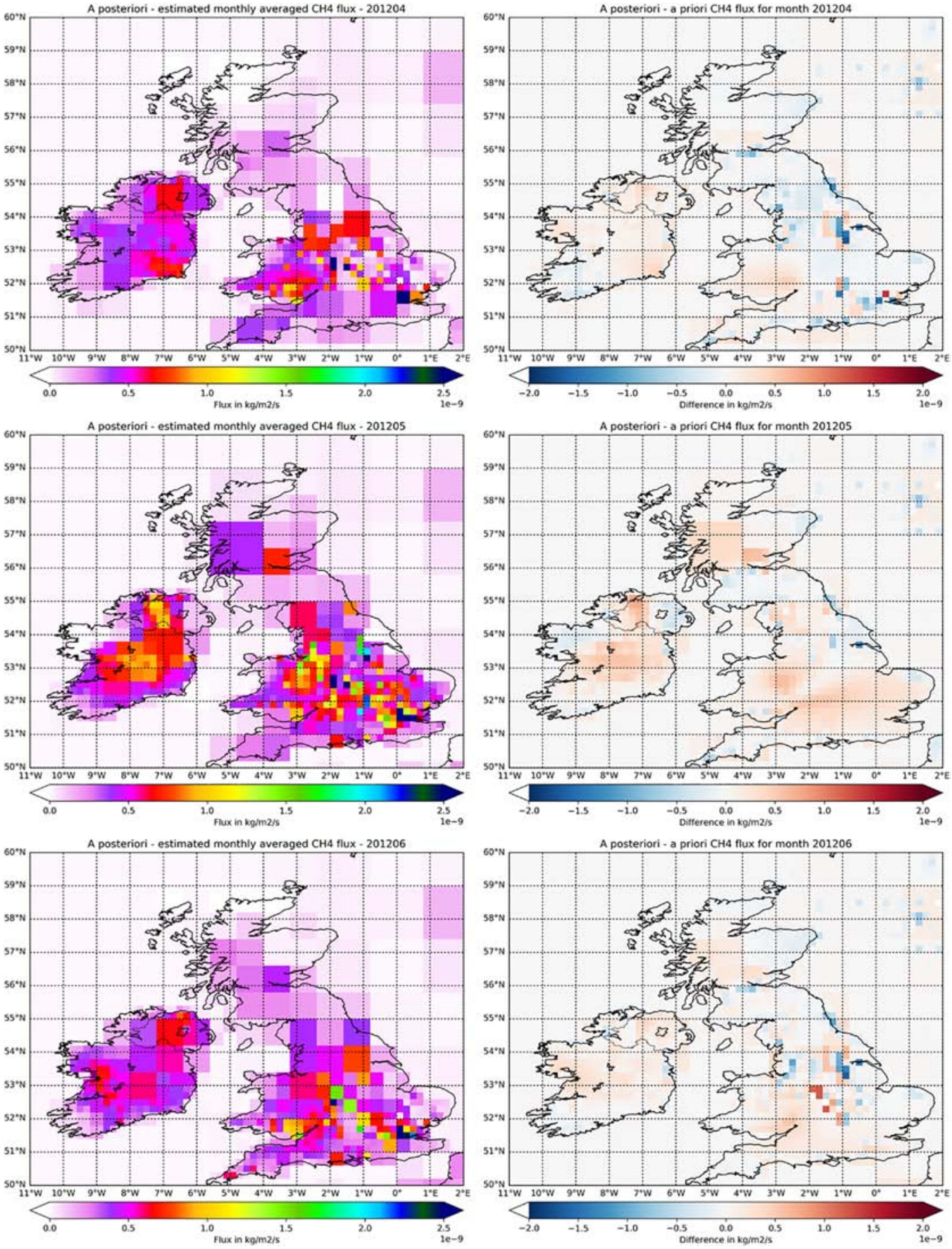
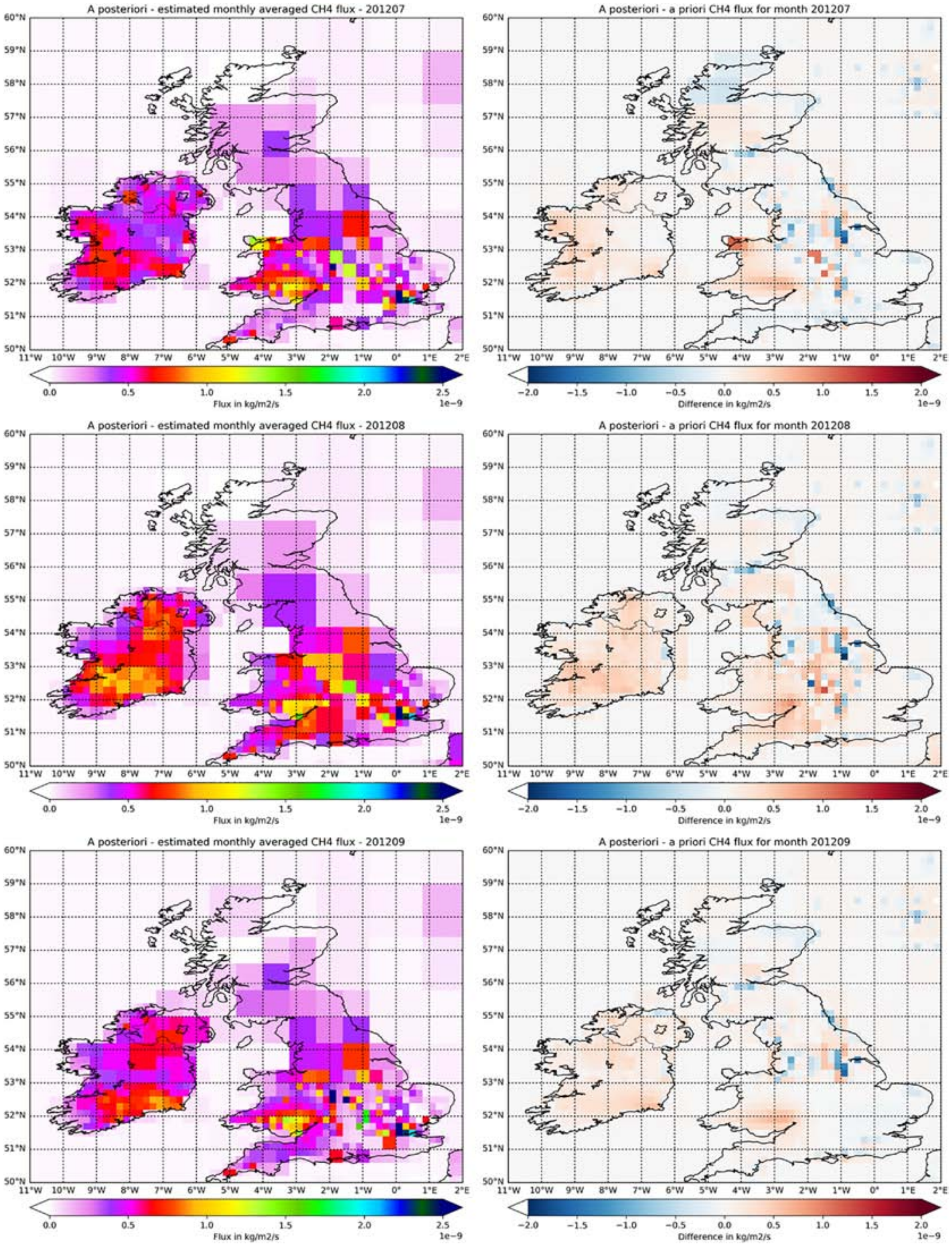


Figure 5.2. Continued.



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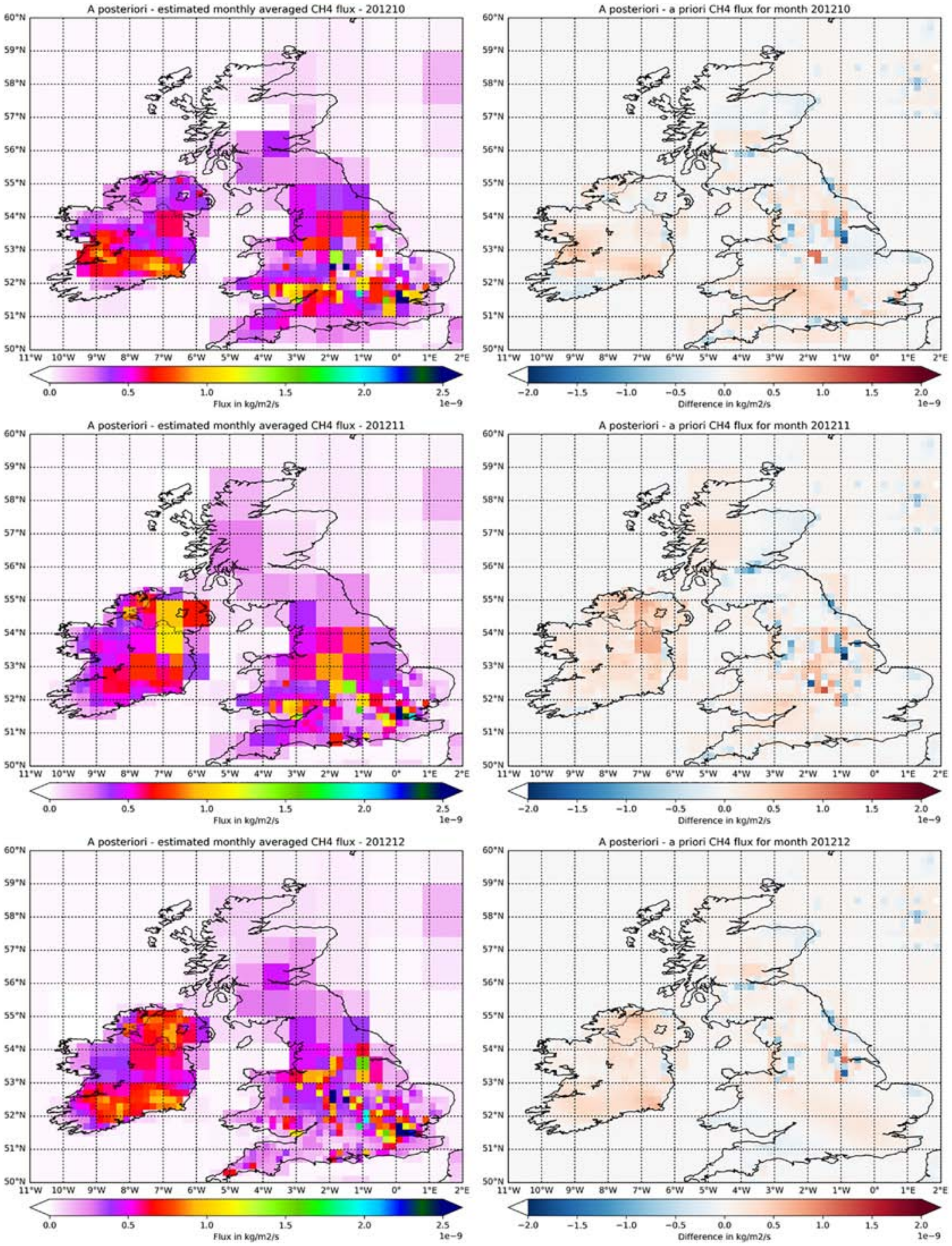

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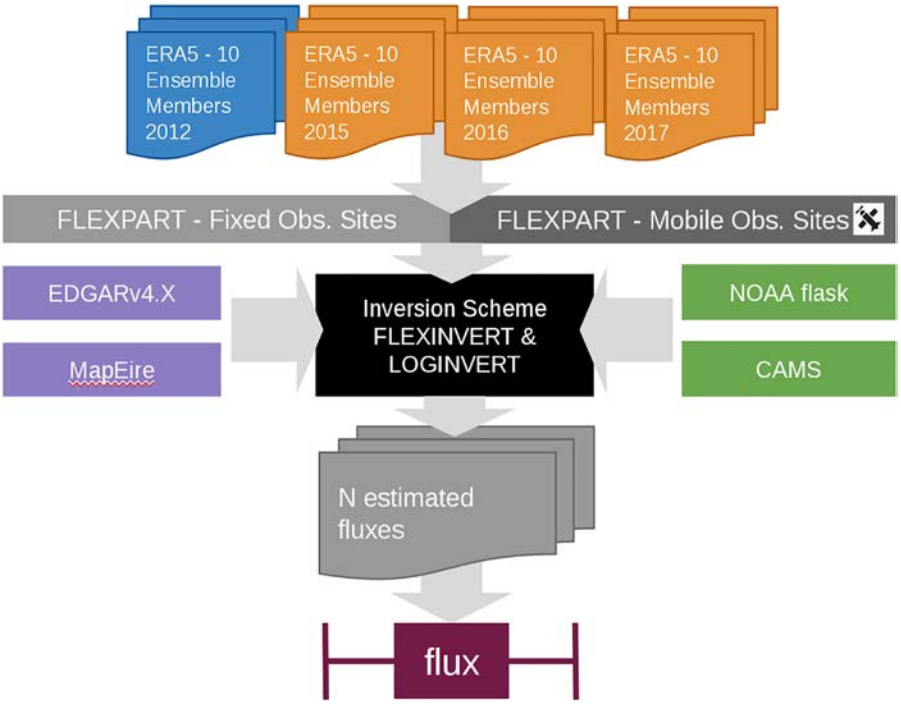

Figure 5.3. Additional activities to be performed to obtain better estimates of the emissions inventories using a top-down approach and to bridge the gap with the bottom-up assessments. CAMS, Copernicus Atmospheric Monitoring Service; ERA, ECMWF Re-Analysis; NOAA: National Oceanic and Atmospheric Administration.

6 Integrated Carbon Observing System Ireland

As part of the ICOS preparatory phase, three sites in Ireland have been taking GHG measurements since 2009. In general, these measurements have been undertaken to be compliant with Class 1 atmospheric monitoring station specifications. ICOS has transitioned here from the preparatory phase to the operational phase and a number of European Union Member States have signed up to the ICOS ERIC (European Research Infrastructure Consortium). The costs associated with this relate to the number of the stations in the national network, as well as costs associated with the national gross domestic product (GDP). These fees allow access to centralised facilities (calibration, data analysis and instrument characterisation). The use of these facilities is required to ensure ICOS compliancy on the network.

Currently there has not been a decision made at a national level regarding engagement with the ICOS ERIC, which has resulted in some difficulty in accessing the centralised facilities. The general feeling from engagement within the ICOS hierarchy is that the uncertainty in the pathway for Irish engagement with ICOS will preclude access to centralised facilities in the very near future. This will cause divergence from ICOS specifications and ultimately render data non-compliant.

There have been a number of meetings in relation to this over the past 3 years, with the various stakeholders in the Irish ICOS community (including representatives of the three thematic areas: atmospheric, ecosystem and ocean), and the desire to engage with the ICOS ERIC has been expressed, although a clear pathway and mechanism have yet to be defined.

Numerous documents have been produced in relation to engagement between ICOS and Ireland. An example one of these documents is included in Appendix 1 and gives a broad overview of all the thematic areas. A letter of support with regard to the atmospheric thematic area from ICOS head office is shown in Appendix 2.

7 Recommendations

The main recommendations for the continuation of the AC3 network are:

- Continued development of and investment in the network infrastructure. This is important, as some of the instrumentation is moving towards obsolescence and the infrastructure needs to be appropriately maintained.
- Continued and evolved adherence to the latest requirements of the ICOS Atmospheric Thematic Centre Station specification recommendations. This is important so that data are at the highest levels of international best practice to ensure compatibility among national networks and to allow for the most accurate modelling estimates. The documentation in Appendix 1 significantly expands on this point.
- Continued investment in the update/repair/maintenance of equipment and the staged replacement of obsolete equipment. Each addition of instrumentation to the network requires the preparation of a business case. Future arrangements may see network equipment replaced as part of a scheduled capital replacement strategy.
- Further development of ICOS measurements. These could include complementary measurements that help to resolve the impacts of local sources and additional measurements (such as isotopic composition) that would yield information on the contribution of different source categories to national GHG emissions.
- Nitrous oxide is a large component of Ireland's GHG emissions (Duffy *et al.,* 2020). The sources are mainly diffuse and complex agricultural practices, activities and land use management. The inclusion of nitrous oxide measurements as part of the ICOS network is warranted in being able to better constrain these emissions, which are subject to large levels of uncertainty.
- Progress should be made towards transitioning from being in the preparatory phase of ICOS to the operational phase. Given the time scales of the preparatory phase and the current status of the ICOS ERIC, this is important for long-term network sustainability.
- Make all network data available on https://data.gov.ie/ (in progress). The open data initiative is about making data held by public bodies available and easily accessible online for reuse and redistribution. As public bodies have progressed in areas such as e-government and data analytics, the potential of data and, in particular, open data to help deliver economic, social and democratic benefits has become clearer. The data.gov.ie portal brings these datasets together in a single searchable website.

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Abbreviations

ACSM	Aerosol chemical speciation monitor
AMS	Aerosol mass sprectrometer
BB	Biomass burning
BC	Black carbon
CPC	Condensation particle counter
EC	Elemental carbon
EC_{ff}	Fossil fuel elemental carbon
EMEP	European Monitoring and Evaluation Programme – the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe
EPA	Environmental Protection Agency
ERIC	European Research Infrastructure Consortium
ESB	Electrical Supply Board
GHG	Greenhouse gas
ICOS	Integrated Carbon Observation System
IMP	Intensive measurement period
NILU	Norwegian Institute for Air Research
NUIG	National University of Ireland Galway
OC	Organic carbon
OC_{ff}	Fossil fuel organic carbon
OM	Organic matter
PM	Particulate matter
PM_1	Particulate matter < 1 μm
$PM_{2.5}$	Particulate matter ≤ 2.5 μm
PM_{10}	Particulate matter ≤ 10 μm
PSI	Paul Scherrer Institute
SLCF	Short-lived climate forcer
SMPS	Scanning mobility particle sizer
SOA	Secondary organic aerosol
TC	Total carbon
TEOM	Tapered element oscillating microbalance
UCD	University College Dublin

Appendix 1 A Summary Document Outlining the Need for Ireland to Engage with the Integrated Carbon Observation System

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A1.1 Executive Summary

The impact of increasing atmospheric carbon dioxide (CO_2) and other radiatively important greenhouse gases (GHGs) on climate change is recognised as one of the most challenging problems facing humanity today. By 2050, Ireland is committed to reducing CO_2 emissions by 80% relative to 1990 and also aims to achieve carbon neutrality in the agricultural sector. This, however, will not be possible without the implementation of a strong suite of cross-sectoral policies and associated emission reduction pathways that are informed by a better understanding of the GHG emission and removal processes across the atmospheric, terrestrial and oceanic domains.

The scientific community in Ireland has a strong track record in this area of research and has made a significant contribution to the cross-domain work of key international research programmes over the past 20 years. This network is also well placed to contribute to the scientific remit of the Integrated Carbon Observation System (ICOS) and to climate change research globally. For example, the Mace Head atmospheric station has been at the forefront of national and continental scale top-down estimates of GHG emissions, which are supported by numerous ecosystem stations and fixed/repeat ocean monitoring stations to provide a bottom-up approach to assess the GHG emission/removal capacity of the biosphere and oceans. While Ireland has historically made a considerable contribution to key international carbon and GHG research networks, such as CarboEurope-IP, CarboOcean-IP, NitroEurope and GHG Europe, there is a significant need for increased investment for both the infrastructure and personnel required to build and maintain an ICOS-compliant cross-domain GHG network. This report summarises the historical and current state of carbon and GHG measurements in the atmospheric, terrestrial and oceanic domains, highlights the need for and the benefits to Ireland in joining the ICOS network, and outlines the substantial long-term capital investment and annual expenditure required to achieve this. Furthermore, the report suggests how the investment in this infrastructure can be expanded outside the ICOS–Ireland network, through the formation of a central repository for equipment upgraded during the lifetime of the network, which is still suitable for high-quality research and can be used to develop new sites that are of particular importance in relation to policy directives, GHG source/sink strength or land use, and which will make the investment in the ICOS network available to a greater diversity of research performing institutions in Ireland.

A1.2 The Need for Long-term Carbon and Greenhouse Gas Monitoring Stations

Concentrations of atmospheric carbon dioxide (CO_2), the main greenhouse gas (GHG) implicated in climate change, have increased from ≈277 parts per million (ppm) at the beginning of the industrial era (*c*.1750), to a global monthly average concentration of over 409 ppm (Figure A1.1). This increase has been attributed to anthropogenic activities. For example, during the industrial revolution the majority of emissions were derived from land use change; however, in 2015 the majority of global emissions were due to fossil fuel combustion – coal (41%), oil (34%), gas (19%) – and cement production (6%) (Le Quere *et al*., 2016). A decadal trend in the growth of CO_2 emissions has also been observed, with a +1.1% y^{-1} increase between 1990 and 1999, which increased further to +3.4% y^{-1} between 2000 and 2009. These man-made emissions occur in addition to the natural carbon cycle dynamics that exchange CO_2 between the three major reservoirs: the atmosphere, oceans and the terrestrial biosphere.

The impact of increasing atmospheric carbon and GHG concentrations on climate change is recognised as one of the most challenging problems facing humanity today. The Intergovernmental Panel on Climate Change (IPCC) has stated that "warming of the climate system is unequivocal" and that the "human influence is clear", with the 2015 Paris Agreement establishing a global policy response to climate change. A key objective of the Paris Agreement is that global GHG emissions are balanced with removals during the second half of this century. In Ireland, the national policy position is to reduce emissions of CO_2 by 80% relative to 1990 emissions and to achieve neutrality for the agriculture and land use sector by 2050. Achievement of both the national and global emission reduction pathways will require the implementation of a strong sectoral and cross-sectoral suite of policies, as well as an increased understanding of emissions and removals and the processes by which the latter can be enhanced.

For developed countries, official data on GHG emissions and removals are provided annually though the National Inventory process, reported to relevant European Union (EU) and United Nations (UN) bodies. It is recognised that while these inventories are robust, they have limitations, particularly in areas such as land use, agriculture and emissions/losses from freshwater systems. There has also been a push to develop the independent analysis of emissions and removals using top-down analysis of observational data collected at atmospheric monitoring stations such as Mace Head. A number of Parties have reported top-down analysis along with official bottom-up data in their National Inventory Report (e.g. the UK and Switzerland). It has been found that top-down analysis helped to identify

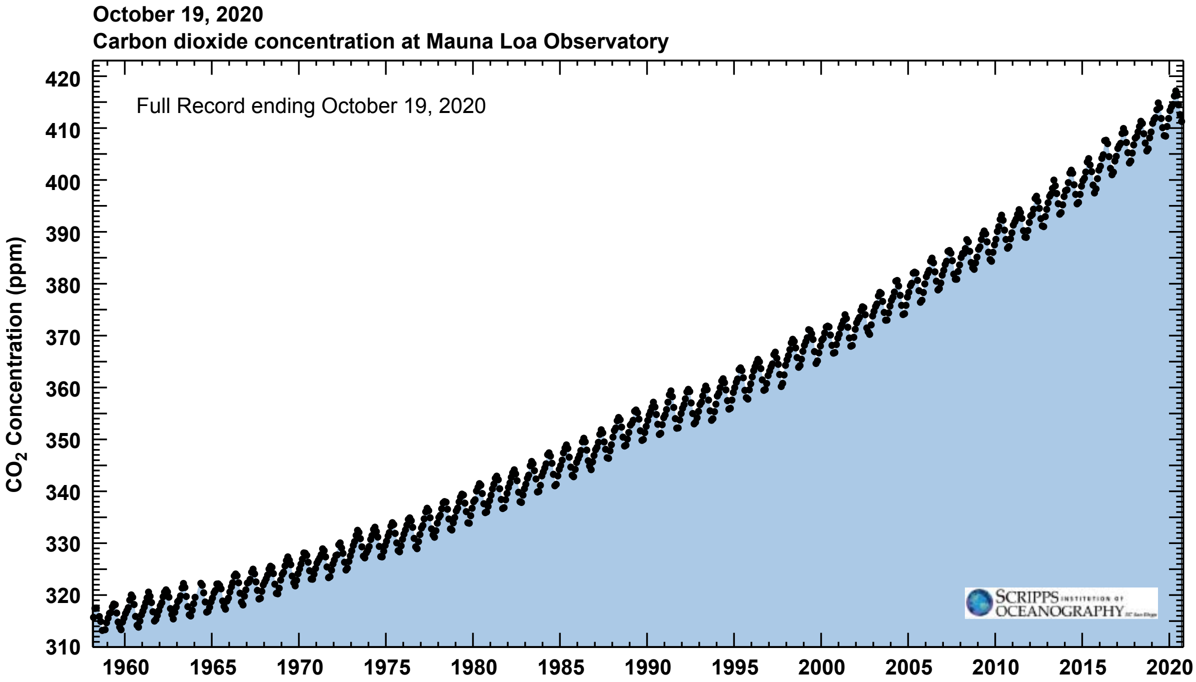


Figure A1.1. The observed increase in atmospheric CO_2 showing the mean atmospheric concentration (blue shading) and annual variation in concentrations (black line). Source: Scripps Institution of Oceanography.

anomalies such as overestimation of the release of refrigerant use in the UK and the distribution of methane (CH_4) emission sources in Switzerland. This allowed these countries to improve their inventories and consequently better target mitigation policies.

It is clear that the determination and prediction of atmospheric concentrations of CO_2 and other radiatively important GHGs, as well as the interactions between GHG emission/concentrations and the biogeochemical cycles within ocean, freshwater and terrestrial ecosystems, is necessary to support the development of suitable climate mitigation and adaptation policies, and to project the future climate.

A1.3 Historical Carbon and Greenhouse Gas Measurement Networks and the Development of a Pan-European Integrated Carbon Observation System

While the top-down/bottom-up approach has shown potential in constraining the carbon/GHG budget across multiple temporal and spatial scales, it is recognised that further development is needed to reach its full potential, particularly for complex gases such as CO_2, CH_4 and nitrous oxide (N_2O). Historically, these issues have been explored through the persistence of the scientific community and a number of international research programmes in the atmospheric, oceanic and terrestrial domains (Figure A1.2). Some examples of the measurement networks were domain specific or geographically limited (e.g. EuroFlux); however, the development of integrated programmes across the atmospheric, oceanic and terrestrial domains has been extremely successful in better constraining GHG dynamics and budgets across multiple spatial and temporal scales (e.g. CarboEurope, CarboEurope-IP and InGoS). Ireland has made a significant contribution to the historical GHG observational network, with many organisations and institutes involved in the CarboEurope, CarboEurope-IP, IMECC (Infrastructure for Measurements of the European Carbon Cycle), NitroEurope and GHG Europe projects. These projects also highlighted the need for a sustained and harmonised network of GHG observational platforms across Europe that serve to provide the data required to support the analysis of GHG emissions

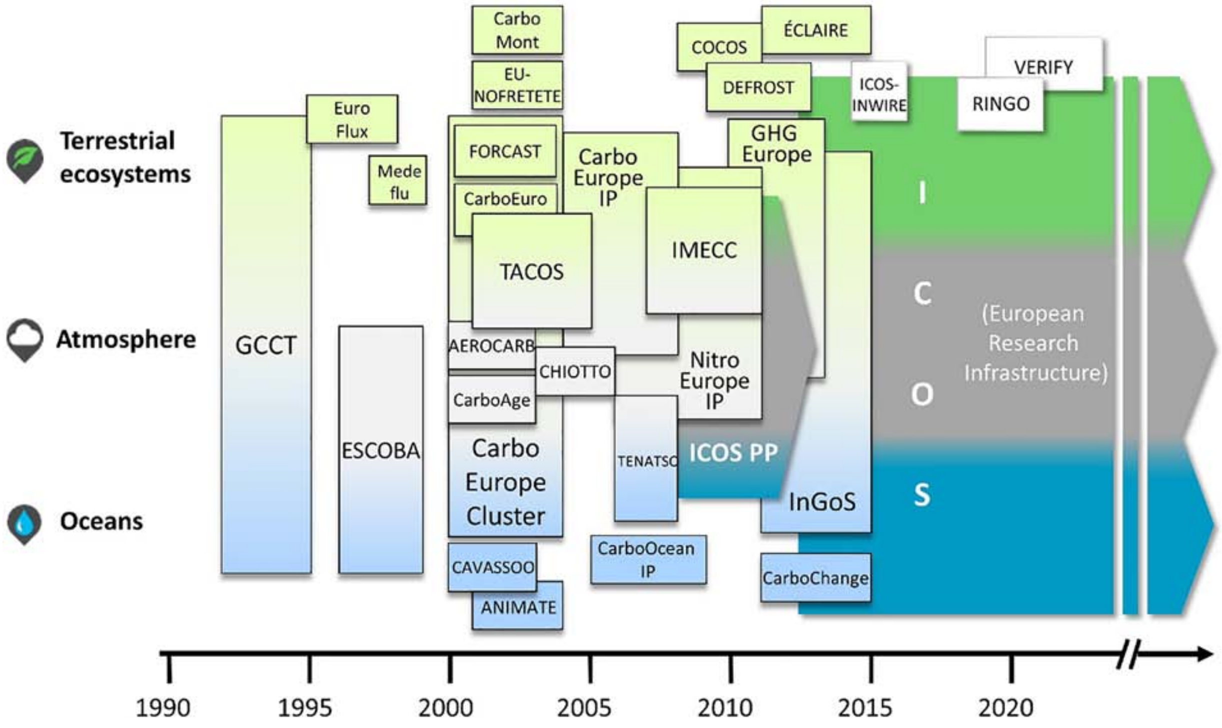


Figure A1.2. The succession of European carbon, nitrogen and GHG observational networks and projects for the oceanic, atmospheric and terrestrial domains. Figure taken from Franz *et al.* (2018). Reproduced under the terms and conditions of the Creative Commons attribution licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

and removals that complement and, in some cases, supplement the official GHG emission data reported in national inventories to the EU and UN bodies. The importance of these networks has also been highlighted by the Global Climate Observing System where the data produced are classified as essential climate variables.

The Integrated Carbon Observation System (ICOS) research infrastructure seeks to build on this success by developing a European network that will contribute to a future Earth observatory for the measurement of GHGs, to create a cross-domain network of atmosphere, terrestrial ecosystem and ocean observations to enhance our understanding of biogeochemical cycles in a changing environment. ICOS was established in 2008 and was included in the strategic European Strategy Forum on Research Infrastructures, where it moved from the Roadmap and became an official European Research Infrastructure Consortium in 2015. The ICOS research infrastructure brings together over 100 GHG measurement stations from 12 member countries through an agreed management, coordination, calibration and support structure. The ICOS infrastructure includes the following:

- GHG observation stations that meet ICOS operational and instrumental standards;
- a calibration centre for the provision of reference standards for measured gases;
- thematic centres for atmospheric, ecosystem and oceanic observations;
- a data assimilation and processing centre for the management and storage of data;
- a headquarters hosted by Finland.

A1.4 The Scientific Rationale of ICOS

The synergy between the measurement of atmospheric GHG concentrations and knowledge of the contribution of the oceans and terrestrial ecosystems to localised and regional scale fluxes has proven to be effective in reducing the scientific uncertainties associated with the assessment of carbon and GHG dynamics. The ICOS infrastructure will further enhance the analysis of carbon and GHG emissions and removals in a harmonised manner on a pan-European scale. ICOS will meet the data needs of the carbon cycle and climate research community as well as those of the general public and all other relevant stakeholders. ICOS will serve as the backbone to users across many disciplines; for example, the tall tower network will enable the development of data assimilation models of GHG sources and sinks, e.g. reverse (or inverse) modelling that allows the deduction of surface carbon flux patterns. The ecosystem tower network will also provide the information required to fully constrain emissions from the land use sector, which is particularly important for Ireland as this sector dominates the national emission profile. The consolidation of network data into an emission verification system will also be required to develop a reporting system that will enhance and verify the compilation of national emission inventories to a level that captures current and future potential policy interventions. For example, emission inventories based on emission factors and activity data can be determined from atmospheric measurement data in conjunction with an atmospheric transport model that relates emissions to atmospheric concentrations by means of an inversion algorithm. The inversion algorithm adjusts the emissions used in the model to optimise the agreement between the observed and the simulated concentrations. Typically the inversion involves the combination of observations of atmospheric trace gas concentrations with a priori knowledge of sources and sinks, derived from the oceanic and terrestrial observational network, in conjunction with a chemical transport model. The integration of an observational network across the atmospheric, ocean and terrestrial domains will enable the production of seasonal and annual high-resolution emission maps of GHG emissions from Ireland. The ICOS network will, therefore, help to resolve fundamental issues relating to Ireland's GHG emissions, including:

- a reduction in the uncertainties associated with GHG emissions such that the nature and extent of the sources and sinks of GHGs in Ireland can be determined;
- an assessment of how meteorological and other factors such as land use influence these sinks on seasonal to decadal timescales and the interplay between these and management systems;
- the identification of geographical areas with high levels of uncertainty in bottom-up analysis of GHG emissions such as N_2O and CH_4;

- the production of an independent integrated and comprehensive analysis of emissions and removals in Ireland in the context of the GHG neutrality goal for key emissions and land use sectors (e.g. agriculture).

A1.5 Policy Relevance

The Environmental Protection Agency (EPA) hosted an initial meeting of ICOS stakeholders in June 2015; the consensus outcome of this meeting was that the provision of sustainable high-quality top-down and bottom-up analysis of key GHG emissions as operational products from the analysis of atmospheric, oceanic and terrestrial measurements is now a realistic goal. Engagement with the ICOS network represents a significant opportunity to provide an independent verification of official inventories produced for and reported to the United Nations Framework Convention on Climate Change and EU, in addition to a more detailed temporal and spatial analysis of terrestrial and oceanic GHG emissions and removals. This is of particular relevance to the recent amendment to the European Parliament's position on the inclusion of GHG emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework (Article 7 of Regulation (EU) No 525/2013).

This research goal was also included at EU level through a Joint Programming Initiative (JPI) on climate change (JPI-Climate) and is being progressed further through relevant Horizon 2020 topics. The development of a pan-European GHG observational network under ICOS is central to these initiatives. The meeting concluded that it is in Ireland's interest to be part of these activities, i.e. that national research activities are linked to work in the UK and other European counties either bilaterally or via the JPI and Horizon 2020 processes. The national observation network must therefore meet the various criteria and standards that are established for such observations. This may be readily accomplished and requires up to seven sites in Ireland that are designated as ICOS sites across the atmospheric and terrestrial domains.

A1.6 Why Should Ireland Join ICOS?

Ireland has, through national, UK, French and EU infrastructural investment, in addition to key research projects (see Figure A1.2, been at the forefront of the top-down (e.g. Mace Head) and bottom-up (e.g. CCFLUX, CelticFlux, CarboEurope and GHG Europe projects) analysis of regional scale emissions of GHGs. The EPA has supported a pilot study of the potential of enhancing the top-down atmospheric analyses for industrial gases through complementary measurements at Carnsore Point. This study showed the potential for such a site to provide a more accurate analysis of emissions from Ireland, the UK and other nearby European regions. Subsequently, the EPA has supported the development of measurements of CO_2 and other GHGs at Carnsore Point and Malin Head, which, with Mace Head, effectively triangulate Ireland. In addition to the EPA, other organisations and institutes such as Teagasc, the Department of Agriculture, Food and the Marine, the Council for Forest Research and Development, Bord na Móna, the National Parks and Wildlife Service (NPWS), Earthy Matters and a number of universities (Trinity College Dublin (TCD), University College Dublin (UCD), University College Cork (UCC), University of Limerick (UL), Waterford Institute of Technology (WIT), National University of Ireland (NUI) Maynooth have established terrestrial flux measurements at ecosystem sites around Ireland, while the Marine Institute (MI) and the National University of Ireland Galway (NUIG) have been involved with the monitoring of the waters surrounding Ireland. In combination, these provide a powerful observational network to develop the necessary models and tools that can constrain emissions and removals from the oceans and terrestrial systems. Because of its scale, location and geography, Ireland provides an excellent platform to develop and verify these models and tools. Doing so is necessary as key questions remain open, which need to be addressed if Ireland is to achieve its climate goals: (1) Are terrestrial systems a sink or a source for CO_2 and other important GHGs? (2) What is the impact of management systems and weather/climate volatility on emissions/removals of GHGs? These questions and analyses are also relevant at regional and global scales. However, due to its unique emissions profile and its goal of neutrality for the agriculture and land use sector, Ireland has specific interest in using its natural advantages to address and resolve these issues in so far as it may be scientifically achievable. ICOS provides a platform for doing this. Joining ICOS would allow access to the systems and tools required to provide standardised data sets that can be used for verification and analysis of official data reported and accounted for at national, EU and UN levels. The analysis would also enable high-resolution analysis of emissions and trends at higher temporal and spatial scales and lead to improved estimates of Ireland's GHG emissions.

A1.7 ICOS Requirements and Costs to Participating Countries

ICOS requires participating countries to:

- establish and maintain nominated sites to the ICOS standard for an initial period of 5 years;
- contribute to the overall costs of the ICOS European Research Infrastructure Consortium (ERIC);
- participate in ICOS governance and development processes.

Signing the ICOS ERIC therefore requires a commitment to capital investment in the establishment of the designated sites and to ongoing operational costs. Ireland would have membership of the ICOS Governing Board and would be able to influence the long-term development and operational capacity of ICOS. It would also enable involvement with the technical working groups. The costs therefore comprise:

- costs of membership;
- costs for site establishment;
- operational and maintenance costs.

A1.8 The Development of ICOS Ireland

A1.8.1 Atmospheric monitoring station network

Mace Head (Co. Galway) represents one of the key observational platforms in both the global and pan-European atmospheric monitoring network. This station has attracted investment by the UK, France and the USA and is also of strategic interest for the European Space Agency and linked with Earth observations work in the EU GMES/Copernicus programme. This enables researchers in Ireland to participate in the most advanced global research programmes in this area and provides Ireland with unique opportunities to develop systems and tools for GHG emissions analysis. While these can have global uses, particularly in the areas of agriculture and land use, strategic and sustained investment is needed to provide observational data from strategic locations, and for key land use types/ecosystems, in a sustained manner, which is high quality and comparable to international standards. It is also essential that analysis of these data is focused on issues for Ireland and to position groups in Ireland to avail of opportunities that will arise in this area.

The atmospheric monitoring station network in Ireland and associated costs

The costs outlined here represent the capital and full operational costs of the proposed atmospheric station monitoring network for one Class 1 station (Mace Head) and two Class 2 stations (Carnsore Point and Malin Head) (see Figure A1.3 and Tables A1.1 and A1.2). The feasibility of including Valentia as a future Class 2 site is currently being assessed, and the possibility of including Valentia as part of the network will be revisited at a future date.

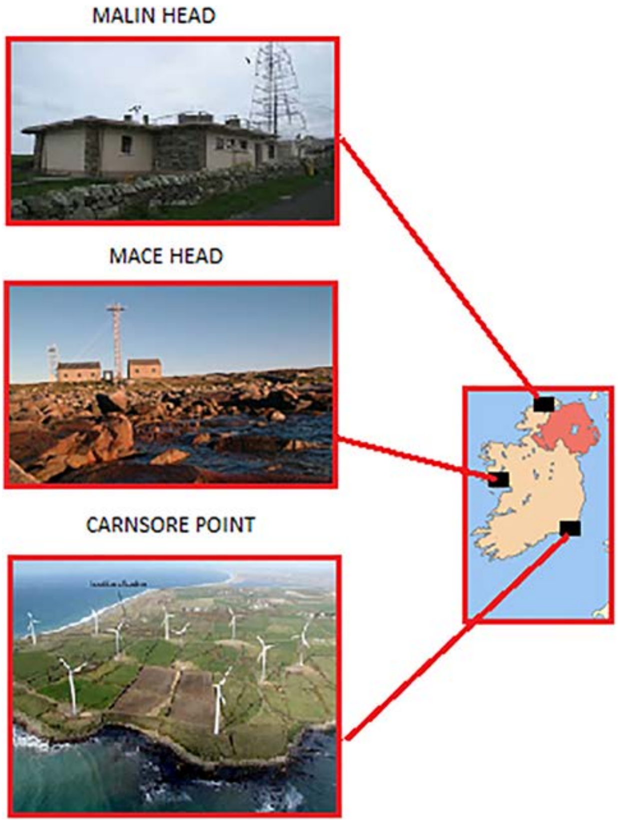


Figure A1.3. The location of the Mace Head, Carnsore Point and Malin Head atmospheric stations. The inset images show the locality of each station in more detail.

Table A1.1. Measurement variables and frequency at Class 1 and 2 ICOS atmospheric stations

Category	Gases, continuous	Gases, periodical	Meteorology, continuous	Eddy fluxes
Class 1 mandatory parameters	CO_2, CH_4, CO: at each sampling height	CO_2, CH_4, N_2O, SF_6, CO, H_2, ^{13}C and ^{18}O in CO_2: weekly sampled at highest sampling height ^{14}C (radiocarbon integrated samples): at highest sampling height	Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height[a] Atmospheric pressure Planetary Boundary Layer Height[b]	
Class 2 mandatory parameters	CO_2, CH_4: at each sampling height		Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height[a] Atmospheric pressure	
Recommended parameters[c]	^{222}Rn, N_2O, O_2/N_2 ratio CO for Class 2 stations	CH_4 stable isotopes, O_2/N_2 ratio for Class 1 stations: weekly sampled at highest sampling height		CO_2 at one sampling height

[a] Atmospheric temperature and relative humidity recommended at all sampling heights.

[b] Required only for continental stations.

[c] Recommended for its scientific value but support from the Atmospheric Thematic Centre in terms of protocols, data base and spare analyser will not be ensured as long as the parameters are not mandatory.

^{13}C, carbon-13; ^{14}C, carbon-14; CO, carbon monoxide; H_2, hydrogen; N_2, nitrogen; ^{18}O, oxygen-18; ^{222}Rn, radon-222; SF_6, sulfur hexafluoride.

A1.8.2 Ecosystem monitoring station network

The ICOS Research Infrastructure currently include data from around 70 ecosystem stations (Figure A1.7), coordinated at a national level by the ICOS national networks. Ecosystem stations measure fluxes of CO_2, CH_4, H_2O and heat, together with the ecosystem variables needed to understand the processes behind the exchange of energy and GHGs between the ecosystems and the atmosphere. Data from these networks of ecosystem stations are collated through the ICOS Ecosystem Thematic Centre (ETC) (http://www.icos-etc.eu/icos/). Habitat types represented in the ecosystem stations network include forest, grassland, cropland, wetland, marine and lakes. Figure A1.7 further illustrates the current distribution of Class 1, 2 and associated stations across Europe with their respective ecosystem type. From this figure it is clear that forests dominate the ecosystem stations with good representation from grassland, cropland and wetland ecosystems. Urban areas and stations over lakes, heath/shrublands and short rotation forestry (bioenergy) are currently underrepresented in the ICOS network.

The Class 1 and 2 sites differ in the range of measurements made, which has implications for the construction, operation and maintenance costs. Table A1.3 indicates the core measurements made at ICOS Class 1 and 2 sites for different ecosystem types; this information can also be found at http://www.icos-etc.eu/variables. The measurements made at both Class 1 and 2 sites are standardised with regard to the instrumentation, measurement procedure and data quality control (QC). There is also an option to develop associated measurement sites that are not part of the official ICOS network but are hosted by the ICOS ETC.

Ecosystem stations in Ireland

The measurement of the land–atmosphere exchange of carbon, GHGs and turbulent energy from terrestrial ecosystems has been made over many of the land cover classes in Ireland, including forest, bog, cropland, arable and bioenergy ecosystems, using both eddy covariance (EC) and static chamber (SC) techniques. However, many of these stations have been associated with fixed-term research projects, compromising the long-term operation of these observational platforms. To ascertain both the operational status and the methodologies employed at each of these measurement stations in Ireland, a survey was circulated to all researchers working in this area. Table A1.4 outlines the results of this survey

Table A1.2. Indicative costs for the initial expansion and operation of the ICOS atmospheric stations (all costs in euro)

ICOS expenditure for Irish atmospheric observation stations (2019–2023)	
Capital investment (2019–2024)	**Cost (excluding VAT)**
Replacement of the CH_4, CO_2 and CO analysers at two stations and installation of a reference instrument at central facility[a]	274,815
Installation of ICOS-compliant anemometry equipment at the three sites	40,320
Cylinders, regulators, flow controllers, water removal instrumentation for CH_4, CO_2 and CO analysers	155,000
Samplers, flasks and transport to central laboratory for weekly samples CO_2, CH_4, N_2O, SF_6, CO, H_2, ^{13}C and ^{18}O in CO_2[b]	97,000
Sampler and flasks for $^{14}CO_2$[c]	26,000
Radon instrument[d] (waiting for cost confirmation from Australian Nuclear Science and Technology (ANSTO)	71,000
Licensed software for data processing (GCWerks)	30,150
Installation of ICOS-compliant N_2O instrumentation at three sites[e]	319,296
Consumables, valves, regulators and flow controllers for N_2O instrumentation	63,000
N_2O isotope instrument at two sites (Carnsore Point and reference laboratory)	274,840
Fittings, spare parts, air sampling inlets, pumps	2100
Total (ex-VAT): 1,372,421	
Total (inc. VAT @ 23% + customs charges): 1,722,388	

Annual operational expenditure						
Year	**Maintenance and servicing[f]**	**Station costs[g]**	**Travel and consumables[h]**	**Human resources[i,j]**	**Membership contribution[k]**	**Total costs**
2019	56,356	51,000	18,000	264,020	74,000	463,776
2020	56,356	51,000	18,000	264,020	74,000	463,776
2021	56,356	51,000	18,000	264,020	74,000	463,776
2022	56,356	51,000	18,000	264,020	74,000	463,776
2023	56,356	51,000	18,000	264,020	74,000	463,776
Total						2,318,880
Total expenditure (capital investment and annual expenditure): 4,041,268						

[a] **A second-generation instrument was installed in Malin Head in 2018.**

[b] **The $^{14}CO_2$ sampler continuously pumps ambient air through a CO_2-absorbing sodium hydroxide (NaOH) solution over several days. To enlarge the NaOH reaction surface, the solution is held in a rotating glass tube filled with a packed bed of glass Raschig rings. Using this method, the atmospheric CO_2 is absorbed nearly quantitatively in the NaOH solution. The sample is then sent to the ICOS Calibration (CAL) Central Radiocarbon Laboratory in Germany for analysis.**

[c] **Measurement of air periodically sampled in flasks at the atmospheric station allows the measurement of additional variables (e.g. SF_6, H_2, CO_2 stable isotopes), which are not performed by *in situ* continuous analysers and an independent quality control for continuous *in situ* measurements. Within the ICOS atmospheric network, the air flasks will be sampled by an automatic flask sampler, which will allow automatic sampling during suitable atmospheric conditions. This automatic flask sampler is currently being finalised. Weekly air sampling must be undertaken with the approved ICOS 2-L flask. The flask specifications are being finalised. Each Class 1 station is required to own approximately 100 flasks in order to prevent logistical issues or CAL congestion. All ICOS flasks samples are to be analysed by the CAL in Jena, Germany, as soon as the CAL is fully operational.**

[d] **At the present stage, radon-222 measurements are not mandatory in ICOS. However, radon-222 is recognised as a very valuable measurement, in particular for trace gas flux estimates. There are two different radon measurement principles in use at European and global atmospheric stations: (1) measurement of radon-222 with a two-filter system (e.g. ANSTO system) and (2) measurement of radon-222 daughters attached to aerosols and accumulated on one filter, and determination of radon-222 from its daughter activity assuming a height-dependent disequilibrium factor (e.g. Heidelberg system). We are proposing the installation of the ANSTO system here.**

[e] **In ICOS, at this stage, N_2O is not a required but a recommended parameter for continuous gas measurement. As illustrated in Figure A1.4, however, we believe N_2O emissions are important within the Irish context.**

[f] **This cost is based on replacing each of the three instruments annually over the period 2016–2018. This is necessitated by the approaching end of service on the current model. The lifetime of each model is of the order of 10 years.**

[g] **The costs here are associated with some modifications to the Mace Head station, necessitated by Class 1 ICOS station requirements. These are centred on the creation of a dedicated space for the Class 1 ICOS measurements. This would**

Table A1.2. Continued

involve an extension of the existing space to facilitate the full suite of measurements. The funding proposed here is on an ≈50% cost-share agreement with NUIG with investment to the same level as that proposed here. This would help to add a degree of sustainability to the infrastructure.

[h]The costs here can be summarised as (1) site visits for service and repair, (2) attendance at biannual ICOS MSA atmosphere meetings and (3) instrument consumables.

[i]The costs here are associated with two full-time equivalent positions based on discussions with other national network operators typically funded 0.7–0.8 full-time equivalent per station.

[j]Although not strictly part of the measurement campaign, the incorporation of these sites' data into top-down state-of-the-art inversion model emission estimates (shown in Figures A1.5 and A1.6) represents an important product from these observations, and the extension of these estimates to other gases (CO_2 and N_2O) for producing annual estimates constitutes a very important component of the whole endeavour. This has been funded previously on an EPA project basis and this is costed here at 1 full-time equivalent/year.

[k]The annual membership costs are based on one Class1 and two Class 2 stations and are calculated by fixed station classification specific costs and a fraction of Member States' gross domestic product. These costs were verified via teleconference with LSCE Atmospheric Thematic Centre (M. Ramonet and L. Rivier, personal communication, 22 May 2018).

^{13}C, carbon-13; ^{14}C, carbon-14; CO, carbon monoxide; H_2, hydrogen; ^{18}O, oxygen-18; SF_6, sulfur hexafluoride.

and details the ecosystem/land cover classes that have been monitored, the key principal investigators and institutions leading this work, whether the site is still actively collecting data and the temporal coverage of measurements made. To date, the ecosystem flux towers in Ireland have collected > 110 site years of data, with grassland, forest and peatland systems having the greatest data coverage (Figure A1.8); the location of currently active ecosystem stations is illustrated in Figure A1.9. Table A1.5 details the infrastructural capacity of both the active and inactive ecosystem stations in Ireland in addition to compliance of these sites with the ICOS infrastructural and measurement requirements. The inactive stations are those at which the key infrastructural components are still in place (e.g. tower, power supply, sensors) but measurements are not currently being made. These stations could, however, become operational under an ICOS–Ireland ecosystem station network. This table clearly indicates that, of the operational ecosystem stations in Ireland, none is compliant with the infrastructural requirements of the ICOS Class 1 and 2 stations.

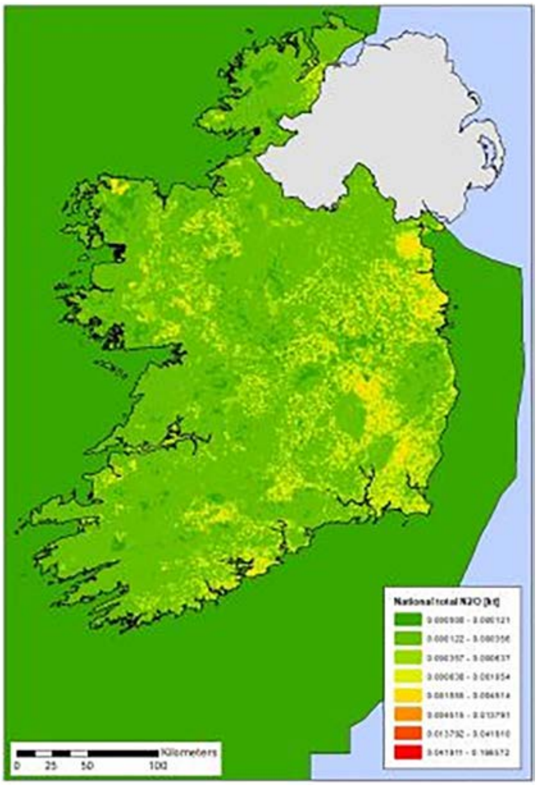


Figure A1.4. National N_2O emissions from Ireland.

One of the main changes to the organisation of the ecosystem stations structure was the inclusion in 2012 of inland water ecosystems to the monitoring network. There are currently no freshwater (rivers and lakes) measurement sites in Ireland with routine monitoring for GHG fluxes. However, these habitats are known to be significant contributors of GHG emissions to the atmosphere. Recent global estimates demonstrate that about 2.1 carbon exchange fluxes (Pg C y^{-1}) are emitted from inland waters to the atmosphere in the form of CO_2 (Raymond *et al.*, 2013; Aben *et al.*, 2017), an amount comparable to CO_2 uptake by oceans (≈2.0 Pg C y^{-1}) (Song *et al.*, 2018). Carbon burial into lake sediments can also be substantial, exceeding organic carbon sequestration on the ocean floor (Tranvik *et al.*, 2009). With > 12,000 lakes in Ireland, it is desirable to quantify GHG emissions from these habitats. Data from a one-off spatial study of 121 oligotrophic upland lakes, extrapolated to the total lake habitat of Ireland, estimated GHG emissions of 0.46 million tonnes of CO_2 equivalent per year, which is approximately 0.7% of Ireland's 2007

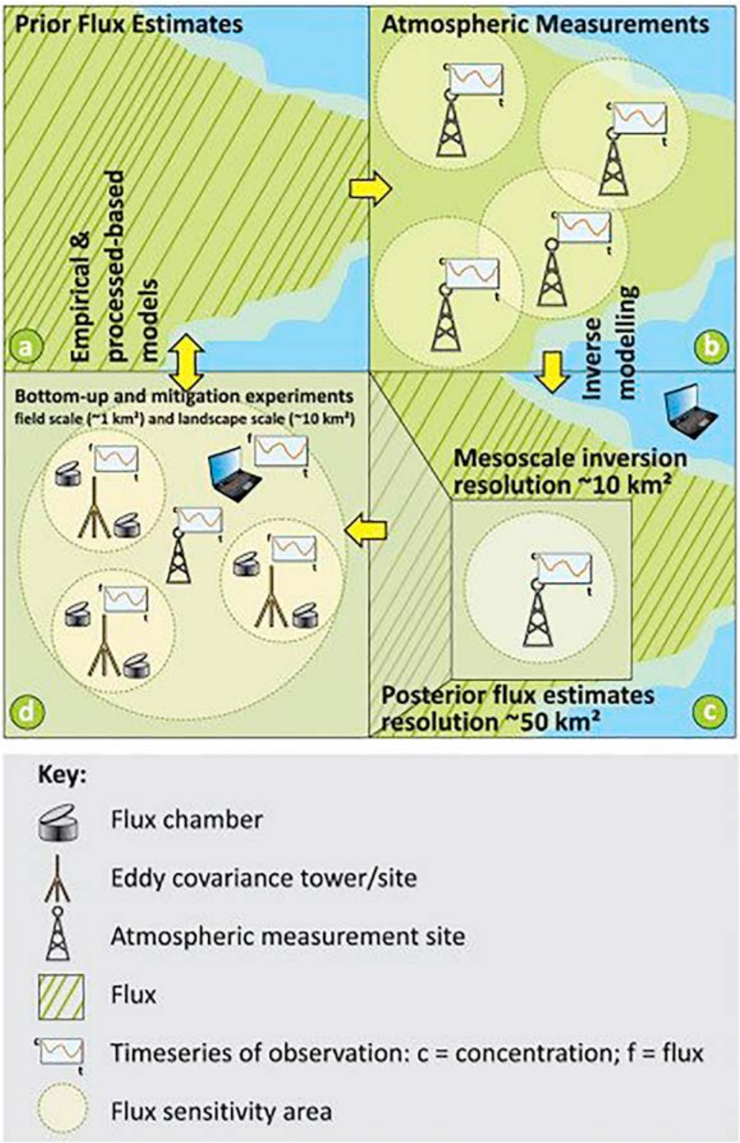


Figure A1.5. Overview of the approaches to determine GHG emission over various spatial and temporal scales.

anthropogenic GHG emissions. However, modelling of GHG dynamics from lakes driven by future climate projections indicates that the rate of emissions may increase. Land use change, including afforestation, will also affect the carbon cycles of aquatic habitats. It is desirable, therefore, that Ireland invests in the monitoring of these ecosystems, and that the framework for ICOS ecosystem sites gives guidance on this.

Long-term monitoring of aquatic fluxes of carbon is a substantial component of the long-term ecological research conducted in the Burrishoole catchment, Co. Mayo. The MI runs a research station in Burrishoole and core staff maintain a catchment monitoring programme that includes carbon dynamics. The core monitoring programme is supplemented and enhanced though collaboration and has been a focus for several EU and nationally funded projects (CLIME, RESCALE, ILLUMINATE, PROGNOS). At the core of most of this work are several high-frequency monitoring stations, with *in situ* sensors capturing fluxes of aquatic dissolved organic carbon, particulate organic carbon and partial pressure of CO_2 (pCO_2). The pCO_2 sensor was installed in early 2017 on Lough Feeagh, the largest lake in the Burrishoole catchment, and these data are currently being analysed to determine the annual flux of CO_2 from the lake. This is an indirect flux measurement, dependent on literature values for the gas transfer coefficient. A small number of direct

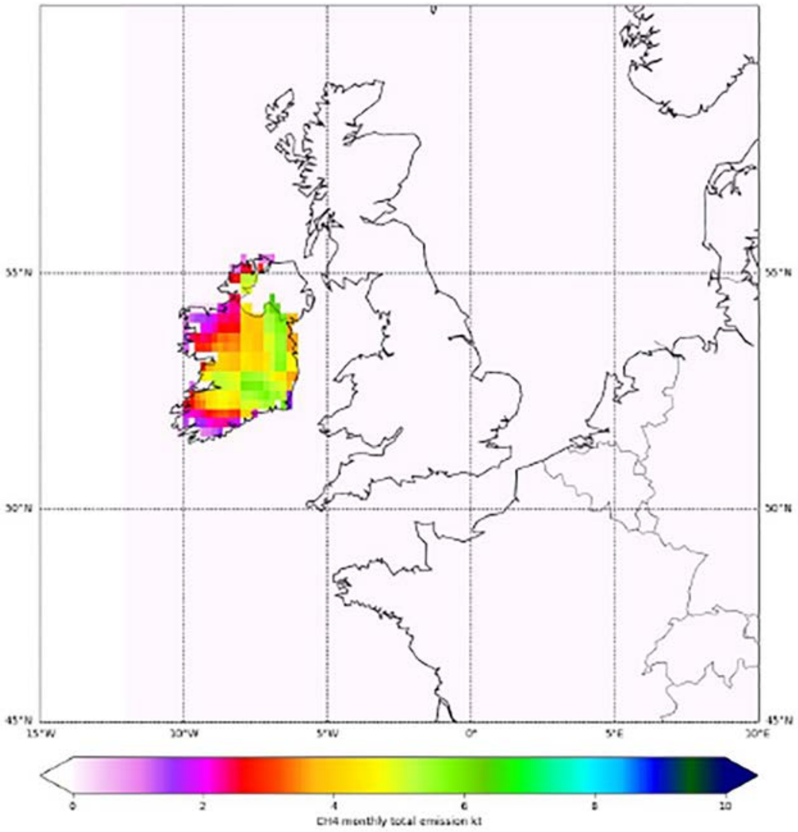


Figure A1.6. The integration of flux station observations and top-down inversion models to produce a spatially explicit estimation of CH_4 fluxes across Ireland.

flux measurements have been undertaken using chambers on Lough Feeagh and at two rivers in the upper catchment. This work forms a good baseline for expansion of the programme to meet ICOS standards. Work is ongoing on resolving the carbon cycle of Lough Feeagh, and, when concluded, will represent the first carbon cycle published for an Irish lake.

The list of variables that should be measured at lake sites for inclusion in ICOS is still under discussion (http://www.icos-etc.eu/variables), but for Lough Feeagh to be included as a potential lake ecosystem station, additional infrastructure would need to be acquired, installed and maintained. The ongoing deployment of the pCO_2 sensor on the Lough Feeagh automatic water quality monitoring station will continue to provide a valuable data source, but this would need to be supplemented by an eddy flux tower (on the lake or shore) and a more defined programme of chamber measurements. There is a Met Éireann automatic weather station on the southern shore of Lough Feeagh (https://www.met.ie/climate/weather-observing-stations), supplemented by additional meteorological sensors on the Lough Feeagh and Lough Furnace stations. The presence of the MI's research station on the shore of Lough Feeagh, along with permanent research staff, means that it is a good potential site for an ICOS ecosystem station. Lough Feeagh is a good example of a large humic deep lake in the west of Ireland, but there are several other lake types in the country that would warrant data collection to gain a full understanding of the role that freshwaters play in the national GHG budget.

Ecosystem station costs

The overall costs of an ICOS ecosystem site is difficult to estimate owing to the variability over time of the cost of individual sensors. Table A1.6 outlines the key costs associated with ICOS ecosystem stations and include an estimation of the infrastructural, sensor, ancillary and running costs.

A1.8.3 Ocean station monitoring network

The oceans cover two-thirds of the Earth's surface and absorb 24% of anthropogenic CO_2 emissions (Global

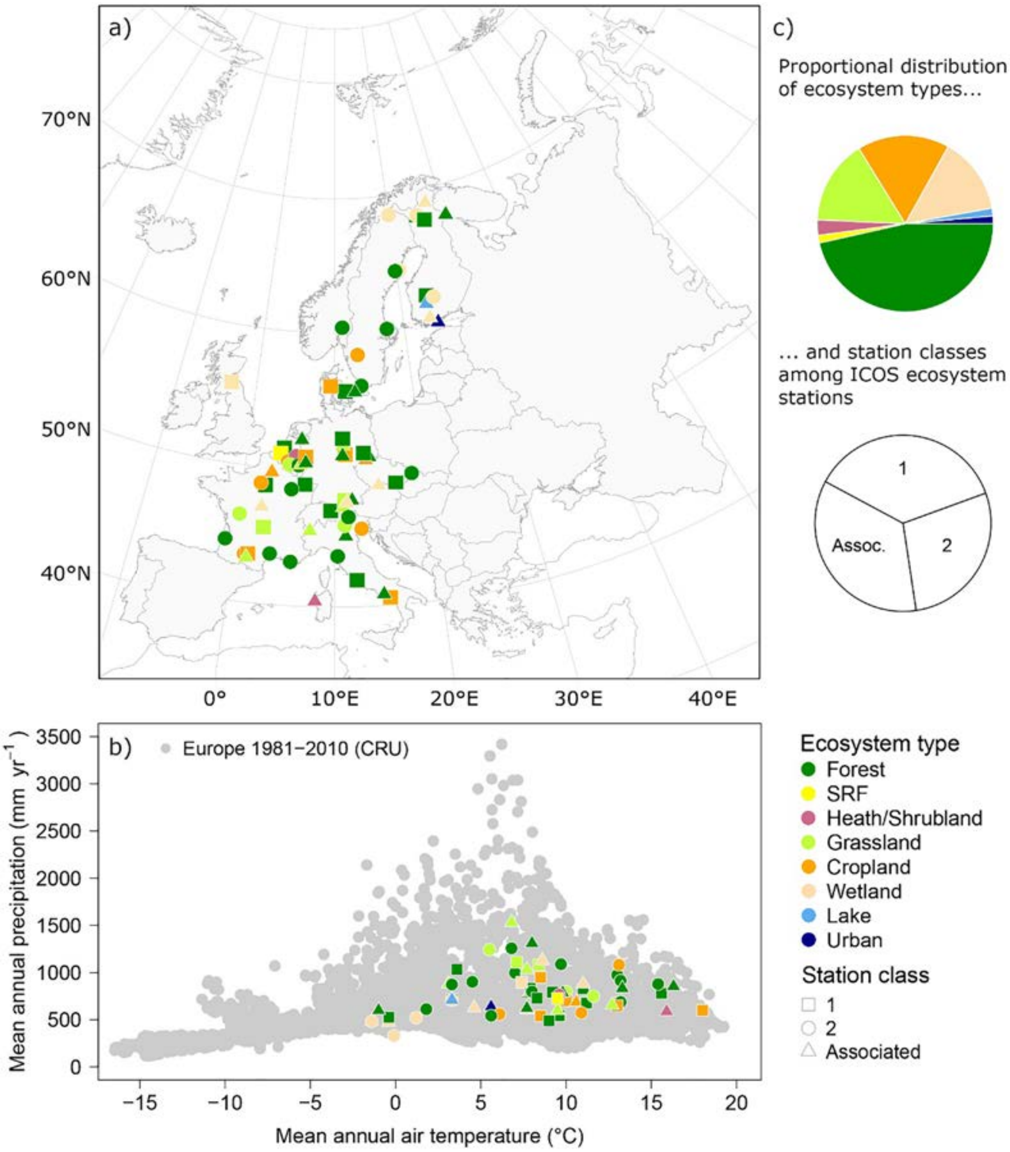


Figure A1.7. Overview of the ICOS ecosystem stations showing the station class, ecosystem type and geographical distribution across Europe (a). Also shown is the climatological distribution of stations in relation to mean annual temperature and precipitation (b). Figure taken from Franz *et al*. (2018). Reproduced under the terms and conditions of the Creative Commons attribution licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Carbon Budget, 2017), with the deep ocean storing around 60 times more carbon than the atmosphere. Of all the CO_2 emitted to the atmosphere by humans since pre-industrial times, the ocean has taken up about half (118 ± 19 Pg C y^{-1} by 1994, Sabine *et al*., 2004). Indeed, the ocean "sink" has been increasing in response to an ever higher atmospheric CO_2 concentration (Figure A1.10) providing a damping effect. The increase in oceanic CO_2 does, however, have a negative impact, as CO_2 dissolves in seawater and forms carbonic acid, making the oceans more acidic. Since the beginning of the Industrial Revolution, the Earth's surface oceans are believed to have acidified by 30% (i.e. a 30% increase in hydrogen ion concentration, equivalent to a decrease of 0.1 pH units) due to the absorption of some of the anthropogenic CO_2 emissions to the atmosphere (IPCC, 2013). Long-term, high-quality measurements of the oceanic carbon system are therefore vital for climate monitoring, future projections and adaptation planning at national and international levels.

The Ocean Thematic Centre is one of four central facilities within ICOS. The marine element of ICOS

Table A1.3. The list of variables measures at ICOS Class 1 and Class 2 sites for different ecosystem types

Variables	Forest	Grassland	Cropland	Peatland	Marine	Lakes
CO_2, H_2O and H fluxes (eddy covariance, including profile for storage)	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
CH_4 and N_2O fluxes (eddy covariance, including profile for storage	1	1	1	1	1	1
Air CO_2 and H_2O concentration	1	1	1	1	1	1
Air CO_2 vertical profile	2	2	2	2		
Air H_2O concentration	1	1	1	1	1	1
Incoming, outgoing and net SW and LW radiations	1 & 2	1 & 2	1 & 2	1 & 2	1	1
Incoming SW radiation (high-quality)	Fac	Fac	Fac	Fac	Fac	Fac
PAR/PPFD Incident	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
PAR/PPFD below canopy + ground reflected	Fac	Fac	Fac	NR	NR	NR
PAR/PPFD reflected	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Diffuse PAR/PPFD radiation	1	1	1	1	Fac	Fac
Spectral reflectance	Fac	Fac	Fac	Fac	Fac	Fac
Soil heat flux	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Air temperature and humidity profile	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Main meteorological parameters (T_A, RH, SWin, precipitation)	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Total high-accuracy precipitation	1	1	1	1	1	1
Rain precipitation	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Snow precipitation	1	1	1	1	1	1
Snow height	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Soil water content profile	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Soil temperature profile	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Air pressure	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Trunk and branches temperature	Fac	NR	NR	NR	NR	NR
Ground water level	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Trees diameter	1	NR	NR	NR	NR	NR
Phenology/camera	1	1	1	1	NR	NR
Soil CO_2 automatic chambers	1	1	1	1	1	1
CH_4 and N_2O by automatic chambers	1	1	1	1	1	1
Wind speed and wind direction (additional to 3D sonic)	1	1	1	1	1	1
Leaf area index	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Above ground biomass	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Soil carbon content	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Litter fall	1	1	1	1	NR	NR
Land N content	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Soil water N content	Fac	Fac	Fac	Fac	NR	NR
Dissolved organic carbon concentration	Fac	Fac	Fac	Fac	NR	NR
C and N import/report by management	1 & 2	1 & 2	1 & 2	1 & 2	NR	NR
Oxygen and pCO_2 surface concentration	NR	NR	NR	Fac	2	2
Oxygen, pCO_2 and pNO_2 concentration profile	NR	NR	NR	Fac	1	1
Salinity	NR	NR	NR	NR	1 & 2	NR
Wave properties	NR	NR	NR	NR	Fac	Fac
Water temperature profile	NR	NR	NR	NR	1	1
Management and disturbances information	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2

Fac, facultative variable; LW, longwave; NR, not relevant for the ecosystem; PAR, photosynthetically active radiation; PPFD, photosynthetic photon flux density; RH, relative humidity; SWin, shortwave incoming; T_A, air temperature.

Table A1.4. The experimental sites across Ireland at which terrestrial carbon/GHG measurements have been made, including the site principal investigator, associated research organisations, data coverage and site management

Site name and location	Ecosystem land cover class	Principal investigator	Other institutions involved	Site active (Yes/No)	Data coverage	Management
Clara Bog, Co. Offaly	Raised bog	Matthew Saunders (TCD) Laurence Gill (TCD) Shane Regan (TCD)	DCU, UCD, NPWS	Yes	2018–present (EC) 2016–present (SC)	Some rehabilitation through drain blocking
Glencar, Co. Kerry	Blanket bog	Ger Kiely (UCC) Paul Leahy (UCC) Matteo Sottocornola (WIT)	–	No	2001–2016	
Dripsey, Co. Cork	Grassland	Ger Kiely (UCC) Paul Leahy (UCC) Matteo Sottocornola (WIT)	–	No	2002–2016	
Dripsey, Co. Cork	Forest (deciduous)	Ger Kiely (UCC) Paul Leahy (UCC) Matteo Sottocornola (WIT)	–	No	2006–2016	
Dooary, Co. Laois	Forest (coniferous)	Bruce Osborne (UCD)	TCD	Yes	2002–present	Forest thinned in 2006, 2007 and 2008
Mt Lucas, Co. Offaly	Forest (deciduous)	Bruce Osborne (UCD)	TCD	No	2010–2011	
Mt Lucas, Co. Offaly	Grassland	Bruce Osborne (UCD)	TCD	No	2010–2011	Fertilisation and silage harvest
Ballinagar, Co. Offaly	Forest (deciduous)	Bruce Osborne (UCD)	TCD	No	2010–2011	
Cloosh, Co. Galway	Blanket bog	Bruce Osborne (UCD)	TCD	No	2011–2012	
Cloosh, Co. Galway	Forest (coniferous)	Bruce Osborne (UCD)	TCD	No	2011–2012	Afforested blanket bog
Lullymore, Co. Kildare	Cutaway peatland	Ger Kiely (UCC) Paul Leahy (UCC) Matteo Sottocornola (WIT)	Bord na Móna, TCD, UCD	Yes	2016–present	Rehabilitation through re-wetting
Moyarwood, Co. Galway	Raised bog	David Wilson, Earthy Matters	Bord na Móna, UCD, Giessen	No	2013–2018	Rehabilitation through re-wetting
Oakpark, Co. Carlow	Arable	Mike Jones (TCD) Bruce Osborne (UCD)	Teagasc	No	2002–2008	Conventional and non-inversion tillage (NIT), fertilisation, cover cropping (NIT plots)

Table A1.4. Continued

Site name and location	Ecosystem land cover class	Principal investigator	Other institutions involved	Site active (Yes/No)	Data coverage	Management
Oakpark, Co. Carlow	Grassland	Mike Jones (TCD)	Teagasc	No	2003–2008	Fertilisation, silage harvest, grazing
Oakpark, Co. Carlow	Bioenergy	Mike Jones (TCD)	Teagasc	No	2006–2008	
Johnstown Castle, Co. Wexford	Grassland	Gary Lanigan (Teagasc)	TCD	Yes	2002–present	Fertilisation, silage harvest, grazing
Johnstown Castle, Co. Wexford	Bioenergy	Gary Lanigan (Teagasc)	UCD, TCD	No	2009–2011	
Johnstown Castle, Co. Wexford	Bioenergy	Gary Lanigan (Teagasc)	UCD, TCD	No	2009–2011	
Solohead, Co. Tipperary	Grassland	Gary Lanigan (Teagasc)	–	No	2012–2017	
Scohaboy, Co. Tipperary	Raised bog	Ken Byrne (UL) Caitlin Rigney (UL)	UCD, Earthy Matters	No	2014–2015	Previously afforested now re-wetted
Pollagoona, Co. Clare	Blanket bog	Ken Byrne (UL) Caitlin Rigney (UL)	UCD, Earthy Matters	No	2014–2015	Previously afforested now re-wetted
SS18, Co. Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS24, Co. Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS27, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS28, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS39, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS43, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
SS44, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog
LP23, Co Limerick	Forest (coniferous)	Ken Byrne (UL) Jonany Jovani (UL)	UCD	No	2014–2016	Afforested blanket bog

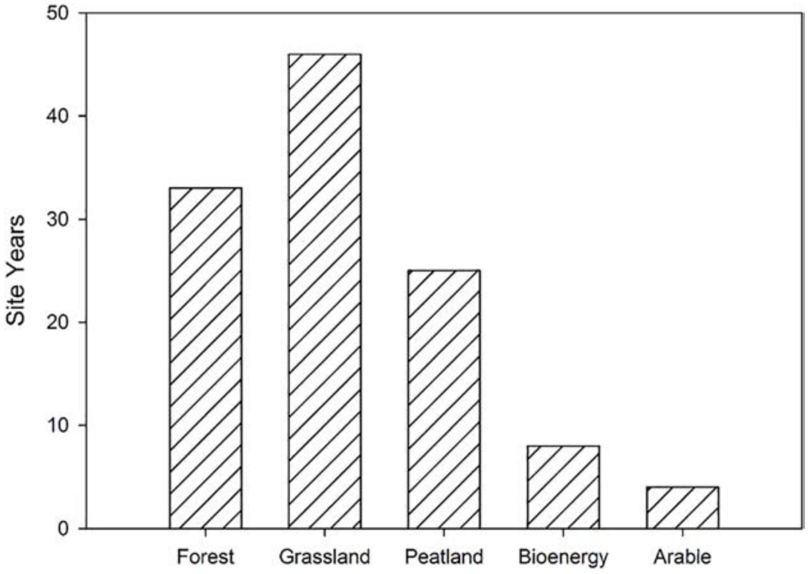


Figure A1.8. The temporal data coverage of the ecosystem flux stations in Ireland from key land cover classes.

provides long-term oceanic observations, which are required to understand the present state and better predict the future behaviour of the global carbon cycle and climate-relevant gas emissions.

The Ocean Thematic Centre currently coordinates 21 ocean stations from seven countries monitoring carbon uptake and fluxes in the North Atlantic, Nordic Seas, Baltic Sea and Mediterranean Sea. Measuring methods include sampling from research vessels, moorings, buoys and commercial vessels that have been equipped with state-of-the-art carbonate system sensors.

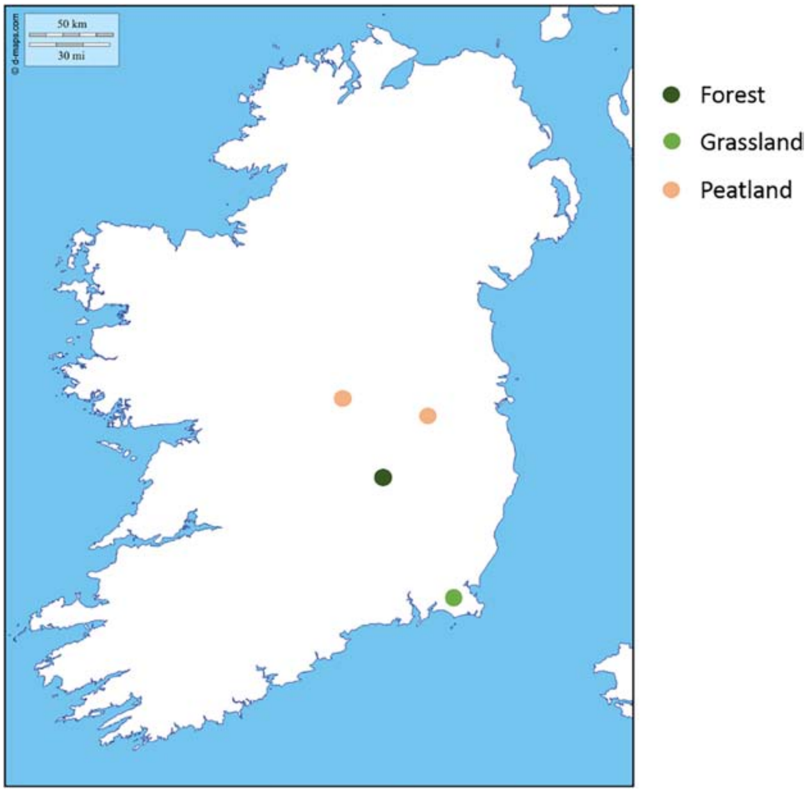


Figure A1.9. The approximate location of active ecosystem stations in Ireland.

Table A1.5. The infrastructural measurement capacity of the active and inactive[a] ecosystem stations in Ireland and ICOS compliance (Class 1 or 2). Green indicates compliance with ICOS, orange represents partial compliance where the infrastructure (sensors) are suitable but not compete and red indicates non-compliance

Site name	Power supply	CO_2/H_2O EC sensor	CH_4/N_2O EC sensor[b]	Sonic anemometer	Vertical storage	MET parameters	Backup MET station	Automatic soil CO_2 chambers	Automatic CH_4/N_2O chambers
Clara	Solar and Battery Bank	LI-7200	None	Gill Windmaster	NA	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind, WT	Yes	No	No
Lullymore	Mains	LI-7500A	LI-7700 (CH_4)	CSAT-3	No	PPFD, GR, NR, P, SHF, SWC, T_S, T_A, RH, Wind, WT	No	No	No
Dooary	Mains	LI-7000	None	Gill R3	Yes	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	No	Yes	No
Johnstown Castle (grassland)	Mains	LI-7500A	LGR-QCL	CSAT-3	NA	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	Yes	No	No
Inactive stations									
Solohead	Mains	LI-7500	None	CSAT-3	NA	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	No	No	No
Glencar	Mains	LI-7500	None	CSAT-3	NA	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	No	No	No
Dripsey (grassland)	Mains	LI-7500	TDL	CSAT-3	NA	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	No	No	No
Dripsey (forest)	Mains	LI-7500	None	CSAT-3	No	PPFD, NR, P, SHF, SWC, T_S, T_A, RH, Wind	No	No	No

[a] Inactive stations indicate sites where measurements are no longer being made but the infrastructural capacity remains (towers, power lines, sensors, etc.) and could become operational under the development of an ICOS–Ireland ecosystem station network.

[b] A justification can be made to the ETC to omit the measurement of particular trace gas scalars at ecosystems where the emissions of these gases are negligible.

NA, not applicable; NR, net radiation; P, pressure; PAR, photosynthetically active radiation; PPFD, photosynthetic photon flux density; RH, relative humidity; SHF, sensible heat flux; SWC, soil water content; T_A, air temperature; T_S, soil temperature.

Table A1.6. Indicative costs of the infrastructure, sensors, measurements and operation of ICOS ecosystem stations

Measurement parameter	Instrument/task	Site class	Indicative cost (€)	Lifetime/frequency of cost (years)
CO_2, H_2O and sensible heat fluxes	Power supply	1/2	10,000	20
	IRGA	1/2	25,000	7
	Sonic anemometer	1/2	15,000	7
	PC	1/2	2000	3
	Cable, tubes, materials	1/2	10,000	7
	Tower	1/2	50,000[a]	20
	Lightning protection	1/2	20,000	20
CO_2/H_2O profile	High-precision profile system	1	30,000	7
	Simple profile system	2	15,000	7
	Gases and accessories	1	5000	7
Precision H_2O measurement	Dewpoint generator for H_2O calibration	1	12,000	7
Soil CO_2 fluxes (automated chambers)		1	40,000	7
SWin, SWout, LWin, LWout	Four component radiometer	1/2	8000	7
SW incoming (high accuracy)	High-precision sensor	1	1000	7
PAR incoming		1/2	800	7
PAR below canopy		1	5000	7
PAR reflected		1/2	800	7
PAR diffuse	SMP1	1	600	7
Bole temperature	6–8 sensors	1	5000	7
Spectral reflectance		1	30,000	7
Soil heat flux	Minimum 4 HFP	1/2	2500	7
Temperature profile	5-point profile of ventilated sensors	1/2	8000	7
T_A, RH, SWin, precipitation	Back-up MET station	1/2	12,000	7
Precipitation (rain)	Gauge on/close to EC tower	1/2	1500	7
Precipitation (rain)	Measured to WMO criteria	1	1500	7
Precipitation (snow)	Total weight sensor	1	5000	7
Soil temperature profile	4 profiles with 5 depths	1	12,000	7
Soil temperature profile	1 profile with 5 depths, 3 superficial sensors	2	5000	7
Soil water content profile	4 profiles with 5 depths	1	15,000	7
Soil water content profile	1 profile with 5 depths, 3 superficial sensors	2	8000	7
Atmospheric pressure	Vaisala	1/2	2000	7
Wind speed and direction (2D sonic)		1	3000	7
Dendrometer bands		1	2000	7
Groundwater level	Pressure transducer	1/2	2000	7
Snow height		1/2	500	7
Data logger	CR3000	1/2	12,000	7
Batteries and charger		1/2	4000	3
Remote connection	Internet, Wi-Max, DSM, 10-km site range	1/2	2000	7
CH_4 fluxes[b]		1	70,000	7
N_2O fluxes[b]		1	150,000	7
Soil CH_4/N_2O (automated chambers)[b]		1	150,000	7
pCO_2 sensor		1/2	60,000	7
Biomass	Tree height, diameter, biomass/carbon content of plant parts	1/2	2000	5

Table A1.6. Continued

Measurement parameter	Instrument/task	Site class	Indicative cost (€)	Lifetime/frequency of cost (years)
Leaf area index	Hemispherical photos or yields	1/2	10,000	7
Pheno-cam	StarDot SC5	1	2000	7
Soil carbon content	Every 5 years, carbon/nitrogen density, particle density measured once	1/2	15,000	5
Litter fall	12 times per year	1	500	3
Leaf nitrogen content	20 samples 3 times per year	1	1000	1
Soil water nitrogen	20 suction cups, 200 samples per year	1	5000	1
Dissolved organic carbon	2 depths	1	2000	1
External building costs		1/2	120,000	20
Consumables	Gases, spare parts	1/2	30,000	1
Fee to the ETC		1	6000	1
Fee to the ETC		2	3000	1
Person months	Total person months per year for all measurements (35.5)	1	[c]	1
Person months	Total person months per year for all measurements (14.5)	2	[c]	1

[*] Variable cost depending on ecosystem and required tower height.

[b] Measurement of these gases only where relevant.

[c] Cost depending on position and pay scale.

HFP, heat flux plate; IRGA, infrared gas analyser; LWin, longwave incoming; LWout, longwave outgoing; PAR, photosynthetically active radiation; RH, relative humidity; SWin, shortwave incoming; SWout, shortwave outgoing; T_A, air temperature.

There is considerable interest from the ICOS-OTC and international community in the development of Irish long-term oceanic carbon monitoring. As can be seen in Figure A1.11, the North Atlantic is a highly important carbon sink region and, as such, monitoring in Irish waters would provide significant input to improving understanding of the whole carbon-climate system.

The ICOS objective is to ensure high-quality measurements of GHG concentrations that are independent, transparent and reliable. In turn, this monitoring system will support governments in their efforts to mitigate climate change as well as holding them accountable for reaching their mitigation targets.

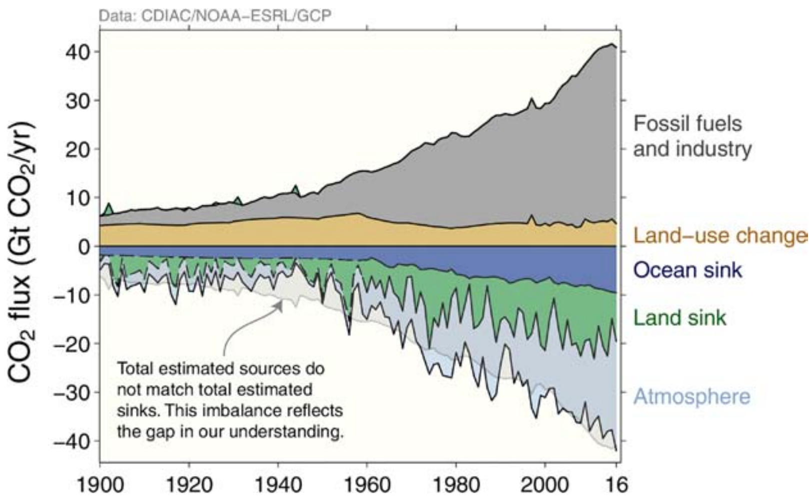


Figure A1.10. Carbon emissions partitioned among the atmosphere and carbon sinks on the land and in the ocean. Source: Global Carbon Budget, 2017.

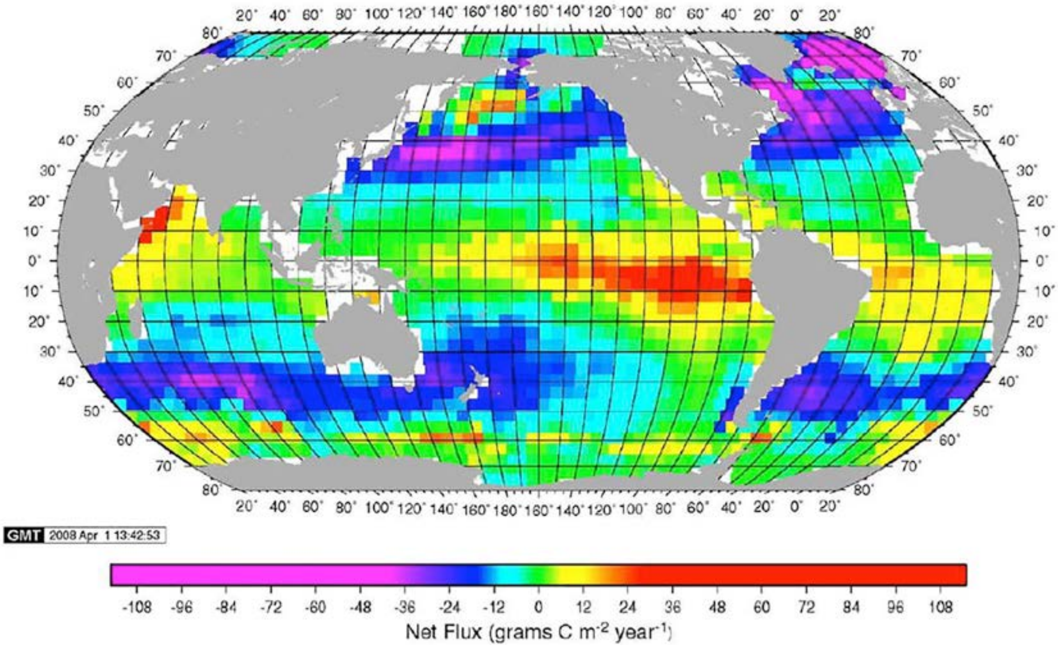


Figure A1.11. Climatological mean annual air–sea CO_2 transfer flux ($g\,C\,m^{-2}\,y^{-1}$) for reference year 2000. Reprinted from Takahashi *et al.* (2009), with permission from Elsevier.

Ireland, as an island nation, is facing the impacts of a changing climate, from sea level rises threatening the largely coastal population to the potential impacts on the marine ecosystems and the associated sectors such as fisheries and aquaculture. Improving our understanding of the carbon-climate system will allow for more informed climate adaptation planning and mitigation efforts. However, current knowledge of air–sea CO_2 transfer throughout the global ocean is still insufficient to derive precise information for climate change prediction, despite the large efforts in the past few decades.

There are three approaches commonly used in deriving the global ocean CO_2 sink and a value of $2.2 \pm 0.4\,Gt\,C\,y^{-1}$ has been estimated using several indirect methods; for example, Manning and Keeling (2006) used atmospheric O_2/N_2 concentration trends, Mikalo-Fletcher *et al*. (2006) used an inversion method using ocean biogeochemistry data and McNeil *et al*. (2003) used a method based on chlorofluorocarbons (CFCs) in the ocean. A more direct, and the most adopted, method uses direct observations of ocean and atmosphere partial pressure difference:

$$F = (pCO_{2w} - pCO_{2a}) \cdot s \cdot k \qquad \text{(A1.1)}$$

where F is the air–sea flux of CO_2, pCO_{2w} and pCO_{2a} are the partial pressure of CO_2 in the ocean and atmosphere, respectively; s is the solubility of CO_2, and k is the gas transfer coefficient (also known as the transfer velocity). Based on this method, Wanninkhof *et al*. (2013) estimated the ocean sink to lie in a significant range of 1.9 ± 0.3 to $2.5 \pm 0.7\,Gt\,C\,y^{-1}$. The main issue with equation A1.1 is the determination of k and the difference in partial pressures ΔpCO_2. The commonly used relationships to parameterise the transfer velocity incorporate wind speed as the only environmental variable (Liss and Merlivat, 1986; Wanninkhof, 1992; Wanninkhof and McGillis, 1999; Nightingale *et al*., 2000). A typical parameterisation for k (e.g. Wanninkhof, 1992) is given by:

$$k = 0.31\,u^2 (Sc/Sc_{20})^{-\frac{1}{2}} \qquad \text{(A1.2)}$$

where u is the corrected $10\,m\,s^{-1}$ wind speed and Sc is the dimensionless Schmidt number normalised to a temperature of 20°C in saltwater. Thus, the air–sea flux of CO_2 is the product of two principal factors: the difference in atmospheric and oceanic CO_2 partial pressures, which is the thermodynamic driving force, and the gas exchange rate or transfer velocity, which is the kinetic parameter. The apparent simplicity in expressing this flux masks the underlying complexity, where interrelated biological, chemical and physical effects are linked (McGillis *et al*., 2004). In the lower wind speed regime ($u < 7\,m\,s^{-1}$), the available parameterisations (Liss and Merlivat, 1986;

Wanninkhof, 1992; Wanninkhof and McGillis, 1999; Nightingale *et al*., 2000) are in fairly good agreement but as the wind speeds increase ($u > 10\,\mathrm{m\,s^{-1}}$), the parameterisations diverge (Figure A1.12). The consequences for estimation of the global oceanic CO_2 uptake (Feely *et al*., 2001) are shown in Figure A1.12, ranging from –1 Pg C y^{-1} to –3 Pg C y^{-1}.

Ocean measurement activities and infrastructural capacity

Infrastructure

The following infrastructure is supported by MI funding:

- The RV *Celtic Explorer* General Oceanics pCO_2 system was installed in 2017 and will collect underway pCO_2 data during all sea-going time;
- laboratory testing capabilities: DIC (dissolved inorganic carbon), TA (total alkalinity), nutrients to international standards;
- modelling and data management capabilities and infrastructure;
- platforms for sensing equipment including five weather buoys, Argo floats and a glider.

In addition, the following infrastructure is, or has been, supported through project-based funding:

- RV *Celtic Voyager* has been fitted with a reconditioned General Oceanics pCO_2 sensor as part of the MI-NUIG VOCAB project;
- Mace Head mooring [Interreg (European Territorial Cooperation) VA COMPASS 2017–2021] – mooring includes CO_2, pH and nitrate sensors and regular sampling of DIC, TA and nutrients, and was deployed in May 2018 by the MI.

Research programmes

MI-funded ship-based repeat surveys:

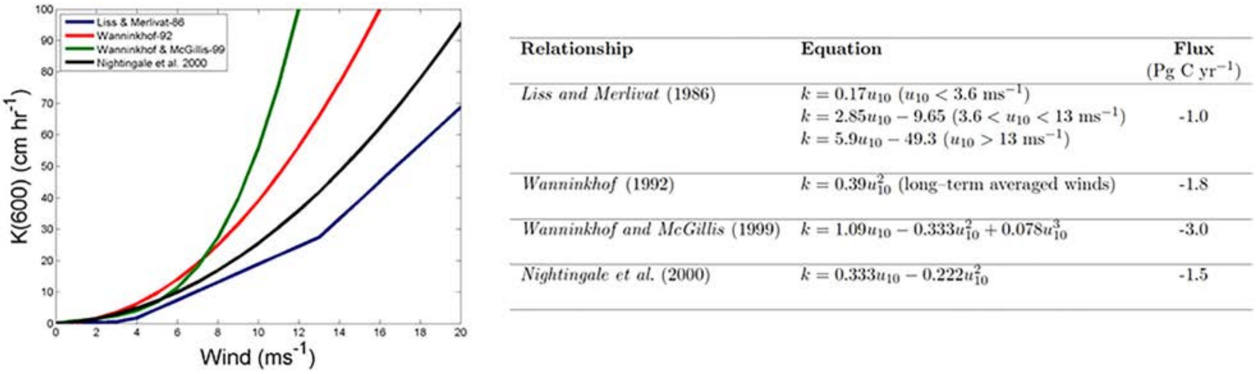
- RV *Celtic Explorer*: Rockall Ocean Climate Section (from 2008 to the present);
- RV *Celtic Voyager*: Winter Environmental Coastal/Shelf Survey – alternates between north and south about annually.

The following programmes are supported through project-based funding:

- Variability of Ocean Acidification & Biogeochemistry (VOCAB) project, an MI-funded collaboration with NUIG focused on seasonal and fine scale variability;
- Interreg VA COMPASS (2017–2021) – incorporating a network of buoys (Mace Head being the Irish contribution) across Scotland, Northern Ireland and Ireland allowing for intercomparison.

GO-SHIP AO2 International Trans-Atlantic survey 2017

The current Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) aims to document the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast or coast to ice



Relationship	Equation	Flux (Pg C yr^{-1})
Liss and Merlivat (1986)	$k = 0.17u_{10}\ (u_{10} < 3.6\ \mathrm{ms^{-1}})$ $k = 2.85u_{10} - 9.65\ (3.6 < u_{10} < 13\ \mathrm{ms^{-1}})$ $k = 5.9u_{10} - 49.3\ (u_{10} > 13\ \mathrm{ms^{-1}})$	-1.0
Wanninkhof (1992)	$k = 0.39u_{10}^2$ (long-term averaged winds)	-1.8
Wanninkhof and McGillis (1999)	$k = 1.09u_{10} - 0.333u_{10}^2 + 0.078u_{10}^3$	-3.0
Nightingale et al. (2000)	$k = 0.333u_{10} - 0.222u_{10}^2$	-1.5

Figure A1.12. Parameterisation of the gas transfer velocity showing the strong divergence for wind speeds above 10 m s^{-1} (left panel). The consequences for the calculation of the global ocean uptake of CO_2 (right panel). Adapted from Feely *et al*. (2001) and reproduced under the terms and conditions of the Creative Commons attribution license CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

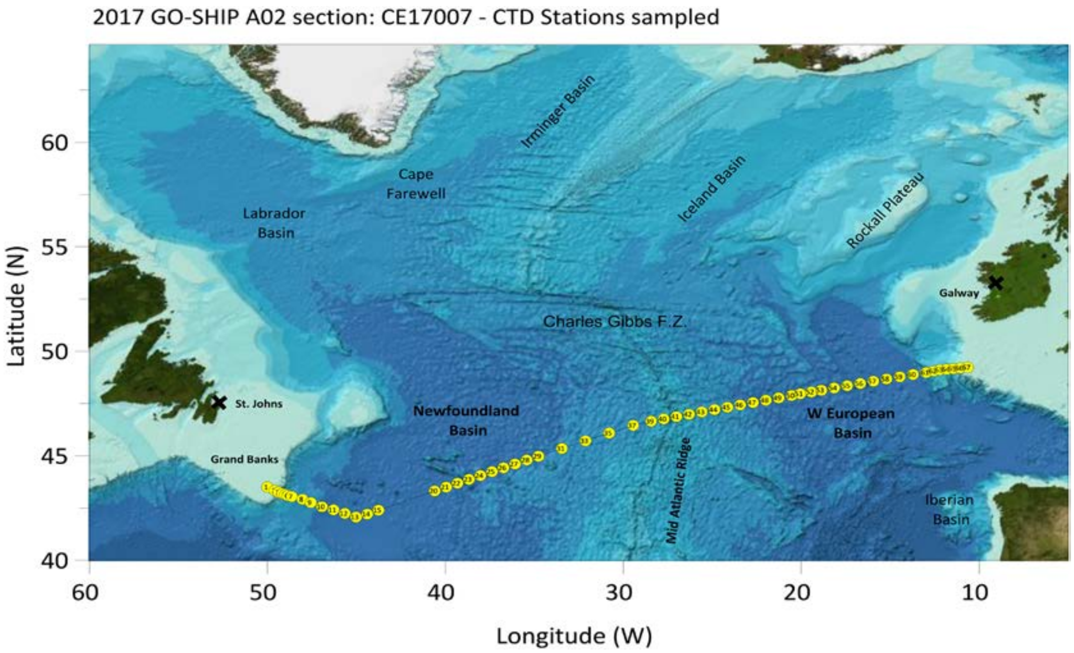


Figure A1.13. The GO-SHIP AO2 transect from St John's to Galway.

and sampling to the full ocean depth. The objective is for each line to be occupied on at least a decadal basis. During April/May 2017, the RV *Celtic Explorer* completed the A02 line (Figure A1.13), which was last occupied in 1997, with Ireland leading an international collaboration including teams from Canada, the USA, the UK, Germany, Denmark and France. The GO-SHIP high-quality carbon-relevant variables collected during the 2017 A02 cruise included pCO_2, DIC/TA, nutrients (comparison), $\delta^{13}C$, oxygen and transient tracers (CFCs). The General Oceanics pCO_2 system was installed on the RV *Celtic Explorer* as a result of this activity.

Potential ICOS ocean sites

The ICOS–OTC network is divided into three categories: voluntary observing ships, fixed ocean stations (FOS) and marine flux towers. It is also working towards getting repeat ocean stations (ROS); repeat sections are performed at least once per decade using research ships equipped with advanced high-precision systems and standard carbon instrumentation following Dickson *et al.* (2007) accepted as a station type. Given the current infrastructure within Ireland, there is potential for the following ICOS sites (with an initial aim for Class 1 site status):

Repeat ocean station

Should ROS be accepted, then the requirements have been outlined as follows for both Class 1 and Class 2 (associated capital costs shown in Table A1.7):

- following approved methods and standard operating procedure (SOP) criteria (Dickson *et al.*, 2007) when measuring two out of four carbonate parameters (DIC, TA, pH_T, pCO_2);

Table A1.7. Costs associated with ROS and GO-SHIP AO2 surveys

Cost item	Estimated cost (€)	Cost type
pCO_2 sensor	Already in place	Capital cost
One of DIC, TA or pH_T sensors	≈40,000	Capital cost
Associated equipment and calibration	≈20,000 per year	Capital cost
Technical support	≈50,000 per year	Staff cost
Data management and QC	≈60,000 per year	Staff cost

pH_T, pH in the total scale.

- completing metadata6, including description of core parameter calibration;
- proving regular calibration of the instruments;
- covering the full depth of the water column;
- performing QC, equivalent to second QC routines in GLODAPv2 (Olsen *et al*., 2016).

In addition, the difference between Classes 1 and 2 is the inclusion of transient tracers and discrete dissolved oxygen to Class 1, above the core parameters required by Class 2.

The repeat sections completed by the RV *Celtic Explorer* and RV *Celtic Voyager* outlined above could be proposed as ICOS sites provided that technical and scientific resourcing is available to ensure that the instrumentation calibration, data quality and management meets the appropriate standards. Both the Rockall annual climate section and the winter nutrient surveys are funded through core MI funding. A decadal commitment to occupation of the GO-SHIP A02 would require additional funding for 2027; the 2017 transect had a total commitment of €650,000 from national funding.

Fixed ocean stations

The ICOS requirements for FOS are, for both Class 1 and Class 2:

- following approved methods and SOP criteria (Dickson *et al*., 2007) when measuring two out of four carbonate parameters [DIC, TA, pH_T (negative of the base 10 logarithm of the hydrogen ion concentration), pCO_2];
- completing metadata, including description of core parameter calibration;
- proving regular calibration of the instruments; and
- performing an appropriate secondary QC (for example, GLODAPv2, SOCAT, alkalinity–salinity relationships, multi-linear regression).

Associated costs are shown in Table A1.8. The difference between Classes 1 and 2 is the inclusion of dissolved inorganic nutrients and discrete dissolved oxygen to Class 1, above the core parameters required by Class 2.

The Irish weather buoy network offers considerable potential as a platform for ICOS FOS. The M6 buoy, currently being augmented with a full-depth mooring during 2018, would be a suitable option for establishing this first long-term ocean carbon monitoring site in deep water, with the other buoys (M2–M5), closer to the coast, also suitable potential platforms (see Figure A1.14 for locations).

This would initially be dependent on the availability and timing of funding for replacement of the buoy technology to support additional sensors; funding availability and timelines are currently under discussion. A further capital cost for purchase of the required equipment (sensor plus data acquisition system as necessary) (see Table A1.8) and then an annual cost for technical support and maintenance together with human resource to manage, QC and analyse the data to ICOS standards. The ICOS Ocean Thematic Centre does provide some level of data management and QC support but a resource within Ireland would still be required to support the use of data by the research community. As an augmentation of the weather buoy network, the ship time could be leveraged off existing activities funded through MI core funding.

A submission to the SFI Research Infrastructures Call 2018 (*EirOOS: Irish Ocean Observing System*) has been made by the MI, in collaboration with Maynooth University, NUIG and Met Éireann, which includes the upgrading of all national weather buoys to carbon monitoring platforms (to ICOS standards). Results will be released in early November 2018 and if this is successful would provide the initial capital funding

Table A1.8. Costs associated with FOS

Cost item	Estimated cost (€)	Cost type
pCO_2 sensor	60,000	Capital cost
One of DIC, TA or pH_T sensors	30,000	Capital cost
Associated equipment	≈20,000 per year	Current cost
Technical support	≈50,000 per year	Current cost (STO level)
Data management and QC	≈60,000 per year	Current cost/research funding (PDR level)

pH_T, pH in the total scale.

Figure A1.14. The Irish weather buoy network with the M6 highlighted in the red ring.

required to meet standards required for membership as an ICOS marine site.

A1.9 Long-term Infrastructural and Logistical Support Requirements

As indicated above, significant infrastructural investment is required to fully engage and comply with the ICOS network across the atmospheric, terrestrial and oceanic domains. This investment is not just for the instrumentation of research sites but also for the development of a highly skilled team of technical staff and research scientists required to maintain the operational capacity of this network in the long term. Furthermore, the ICOS network and associated infrastructure should be developed as an inclusive research network for the scientists of Ireland and, as such, while suitable candidate sites and principal investigators for many aspects of the ICOS network have been outlined in this report, provision should be made to make this infrastructure available to as many as possible. For example, one key aspect of the ICOS network is the continued upgrade of the analytical instrumentation on a 5- to 7-year timeframe over the lifetime of the network. After this period this equipment will still be of research grade/quality, and it is proposed that a central analytical facility be developed to maintain/recalibrate this equipment. This would enable it to be used to replace faulty equipment at key ICOS stations to maintain data acquisition, as well as on an application basis by research groups not directly associated with the ICOS network to expand this area of research in Ireland and to facilitate research activities that meet the policy and scientific objectives of the EPA, and that in novel circumstances can expand our knowledge of carbon and GHG dynamics in Ireland.

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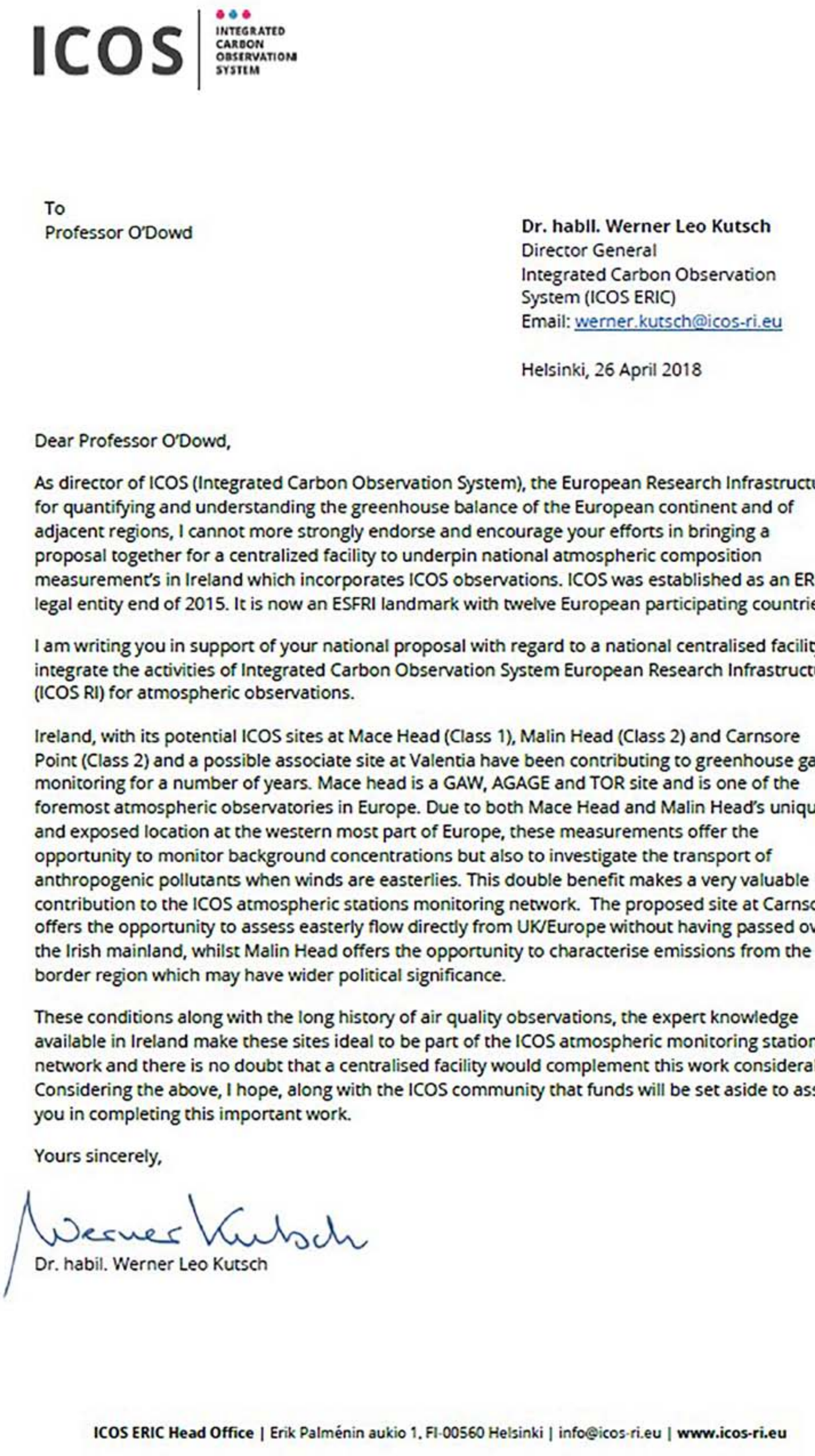
Abbreviations

CFC	Chlorofluorocarbon
EC	Eddy covariance
EPA	Environmental Protection Agency
ERIC	European Research Infrastructure Consortium
ETC	Ecosystem Thematic Centre
EU	European Union
FOS	Fixed Ocean Station
GHG	Greenhouse gas
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
ICOS	Integrated Carbon Observation System
IPCC	Intergovernmental Panel on Climate Change
JPI	Joint Programming Initiative
MI	Marine Institute
NPWS	National Parks and Wildlife Service
NUIG	National University of Ireland Galway
pCO_2	Partial pressure of CO_2
Pg C y^{-1}	Carbon exchange fluxes
ppm	Parts per million
QC	Quality control
ROS	Repeat ocean stations
SC	Static chamber
SOP	Standard operating procedure
TCD	Trinity College Dublin
UCC	University College Cork
UCD	University College Dublin
UL	University of Limerick
UN	United Nations
WIT	Waterford Institute of Technology

Appendix 2 Letter of Support for ICOS Ireland



ICOS
INTEGRATED
CARBON
OBSERVATION
SYSTEM

To
Professor O'Dowd

Dr. habil. Werner Leo Kutsch
Director General
Integrated Carbon Observation
System (ICOS ERIC)
Email: werner.kutsch@icos-ri.eu

Helsinki, 26 April 2018

Dear Professor O'Dowd,

As director of ICOS (Integrated Carbon Observation System), the European Research Infrastructure for quantifying and understanding the greenhouse balance of the European continent and of adjacent regions, I cannot more strongly endorse and encourage your efforts in bringing a proposal together for a centralized facility to underpin national atmospheric composition measurement's in Ireland which incorporates ICOS observations. ICOS was established as an ERIC legal entity end of 2015. It is now an ESFRI landmark with twelve European participating countries.

I am writing you in support of your national proposal with regard to a national centralised facility to integrate the activities of Integrated Carbon Observation System European Research Infrastructure (ICOS RI) for atmospheric observations.

Ireland, with its potential ICOS sites at Mace Head (Class 1), Malin Head (Class 2) and Carnsore Point (Class 2) and a possible associate site at Valentia have been contributing to greenhouse gases monitoring for a number of years. Mace head is a GAW, AGAGE and TOR site and is one of the foremost atmospheric observatories in Europe. Due to both Mace Head and Malin Head's unique and exposed location at the western most part of Europe, these measurements offer the opportunity to monitor background concentrations but also to investigate the transport of anthropogenic pollutants when winds are easterlies. This double benefit makes a very valuable contribution to the ICOS atmospheric stations monitoring network. The proposed site at Carnsore offers the opportunity to assess easterly flow directly from UK/Europe without having passed over the Irish mainland, whilst Malin Head offers the opportunity to characterise emissions from the border region which may have wider political significance.

These conditions along with the long history of air quality observations, the expert knowledge available in Ireland make these sites ideal to be part of the ICOS atmospheric monitoring station network and there is no doubt that a centralised facility would complement this work considerably. Considering the above, I hope, along with the ICOS community that funds will be set aside to assist you in completing this important work.

Yours sincerely,

Werner Kutsch

Dr. habil. Werner Leo Kutsch

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AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 365

Developing Ireland's Greenhouse Gas and Transboundary Air Pollution Monitoring Network

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Damien Martin and Colin O'Dowd

The Atmospheric Composition and Climate Change (AC3) network is an established valuable national research and monitoring infrastructure that has been developed incrementally and monitors greenhouse gases (GHGs), short-lived climate forcers (SLCFs), and aerosol chemical and physical characteristics in line with best practice from both pan-European and global monitoring programmes. GHG measurements are undertaken under the umbrella of the Integrated Carbon Observing System (ICOS) pan-European research infrastructure, whereas additional observations are conducted under the European Evaluation and Monitoring Programme (EMEP – the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe). The report describes the operation, development and expansion of the network activities and infrastructure.

Identifying Pressures

Climate change is recognised as one of the most challenging problems facing humanity. The Intergovernmental Panel on Climate Change has stated that "warming of the climate system is unequivocal" and that "human influence is clear". The 2015 Paris Agreement established a global policy response to climate change. A key objective of that agreement is that global GHG emissions are balanced with removals during the second half of this century. Achievement of both the national and global emission reduction pathways will require an increased understanding of emissions and removals by sinks and the processes by which the latter can be enhanced. Measurements of GHGs on the AC3 network can be used with modelling techniques to verify emissions inventories and, in particular, to assess the balance of emissions and removals from the land sector.

Air pollution is increasingly recognised as a problem for human health in Ireland and elsewhere. This has been highlighted by the World Health Organization. Air pollution levels in Ireland are influenced by local emissions and by emissions in Europe and North America (hemispheric transport is important for some pollutants). Actions to address air pollution are taken at these levels and include the Convention on Long-range Transboundary Air Pollution (CLRTAP) and its protocols, which link to the European Commission's Clean Air for Europe (CAFE) programme and the European Union National Emissions Ceilings (NEC) Directive. These have a range of linked reporting, monitoring and assessment requirements. EMEP is a body under the CLRTAP that addresses the requirement that Parties have to undertake air quality monitoring. A fundamental understanding of the nature, scope and magnitude of transboundary air pollution – the research and monitoring of which is carried out using the AC3 network – is essential to understand its relative source contribution and to support national and international efforts to improve air quality.

Informing Policy

A national GHG monitoring and analysis network, especially one linked to the ICOS European Research Infrastructure Consortium, can help to resolve fundamental issues relating to Ireland's GHG emissions. These can inform future climate change policy and include:

1. reducing uncertainties to an acceptable level so that the nature and extent of the sources and sinks of GHGs in Ireland can be robustly determined;
2. assessing how meteorological and other factors influence these sinks on seasonal to decadal timescales, and the interplay between these and management systems;
3. highlighting geographical areas with high levels of uncertainty in a bottom-up analysis of gases, such as nitrous oxide and methane;
4. producing an independent integrated and comprehensive analysis of emissions and removals in Ireland in the context of a GHG neutrality goal for the agriculture sector.

Monitoring of aerosol chemical and physical characteristics and other SLCFs can be used to elucidate transboundary air pollution and underpin national and international monitoring strategies.

Developing Solutions

This fellowship has enabled and sustained scientific operations for a national monitoring network. The infrastructure has been continually developed over the course of the fellowship and this will facilitate long-term sustainable measurements. Given both the national and international importance of climate change, it is critical to maintain a level of investment in infrastructure, analytical systems and associated complementary measurements to ensure that Ireland is at the forefront of this critical area to inform policy and facilitate meaningful solutions. Ireland is at the forefront of GHG and transboundary air pollution monitoring. Further development of the inversion modelling techniques to include SLCFs would be an important extension of network capability, particularly in the area of source apportionment and emissions verification. Robust source apportionment of air pollution is essential to understanding the complex nature of its sources and identifying where to target policies to improve air quality and maximise societal benefit.

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