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epa Research

Assessing Potential for North Atlantic Integrated Atmospheric Research

Authors: Liz Coleman and Frank McGovern

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The 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: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

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> Audit and inspection of EPA licensed facilities;
> Drive the implementation of best practice in regulated activities and facilities;
> Oversee local authority responsibilities for environmental protection;
> Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
> Assess and report on public and private drinking water quality;
> Coordinate a network of public service organisations to support action against environmental crime;
> Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment

> Implement and enforce waste regulations including national enforcement issues;
> Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
> Develop and implement the National Waste Prevention Programme;
> Implement and report on legislation on the control of chemicals in the environment.

Water Management

> Engage with national and regional governance and operational structures to implement the Water Framework Directive;
> Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change

> Publish Ireland's greenhouse gas emission inventories and projections;
> Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
> Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment

> Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
> Produce the State of Ireland's Environment and Indicator Reports;
> Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
> Oversee the implementation of the Environmental Noise Directive;
> Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development

> Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
> Collaborate with national and EU environmental research activity.

Radiological Protection

> Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
> Assist in developing national plans for emergencies arising from nuclear accidents;
> Monitor developments abroad relating to nuclear installations and radiological safety;
> Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information

> Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
> Promote the link between health and wellbeing, the economy and a clean environment;
> Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
> Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

> Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

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:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Assessing Potential for North Atlantic Integrated Atmospheric Research

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Identifying pressures

The impact of human activity since the Industrial Revolution has altered the environment, pushing its stability to critical limits, with real implications for societal, economic and environmental systems. The planetary boundaries framework has provided a powerful tool for communicating the individual and collective threats arising from unsustainable post-industrial development, yet actions and responses take place at regional, national and local levels.

The North Atlantic is a key earth system component, surrounded by densely populated countries. It is particularly vulnerable to the effects of climate change owing to its interface with the Arctic, its housing of the Greenland ice shelf and the interlinked circulation patterns that have a profound impact on global climate variability and the carbon cycle. The North Atlantic atmosphere is influenced by natural and anthropogenic emissions. Environmental impacts arising from changes to the North Atlantic atmosphere will have major global consequences.

This study aims to conduct a detailed assessment of current national and international atmospheric research activities and evaluate the performance of research outputs from the North Atlantic research community in addressing major environmental challenges facing society today: air quality and climate change.

Informing policy

Atmospheric protection is served by three multilateral environmental agreements (MEAs): the United Nations Economic Commission for Europe's Convention on Long-range Transboundary Air Pollution, the Vienna Convention for the Protection of the Ozone Layer and the United Nations Framework Convention on Climate Change (UNFCCC). Each addresses different environmental issues. This siloed approach has had varying degrees of success, with the success of the Vienna Convention being overshadowed by the failure of the UNFCCC to halt the rising concentration of global greenhouse gases. Many scientific and organisational partnerships exist between the atmospheric observation communities that support the respective MEAs, but a unified approach to assessing our knowledge of the interactions and feedbacks between the changing atmospheric composition and the Earth system globally is yet to be seen.

Effective mitigation policy that addresses multiple environmental issues must be supported by integrated research systems that span multiple strands of the atmospheric system, so that connections can be made between atmospheric processes.

Commitments to protecting the atmosphere have been made – but similar commitments to the sustained monitoring programmes that fundamentally inform policy and evaluation are limited.

Developing solutions

The North Atlantic boasts unique atmospheric observational capacity and is home to some of the most globally advanced atmospheric measurement sites. Considering the investment capacity that exists in the surrounding developed countries, the North Atlantic community is uniquely positioned to assess and inform effective integrated responses to these challenges. However, this study found that gaps remain in North Atlantic atmospheric measurement, not only in terms of the spatial distribution of the measurement sites, but also the coordination and synthesis of measurements. Filling these gaps is necessary for integrated scientific assessment that leads to targeted policy responses addressing atmospheric protection, cross-cutting all issues of atmospheric and environmental protection. The North Atlantic region has set the stage for collaborative initiatives that have advanced atmospheric research considerably, including Aerosol Characterisation Experiments 1 and 2.

There is scope to build on the legacy of the observation capacity and international scale of atmospheric composition projects, to bring together the existing monitoring activities of large-scale international projects for targeted scientific output and public engagement and effective responses to environmental change.

EPA RESEARCH PROGRAMME 2021–2030

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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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 impact of human activity has altered the state of the environment, pushing environmental stability to critical limits, threatening our safe coexistence within the planetary system, posing real risks of abrupt, non-linear, irreversible alterations to our environment.

The atmosphere and its changing composition reflect and drive key environmental pressures. The planetary boundaries framework (Figure ES.1) is a powerful concept for communicating the threats arising from unsustainable development and global consumption. This framework proposes quantitative thresholds for 10 key processes that regulate the stability of the Earth system. Transgression of one or more of these boundaries increases the risk of non-linear alterations to our environment, with major societal and economic implications. There is evidence that planetary boundaries have already been crossed because of the climate crisis, biodiversity loss and disruption of the nitrogen cycle.

Planetary boundaries are set at a global scale, yet responses to global environmental crises are enacted at regional, national and local levels. Here, we consider the pressure applied to planetary boundaries in relation to atmospheric composition and its impact on various human and planetary systems with specific reference to changes in the North Atlantic region.

The North Atlantic connects the continents of Western Europe and North America to developing regions in South America and North Africa. The energetic dynamics of the North Atlantic atmosphere give rise to frequent mid-latitudinal storms and intense hurricanes. The North Atlantic links North Africa to South America,

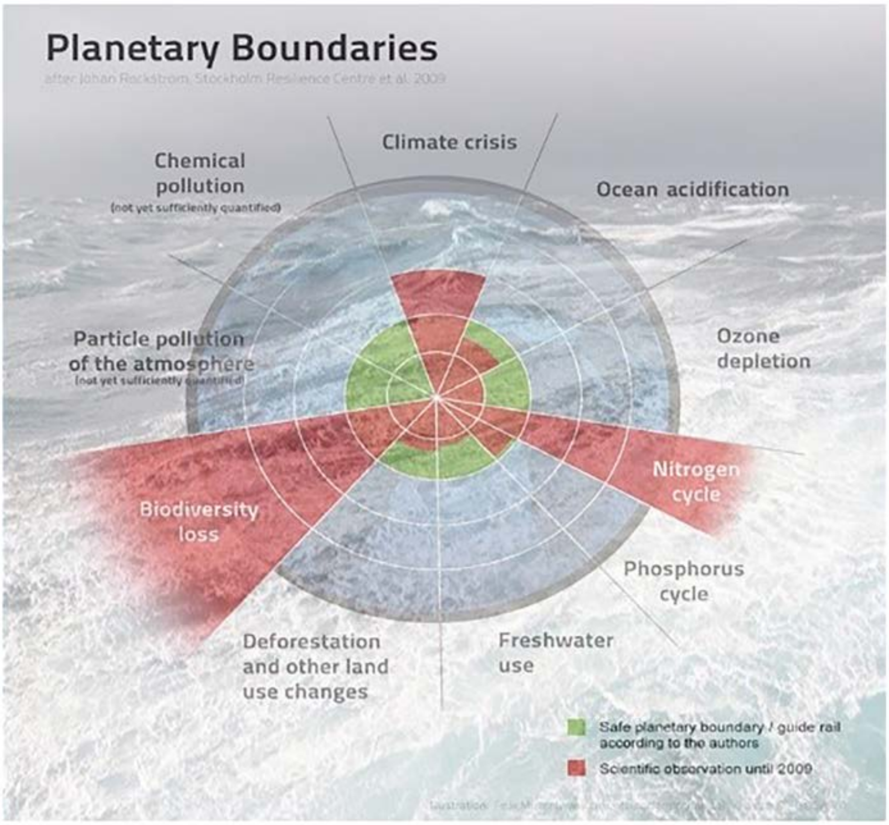

Figure ES.1. Illustration of planetary boundaries (Rockstrom *et al.*, 2009). The red areas represent the estimated current state, with the inner green circle being the estimated boundaries. Illustration by Felix Muller (www.zukunft-selnermachen.de). Reproduction licensed under CC-BY-SA 4.0. (https://creativecommons.org/licenses/by-sa/4.0/).

providing an atmospheric pathway for advection of mineral-laden dust plumes from the Sahara across the ocean to the Amazon, depositing phosphorus and iron that fertilises the biologically active Atlantic waters and depleted soil of the rainforests, regulating nutrient cycles that sustain ecosystem biodiversity in the Atlantic and the rainforests. Saharan dust modulates the frequency of tropical cyclones, and aerosol forcing influences inter-decadal climate variability, regulating climate and biogeochemical cycles. Atlantic circulation profoundly affects global climate systems – changes that can accelerate feedback cycles, potentially causing abrupt climate change. Home to the Greenland ice shelf and sharing an interface with the vulnerable Arctic, the Atlantic system is exposed to the effects of climate change and rising global temperatures, primarily driven by atmospheric change. The composition of the North Atlantic atmosphere is impacted by anthropogenic activity in densely populated surrounding land masses, volcanic activity, marine emissions, Saharan dust and wildfires.

At the policy level, multilateral environmental agreements (MEAs) have been adopted to address various climate and atmospheric environmental issues, with varying degrees of success. Atmospheric protection has been well served by the United Nations Economic Commission for Europe's Convention on Long-range Transboundary Air Pollution, the Vienna Convention for the Protection of the Ozone Layer, the United Nations Framework Convention on Climate Change, the Stockholm Convention on Persistent Organic Pollutants and the Minamata Convention on Mercury. Many scientific and organisational partnerships exist between the atmospheric observation communities that support the MEAs, but we have yet to see an integrated, unifying approach to assessing our knowledge of the interactions between changes in the atmospheric composition and the Earth system.

Owing to the unique atmospheric observational capacity in the North Atlantic and the investment capacity of the surrounding developed countries, the North Atlantic community is uniquely positioned to assess and inform effective responses to the challenges posed by a changing atmosphere. However, gaps remain in North Atlantic atmospheric measurements, which can lead to gaps in our scientific understanding, obscuring our insight into potential impacts of environmental change and effective mitigation pathways. Coordinated, harmonised measurements are required for integrated scientific assessment for effective, informed policy response to atmospheric change, cutting across all issues of atmospheric and environmental protection.

We recommend the development of an international forum for the region to assess environmental threats from atmospheric compositional changes in the North Atlantic region, as has been achieved for the Arctic. It should focus on addressing the fundamental scientific issues and key uncertainties central to environmental policy areas, providing a tangible focus for the planetary boundaries concept. To avoid further transgression of planetary boundaries, the forum should adopt a target–stakeholder–communication approach, which should aim to boost public engagement with atmospheric protection and promote a shared international ambition to protect the atmosphere at the international level on both sides of the Atlantic.

1 Introduction

In its Sixth Assessment Report (2021), Working Group I of the Intergovernmental Panel on Climate Change (IPCC) delivered its most unambiguous statement to date, unequivocally attributing the observed catastrophic, unprecedented and irreversible climate change to anthropogenic activity on Earth.

The primary driver of climate change is the increased atmospheric concentration of greenhouse gases (GHGs) due to human activity since the Industrial Revolution. GHGs absorb long-wave energy that is emitted by the Earth, causing positive radiative forcing and increasing the amount of energy in the Earth system. Measurement records show that, despite concerted political efforts to curb emissions, GHG concentrations in the atmosphere continue to rise relentlessly, which has led to widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere, affecting weather and climate extremes across the globe, causing sea level rise, and changes in water supplies and ecosystems. IPCC Working Group I has been said to signal a "Code Red" for humanity (Zhongming *et al*., 2021).

The impact of human activity on atmospheric composition has also had a negative effect on the quality of our air, harming ecosystems and human health, causing an excess of 4.2 million premature deaths per year across the globe (World Health Organization, 2016). Emissions of ozone-depleting materials from human activity have caused stratospheric ozone destruction to the point of creating a hole in the ozone layer – which is a vital line of defence for life on Earth. Human activity has also resulted in the emission of long-lived "forever chemicals". For example, persistent organic pollutants (POPs) can accumulate in the fatty tissue of animals and are resistant to biological degradation. Likewise, microplastics are pollutants of emerging ecotoxicological concern and can be deposited from the atmosphere to water systems, where they can act as scavengers and transporters of POPs, posing a serious threat to human and ecosystem health.

Issues pertaining to our environmental stability within the Earth system are complex, interlinked and thus entangled, and the effects of atmospheric compositional change exhibit a non-linear response, governed by interdependent Earth system feedbacks and cycles.

The planetary boundaries concept is a scientific articulation of the collective and linked challenges that face world governments in managing shared resources and systems in a manner that avoids large-scale disruption of economic, environmental and societal stability (Rockstrom *et al*., 2009). It has gained traction with public policymakers and in academic circles, and has provided a focus for debate and engagement with advocates of integrated responses, under the main multilateral environmental conventions. Yet, the concept is lacking in tangible connections and has made limited progress in linking structures designed to address specific challenges at regional scales (Biermann and Kim, 2020). There is a challenge in assessing the aggregated impacts of environmental changes on our environmental sustainability. In the case of the atmosphere, there is a challenge in assessing the impact of changing atmospheric composition on air quality and ecosystem health, on radiative forcing and on stratospheric ozone depletion. Protection of our environment requires integrated assessment of the drivers and consequences of atmospheric change, and this necessitates the sustained support of atmospheric observations. During the past few decades, there has been significant progress in the observation, monitoring and understanding of atmospheric processes. This understanding has been made possible by sustained measurements of atmospheric constituents from key strategic sites. Understanding of processes governing the Earth system requires synoptic, sustained measurements that are strategically spatially distributed.

Atmospheric change is not confined to geopolitical boundaries or borders, and therefore it is impossible to effectively address issues of environmental sustainability without cooperation between nations, which requires both scientific and political cooperation.

1.1 History of International Collaboration for Environmental Monitoring

> … the very air we breathe is politics.
>
> Helon Habila, Nigerian writer

1.1.1 Evolution of the World Meteorological Organization

International environmental collaboration is exemplified by the history surrounding the formation of the World Meteorological Organization (WMO).

The origins of meteorological study can be traced back to the time of Aristotle, the first natural philosopher who disentangled the workings of nature from the realms of mythology. Many advancements in physical principles and instrumentation were made in the 18th century, and the first global network of weather instruments – the Societas Meteorologica Palatina (Meteorological Society of Mannheim) – began in 1780, comprising a network of 39 weather stations across the world, each with calibrated, comparable instruments, although this effort was curtailed by the Napoleonic Wars. The established network served as a basis for the development of meteorology during the 19th century. The development of Morse code in 1843 advanced international communication, increasing the relevance of weather forecasting and storm warnings. The first weather maps, based on telegraphic data, were displayed in Washington in 1850. The demand for weather forecasting grew in line with public interest in meteorological forecasting and the growth in international ship traffic stemming from the Industrial Revolution, with the latter requiring regular weather updates for safe navigation. As science and technology advanced throughout the 18th and 19th centuries, and as society began to benefit from the tangible application of scientific meteorological knowledge, the demand for weather forecasts grew.

The first international meteorological conference took place in Brussels in 1853, exploring the subjects of maritime and meteorological problems. The delegation represented 10 countries. Most of the delegates were naval officers and thus there was a strong emphasis on maritime operations. An outcome of the conference was a standardised format for logging of meteorological observations for both public and commercial shipping vessels. The meteorological conference marked the first step in international meteorological cooperation, but the organisation of terrestrial meteorological observations did not take form until an international meeting in Leipzig, in 1872. The meeting had 52 attendees, comprising heads of national meteorological institutes and independent scientists. This led to the first International Meteorological Congress, convened in Vienna in 1873, and in this first action of coordinated international cooperation on meteorology, the seeds of the WMO were sown.

The eventual aim of the congress was to establish an international meteorological institute with a paid secretariat and a fund for meteorological measurements in remote locations. Although this was not realised straight away, the International Meteorological Organization (IMO) came into being at a meeting of the International Meteorological Congress in Rome, at which a young Lieutenant Karl Weyprecht, co-commander of the first Austro-Hungarian Polar Expedition of the late 1800s, famously said that the quest for knowledge that will help to overcome the challenges posed by nature will only be attained via international collaboration and sustained, synchronous, calibrated measurements (Weyprecht, 1875; Summerhayes, 2008). Weyprecht had a vision of international collaboration to obtain scientific data in the high Arctic region, and the wheels were set in motion for realisation of this vision in Rome, where it was decided to carry out an ambitious scientific study of meteorology and magnetism in the high latitudes. This became known as the International Polar Year (IPY) (1882–1883) and was the first highly organised international science programme. The IPY was a resounding success and bore highly valuable scientific fruits in the form of geophysical observations, natural history and ethnographic information, subsequently published in the *Bulletin of the International Polar Commission.* This was followed by a second, larger-scale, IPY that was launched in Copenhagen in 1929 and executed in 1932–1933. In this second IPY, the aim was extended to look at planetary geophysics and electromagnetic effects, as well as oceanography and biological activity, the fruits of which paved the way for advances in telecommunications and technology.

For decades, the IMO constituted the main organisation serving the advancement of meteorology, but there was an appetite in the 1930s for forming a new organisation, with a profile that would do justice to the importance of meteorology in the developing, interconnected world. Efforts to improve the structure of the IMO were halted by the Second World War, but scientific and technological advancements made during the war revolutionised meteorology. Following the war, there was an international impetus to reinstate the operational status of the IMO and further develop its constitution. This eventually led to the adoption of the WMO Convention in 1950 and the appointment of the WMO as a specialised agency of the United Nations in 1951.

Since then, the atmospheric community has evolved, with the onset of sustained measurements at strategic sites beginning in earnest in the International Geophysical Year (IGY) of 1957–1958 (Baird, 2011). The international project of the IGY provided the initial funding for the onset of carbon dioxide (CO_2) recording at Mauna Loa, and led to the establishment of the WMO Global Ozone Observing System.

In the following decade, in 1967, Swedish scientist Svante Odén published a controversial article in a national newspaper highlighting the threat of acid rain and its ramifications for ecosystems, linking its formation to rising industrial emissions in Europe. International attention was also brought to the subject of long-range air pollution. The United Nations Conference on the Human Environment was held in Stockholm in 1972 and became known as the "Stockholm Conference". The conference preparations took 4 years and involved 114 governments. There were a number of goals and objectives outlined in the organisation of the conference, including the need for a global scope; the need for broad, interdisciplinary involvement; the need for tangible, actionable outcomes with a defined international work plan; and the need to focus on both the effect of anthropogenic activity on the environment and the consequences of those effects. The Stockholm Conference succeeded in bringing nations together in a communal endeavour to protect the environment, and this level of global cooperation is necessary to address the issue of long-range transport of air pollution (i.e. transport of atmospheric constituents that know no political bounds).

1.1.2 Communities of atmospheric observation

> No crisis ever before has underlined to such an extent the interdependence of nations. The environment forces us to make the greatest leap ever into world wide solidarity. One issue after another – development, population, the seas and oceans, outer-space, even the monetary issue – reveal to us in close succession the interdependence on our planet … but none of them has had greater effects than the crisis of the environment.
>
> Kurt Waldheim, Secretary-General of the United Nations, in the opening address to the Stockholm Conference, 1972

In the late 1960s and early 1970s, coinciding with the Stockholm Conference, there was a global environmental awakening of sorts, in no small part prompted by the first images of the Earth taken from space as part of the Apollo mission. In terms of atmospheric measurements, considerable efforts were made on coordinated international environmental monitoring and protection. The WMO established the global Background Air Pollution Monitoring Network (BAPMon) for monitoring atmospheric pollution, with a focus on precipitation chemistry. In 1972, the Stockholm Conference led to the foundation of the United Nations Environment Programme (UNEP), which paved the way for the Convention on Long-range Transboundary Air Pollution (CLRTAP), which was signed by 34 countries and the European Commission and came into force in 1983. Representing the first binding policy instrument to protect the atmosphere on a large spatial scale, the convention set up an institutional framework that mobilised scientific research to inform policy. Under the CLRTAP, the 1983 Geneva Protocol provides policy for the long-term financing of the European Monitoring and Evaluation Programme (EMEP), which is the cooperative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe. EMEP provides sound scientific support to the convention by collecting air pollution emission data, providing a quality-controlled measurement network and modelling of atmospheric transport and deposition, and hosting all data on its official database, EBAS, which also hosts atmospheric composition data from prominent networks worldwide. EMEP facilitates and performs the sustained measurements that are vital for monitoring EU atmospheric composition and transatlantic processes for the benefit of science-driven policy. The Task Force on Hemispheric Transport of Air Pollution (TF HTAP) is an international scientific cooperative effort to improve understanding of long-range transport of air pollution. Founded in 2005 under CLRTAP as a response to mounting evidence surrounding the importance of long-range transport in pollution levels, the TF HTAP reports to the EMEP steering body. Today, the EMEP network is a significant cornerstone for atmospheric measurements in Europe. In 2017, a total of 35 parties reported measurement data to EMEP from 171 sites (Fagerli *et al*., 2019).

In 1989, the WMO Global Ozone Observing System and the global Background Air Pollution Monitoring Network merged to form the Global Atmospheric Watch (GAW) programme. The GAW programme has a mission to reduce environmental risks to society and meet the requirements of environmental conventions, strengthen capabilities to predict climate, weather and air quality, and contribute to scientific assessments in support of environmental policy. This mission is to be achieved by maintaining and applying global, long-term observations of the chemical composition and selected physical characteristics of the atmosphere, emphasising quality assurance and quality control, and delivering integrated products and services of relevance to users. Since its formation, the GAW programme has provided international leadership in research and capacity development in atmospheric composition (WMO, 2017). The GAW observing system comprises *in situ* stations (including 30 global supersites (some of which are indicated by the red stars in Figure 2.1), 400 regional sites and 100 contributing stations), as well as complementary spaceborne observations for fused, integrated products.

The WMO also co-sponsored the Global Climate Observing System (GCOS) in partnership with the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, UNEP and the International Council for Science. GCOS provides worldwide observation of essential climate variables in the atmosphere, sea and ice, and it is a primary contributor to the overarching WMO Integrated Global Observing System (WIGOS) infrastructure. GCOS reports on the observational capacity of current observing systems to the United Nations Framework Convention on Climate Change (UNFCCC), identifying monitoring needs and gaps in data.

In recent years, the proliferation of satellite programmes has resulted in the recording of important measurements of atmospheric compounds and related parameters that complement the GAW network measurements. When highly accurate local measurements from GAW ground-based stations are coupled with the near-global coverage of satellite measurements, it results in a more complete and global picture of atmospheric composition and processes and provides complementary checks of instrument calibrations. The Committee on Earth Observation Satellites has developed a strategy for such cooperation within an integrated system for monitoring of the atmosphere, and the GAW programme is committed to delivering integrated products for services such as the Integrated Global Greenhouse Gas Information System, which supports the Paris Agreement by connecting science and policy. The science implementation plan of the Integrated Global Greenhouse Gas Information System Science currently outlines techniques for building national systems for the use of atmospheric measurements in national GHG emission estimates (WMO, 2019).

The US National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory/Global Monitoring Laboratory's Carbon Cycle Greenhouse Gas Air Sampling Network effort began in 1967 in Colorado, and has evolved into an international effort that has involved regular discrete samples from NOAA Earth System Research Laboratory/Global Monitoring Laboratory baseline observatories across the world, cooperative fixed sites and commercial ships. Measurement data are used to identify long-term trends, seasonal variability and spatial distribution of carbon cycle gases. Flask sampling in the marine environment can determine large-scale GHG distribution. Observations of GHGs have evolved in the past few decades to quantify terrestrial sources and sinks. The Integrated Carbon Observing System (ICOS) is a world-class research infrastructure (RI) that provides the long-term observations required for understanding the present state, and predicting the future behaviour, of the global carbon cycle and GHG emissions. ICOS monitors and assesses the effectiveness of carbon sequestration and/or GHG emission reduction activities on global atmospheric composition levels, including attribution of sources and sinks by region and sector in the "global stocktake" process (Bergamaschi *et al*., 2018). The potential of using atmospheric observations in tandem with inverse modelling techniques to reduce uncertainties in emission inventories, thus supporting the Paris Agreement, has been recognised by the UNFCCC's Subsidiary Body for Scientific and Technical Advice (UNFCCC, 2017). ICOS represents the consolidation of carbon observation systems into a European RI, comprising ocean, terrestrial and atmospheric measurements and quantification of surface–atmosphere interactions. ICOS is a regional contributor to the WMO GAW programme and is strongly coordinated with the following European atmosphere RIs: In Service Aircraft for a Global Observing System (IAGOS) (IAGOS, 2023) and Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS). Beyond Europe, ICOS seeks to engage in global cooperation with counterparts in the USA (National Ecological Observatory Network and AmeriFlux), China (Chinese Ecosystem Research Network/ChinaFLUX), Australia (Terrestrial Ecosystem Research Network/OzFlux) and Japan (National Institute for Environmental Studies/JapanFlux).

The Advanced Global Atmospheric Gases Experiment (AGAGE) has been measuring non-CO_2 GHGs and ozone-depleting chemicals (ODCs) since 1978, when the issue of stratospheric ozone depletion became a global environmental concern. Evolved from predecessor networks Atmospheric Lifetime Experiment and Global Atmospheric Gases Experiment, AGAGE has informed the Vienna Convention for Protection of the Ozone Layer and the Montreal Protocol. AGAGE now delivers near real-time precise measurements of non-CO_2 GHGs and ODCs from 13 stations worldwide using advanced gas chromatography–mass spectrometry. Data are used to validate chemical transport models and determine the magnitude and location of trace gas sources using both measurements and modelling with theoretical chemical destruction rates. AGAGE measurements play a key role in policy compliance with the legally binding Montreal Protocol, which is widely celebrated as the most successful piece of environmental legislation to date (Prinn *et al*., 2018).

ACTRIS is a pan-European RI that integrates European ground-based stations equipped with advanced atmospheric probing instrumentation for aerosols, clouds and short-lived gas-phase species, including *in situ* and remote sensing measurements. ACTRIS operations are coordinated at eight central facilities, with each providing services to users and operational support to national ACTRIS facilities. ACTRIS is built on previous EU framework projects, such as the European Supersites for Atmospheric Aerosol Research, evaluation of model clouds using ground-based observations through the Cloudnet project and the European Aerosol Research Lidar Network (EARLINET), and provides common strategies for atmospheric measurements and access to high-quality atmospheric measurements, including physical and chemical *in situ* characterisation of atmospheric aerosols. These measurements enable provision of four-dimensional variability of multi-component systems to detect atmospheric trends, attribute sources, study atmospheric feedback and build capacity to understand and quantify atmospheric interactions and detect atmospheric change (Laj, 2018). ACTRIS fills the gap in Earth observation data, complementing the other networks (GAW, EMEP, ICOS), and works towards the advancement of measurements, providing integrated products for end users. The European contribution to the advanced aerosol measurement component of the GAW programme is performed under ACTRIS, which provides harmonised synoptic measurements of physical, chemical and optical aerosol properties at major sites (60+) across Europe, contributing to EBAS. The US Interagency Monitoring of Protected Visual Environments Aerosol Monitoring Network of nephelometers (est. 1985) also contributes aerosol data to EBAS, but lacks advanced aerosol measurements (Pandolfi *et al*., 2018), yet there is potential for the newly National Science Foundation-funded Addressing Systems Challenges through Engineering Teams network (Ng, 2021), which will monitor aerosol chemistry over 12 sites across the USA to develop into a US counterpart to ACTRIS. The University of Miami's Barbados Atmospheric Chemistry Observatory, located in Ragged Point, Barbados, has served as a lynchpin of the community by providing over 50 years of measurements of African dust and detailed chemical data during intensive measuring endeavours.

The Aerosol Robotic Network (AERONET) is a global ground-based network established by the US National Aeronautics and Space Administration (NASA) and PHOTONS (Goloub *et al*., 2008). EARLINET is a ground-based network of research lidar (light detection and ranging) stations, which aims to build a statistically significant Europe-wide database for the horizontal, vertical and temporal distribution of aerosols. Both these ground-based networks are active contributors to ACTRIS, which operates the AERONET–EUROPE calibration service. Under ACTRIS, significant progress was achieved in the integration of EARLINET and AERONET, improving observational capacity for integrated aerosol characterisation of European spatial and temporal aerosol fields (ACTRIS, 2015).

The European RI IAGOS combines the expertise of scientific institutions with the infrastructure of civil aviation to provide essential data on climate change and air quality, operating an infrastructure for atmospheric monitoring over a global scale from a fleet of 10–20 long-range commercial aircraft, allowing quasi-continuous measurements of trace gases, aerosols and cloud particles. Each aircraft is equipped with a measurement package for fully automated measurements of ozone, carbon monoxide, humidity and cloud particles, with further measurement of total odd nitrogen, nitrogen oxides (NO_x), aerosols and GHGs (CO_2 and methane (CH_4)) (IAGOS-CORE), or ozone, water vapour, cloud water/ice, carbon monoxide, CO_2, CH_4, water isotopologues, NO_x, mercury, aerosols, soot, volatile organic compounds and optical measurements of sulphur dioxide and formaldehyde from the IAGOS-CARIBIC Flying Laboratory.

The three European RIs, ICOS, ACTRIS and IAGOS, were developed closely in tandem, and collaborate on data interoperability. The three RIs are funded under the Horizon 2020 project ATMO-ACCESS Integrating Activity, which will develop and test innovative modalities of access to measurement facilities and complementary services to be developed as part of cross-RI efforts. ATMO-ACCESS will open physical and remote access to 43 operational European atmospheric research facilities, including ground-based observation stations and simulation chambers, as well as mobile facilities and central laboratories fundamental to distributed RIs (ATMO-ACCESS, 2021).

Copernicus, the flagship EU Earth observation programme, offers information services based on satellite and *in situ* data. The programme is coordinated and managed by the European Commission. Copernicus is implemented in partnership with the Member States, the European Space Agency, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts, EU agencies and Mercator Océan, and works over six thematic areas: atmosphere, marine, land, climate change, security and emergency. The atmospheric component, Copernicus Atmosphere Monitoring Service (CAMS), evolved from the Global and Regional Earth System Monitoring Using Satellite and In Situ Data (GEMS) project (Hollingsworth *et al*., 2008) to the Monitoring Atmospheric Composition and Climate service and then to CAMS, established in 2014, which provides information services using Earth observation products on past, current and near-future (forecasts) global atmospheric composition, the ozone layer, European air quality, emissions and surface fluxes of key pollutants and GHGs, solar radiation and climate radiative forcing. CAMS produces high-quality products, merging Earth observations with state-of-the-art modelling systems for policy-grade products.

Although spaceborne observations form the backbone of Copernicus, the service relies on *in situ* observations for calibration and validation of products, and for assimilation into integrated products. ACTRIS, ICOS and IAGOS provide data to CAMS, and data from EU Member States as well as national air quality monitoring data are supplied to CAMS via the European Environment Agency (EEA) near real-time database (compilation of European air quality data into the EEA database represented a major advancement during the Monitoring Atmospheric Composition and Climate – Interim Implementation project (MACC-II, 2014)). In situ data are crucial for validation of CAMS products, and for assimilation into models and development of advanced data-fused products for both reanalysis data and near real-time products (Inness *et al*., 2019).

One recent research publication demonstrates the application of advanced model–measurement fusion techniques, comprising *in situ* and satellite measurements and multiple model simulations to assess deposition of atmospheric trace constituents (Fu *et al*., 2022). Such data-fusion and integrated assessment facilitates the production of comprehensive, accurate data services for end users – a prerequisite for better Earth system management in the context of sustainable development.

1.2 Potential for Advancement of Integrated Analysis of Observations

The development of atmospheric observational communities over recent decades has allowed advances in measurement techniques, calibration standards, stringent quality control and the availability of data products for a variety of users (e.g. CAMS, EBAS, EEA). The use of satellite data has been directly acknowledged by the IPCC in the Sixth Assessment Report, but satellite products must be underpinned by sustained, ground-based, high-quality measurements. Increasing spatial resolution of these measurements is necessary to understand the processes and feedbacks that threaten our environmental stability. There have been calls of late to build a global Earth observatory (Kulmala, 2018) that can track environments and ecosystems at high spatial and temporal resolution, allowing researchers to synthesise data and assess the impacts of environmental change cutting across environmental grand challenges – currently, measurement networks that support MEAs assess environmental threats in isolation, disregarding the complexity of the planetary system. In a published conceptual design, the global Earth observatory would consist of 10,000 basic measurement stations and 1000 superstations – at a cost shy of €20 billion (Hari *et al*., 2016; Kulmala, 2018). To contextualise this financial sum, in 2020, the damage caused by extreme weather cost US taxpayers $99 billion, and there has been a rising trend in the annual cost of extreme weather over the past four decades (NOAA, 2021).

1.2.1 The North Atlantic

The North Atlantic offers a unique and opportune stage on which to apply such an integrated approach. The region is subject to atmospheric compositional changes coming from various angles, including:

- atmosphere–ocean interactions;
- Saharan dust deposition;
- volcanic ash;
- biomass burning events;
- anthropogenic emissions.

The atmosphere changes because of pollutants emitted locally and long-range transport of pollutants. These atmospheric compositional changes have impacts on:

- the energy balance of the atmosphere, hence the climate;
- air quality, affecting human and ecosystem health;
- deposition to the ocean and ecosystems, affecting nutrient availability, ecosystem and biosphere productivity, and the global carbon cycle;
- stratospheric ozone concentrations.

The area has considerable infrastructure and capacity for atmospheric observations. Although there is some interaction and collaboration between measurement communities, geographical gaps between observation stations remain, particularly on the east coast of North America, in eastern Canada, northwards up towards the Labrador Sea and in southern Greenland (see Figure 2.1).

These measurement gaps can lead to *gaps in our scientific understanding*, obscuring our insight into the potential impacts of environmental change and possible, much-needed mitigation options, particularly in regions that are especially vulnerable to the effects of a rapidly changing climate (WMO, 2015).

The North Atlantic is a region that is vulnerable to the effects of climate change, owing to its shared interface with the Arctic region and the fact that it is home to the Greenland ice shelf, which houses enough water to cause a 7.4 m rise in sea level (Morlighem *et al*., 2017). Any changes in the North Atlantic system could disrupt key global circulation patterns and biogeochemical cycles within the region, and hence a more complete understanding of drivers and implications of atmospheric change in the North Atlantic region is in the shared interest of safeguarding the environmental and economic sustainability of the densely populated regions surrounding the North Atlantic. The North Atlantic region also represents a unique case study for policy intervention; the surrounding continents include economic states that are committed to near-term significant cuts to GHG emissions, with the USA, Canada, the UK and the

EU aiming to transition to a carbon-neutral economy by 2050. Furthermore, the regions surrounding the North Atlantic include some of the most economically advanced communities in the world.

An integrated observation network would allow elucidation of the unknowns regarding the changing atmospheric composition of the region, including the rates and scales of change and the distances to limits and tipping points, which are of global concern. While these are primarily linked to key challenges in atmospheric physics and chemistry, it is proposed that this coordinated network will serve to fill knowledge gaps and enable a more targeted policy response to challenges.

2 ANIAR Project

In terms of coordinated international measurement programmes, the first and second Aerosol Characterization Experiment (ACE) (Bates *et al*., 1998; Raes *et al*., 2000) successfully brought together previously fragmented international aerosol communities to increase quantitative understanding of the complex gas/aerosol/cloud system. This community was again brought together in 2017 for the ACE20 meeting, when representatives from observational sites surrounding the North Atlantic region met in Tenerife to discuss the legacy of the ACE experiments 20 years on and to assess the state of atmospheric observation facilities surrounding the Atlantic Ocean in terms of spatial representation and policy relevance (Barrie and McGovern, 2017). This current work has built on the work of ACE to foster international collaboration pertaining to atmospheric observations, focused on the North Atlantic region. We reiterate some of the needs highlighted in the ACE20 report, but ANIAR has progressed with the following ACE20 recommendations:

- Establish an ad hoc group of scientific experts to consider the range and scope of current observational platforms, drawing in space agencies and associated bodies, with the aim of producing a strategic science-based analysis of the developments needed in the region to (1) assess changes in the North Atlantic atmosphere and (2) produce policy-relevant scientific outputs (e.g. data, information, insight) to inform international responses to environmental and social threats due to changing atmospheric composition.
- Expand options for communicating atmospheric protection issues via artistic and innovative media.

2.1 Gap Analysis of Nationally Funded Activities

A gap analysis of two major nationally funded atmospheric observation activities was carried out by surveying the Valentia Meteorological and Geophysical Observatory (Met Éireann) and the Ryan Institute's Mace Head Atmospheric Research Station (NUI Galway), using the resources listed on their respective websites and through direct contact with operational managers at each site. The current status of the sites was assessed relative to the previous recommendations of a previous EPA report (Barrie and Puckett, 2006), which evaluated both sites in the context of the GAW programme. From the gap analysis conducted, an urgent need was identified for sustained funding at Mace Head to capitalise on research capacity that has been built up over the past decades. The potential for developing national observatories at Valentia and Mace Head as scientific tourism sites was also identified, owing to their situation in remote beauty spots along the Wild Atlantic Way.

The stations at Mace Head and Valentia are linked with sites at Malin Head, Co. Donegal, and Carnsore, Co. Wexford, to make up the National Greenhouse Gas and Transboundary Air Pollution Monitoring AC3 Network, which characterises air pollution, GHGs and short-lived climate forcers, as described in an EPA report (Martin and O'Dowd, 2021). Measurement sites at both Malin Head and Carnsore have recently undergone significant redevelopment to enable the creation of this network, which has been crucial in evaluating the extent and causes of atmospheric changes over Ireland. This network is instrumental in the verification and development of robust GHG emission inventories in support of the Paris Agreement and in informing effective mitigation of GHG emissions at a national level, and it is vital that this progress should be sustained by the continued development and maintenance of this network.

Ireland's atmospheric observation community has made significant contributions to atmospheric science over recent decades (O'Connor *et al*., 2008). The EU RIs ACTRIS and ICOS offer the opportunity for harmonised measurements, calibration, observational analysis, operational support and data storage infrastructures across Europe – they are the state of the art in terms of atmospheric measurement and integrated analysis of change and set the standard for international atmospheric observations and analysis.

Although national measurement activities are linked to both ACTRIS and ICOS, Ireland does not have access to privileges, influence and support that would come with full membership of the RIs. Signing up to become full members of both RIs would safeguard Ireland's place at the forefront of international atmospheric research and support the endeavour to realise the goals of the Paris Agreement.

2.2 Review of Coordinated Atmospheric Research Activities in the North Atlantic

Active sites that contribute to current research networks in the North Atlantic are shown in Figure 2.1. The sites have been catalogued, with links to networks and relevant policy elucidated. A detailed catalogue of a selection of the sites is given in Appendix 1, which profiles sites in terms of instruments, the duration of measurement record, contribution to networks (if any) and funding support. This resource allows users to identify the measurements available at each location in the North Atlantic, to foster collaborations and to identify the upgrades needed to feed into collaborative scientific projects (e.g. the Surface Ocean–Lower Atmosphere Study (SOLAS) and the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)) and major international research networks (ICOS, ACTRIS, GAW programme, EMEP, AGAGE, NOAA, AERONET).

2.3 ANIAR Ad Hoc Group for North Atlantic Atmospheric Observation

An ad hoc group comprising representatives from key strategic surface observation sites, space agencies and associated integrating bodies serving the North Atlantic region would have the potential to identify the scientific gaps and development needed for integrated assessment of the North Atlantic atmosphere to inform actionable policy in response to environmental change. Such a group came together at the ANIAR science strategy meeting, held in November 2020.

2.4 The ANIAR Science Strategy Meeting

This key project event took place over 2 days on 9 and 10 November. The list of invitees included leading experts in surface observations, modelling, remote sensing and satellite communities, and representatives from the ocean community who had collaborated successfully in the past decade with the research community to realise common goals for the Atlantic region. The invitation, agenda and a list of meeting

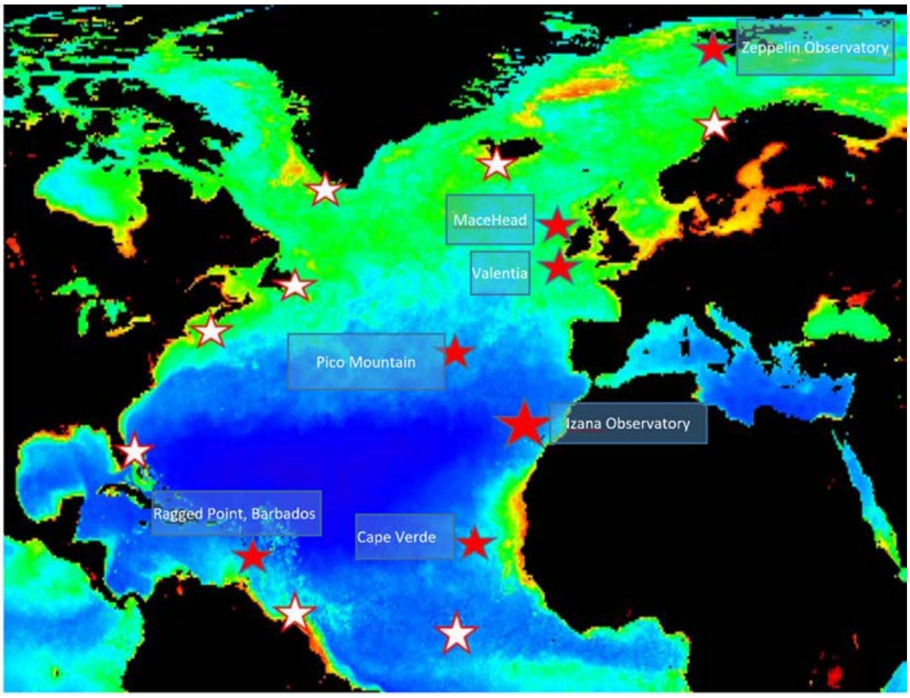

Figure 2.1. Existing measurement stations (red stars) and potential measurement sites (white stars) in the North Atlantic. Adapted from Barrie and McGovern (2017).

attendees is given in Appendix 2. Details of the agenda and talks given, links to the talks, and notes and presentations from the meeting are available on the project website (https://macehead.nuigalway.ie/rt/ANIAR/ANIAR-home.html).

2.4.1 Meeting aims

- To articulate the views of the North Atlantic atmospheric research community on the status of atmospheric research relevant to the North Atlantic region.
- To determine factors limiting research progress.
- To suggest pathways to consolidate the atmospheric research community to serve the North Atlantic region, enabling scientific output pertinent to the formation of effective policy to address major environmental challenges relevant to the North Atlantic region.

Presentations were followed by engaging discussions on topics including microplastics, biomass burning, and the impact of climate change on dust emissions, aerosols and constraining the ozone budget. The key messages related to atmospheric change over the North Atlantic are listed in section 2.4.2.

Ozone budgets and trends in the North Atlantic

Ozone is a major focus of TF HTAP activities due to its long lifetime, health impacts, and impacts on crop health and crop yields. Despite the attention given to ozone in models, there is still major uncertainty in ozone budgets within global models. From hemispheric transport of air pollution (HTAP) studies, CH_4, as a long-lived ozone precursor, can have a big effect on future ozone concentrations, with rising CH_4 trends potentially undoing the effect of NO_x emission reductions on future ozone concentrations. Within the northern mid-latitudes, owing to its relatively long atmospheric lifetime, ozone undergoes long-range transport on hemispheric scales.

Long-term changes and seasonal cycles of ozone in the northern mid-latitudes have been analysed using eight *in situ* baseline ozone datasets located around the North Atlantic (Parrish *et al*., 2013), which has revealed a rising trend in background ozone levels from the 1970s to the mid-2000s. However, since then, background concentrations have been decreasing, most likely due to air quality legislation taking effect over the past few decades (Heue *et al*., 2016). In developing countries, an increase in summertime ozone peaks has been observed due to the continued growth of ozone precursors (Sun *et al*., 2016). Further, ozone sonde measurements at two sites in China have shown an increase in ozone at a level that contributes to the higher ozone levels observed on the western seaboard of the USA (Verstraeten *et al*., 2015). However, despite tighter controls on ozone precursors over the past decades, there has been an overall increase in ozone levels in the mid to upper troposphere of the northern hemisphere, with the greatest increase, according to a recent study using IAGOS data (Gaudel *et al*., 2020), observed in Southeast Asia.

There has been an increasing trend in total column ozone over the North Atlantic in north-western North America, which is not only influenced by chemical processes but also related to changes in geopotential height, influenced by teleconnections with dynamic transport and atmospheric circulation patterns, and modes of climate variability, including the Arctic oscillation (Zhang *et al*., 2019), the North Atlantic oscillation (Pausata *et al*., 2012; Lin *et al*., 2015) and stratospheric circulation patterns (Neu *et al*., 2014).

The current generation of chemical transport models still exhibit strong inter-model differences in simulated ozone mixing ratios, especially prevalent in spring time, as shown in Figure 2.2.

Improving the performance of chemical transport models (CTMs) in simulating ozone concentrations necessitates more comprehensive measurements of ozone precursors to better constrain ozone budgets in models, including NO_x, especially from international shipping emissions, CH_4 and peroxyacetic nitric anhydride (PAN). As local air pollution sources have declined, owing to the success of the unified global effort of CLRTAP, the long-range transport of ozone makes a more sizeable contribution to ozone levels in Europe. In 2018, over one-third of EU citizens were exposed to ozone levels that exceeded EU limit values (EEA, 2020). Owing to the vital role that ozone plays in atmospheric chemistry, radiative forcing and human health, and the exacerbating effect that a changing climate will have on air pollution problems (it is estimated that the annual cost for climate-driven ozone deaths in the USA will approach \$7 (\$10) billion by 2050 and \$18 (\$26) billion by 2090 under Representative Concentration

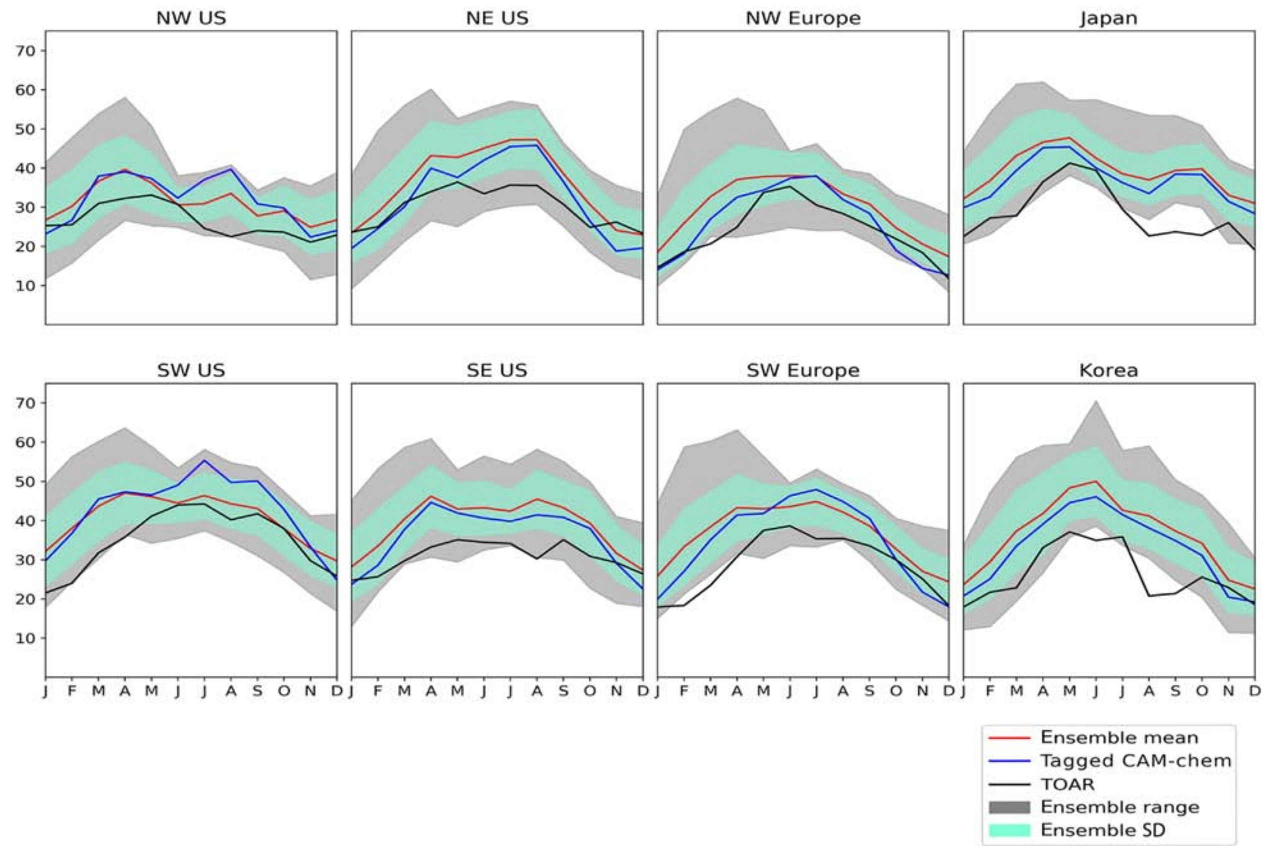

Figure 2.2. Seasonal cycle of monthly mean surface ozone (ppb) in HTAP tier 2 regions from our base model run (blue line), compared with observations from the Tropospheric Ozone Assessment Report (black line). Reproduced from Butler *et al.* (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Pathway 4.5 (Representative Concentration Pathway 8.5) projections (USEPA, 2017)), it is vital that global models have the capacity to accurately simulate ozone mixing ratios, and the spread of ozone values in current models indicates that there is a need for better representation of the ozone-regulating process in our models, including the hemispheric transport of ozone, and more comprehensive data on the vertical profile of ozone precursors.

2.4.2 Key messages from the ANIAR science strategy meeting

Key messages that emerged from discussions at the science strategy meeting are listed below.

Societies at sea

A significant proportion of societies live by the sea, with 40% of EU and US populations residing in coastal locations (EU, 2011; NOAA, 2013). Figure 2.3 shows a composite image of Earth nightlights as a proxy for population density, demonstrating the propensity of communities to settle in coastal locations. From this image, it is obvious that the North Atlantic separates two of the most densely populated regions on the planet. These coastal communities are vulnerable to the effects of climate change, including extreme weather, rising sea levels, ocean acidification and changes that may occur due to alterations in the major circulation patterns determining local climate in the North Atlantic region.

Building on the success of the ocean community

The idea of an integrated observing system for the ocean has already been accepted and adopted by governments, but this system will not be fit for purpose without due consideration of air–sea interactions. This will require comprehensive consideration of the atmosphere – which needs a robust network of *in situ* measurement sites that will constrain and validate

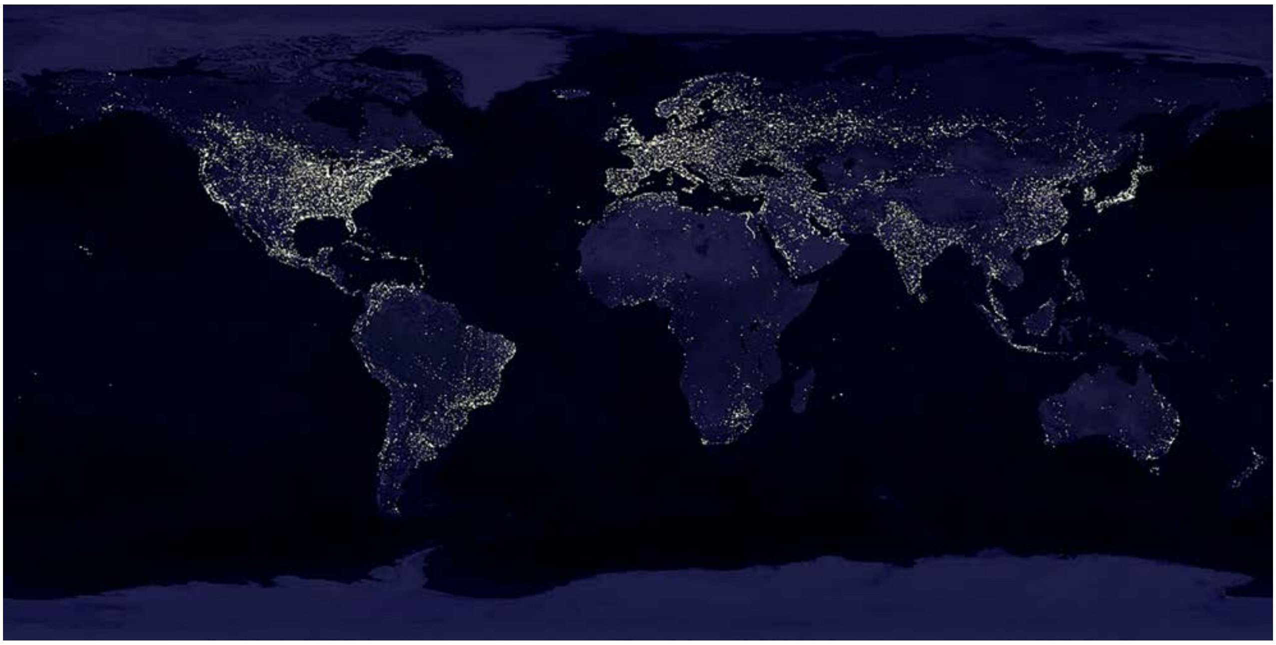

Figure 2.3. Composite image showing satellite images of nightlights on Earth at night, taken from NASA. Credit: NASA/NOAA.

both modelling products and satellite observations. This integrated atmospheric observing system will complement the oceanic counterpart and coordinated development will foster research into air–sea interactions.

Societal mobilisation for coordinated research

Protecting the environment from further transgression of our planetary boundaries requires society-wide mobilisation, encompassing, inter alia, citizens, enterprises, local authorities, industry, research institutions and government. Crucially, this requires commitment to strengthening the connection between the public and the atmospheric environment. A large effort must be made to evoke a sense of stewardship of the atmosphere in society at multiple levels via educational streams and the arts, with particular focus on youth engagement and harnessing the momentum of current environmental awareness among young people. It is also important to communicate with hard-to-reach sectors of society that are often omitted from conversations about environmental protection – this is important in terms of moving towards an equitable, environmentally sustainable future, one in which no citizen is left behind. As part of Mission Starfish, Horizon Europe is putting considerable effort into “filling the emotional gap” between people and the ocean waters – a crucial step towards mobilising political powers to support integrated research efforts. A similar effort must be made to connect the public with the atmosphere – with the very air they breathe, with the winds that carry nutrients from the Sahara to the Amazon, with the shared threatened commons that transmits sounds, signals, pathogens and pheromones – and with the Earth system component that houses the mechanisms that alter the energy balance of the climate system, threaten ecosystem and human health, and destroy the stratospheric ozone layer.

Case for activating action

Careful consideration must be given to the key messages that could be used to persuade the USA and Canada that the North Atlantic atmosphere is worth further investment. The interactions between atmospheric composition and severe weather elicit a powerful argument, considering the economic cost of severe weather in North America, of the order of €100 billion per annum (NOAA, 2021). Inclusion of data-fused products for atmospheric composition in numerical weather prediction will greatly improve the accuracy of 10-day weather forecasts and predictions of precipitation. In terms of protecting the quality of breathable air, despite the success of the CLRTAP in reducing emissions of harmful air pollutants, in 2021, 99% of the global population breathed air that falls short of the World Health Organization air quality guidelines, with over 4.2 million deaths per annum attributable to inferior outdoor air quality (WHO, 2018). In economic terms, the health impact of anthropogenic particulate pollution in the UK alone incurs costs of between £8.5 billion and £20.2 billion per annum (Environmental Audit Committee, 2010), whereas, on a European scale, industrial air pollution cost society somewhere in the region of €227–433 billion in 2017 alone (Schucht *et al*., 2021).

Science for services

Increasingly, there is demand for scientific data and knowledge to be disseminated to stakeholders via services to inform behaviour and response. Science must converge systematically for integrated analysis of the Earth system. There is a need to open science for shared solutions that are attainable within communities, and this requires effective communication between scientists, policymakers and the public to develop services that can be used across all sectors of society for the protection of the environment and human health. The sharing of atmospheric high-value datasets is supported at an EU policy level by the EU Open Data Directive, which shapes the digital future of Europe and enables cross-sectoral sharing of high-value datasets.

Two-way communication

To address societal challenges, it is vital to gauge the needs of the community and stakeholders to determine the services required for effective policy and action and to generate the scientific data and understanding that are necessary to provide these services. For services to be effective, local response must be aligned with local knowledge and customs – the lived experiences of people who make up society. Current policy directives that do not motivate the desired behavioural change must be reframed so that the understanding of behaviour change within communities, and our policies, is sympathetic to the socioeconomic pressures on citizens. Communication with citizens to activate behaviour change must involve the imparting of a deep understanding of the relationship between local practice and global climate, fostering the knowledge, attitudinal shifts and lasting connections required to respond collectively to the climate crisis.

Emerging threats

We have already discussed some of the predominant airborne threats to our environment, yet there is a need to continuously monitor emerging threats and contaminants of emerging concern that may have a negative health impact on human or ecosystem health, but are not yet regulated by environmental legislation (e.g. estrogens, pharmaceuticals, anti-oxidants, ultraviolet (UV) filters, pesticides and herbicides (Sousa *et al*., 2019)).

Informed decision-making for policy development across multiple scales

Scientific output plays a pivotal role in advancing our understanding of the Earth system and the composite impacts that may arise from any changes within it. Effective environmental policy requires an integrated assessment of the environment, which requires interdisciplinary collaboration and broadspectrum, robust datasets that will not only inform new policy but can also be used to evaluate the efficacy of existing policy interventions. Although the environmental crisis is of a global scale, responses to environmental threats are formulated at national and local levels. Yet, the atmosphere knows no political borders. Sustained, coordinated observations provide a bird's-eye view of multi-scale atmospheric processes, and also generate awareness and employment and build scientific capacity in the region local to the observational sites. Integrated analysis of these sustained, coordinated observations can assess how atmospheric compositional changes can threaten environmental sustainability across temporal and spatial scales and can generate the scientific knowledge necessary to inform effective environmental policy responses at regional, national and local levels – this is the link between global concerns and regional responses that has been hitherto missing in the planetary boundaries concept. The outputs from an integrated research community must enable the delivery of fit-for-purpose services from the bottom of the ocean to the top of the sky – the entire Earth system – and the realisation of this goal requires a society-wide investment.

Linking communities

There are many existing atmospheric observation communities that serve the North Atlantic, but there is a lack of an integrating structure to enable aggregated assessment of the atmosphere, cutting across issues of atmospheric and environmental protection. Linking these existing communities will enable integrated assessment of atmospheric change for the benefit of society.

Political alliances

The North Atlantic spans an area in excess of 41 million km^2, stretching from Newfoundland to Iberia and bound in the north by the Arctic Eurasian Basin. Linking four major continents, including two major players in terms of global economic development, the North Atlantic has been a source of economic development for the adjacent land masses in various industries, including marine transport and fishing, whaling, sand and gravel harvesting, fossil fuel extraction from deposits underneath sedimentary rocks, and mining of valuable minerals, rocks and stones, and has been a major trade route for centuries, galvanising a unique transatlantic financial relationship (Bui and Bayoumi, 2011). The North Atlantic Treaty Organization (NATO), which was formed in the aftermath of the Second World War, is a military alliance with the purpose of promoting cooperation between the member states. NATO is a concerted effort to link North Atlantic communities to safeguard political stability and has been hailed as the most successful alliance in world history owing to the shared values of the member states and their commitment to collective security (Fehrenbach, 2017). Faced with the increasing threat caused by transgression of our planetary boundaries, there is a need for a North Atlantic alliance to safeguard the environmental stability of the region and a shared vision and commitment across member states to protect the North Atlantic atmosphere.

Integration of the ocean community

Actors from the ocean research community have successfully come together to integrate ocean research efforts to realise common goals surrounding the Atlantic region, forming the All-Atlantic Ocean Research Alliance (AORA). The successful achievement of AORA was due to fortunate timing in terms of political leadership and alignment of commitments to protect the Atlantic at a high level, engaging the heads of national agencies and EU commissioners, and building on decades and even centuries of international links – both political and scientific.

Space community

Spaceborne Earth observation communities are supported by large-scale investment and coordination, but there is also a need for this kind of longer-term investment and international collaboration across the Atlantic in the realm of surface observations. The relevance and importance of ground-based measurements must be highlighted, as it can be forgotten that these are vital for the underpinning of sophisticated satellite and Earth model products.

Although many observation communities cater for the North Atlantic region, there is a lack of integrating bodies to address the entire region and to tailor policy responses to environmental threats. Following on from the example of the ocean community, we must capitalise on political opportunities as they arise. The challenge is to identify the opportunities to scale up the research that will ultimately deliver outputs to partners that can be used at various scales – from local to international – and prove to be ultimately more cost-effective than continuing in a fragmented manner.

2.4.3 Science–policy thematic challenges

The following key science–policy challenges and knowledge gaps were discussed by meeting attendees. These challenges were identified as areas of concern for the North Atlantic region in the context of atmospheric composition change, where there is potential for scientific investment to yield policy-relevant output.

Understanding physical and dynamic changes

Both physical and dynamic changes need to be considered and understood, including sea level rise, cryosphere loss in the Arctic and Greenland, Arctic amplification of climate change, changes and trends in the major Atlantic currents (focusing particular attention on the Atlantic meridional overturning circulation), interdependencies of the circulation patterns and the regional teleconnections between weather and climate systems. These physical and dynamic changes have serious implications for regional climate and weather variability, sea level rise, carbon sequestration and ocean acidification, with each of these aspects carrying significant socioeconomic implications for the North Atlantic communities and globally.

Sustaining human and ecosystem health

Despite the success of the CLRTAP, air pollution remains a global problem, with over 99% of the global community breathing polluted air and ambient air pollution causing in excess of 4.2 million deaths annually (WHO, 2018). Therefore, sustaining human and ecosystem health through greater understanding of chemical fluxes and pathways that determine the regional atmospheric composition (e.g. atmospheric ozone concentrations, POPs, carbonaceous species and inorganic compounds), periodic large-scale biophysical events, such as Saharan dust plumes from North Africa, and biogenic emissions from natural and managed systems, remains a key science–policy challenge.

Constraining carbon budget ranges for global temperature increments

Constraining carbon budget ranges by reducing uncertainty in factors determining the Earth system energy balance represents a major challenge, as identified in the UNFCCC Paris Agreement. Quantification of the relationship between global climate sensitivity and the increased retention of energy in the climate system is central to estimating carbon budgets that are compatible with the temperature goals established in the Paris Agreement. GHG emissions are rising relentlessly in the background measurement stations surrounding the North Atlantic (Figure 2.4), and will hence continue to force the radiation budget in the region. Uncertainty in estimating carbon budgets reduces the policy effectiveness of limiting warming by curbing emissions (Rogelj *et al*., 2019). Much of the associated uncertainty in radiative forcing is linked to the direct and indirect (cloud) effects of aerosols, the concentrations of ice nucleation particles in marine clouds (Vergara-Temprado *et al*., 2018), the radiative properties of carbonaceous aerosols and the atmosphere–surface gas exchanges that influence the carbon budget. The North Atlantic is uniquely situated to determine the impacts of a range of aerosol and cloud types on energy fluxes, as well as alterations in biogeochemical cycles that influence the carbon budget. The implications of ocean–atmosphere interactions for the carbon budget, and hence radiative forcing, are still relatively unknown (Schulz *et al*., 2012). A reduction in the uncertainties surrounding

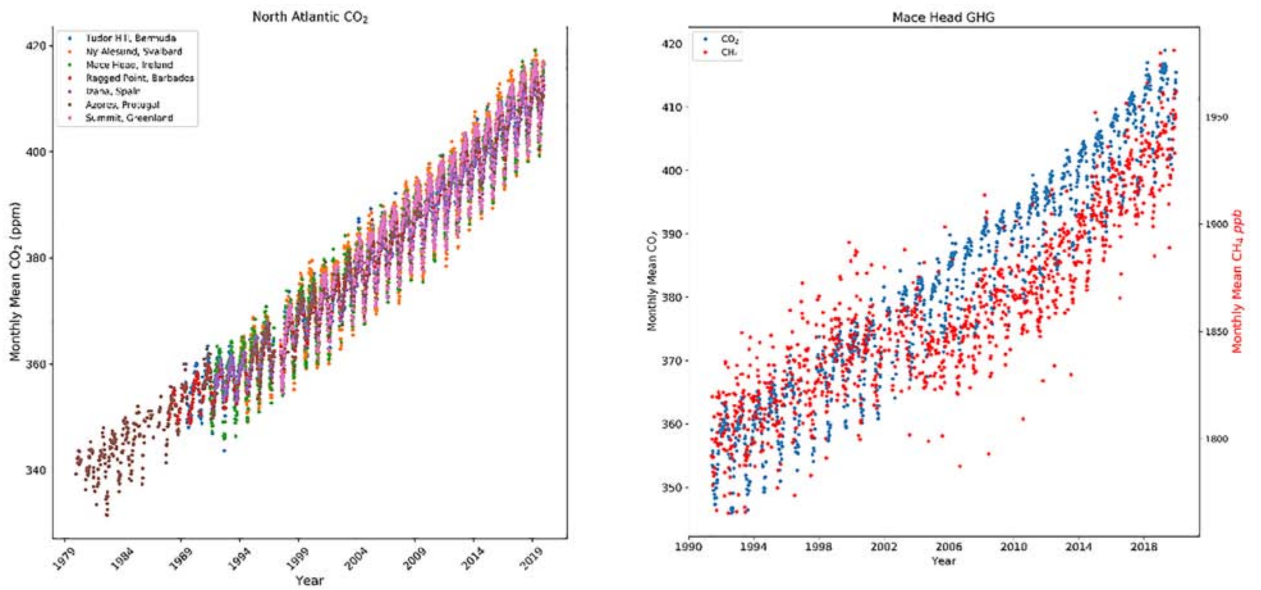

Figure 2.4. (Left) CO_2 trends from sites surrounding the Atlantic Ocean, taken from 1979 onwards. Data taken from the Carbon Cycle Greenhouse Gas Cooperative Air Sampling Network and resampled to monthly mean values. The data were sampled in each station using flask containers and sent back to NOAA's Global Monitoring Division. (Right) CO_2 and CH_4 records taken at Mace Head. The data are filtered to display only samples representative of a remote, well-mixed troposphere, and data for both panels are available from the NOAA Global Monitoring Laboratory.

these processes requires the planned development of a network of linked high-precision *in situ* and remote observations, tailored to integrate the analysis of emissions, air–sea exchange, transport and atmospheric processing of a range of aerosol types and gases, as well as their impacts on carbon budgets and energy/radiative transfer.

Constraining simulated ozone budgets

Ozone is a major focus of the TF HTAP's activities due to its long lifetime and health impacts. In 2018, over one-third of EU citizens were exposed to ozone levels exceeding EU limit values (EEA, 2020). Owing to the vital role that ozone plays in atmospheric chemistry, radiative forcing and human health, and the exacerbating effect that a changing climate will have on air pollution problems, with considerable social and economic ramifications, it is vital that global models have the capacity to accurately simulate ozone mixing ratios. Despite the attention given to ozone in models, the current generation of chemical transport models still exhibit strong inter-model differences in simulated ozone mixing ratios, especially prevalent in spring time, as shown in Figure 2.3. From HTAP studies, CH_4, as a long-lived ozone precursor, can have a big effect on future ozone concentrations, with rising CH_4 trends potentially undoing the effect of NO_x emission reductions on future ozone concentrations. Within the northern mid-latitudes, owing to its relatively long atmospheric lifetime, ozone undergoes long-range transport on hemispheric scales. Difficulties in constraining ozone may be attributed to a paucity of data on ozone precursors in the free troposphere (including PAN, as well as CO and NO_x), changes in geopotential height (influenced by teleconnections with dynamic transport), atmospheric circulation patterns and modes of climate variability (Pausata *et al*., 2012; Lin *et al*., 2015; Zhang *et al*., 2019), and stratospheric circulation patterns (Neu *et al*., 2014). Ozone is significant as an atmospheric component influencing both air quality and climate change, and hence it is imperative to constrain ozone budgets for the protection of health and climate change mitigation.

2.4.4 Scientific needs to address science–policy challenges

To address the science–policy challenges identified, it is necessary to advance scientific understanding of processes affected by the changing atmospheric composition in the North Atlantic region. Attendees at the ANIAR science strategy meeting agreed on the following list of cost-effective measures that could be taken to achieve policy-relevant advances in the scientific understanding of the North Atlantic atmosphere.

Funding for ground-based observations of atmospheric composition

There is an overall need for sustained funding for such observations in the North Atlantic region, as they are vital for underpinning satellite, remote sensing and modelling data products delivered as services to end users and stakeholders. Many of the key sites in the North Atlantic have been sustained by the heroic efforts of individual scientists, and there is a need for sustained institutional and national support to safeguard the continued efforts of observation sites around the Atlantic region. Sustained observations are the gateway to understanding multi-scale processes, and it is not viable to rely on personal heroics to maintain them.

Denser coverage of the North Atlantic region

Such coverage includes shipborne instruments, high-precision instruments on research vessels and developing the observation capacity north of Barbados, on the east coast of North America and Canada towards Greenland. The need to extend GAW measurements into poorly represented areas has already been highlighted (Barrie and McGovern, 2017). This extended coverage is necessary to elucidate the interactions between atmospheric composition and weather systems, obviously important because of the societal impact of climate variability and extreme events in the North Atlantic region. These sites surrounding the North Atlantic region should have a coordinated set of fundamental measurements (particulate matter (PM) physics, GHGs, ODCs).

Improved knowledge of ocean–atmosphere interactions

There is a need for improved knowledge of interactions relevant to biogeochemical cycling and feedbacks. Precise ocean and atmospheric measurements in strategic locations enable underpinning of key relevant processes. Looking at marine cloud formation processes, and the effect on radiation, is especially important. The strategic sites should have a host of advanced instrumentation, including:

- aerosol chemical speciation;
- vertical profiling suites;
- ocean–atmosphere flux measurements;
- measurements of ice nucleation particles in marine clouds.

Improved measurements of ozone precursors

Better constraint of ozone requires measurements of ozone precursors (e.g. PAN) in the free troposphere (mountain-top sites), including vertical profiles of CO and NO_x, which can be obtained using lidar, sondes and aircraft measurements to better constrain ozone budgets in models.

2.4.5 Integrated assessment and funding

The science–policy issues identified above (physical and dynamic changes, ecosystem, human health, constraining the carbon and ozone budgets) do not exist in isolation. The processes involved are intertwined through linked Earth system processes, yet they are addressed separately, siloed under corresponding MEAs. Many of the atmospheric observational sites in the North Atlantic were developed independently, linked only through ad hoc connections. An integrated assessment of the cause and effect of atmospheric composition changes in the North Atlantic region would enable synergistic policy responses that could potentially address each thematic challenge for holistic environmental stability. Integrated assessment requires sustained monitoring of the circulation patterns, radiative parameters, atmospheric composition and air–surface interactions in key strategic sites, as we propose here. Since ACE20, CAMS has blossomed into a flagship programme of the EU. A billion euro per annum programme, Copernicus has been operational since 2015, comprising spaceborne and *in situ* observations to provide services to a range of users, spanning public and policy. As the atmospheric module of Copernicus, CAMS produces high-quality, policy-grade products for end users, merging satellite observations with state-of-the-art modelling systems and *in situ* observations, yet *in situ* observations are not significantly funded under Copernicus activities, especially non-regulatory observations. There is potential for the atmospheric research community to contribute to Copernicus and CAMS activities. For example, better consideration of aerosol radiation interactions is an important determining factor in numerical weather prediction (Jeong, 2020; Yang *et al.*, 2020; Huang and Ding, 2021) and the aerosol cloud effect is another area that needs more work/research.

The barrier to sustaining, developing and expanding atmospheric observational capacity is securing continuous financial support. Although some of the stations (e.g. Zeppelin in Svalbard) have commitments from national funding bodies, other sites struggle to secure funding to maintain operational measurement status. Obtaining funding for the upgrading and development of existing sites poses a major challenge, and an even greater challenge lies in attracting funders and resources for the establishment of new observational facilities. The coordination of international effort required to address North Atlantic observational research extends beyond the scope of individual research projects or research programmes, and at present there is a lack of policy support for integrating systems that can synthesise RIs, networks and research projects across local, national and international scales. Realisation of this goal is beyond the scope of one research project or programme and will require high-level political support. Like the founding of synoptic measurements in the IGY of 1958, and the opportunities created by the ocean community in the past decade, it is vital to capitalise on political opportunities that may arise, as these may offer space to make a case for strengthened cooperation between North Atlantic atmospheric observational facilities.

Potential mechanisms for integration

- The atmospheric initiative can be developed by coupling to the coordinated efforts of the Atlantic Ocean community. In 2013, government representatives from Canada, the USA and the EU signed the “Galway Statement on Atlantic Cooperation” at the Marine Institute in Galway. This statement committed the signatories to engage in multilateral cooperation with the aim of advancing Atlantic research and has since catalysed transatlantic research integration via the AORA. Based on the commitments made in the Galway Statement about ocean observations,

it has already been accepted that a sustained, supported observing system is a key prerequisite for the fit-for-purpose ocean services required by society: this case can be extended to encompass the atmosphere by arguing that a comprehensive Earth system model requires due consideration of air–sea interactions and atmospheric composition.
- The alliance for North Atlantic integrated atmospheric research could be established to complement the efforts of the ocean community, but existing as an independent framework with close coupling to AORA. Following the successful blueprint of the Arctic Monitoring and Assessment Programme, which had its secretariat hosted by Norway, with combined institutional funding from North American and European agencies, the North Atlantic atmospheric alliance could have an international membership of major research organisations with a secretariat in a prominent North Atlantic atmospheric research-oriented country.
- Currently, EU Member States are interested in the North Atlantic region. CAMS provides a unique integrating platform for models, *in situ* measurements and satellite observations that could provide the integrating framework necessary for a transatlantic North Atlantic initiative. CAMS is strongly connected with European RIs focused on atmospheric observations (ICOS, IAGOS and ACTRIS). There is an Arctic region initiative that could potentially be expanded to the North Atlantic region. Joint invitations to tender from CAMS, the Copernicus Climate Change Service and the Marine Monitoring Service could potentially be used to support a North Atlantic initiative.
- This initiative could possibly be developed from a political institutional level, as was the Arctic Council, which has achieved considerable success in identifying emerging issues pertaining to the protection of the Artic environment and framing them with a view to developing a policy response (Kankaanpää and Young, 2012).

The vision of a complete integrated assessment system and observation network for the North Atlantic Ocean is articulated in a publication by Coleman *et al*. (2021), which is an output of this desk study.

3 Engaging the Public with the Atmosphere

In this post-truth era, it can be a challenge to defend scientific method amid science denialism and its far-reaching influence on education and policy (*Nature Cell Biology*, 2018). Now, more than ever, it is vital that scientists defend their scientific methods by engaging the public, bringing to the fore a more open research process where public participation will facilitate collaborative knowledge creation, thereby democratising research and bringing science to the primary stakeholder – the citizen (EC, 2014). With the proliferation and expansion of the ecology of communication, there is a danger that trust in science becomes diluted, and there is evidence that the credibility of science for the public is entirely dependent on the credibility of science communication (Weingart and Guenther, 2016).

Furthermore, scientific output and a knowledge of best practice do not in themselves stimulate the large-scale behavioural change that is necessary to alleviate pressure on our planetary boundaries. Exploration of environmental issues via artistic media can elicit emotion in a range of audiences powerful enough to evoke motivation for behavioural change (Paterson *et al*., 2020).

Transformational change is needed to realise the goals of the Paris Agreement. However, too often the demands for climate action are costly and on a scale apparently unattainable and abstract to many citizens. There is a need for fair and effective participatory governance regarding climate solutions, with two-way conversations between policymakers and citizens (Sheppard *et al*., 2011). The arts have always had a central role in the environmental conversation, from Henrik Ibsen's play *Fire* in the 19th century describing transported air pollution to Marvin Gaye addressing pollution in his classic song "Mercy, Mercy Me". Likewise, NASA images from the first staffed space missions were pivotal to the global environmental revolution of the late 1960s.

Throughout this project, partnerships were developed with artists and scientific engagement specialists to explore novel methods of engaging the public with the atmosphere – to visualise the invisible.

3.1 Development of the Deep Blue Sea Workshop

The Deep Blue Sea pilot workshop (October 2021) was developed in collaboration with Baboró International Arts Festival for Children, STEM (science, technology, engineering and mathematics) education and public engagement specialist Mairéad Hurley, and singer-songwriters and musical education specialists Nicola Joyce and Noelie McDonnell. The workshop was aimed at primary schoolchildren and explored the interconnections of the Earth system, carbon emissions and ocean acidification and the impact of human behaviour on the environment, and designed multi-scale solutions for reducing carbon emissions. The topics were explored through active learning and artistic creation (visual art, movement and song). Images taken from the workshops and the blurb for the workshop from Baboró are shown in Figure 3.1. Workshops took place over 3 consecutive weeks. The workshop programme will be disseminated in a science communication publication and, following the workshop's positive reception, it is planned to seek further funding opportunities to scale up the workshop programme.

3.2 Atmospheric States

"Atmospheric States" is a transdisciplinary art, architecture and science research project investigating how atmospheric dynamics and pollution, and their politics, challenge fixed notions of the nation-state and sovereign borders on the land, as experienced by different bodies. Atmospheric States is a collaboration between arts and architectural researchers and artists from the arts and spatial research practice "a place of their own" (Dr Paula McCloskey and Dr Sam Vardy) and atmospheric scientist Dr Liz Coleman (University of Galway). Initial activities have taken place in Galway, where the Atlantic Ocean meets western Ireland.

Atmospheric States will interrogate historical and contemporary apparatuses of scientific knowledge of the atmosphere and how such apparatuses establish

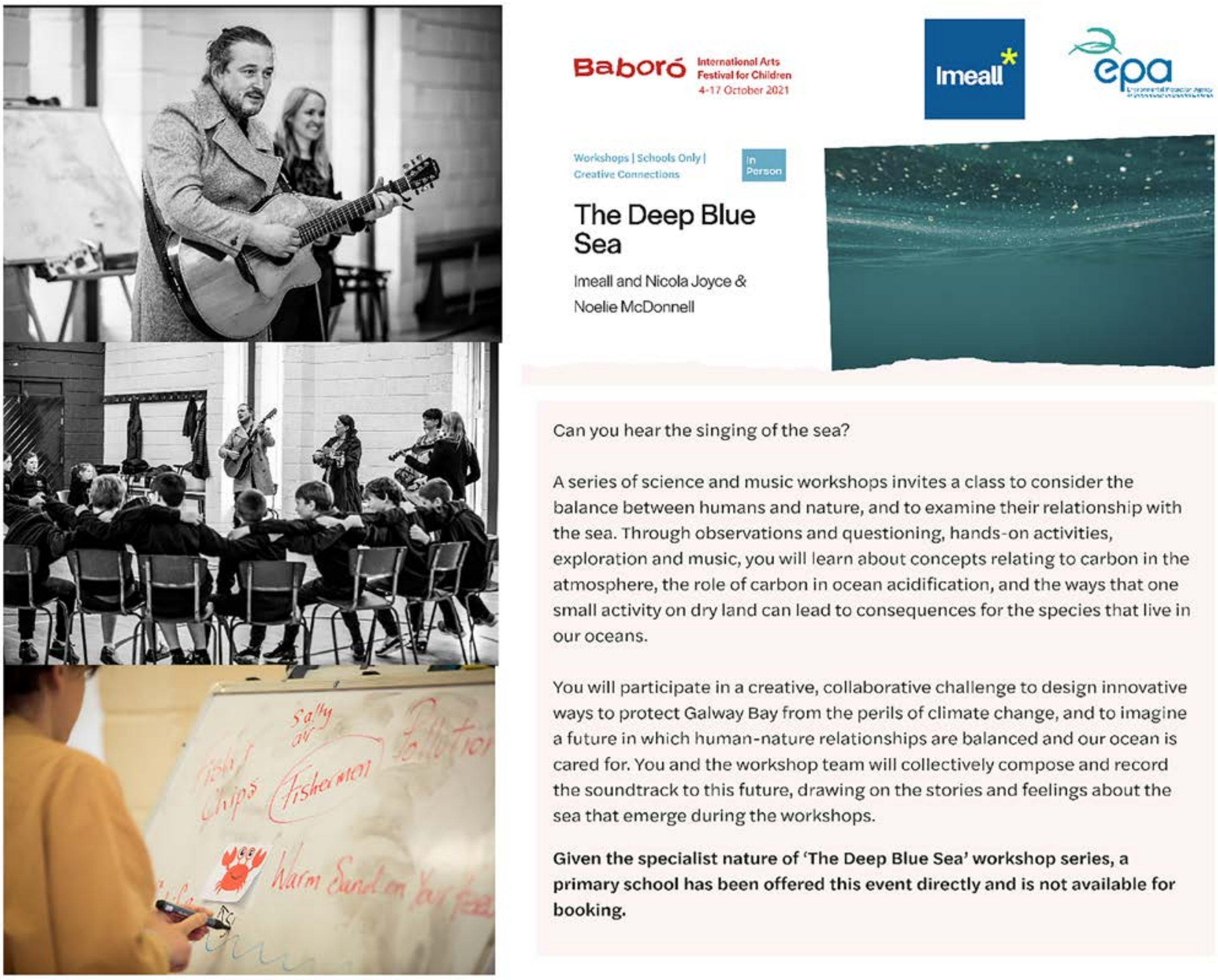

Figure 3.1. Images from the Deep Blue Sea workshop that took place as part of the Baboró International Arts Festival for Children in October 2021. Photo credit: Anita Murphy.

dominant narratives and understandings that inscribe colonial and capitalist imaginaries. Our research and spatial art practice will ask how we might bring different types of knowledge (science, art, architecture, popular culture, indigenous people) together to develop and test experimental apparatuses of the atmosphere and will investigate the potential effects of such alter-apparatuses in different registers (cultural, political, imaginary, etc.).

Atmospheric States was initiated in May 2021 and is an evolving project that seeks to create virtual and physical spaces for collaboration and to develop new collaborations.

The project is situated in the hyper-local context of Connemara, but it will move across scales to unpick geographies, embodied experiences and imaginaries of the atmosphere at sites across the planet. As the project develops it will map the various organisations, spaces and actors (researchers, local community members, political activists, policymakers, and so on) that are brought together.

The first phase is "fieldwork", which will involve a range of exploratory activities and encounters, including visits to Mace Head, discussions and workshops with scientists, artists and community members in County Galway, text reviews, archival research, mapping and reflective writing. The Atmospheric States website will collate and curate these activities.

As part of Atmospheric States, an event entitled "The Air We Breathe/Aer Anála" was held as part of the Architecture at the Edge festival on 9 October 2021 (see images in Figure 3.2).

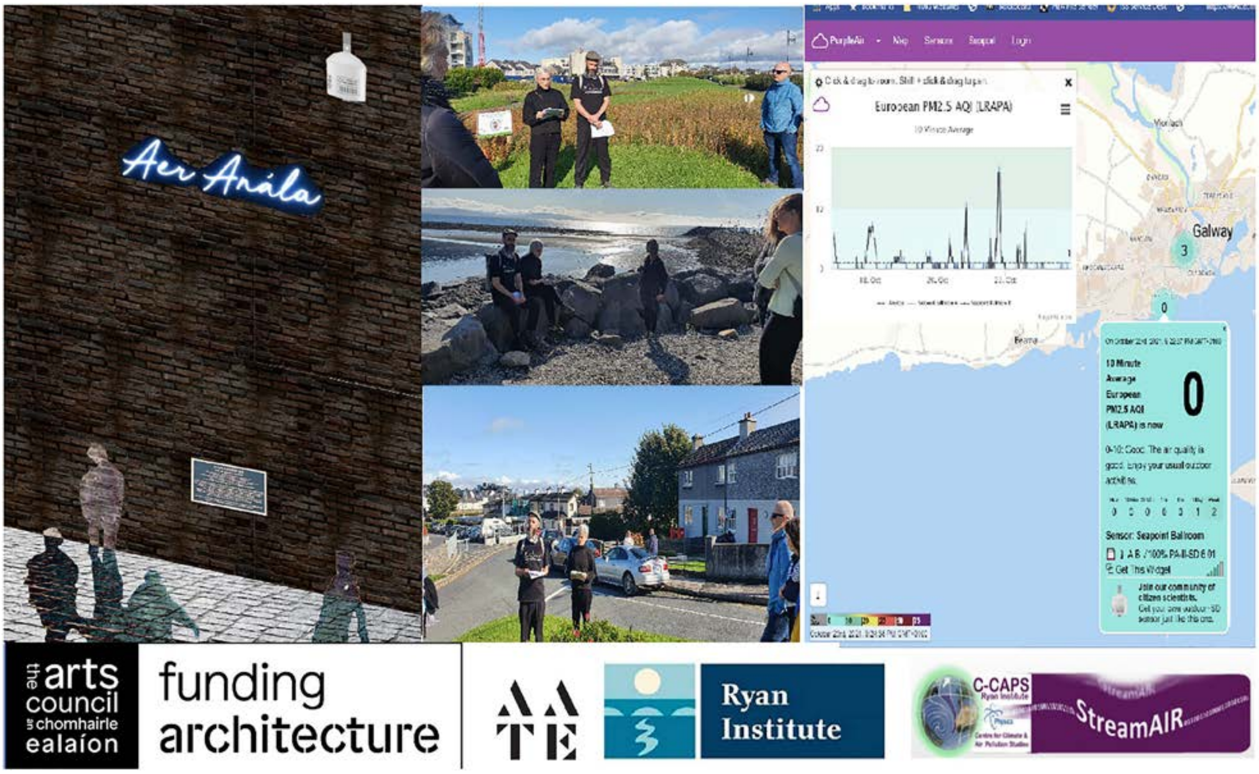

Figure 3.2. Images from the Aer Anála performance walk that took place as part of the Architecture at the Edge festival, Galway, 9 October 2021. The livestreamed air quality data are displayed on the right-hand side.

This project, co-funded by Architecture at the Edge, suggests that "the air we breathe" is a shared resource that offers an alternative way of thinking about the public realm. The event consisted of a performance walk starting at Seapoint ballroom and ending in a collective discussion at the Galway City Museum.

It is hoped that a new sculptural installation will raise interest in the atmosphere and will act as a visible and interactive symbol of the project. The sculpture takes the form of an LED neon sign that simply reads "Aer Anála". A small air quality sensor to monitor PM will be installed with it.

At street level, there is a small plaque with information about the project, and a link/QR code that enables people to view live data about air quality from the sensor on their phone or device.

3.3 Samhail

Samhail is an arts–science collaborative team that comprises Liz Coleman, the artistic and spatial research practice "a place of their own" and STEM education and public engagement specialist Mairéad Hurley. Stemming from exploratory workshops with Atmospheric States, Samhail designed a project to create public participatory transdisciplinary events in two Galway locations. The aim of the project is to examine the public relationship with the atmosphere and to illustrate our capacity to collaborate on environmental solutions via the co-creation of *Stories of the Air/Spéirscéalta* – a bilingual publication that will contain the sharing, merging and creating of stories to reflectively reimagine our relationship with climate and society. Concurrently, the project aims to bring diverse actors together to create an active regional STEAM (science, technology, engineering, the arts and mathematics) learning ecosystem in the west of Ireland.

As an arts–science collaboration, Samhail proposes to use storytelling as a mechanism to intertwine scientific knowledge and local knowledge, developing new methods of storytelling that entwine atmospheric science history, data and expertise with stories of the air from different specific communities. Samhail proposes a series of workshops, tours and events to be held in Galway city and county to co-create new stories of the air that draw from different histories, reflect current experiences and imagine sustainable futures. Scientific stories from the Mace Head Atmospheric Research Centre in Connemara will be woven into local community stories from Connemara and from Galway city, and during the process the two communities will be linked virtually and physically during the Mace Head tour.

4 Impact of COVID-19

The COVID-19 pandemic curtailed some of the activities of this project, predominantly affecting the timing of delivery and method of engagement:

- The scientific meeting was delayed because of the uncertainty the pandemic cast on the possible format of the meeting. Eventually, the format of the meeting was entirely virtual, over two mornings and afternoons in November 2020. The virtual format rendered the meeting accessible in terms of saving time, budget and energy. The format did not inhibit communication, as evidenced by the lively and comprehensive discussions.
- School outreach activities were delayed, yet the revised timing allowed time to forge strategic partnerships with artists and cultural partners, which allowed the pilot school workshop “The Deep Blue Sea” to be scaled up.
- There was a plan to hold a policy-level dissemination meeting. This meeting was delayed beyond the lifetime of this project because of travel restrictions and the uncertainties posed by the pandemic.

5 Recommendations

The North Atlantic is a key Earth system component, encompassing one of the most biologically active oceans, with circulation patterns that regulate regional climate and weather. The region is vulnerable to rapid changes owing to its shared interface with the Arctic region and the Greenland ice shelf, which houses enough fresh water which, if melted, would result in over 7 m of sea level rise. Such changes could have a massive socioeconomic impact on densely populated North Atlantic communities. This renders the North Atlantic an observation hotspot for monitoring global change. Formulation of effective policy responses requires consideration of the big picture, and this requires a network of integrated observations. The North Atlantic has the capacity to form the basis of such a network, with four of the six observatories (marked by red stars in Figure 2.1) acting as GAW global supersites. There is a need to sustain existing measurement capacity and to expand the network into the poorly represented sites in the western Atlantic. Likewise, there is need for an integrating structure to formulate effective environmental policy in response to changes. Establishing such an integrated observation and assessment network will require considerable coordination, funding and public and political support and will require a shared vision between scientists, stakeholders, governing authorities and policymakers. Following on from the work of ANIAR, we recommend the following.

5.1 Recommendation 1

We need to continue the development of the national infrastructure for atmospheric composition measurements. Although there has been some development in the deployment of the AC3 Network, the sites need to be staffed, maintained and further developed. Resources are needed to harmonise measurement data with international research standards. National membership of both the ICOS and ACTRIS RIs would consolidate Ireland's place at the forefront of atmospheric science and allow access to training and services that will progress national research. Funding is required for membership of the EU RIs, as well as for personnel and the maintenance of national network sites. However, this investment will build national capacity and strengthen the Irish position for leveraging large-scale EU research funding for atmospheric research.

The existing infrastructure and surrounding natural resources of the national observatories at Mace Head and Valentia can be developed as scientific tourism sites, serving to generate considerable revenue and to raise awareness of the importance of sustained atmospheric observation.

5.2 Recommendation 2

An ad hoc international group should be formed to support sustained, systematic atmospheric measurements in the North Atlantic and prepare a strategic roadmap for the advancement of atmospheric observations and integrated assessments to generate policy-relevant outputs. The ad hoc group requires scientific expertise from both sides of the Atlantic, including Canada, USA, the EU, Latin America, North Africa and the Caribbean. The group should include scientific expertise with respect to *in situ* observations, modelling, ground-based remote sensing, spaceborne remote sensing and international multidisciplinary scientific projects (SOLAS, GESAMP), space agencies and associated bodies, as well as international organisations (UNEP, WMO, United Nations Economic Commission for Europe) and emerging EU RIs (ICOS, ACTRIS). This project has sown the seeds for such an ad hoc group, which can be developed from the ANIAR steering committee and science strategy meeting participants. The expert group should engage fully to identify potential cost-effective actions to fulfil the observational requirements of the North Atlantic atmosphere and make strategic recommendations that can be prioritised by funding agencies and governing authorities, strengthening the power of local experts to leverage funding from agencies in a coordinated way.

5.2.1 Next steps

We should initiate communication with ANIAR steering committee members and attendees from the ANIAR science strategy meeting to arrange a follow-up meeting, the major aims of which will include:

- identification of potential scientific studies relevant to North Atlantic atmospheric composition, with a view to producing coordinated and complementary scientific outputs on dust transport; interactions between atmospheric composition and regional climate variability and extreme weather; air–sea interactions; and constraining ozone budgets;
- identification of pathways to build on linked initiatives and coordinate funding efforts, involving the satellite community; the ocean community; harmonisation of RIs for comprehensive environmental and ecosystem observations; and transatlantic cooperation.

Meeting attendees should be subdivided into relevant subgroups according to their expertise and affiliations.

5.3 Recommendation 3

We should hold a science–policy dissemination meeting with multi-level policymakers and funders to distil the scientific outputs from ANIAR into policy-relevant information for international authorities regarding the environmental security of the North Atlantic region. This should include information on how an integrated approach to atmospheric research in the North Atlantic would support policy-relevant scientific output. This would facilitate dialogue between regional actors with a view to designing a cooperative response to environmental threats and appropriate funding mechanisms to build on existing initiatives, including the need for national stations to align with existing infrastructures (ICOS, ACTRIS) and expand capacity to fill in the observational gap in the Northwest Atlantic. It is important to highlight the role of *in situ* observations in underpinning satellite and modelling products that are delivered as services to society.

5.3.1 Next steps

- Liaise with high-level stakeholders to organise a science–policy meeting, at which a case will be made for establishing a coordinated North Atlantic observation and assessment body. The meeting should highlight the vulnerabilities of the North Atlantic region in terms of environmental sustainability, the observed changes that have been occurring and the major knowledge gaps (i.e. the scientific blind spots that act as a barrier to effective environmental protection), and illustrate how an integrated assessment system and observational network could deliver the science necessary for an effective, targeted and coordinated response to environmental change driven by changes to the atmospheric composition in the North Atlantic region.
- The meeting attendees should include international integration bodies and national and regional authorities, including space agencies, Joint Programming Initiative Connecting Climate Knowledge for Europe (JPI Climate), Directorate-General for Research and Innovation, Copernicus, European Space Agency, NASA, US National Science Foundation, NOAA, US Department of Energy and the Canada Space Agency.
- Promote a series of commitments from UNFCCC signatory parties for sustained monitoring of radiatively active atmospheric constituents and participation in international atmospheric monitoring programmes (ICOS, ACTRIS, AGAGE).

5.4 Recommendation 4

Establishing a fit-for-purpose coordinated atmospheric observation network to serve the North Atlantic will require considerable public awareness and engagement with the atmosphere and the drivers and impacts of atmospheric change. As part of an ongoing effort to “fill the emotional gap” by connecting the public with the atmosphere, and to visualise the invisible atmosphere, we recommend exploring the connections between North Atlantic communities via an expansive arts–science collaboration. The collaboration should include a transdisciplinary team of scientists and artists to expose the interconnectedness of the North Atlantic as an Earth system component, from scientific and sociocultural perspectives.
The project could explore the movement of dust via atmospheric channels from the Sahara to the Amazon, the development of storms in the North Atlantic and the dominant circulation patterns linking the shipping routes. For each connection, research should look at both unique features and the similarities between connected regions, explore the physical and biogeochemical patterns that make the North Atlantic such a major component in the Earth system, explore how scientific knowledge of the North Atlantic

and the lived, embodied experiences of people and communities are entangled, and explore how cultural practices and behaviours are manifest in diverse cultural contexts and socio-spatial settings.

The project should include the abundant cultural heritage of the regions surrounding the North Atlantic (writing, music, visual art, photography, folk traditions) and should celebrate the unique cultural heritage of the individual communities, as well as the interconnections of the North Atlantic system and belonging to a large-scale North Atlantic community. This can be enhanced by developing scientific tourism sites at Mace Head and Valentia, as recommended for national-funded activities, above.

To garner support for a considerable investment in scientific assessment and policy protection of the North Atlantic region, it is vital to evoke a connection and a sense of shared stewardship of the region among the public – from individual support to institutional and political support. To generate this sense of planetary care, we need a cultural change, connecting the public to the spheres of the Earth system: the atmosphere, the oceans, the glaciers and ice caps. There is a long history of artistic output promoting learning and understanding of environmental change in ways that presenting scientific data and information cannot (Chameides, 2014).

Outputs from the project could be in the form of significant artwork, comprising a film, exhibition or digital interactive piece, to be staged at a major international climate event.

5.4.1 Next steps

- Identify possibilities to liaise with creative agencies for shared funding opportunities.
- Extend the geographical scope of artistic partnerships, building on existing and linked initiatives.

6 Summary Statement

We argue that there is an urgent need to establish an effective observational and scientific network, building on current infrastructure, for the North Atlantic region. This network should be focused on addressing and reducing key uncertainties about key North Atlantic boundaries, including the rate and scale of changes and the distance to limits and tipping points. While these are primarily linked to key challenges in atmospheric physics and chemistry, it is proposed that this coordinated network should serve to fill knowledge gaps and enable a more targeted policy response to the challenges addressed in this network. This will require the formation of a network of scientific experts across observation and integration communities, an innovative campaign to connect the public with the atmosphere via artistic media and a high-level science–policy dissemination meeting.

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Abbreviations

ACE	Aerosol Characterisation Experiment
ACE20	International meeting that was held on the 20th anniversary of ACE2
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
AERONET	Aerosol Robotic Network
AGAGE	Advanced Global Atmospheric Gases Experiment
AORA	All-Atlantic Ocean Research Alliance
CAMS	Copernicus Atmosphere Monitoring Service
CLRTAP	Convention on Long-range Transboundary Air Pollution
EARLINET	European Aerosol Research Lidar Network
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
GAW	Global Atmospheric Watch
GCOS	Global Climate Observing System
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse gas
HTAP	Hemispheric transport of air pollution
IAGOS	In Service Aircraft for a Global Observing System
ICOS	Integrated Carbon Observing System
IG3IS	Integrated Global Greenhouse Gas Information System
IGY	International Geophysical Year
IMO	International Meteorological Organization
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
IVAR	Instituto de Investigação em Vulcanologia e Avaliação de Riscos
IZO	Izaña Atmospheric Observatory station
lidar	Light detection and ranging
MEA	Multilateral environmental agreement
NASA	National Aeronautics and Space Administration
NILU	Norwegian Institute for Air Research
NOAA	National Oceanic and Atmospheric Administration
ODC	Ozone-depleting chemical
PM	Particulate matter
RI	Research infrastructure
SOLAS	The Surface Ocean–Lower Atmosphere Study
TF HTAP	Task Force on Hemispheric Transport of Air Pollution
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
WMO	World Meteorological Organization

Appendix 1 Catalogue of a Selection of North Atlantic Observational Sites

A1.1 Mace Head Research Station, Ireland

- Link to website macehead.org
- Funded by short-term research projects (MaREI, Irish EPA, Aer Lingus) without any long-term sustainable funding to support research costs.
- List of atmospheric composition measurements, instruments used and links to networks.

A1.1.1 Measurements of atmospheric composition made at Mace Head

Aerosol measurements

Measurement(s)	Since	Instrument(s)	Network(s)
Speciated PM	2008	Aerodyne aerosol mass spectrometers HR-ToF-AMS and ACSM	epa Environmental Protection Agency ACTRIS
	2002–2009	Berner, MOUDI, ELPI impactors	No international programme
Speciated inorganic PM	2001	Filter method and off-line HPLC analysis	emep ACTRIS
BC	1994	Absorption photometer Magee Scientific AE-9&16 or Thermo Fisher MAAP	World Meteorological Organization | Global Atmosphere Watch ACTRIS
Aerosol microphysics	1998 or short-term periods during campaigns prior to 2001	Scanning mobility particle sizer (SMPS) for aerosol particle dry mobility sizes from 20 to 500 nm Nano SMPS 3 to 20 nm (2002)	ACTRIS World Meteorological Organization | Global Atmosphere Watch
	2010–2017	Aerosol particle sizer 0.3–20 μm	ACTRIS

Measurement(s)	Since	Instrument(s)	Network(s)
Total condensation particle counts (CPCs)	1998	TSI CPC 3010	World Meteorological Organization | Global Atmosphere Watch ACTRIS
CCN	1995?	Custom-made CCN counter Later droplet measurement Technologies, including manufactured CCN chamber (CCNC)[26] Twomey Counters, measuring size segregated CCN	ACTRIS
Hygroscopic growth	2009	H-TDMA	No programme attached
Scattering	1998	TSI integrating nephalometer 3561 (single wavelength) from 1998 to 2008 and 3563 (3-wavelength) from 2001 to 2018, recently purchased AirPhoton nephelometer	World Meteorological Organization | Global Atmosphere Watch ACTRIS
Particulate mass	1998	TEOM PM2.5 and PM2.5 and PM10 since 2009	ACTRIS
AOD	2000–2015	Precision filter radiometer	World Meteorological Organization | Global Atmosphere Watch
POPs	2009–	Passive sampling on impregnated foam substrate	MONET
Windspeed, direction, precipitation visibility, UV radiation	2003	MÉ	MET éireann
Micro-meteorological and fluxes	2005–2009	Eddy-covariance measurement system at 10 Hz	
Cloud base determination and aerosol vertical profiling (PBL) Meteorological profiles up to 15 km Cloud properties and precipitation	2008	Ceilometers: Vaisala and Jenoptik Microwave radiometer (HATPRO) Cloud Radar Mira-35 (MEKTEK)	ACTRIS These measurements are discontinued due to lack of funding

Gaseous measurements

Measurement(s)	Since	Instrument(s)	Institution	Network(s)
Halocarbons, N_2O, SF_6, NF_3, CH_4, CO, H_2	1987 (GAGE)	GC-FID GC-ECD/FID/RGD and GC-MS coupled to a Medusa pre-concentration unit		AGAGE
CO, H_2	1995			AGAGE
CH_4	2009	Picarro G1301 series	EPA, LSCE	ICOS Integrated Carbon Observation System
CO_2	2019	Picarro G1301 series. Do not dry air, but use correction formula from Picarro to account for water vapour effect on gas concentrations	Irish EPA	epa Environmental Protection Agency
		Picarro G2301 series: ambient air using cryogenic trap	LCSE	
Radon	1995	Scintillation counter	LSCE	
O_3	1988	Commercial UV spectrometers: analyser model 49i, Thermo Electron, Inc., Franklin, MA. Details: Derwent *et al.* (2018)	UK Automatic Urban and Rural Network	World Meteorological Organization; Global Atmosphere Watch; emep
Hg (gas)	1995	Tekran 2537 instrument utilising a CVAFS detector	Helmholtz Institute of Coastal Research (https://www.hzg.de/)	epa Environmental Protection Agency

A1.2 Valentia Island Observatory

- Link to website https://www.met.ie/about-us/our-history/valentia-observatory
- Funded by the Irish meteorological authority Met Éireann.
- List of atmospheric composition measurements, instruments used and links to networks.

A1.2.1 Measurements of atmospheric composition made at Valentia

Measurement(s)	Dataset since	Instrument(s)	Network(s)
AOD	2007	Sun-tracking precision filter radiometer	GAW, ACTRIS
NO_2 (daily)	1989	1989: NO_2 TG ANSA method 2000–2002: Upgrade and comparison of NO_2 sampling systems to NaI method 2015: 8-day system NO_2 built on-site due to repeated failures with the NILU SS-2800 2017: comparison completed August 2018: NO_x sampler Teledyne T200UP, comparison commenced	EMEP
SO_2, SO_4	1980	Two-filter pack 2004: upgrade to NILU EK three filter pack sampler to include NH_4 and cations 2013: partisol 2014: on-site three filter pack sampler constructed 2018: rebuilt three filter pack sampler, comparison begins again	
Rain Na^+, Ca^+, K^+, Mg^+, NH_4-N, Cl^-,	1980s	1980: bulk collector, only some elements reported 2008–2011: bulk collector and wet-only Eigenbrodt collector	
NO_3-N, SO_4-S, conductivity – daily		2015: 8-day wet-only sampler NSA 181/KS	
Heavy metals (monthly)			EPA
pH daily			
Gamma dose rate			
Air radiation monitoring		Radiation monitor	
Rainwater radiation monitoring		Rainfall monitor, sample analysed for radionuclides	

Measurement(s)	Dataset since	Instrument(s)	Network(s)
Lightning detection		ATDNET thunderstorm system Sferic sensor	Lightning detection antenna – international network administered by UK Met Office
Ozone monitoring	1926 Ground-level, total column and stratospheric ozone measurements since 1993	GAW/EMEP/EPA	Part of the Global Ozone Observation System • Automated/continuous measurements • World ozone and UVB data • Centre – depletion recovery
Ground-level O_3		GAW/EMEP/EPA	
Total column O_3	Brewer spectrophotometer	GAW/EMEP/EPA	WMO Northern Hemisphere Ozone Mapping Centre
Total column SO_2	Brewer spectrophotometer	GAW/EMEP/EPA	
Ozonesonde	Launched monthly May to November and weekly December to April	GAW/EMEP/EPA	
Solar radiation	1954	Pyranometer	MÉ
Upper air PGMs: temperature, RH, PRS, windspeed/direction			
Developments			
GHGs (CO_2, CH_4)	2019	Picarro G1301 series. Do not dry air	Collaboration with NUIG/ Met Éireann, moving towards contributing to ICOS
BC	Instrument installed 2019, not yet operational	Absorption photometer Magee Scientific AE-9&16 or ThermoFisher	Transboundary/EPA
Speciated PM	2017 (not continuous)	Aerodyne ACSM	AEROSOURCE (EPA)
NO_x analyser	2019		EPA/EMEP
LIDAR		Cloud Radar Mira-35 (MEKTEK)	Aiming for integration into EARLINET
Radiometer		Microwave radiometer (HATPRO)	Aiming for integration into EARLINET

A1.3 Pico Mountain Observatory, Azores, Portugal

- Link to website http://pico-mt.mtu.edu/
- Operated by IVAR (Instituto de Investigação em Vulcanologia e Avaliação de Riscos) of the University of Azores (Ponta Delgada, Portugal), with the cooperation of the Michigan Technological University (Houghton, MI, USA), the Institute of Arctic and Alpine Research and the University of Colorado (Boulder, CO, USA). With political, and some financial, support from the regional government of Azores, the observatory has been able to operate essentially with research projects submitted to the USA research funding agencies.
- List of atmospheric composition measurements, instruments used and links to networks.

The station is located at an elevation of 2225 m in the free troposphere so that the station is not influenced by local emissions and can provide information about the long-range transport of pollutants from North America, Europe, Africa and the equatorial Atlantic. The observatory is operated by IVAR of the University of Azores, Portugal, with the cooperation of the Michigan Technological University, the Institute of Arctic and Alpine Research and the University of Colorado. With support from the regional government of Azores, the Pico Mountain Observatory (OMP) has been able to operate essentially with research grants submitted from USA research funding agencies. OMP was founded in 1998 – as a challenge for the university. In July 2001, under the leadership of the late Professor Richard Honrath, OMP became an experimental observatory (PICO-NARE) used to measure the transatlantic transport of pollution. Despite its years of successful operation – almost 18 years – the future of OMP remains uncertain. Principal investigators are seeking more long-term support to integrate OMP as a station in the WMO GAW programme network and as part of ACTRIS. It is hoped that the Portuguese science programmes will support the involvement of the Portuguese atmospheric community, allowing the IPMA (Instituto Português do Mar e da Atmosfera) and the Portuguese universities to be involved in solid cooperation with international partners, which should allow the establishment of a sound foundation for international cooperative research that fills a major gap in the eastern North Atlantic. In winter 2018, the station was considerably affected by a storm. Funding was procured to address the power and communication damages, but repairs had to be delayed due to the COVID-19 pandemic.

There is a need to reinforce the national research support of OMP. At present, Portugal has no representative in ACTRIS. OMP is difficult to access and has limited power supply. Therefore, any measurements made from here would have to be automated, low-maintenance and energy efficient.

A1.3.1 Description of observatory

The observatory consists of an airtight container, 2 m × 2 m × 2 m. The power cable has an effective carrying capacity of 6 kVA. Images and schematic of the observatory are shown in Figure A1.1. The observatory is connected to the internet through a wireless link to an ASDL router at a nearby high school. Operating for nearly 18 years, data from the observatory have made significant scientific contributions and have been used in 31 articles, receiving 896 citations and an H-index score of 15 (Web of Science, accessed July 2020). Data on scientific output are shown in Figure A1.2. The observatory is currently not operational. An upgrade of the present infrastructure is required to replace existing components and repair the power line. With sustainable funding, the site could be upgraded and operations could be resumed. Additional upgrades would allow OMP to contribute to the ACTRIS and GAW programmes, which would increase scientific output and extend the use of the observatory to other research fields (e.g. to measure volcanic activity). Multi-million funding would be required to fully upgrade this observatory, but after a ~5-year set-up time, the station would be expected to attract investment through service and data provision. Observatory instrumentation and data can be used as a resource for students' courses, can be used as a testbed for instrumentation development and can provide unique free tropospheric data for numerical modelling. Upgrades would raise the profile of the station, thus rendering the station more competitive within the international scientific research community.

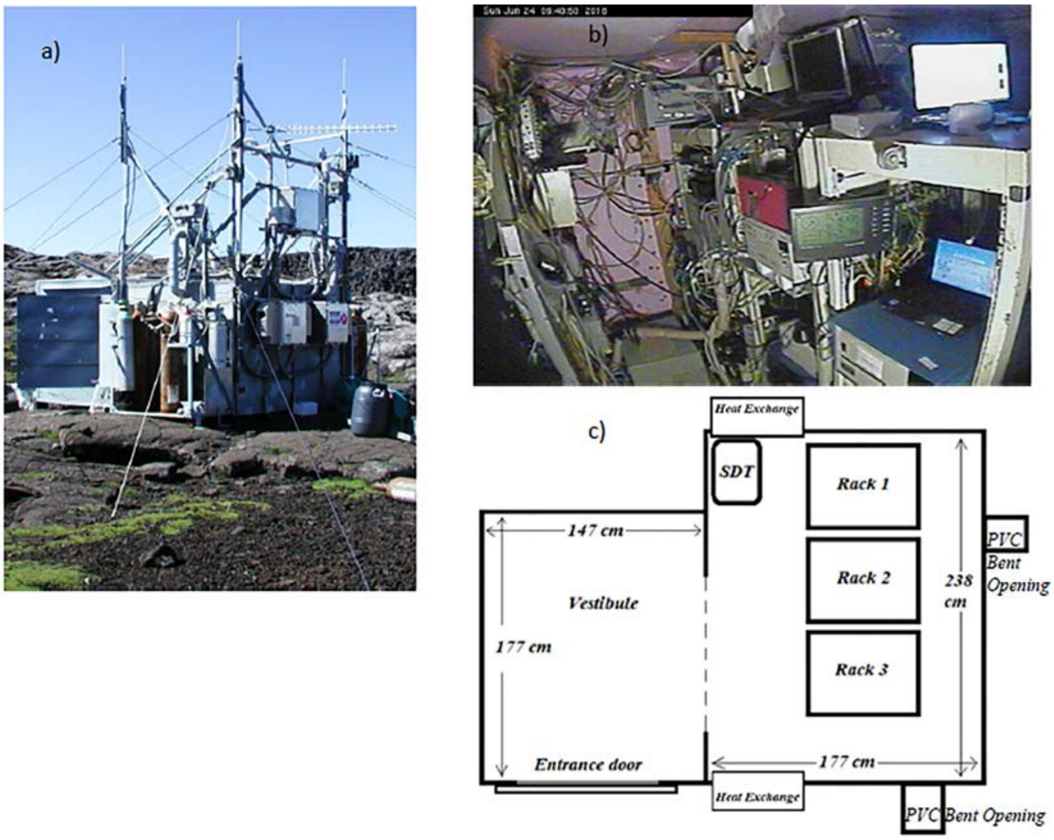


Figure A1.1. Pico Mountain Observatory. (a) Outside view, (b) inside view and (c) schematic diagram.

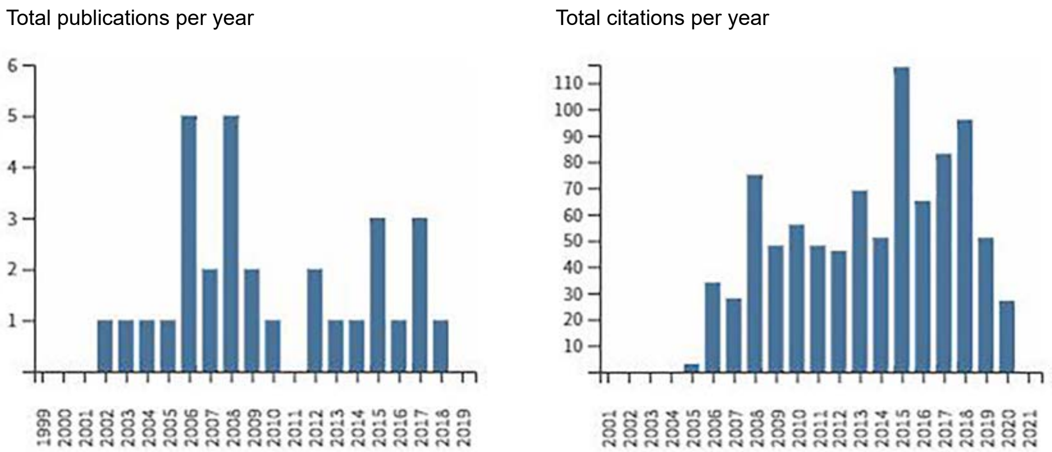


Figure A1.2. Data on scientific output from Pico Mountain Observatory (from Web of Science).

A1.3.2 Details of measurements made at Pico since its establishment

Measurement	Dataset periods	Instrument
CO	2001–2006, 2008–2014	Thermo Environmental, Inc., Model 48C-TL modified
O_3	2001–2006, 2008–2016	Thermo Environmental Instruments, Inc., Model 49C
Meteorological parameters (T, RH, P, wind)	2001–2006, 2008–2018	T, RH – Rotronic Instrument Corporation Hygroflex TM12R; Rotronic Hygroflex M1; Davis Vantage pro 2 weather station (T – Platinum thermistor; RH – Film capacitator element) P – Young Company 61201 barometric pressure sensor; Davis Vantage pro 2 weather station Wind – Propeller anemometer (Young); wind speed – wind cups and magnetic switch; wind direction – wind vane and potentiometer cup anemometer (Davis Vantage pro 2 weather station)
NO_{xy}	2002–2005, 2008–2010	NO detection by O_3 chemiluminescence; NO_2 by conversion to NO via UV photodissociation; NO_y by Au-catalysed reduction to NO in the presence of CO
NMHC	2004–2006 2009–2014	SRI Model 310 GC (SRI Instruments, Torrance, CA, USA) equipped with a flame ionisation detection
PAN	2008–2009	Estimated by subtracting NO_x from NO_y in simultaneous observations during in-cloud periods
Aerosol optical size and count	2011–2018	Intracavity laser size spectrometer (PMS-LASEX) and two-channel optical particle counter (GT-521)
Scattering and backscattering	2012–2018	Nephelometer: Aurora 3000 (450, 525, 635 nm)
Aerosol speciation	2012–2015	High-volume sampler (quartz filters)
Aerosol single particle morphology and composition	2012–2017	Custom sampler (various media for electron, optical and X-ray micro-spectrometry)
Aerosol samples for ice nucleation	2013–2017	Custom sampler and four-stage impactor
BC and elemental iron concentrations, aerosols, absorption Angström exponent, aerosol attenuation coefficients	2001–2018	Aethalometer model AE31 with HS chamber (370, 470, 520, 590, 660, 880, 950 nm)

A1.4 Zeppelin Observatory

- Link to website https://www.npolar.no/en/zeppelin//
- Located on the Zeppelin Mountain (474 m a.s.l.), close to Ny-Ålesund on Svalbard, the Zeppelin Observatory's unique location, together with the infrastructure at Ny-Ålesund, makes it ideal for research on global and hemispheric changes and Arctic studies. Measurements from this observatory serve to increase our understanding of the processes relevant to the ever-changing Arctic region. The warming occurring in the Arctic exceeds warming observed in other locations and hence, as predicted by model simulations, the Arctic amplification of climate change.
The observatory is owned by the Norwegian Polar Institute (development, maintenance, management and safety) and coordinated

scientifically by the Norwegian Institute for Air Research (NILU), with the main users of the observatory being NILU, Stockholm University and the Norwegian Polar Institute.

- A report on the flagship programme of atmospheric research at Zeppelin observatory, including an overview of atmospheric parameters measured, is available (Neuber *et al.*, 2011).

A1.5 Izaña Atmospheric Observatory

- Link to website https://izana.aemet.es/
- The Izaña Atmospheric Research Center is part of the Department of Planning, Strategy and Business Development of the State Meteorological Agency of Spain (AEMET). AEMET is an agency of the Spanish Ministry for the Ecological Transition and Democratic Challenge (MITECO).
- List of atmospheric composition measurements, instruments used and links to networks.

A1.5.1 Description of observatory

The Izaña Atmospheric Observatory station (IZO) has been submitting uninterrupted meteorological and climate observations from its present location since 1916 and has contributed to the WMO GAW programme since the establishment of the network in 1989. As a GAW global station, it acts as a centre of excellence, performing cutting-edge research on atmospheric compositional change. IZO is one of the four research stations in Tenerife managed by the Izaña Atmospheric Research Centre. Located ~300 km west of the African coast and 15 km north-east of the volcano Teide, IZO is at an altitude of 2373 m above sea level, normally above a temperature inversion and below the descending branch of the Hadley cell, and hence perfectly located for free tropospheric measurements, particularly for investigation of dust transport from Africa to the North Atlantic, trans-Atlantic pollutant transport and northward transport from the tropics.

A1.5.2 Measurements of atmospheric composition made at Izaña

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
GHs and carbon cycle			
CO_2	1984+	NDIR Licor 7000 (primary instrument) NDIR Licor 6252 (secondary instrument) CRDS Picarro G2401	CarbonTracker CarbonTracker EU GCOS
CH_4	1984+	GC-FID Dani 3800 GC-FID Varian 3800 CRDS Picarro G2401	Globalview-CH_4
N_2O	2007+	GC-ECD Varian 3800 Los Gatos Research 913-0015	ICOS Integrated Carbon Observation System
SF_6	2007+	GC-ECD Varian 3800	
CO	2008	GC-RGD Trace Analytical RGA-3 CRDS Picarro G2401 Los Gatos Research 913-0015	Globalview-CO World Meteorological Organization / Global Atmosphere Watch ICOS Integrated Carbon Observation System

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
***In situ* reactive gases**			
O_3	1987+	UV photometry Teco 49-C (primary instrument) Teco 49-C (secondary instrument) Teco 49-I (new primary instrument)	
CO	2004+	Non-dispersive IR abs. Thermo 48C-TL	
SO_2	2006	UV fluorescence Thermo 43C-TL	
NO-NO_2-NO_x	2006	Chemiluminescence Thermo 42C-TL	
Ozone vertical profiles	1992	Electrochemical concentration cell ECC-5A/ECC-6A	
Total ozone column and UV			
Column O_3, spectral UV: 290–365 nm, column SO_2	1991	Brewer Mark-III #157 (primary reference) Brewer Mark-III #183 (for developments) Brewer Mark-III #185 (travelling reference)	WOUDC COST1207 EUVDB http://www.ozone.fmi.fi/uvdb/
Spectral UV: 290–450 nm	May 1998	Bentham DM 150 (campaign basis)	

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
Column O_3, Column NO_2	2011	Pandora 101 Pandora 121	
Fourier Transform Infrared Spectroscopy (FTIR)			
GHGs, reactive gases and O_3-depleting substances (O_3, HF, HCN, HCl, $ClONO_2$, C_2H_6, HNO_3, CH_4, CO, CO_2, N_2O, NO, NO_2, H_2O, HDO, OCS)		Fourier Transform Infrared Spectroscopy Bruker IFS 120/5HR (co-managed with KIT)	NDACC, TCCON, TOAR (International Global Atmospheric Chemistry), LOTUS (WMO/SPARC/IO3C)
	1999	Middle infrared (MIR) solar absorption spectra	
	2007	Near infrared (NIR) solar absorption spectra	
Greenhouse gases (CO_2, CH_4, H_2O), and reactive gases (CO)	2018	Fourier Transform Infrared Spectroscopy Bruker EM27/SUN	COCCON
Water vapour isotopologues (δD and $\delta_{18}O$)	2012	Picarro L2120-I δD and $\delta_{18}O$ Analyser	Stable Water Vapor Isotope Database (SWVID)
***In situ* aerosols (potentially in ACTRIS – GAW)**			
Chemical composition of total particulate matter (PM_T)	1987	High-volume sampler Custom built/MVC™/MCZ™ Concentrations of soluble species by ion chromatography (Cl^-, NO^-_3 and SO_4 =) and FIA colorimetry (NH_4^+), major elements (Al, Ca, K, Na, Mg and Fe) and trace elements by ICP-AES and ICP-MS were determined at CSIC	
$PM_{2.5}$ chemical composition	2002	High-volume sampler Custom built/MVC/MCZ	
PM_{10} chemical composition	2005	High-volume sampler Custom built/MVC/MCZ	
Particle number > 3 nm	2006–2017	TSI, UCPC 3025A	
Number of particles > 2.5 nm	2012	TSI, UCPC 3776	
Number of particles > 10 nm	2012	TSI, CPC 3010	
Size distribution of 10–400 nm	2006	TSI, class 3080 + CPC 3772	
Size distribution of 0.7–20 µm	2006	TSI, APS 3321	

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
Absorption coefficient 1λ	2006	Thermo, MAAP 5012	
Attenuation 7λ	2006	Magee, Aethalometer AE31-HS	
Scattering coefficient 3λ	2008	TSI, Integration Nephelometer 3563	
PM_{10} concentration	2015	Thermo, BETA 5014i	
$PM_{2.5}$ and $PM_{2.5–10}$ concentrations	2015	Thermo, TEOM 1405DF	
Column aerosols			
AOD and Angström at 415, 499, 614, 670, 868 and 936 nm	1996	YES Multi Filter-7 Rotating Shadow-Band Radiometer (MFRSR)	
AOD and Angström at 340, 380, 440, 500, 675, 870, 936 and 1020 nm Fine/coarse AOD Fine mode fraction Optical properties	2003	CIMEL CE318 sun photometer	
AOD and Angström during day/night period	2012	CIMEL CE318-T sun-sky-lunar photometer	
AOD and Angström at 440, 500, 675 and 870 nm	2015	Zenith-looking narrow-band radiometer (ZEN)	
AOD and Angström at 300 and 1100 nm wavelength range (average step of ~0.4 nm)	2017	EKO MS-711 spectroradiometer	
AOD and Angström at 368, 412, 500 and 862 nm	2001	WRC Precision Filter Radiometer (PFR)	
AOD at 769.9 nm	1976	MARK-I (at the IAC)	

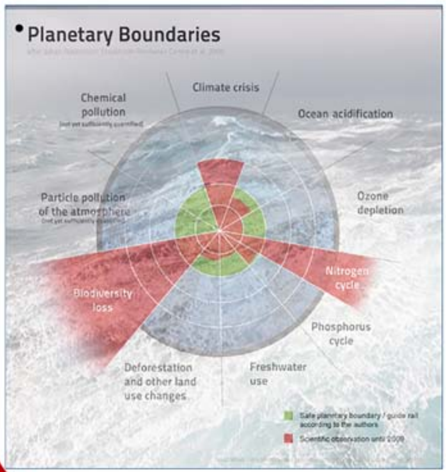
Measurement(s)	Dataset periods	Instrument(s)	Network(s)
Vertical backscatter-extinction at 523 nm, cloud altitude and thickness	2018	Micropulse Lidar MPL-3, SES Inc., USA (co-managed with INTA (www.inta.es))	
Vertical backscatter-extinction at 532 nm, cloud altitude and thickness, and volume depolarisation ratio at Santa Cruz	2018	Micropulse Lidar MPL-4B (MPL-P), SES Inc., USA (co-managed with NASA)	MPLNET
Vertical backscatter-extinction at 532 nm, cloud altitude and thickness, and volume depolarisation ratio at Izaña	2020	Micropulse Lidar MPL-4B (MPL-P), SES Inc., USA	NASA pulse Lidar network
Radiation: Baseline Surface Radiation Network			
Global radiation 285–2600 nm	1977	2 CM-21 & CM-11 Kipp & Zonen Pyranometer (in parallel) and EKO MS-801	WRMC-BSRN World Radiation Monitoring Center-Baseline Surface Radiation Network
Diffuse radiation (285–2600 nm)	2005	2 CM-21 Kipp & Zonen Pyranometer (in parallel) and EKO MS-801	
Global radiation 300–1000 nm Estimated direct radiation Diffuse radiation	1996	YES MFRSR	
Direct radiation 200–4000 nm	2005	2 CH-1 Kipp & Zonen and EKO MS-56 Pyrheliometers	
Direct radiation 200–4000 nm	2014	Absolute Cavity Pyrheliometer PMO6 (campaigns only)	
Spectral direct radiation	2016	Spectror radiometer EKO MS-711	
Downward longwave radiation 4.5–4.2 μm	2009	2 CG-4 Kipp & Zonen Pyrgeometer (in parallel)	
UVB radiation 315–400 nm	2005	2 Yankee YES UVB-1 Pyranometer (in parallel)	
UVA radiation 280–400 nm	2009	Radiometers UVS-A-T	
PAR 400–700 nm	2005	Pyranometer K&Z PQS1	
Net radiation	2016	Net Radiometer EKO MR-60	
DOAS (managed by the Spanish National Institute for Aerospace Technology, INTA)			
Column NO_2	1993	UV-VIS DOAS EVA and MAXDOAS RASAS II (INTA's homemade; www.inta.es)	
Column O_3	2000	UV-VIS MAXDOAS ARTIST II (INTA's homemade)	

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
Column BrO	2002	UV-VIS MAXDOAS ARTIST II (INTA's homemade)	
Tropospheric O_3, NO_2, IO	2010	UV-VIS MAXDOAS ARTIST II (INTA's homemade)	
Column HCHO	2015	UV-VIS MAXDOAS ARTIST II (INTA's homemade)	
Column water vapour			
Precipitable water vapour (PWC)	1996	YES MFRSR-7 Radiometer (941 nm)	
PWV	2008 2003 1999	GPS-GLONASS LEICA receiver CIMEL CE318 sun photometer FT Infrared Spectroscopy (3 days per week in cloud-free conditions)	E-GVAP Programme (GNSS Water Vapor Programme from EUMETNET)
Vertical RH	1963	Vaisala RS-92	
Meteorology (GCOS, GRUAN)			
Temperature, RH	1916	THIES CLIMA 1.1005.54.700 3 VAISALA HMP45C (in parallel) VAISALA PTU300 THIES CLIMA 1.0620.00.000 (thermo-hygrograph) CAMPBELL SCIENTIFIC CS215 (tower top)	
Wind direction and speed	1916	DELTA OHM Sonic 3D HD2003 Young Wind Monitor HD Alpine 05108-45 Young Wind Monitor HD Alpine 05108-45 Young Wind Monitor HD Alpine 05108-45 (tower top)	
Pressure	1916	SETRA 470 VAISALA PTU 300 BELFORT 5/800AM/1 (Barograph) SETRA 470 (tower top)	
Rainfall	1916	THIES CLIMA Tipping Bucket THIES CLIMA Tipping Bucket Hellman rain gauge Hellman pluviograph	
Sunshine duration	1916	KIPP & ZONEN CSD3 Campbell Stokes sunshine recorder	
Present weather and visibility	1941	THIES CLIMA drisdrometer BIRAL 10HVJS	

Measurement(s)	Dataset periods	Instrument(s)	Network(s)
Vertical profiles of T, RH, P, wind direction and speed (up to 30 km altitude)	1963	RS92+GPS radiosondes launched at Güimar automatic radiosonde station (WMO GUAN station #60018) (managed by the Meteorological Centre of Santa Cruz de Tenerife) × 2 daily	
Soil temperature Surface 20 cm, 40 cm	1963 2003	2 THIES CLIMA Pt100 (in parallel)	
Atmospheric electric field	2004	Electric Field Mill PREVISTORM-INGESCO	
Lightning	2004	Boltek LD-350 Lightning Detector	
Cloud cover	2008	Sieltec Canarias S.L. SONA total sky camera	
Fog-rainfall	2009	THIES CLIMA Tipping Bucket with 20 cm^2 mesh Hellman rain gauge with 20 cm^2 mesh	
Sea-cloud cover	2010	AXIS Camera: West View (Orotava Valley) AXIS Camera: South View (Meteo Garden) AXIS Camera: North View AXIS Camera: East View (Güimar Valley)	
Drop size distribution and velocity of falling hydrometeors	2011	OTT Messtechnik OTT Parsivel	

Appendix 2 Science Strategy Meeting Invitation, Agenda and List of Attendees

A2.1 Exploring the Atlantic Boundaries of the Atlantic Atmosphere Science Strategy Meeting 9 and 10 November



The impact of human activity since industrialisation has altered the state of the environment, pushing the boundaries of environmental stability to the point of threatening the future of life on earth. There is evidence that this threshold has already been crossed due to anthropogenic radiative forcing, bio diversity loss and disruption to the Nitrogen cycle. Breach of the boundaries of planetary stability risks abrupt and non-linear alterations to our environment, with major implications for societal and economic systems. The atmospheric sphere and its changing composition both reflect and drive the pressures applied to the boundaries of environmental stability. Here the aim is to focus the planetary boundaries concept on the Atlantic Ocean and particularly, the atmospheric composition of the North Atlantic region.

The Atlantic Ocean, particularly the North Atlantic, is at the forefront of environmental change owing to its particular characteristics, including biogeochemical cycles, the Greenland ice shelf, shared boundary with the Arctic region and the circulation patterns that regulate climate and weather at multiple scales. The region is centrally impacted by these changes, with potentially large-scale implications for the surrounding regions. Owing to its geographical span and its observational and scientific capacity, the North Atlantic scientific community is uniquely positioned to assess these impacts and to inform effective integrated responses to these challenges.

A virtual science strategy meeting "**Exploring the Boundaries of the Atlantic Atmosphere**" will take place on 9–10 November as part of the Irish EPA-funded ANIAR project exploring the boundaries of North Atlantic atmospheric research.

The aim of the meeting is **to articulate the views of the scientific community** on the following subjects:

- What research is currently underway regarding the atmospheric composition of the North Atlantic and how does it relate to environmental sustainability?
- What factors are limiting progress in research, and what is needed to surmount these limitations and enable science that is pertinent to formation of effective policy to address major environmental challenges in the North Atlantic region?
- How can the scientific community come together as an integrated atmospheric research network for the North Atlantic, poised to address societal challenges?

The meeting **outcome** will be a report outlining steps that are required to develop an integrated approach to **better protecting the North Atlantic and the surrounding regions**.

9 November 2020		
Time (GMT)	**Opening**	**Names (TBC)**
14:00	Motives for the Atlantic Boundaries initiative	Frank McGovern
	Lessons from the ocean	Peter Heffernan
	A view from North America	Len Barrie
	A view from Europe	Wence Aas
	Discussion	
15:30	~Break~	
16:00	Observation systems: scope and purpose	
	Overview of *in situ* observation	Liz Coleman
	View from space: NASA	Barry Lefer
	Discussion	
18:00 end of day 1		
10 November		
14:00	**Research Initiatives and Integrating Systems**	
	Linking communities	Liz Coleman
	SOLAS	Jurgita Ovadnevaite
	AIR	Rui Martins
	Copernicus	Vincent-Henri Peuch
	CLRTAP	Tim Bulter
	Discussion	
16:00	Break	
16:30	Conclusions and outcomes	
17:15	Close of meeting	

Attendee	email	Institution
Peter Heffernan	peterbheffernan@gmail.com	EU Mission Board
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Attendee	email	Institution
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Bo Zhang	bo.zhang@nianet.org	National Institute of Aerospace
Savannagh Lewis	sll022@ucsd.edu	SCRIPPS

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;

> Sceitheadh fuíolluisce uirbigh;

> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;

> Foinsí radaíochta ianúcháin;

> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;

> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;

> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;

> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú

> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;

> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;

> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;

> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;

> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;

> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;

> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;

> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;

> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;

> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;

> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;

> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;

> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;

> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;

> 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 um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;

> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;

> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;

> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

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

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research

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LinkedIn: www.linkedin.com/showcase/eparesearch/
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