atmosphere

MDPI

Review

Envisioning an Integrated Assessment System and Observation Network for the North Atlantic Ocean

Liz Coleman [1,*], Frank M. Mc Govern [2], Jurgita Ovadnevaite [1], Darius Ceburnis [1], Thaize Baroni [1], Leonard Barrie [3] and Colin D. O'Dowd [1]

[1] Ryan Institute Centre for Climate & Air Pollution Studies, School of Physics, National University of Ireland, H91 CF50 Galway, Ireland; jurgita.ovadnevaite@nuigalway.ie (J.O.); darius.ceburnis@nuigalway.ie (D.C.); t.baroni1@nuigalway.ie (T.B.); colin.odowd@nuigalway.ie (C.D.O.)
[2] Irish EPA, McCumiskey House, Richview, Clonskeagh Rd, D14 YR62 Dublin, Ireland; f.mcgovern@epa.ie
[3] Department of Atmosphere and Ocean Science, McGill University, Montreal, QC H3A 0B9, Canada; leonardbarrie@gmail.com
* Correspondence: mary.coleman@nuigalway.ie

Abstract: The atmosphere over the Atlantic Ocean is highly impacted by human activities on the surrounding four major continents. Globally, human activity creates significant burdens for the sustainability of key Earth systems, pressuring the planetary boundaries of environmental sustainability. Here, we propose a science-based integrated approach addressing linked science and policy challenges in the North Atlantic. There is a unique combination of ongoing anthropogenic changes occurring in the coupled atmosphere–ocean environment of the region related to climate, air and water quality, the biosphere and cryosphere. This is matched by a unique potential for the societies that surround the North Atlantic to systematically address these challenges in a dynamic and responsive manner. Three key linked science-policy challenges to be addressed as part of this proposed integrated regional approach are: (1) understanding physical and dynamic changes, (2) sustaining human and ecosystem health and (3) reducing existing knowledge gaps on the carbon budget and the Earth's energy balance. We propose a North Atlantic multidisciplinary scientific assessment system and observation network to address these thematic challenges. We propose to build on and link with the existing research activities and observational networks and infrastructures to specifically address the key North Atlantic challenges that encompass a range of policy areas. This will strengthen the institutional response to weather, climate, environmental and ecological threats and reduce societal risk.

Keywords: observation; North Atlantic; integration; atmospheric composition; climate change

Citation: Coleman, L.; Mc Govern, F.M.; Ovadnevaite, J.; Ceburnis, D.; Baroni, T.; Barrie, L.; O'Dowd, C.D. Envisioning an Integrated Assessment System and Observation Network for the North Atlantic Ocean. *Atmosphere* **2021**, *12*, 955. https://doi.org/10.3390/atmos12080955

Academic Editors: Kathleen Mar, Charlotte Unger and Eric Zusman

Received: 21 April 2021
Accepted: 9 July 2021
Published: 24 July 2021

1. Introduction

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 and societal stability [1]. It has gained traction with public policy makers as well as in academic circles. It 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 [2]. At a policy level, a series of Multilateral Environmental Agreements (MEAs) were adopted during the second half of the 20th century to address various climate and atmospheric environmental issues. Atmospheric protection has been well served by three MEAs—the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Vienna Convention for Protection of the Ozone Layer and the UN Framework Convention on Climate Change (UNFCCC). The UNFCCC was one of the three Rio Conventions opened for signatures at the UN Rio Earth Summit in 1992. The other two

Rio Conventions are the UN Convention on Biological Diversity and the Convention to Combat Desertification. Policy links between these three conventions are articulated under the UN Commission on Sustainable Development (CSD); most recently as the Sustainable Development Goals (SDGs).

A range of scientific assessment and observation support systems have developed to inform and support the implementation of the three MEAs. These include the evolution of a number of environmental measurement communities: The World Meteorological Organisation's Global Atmospheric Watch Programme (WMO GAW), which is mandated 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; GCOS, which monitors Essential Climate Variables (ECVs) under the UNFCCC; EMEP, which provides sound scientific support to the CLRTAP by collecting air pollution emission data via quality-controlled measurement network and modelling of atmospheric transport and deposition; AGAGE, which has been augmenting the WMO GAW by measuring non-CO_2 greenhouse gases and ozone-depleting chemicals (ODCs) to ensure compliance with the Montreal Protocol of the Vienna Convention.

Many scientific and organisational partnerships exist between the atmospheric observations communities. However, we have yet to see an integrated, unifying approach to assessing our knowledge of the interactions and feedbacks between changing atmospheric composition and the Earth system globally. Regionally, there has been a successful ongoing effort under the Arctic Monitoring and Assessment Program (AMAP) to do this for the Arctic since 1991 (https://www.amap.no/ (accessed 20 July 2021). In contrast, for the North Atlantic region, an integrated approach to assessment of aggregated policy measures on atmospheric protection and the Earth system is not facilitated within existing structures and frameworks.

The Earth exists as a complex, synergistic organism in which components and processes are interdependent and self-regulating in response to changes [3]. The atmosphere cannot be considered as a distinct entity, but as a realm that is fundamentally and intrinsically connected to all components of the Earth system. Understanding the impacts of changes and the implications of atmospheric protection strategies requires integration of advanced, sustained measurements that allow the analyses needed to gain a better understanding of interactions and feedbacks and better early warnings for environmental events necessary to address interconnected societal and environmental challenges [4].

Here, we propose the development of an international regional forum to assess integrated environmental threats related to atmospheric compositional changes in the North Atlantic region as has been achieved for the Arctic. This North Atlantic forum will focus on addressing the fundamental scientific issues and key uncertainties that are central to environmental policy areas, thus providing a tangible focus for the planetary boundaries concept in the context of the region.

The North Atlantic focus here is necessitated by the combination of ongoing changes occurring in the region, the significant vulnerabilities owing to the geographic and socio-demographic characteristics of the region and, particularly, the unique capacity of areas that surround the North Atlantic to systematically address these challenges in a dynamic and responsive manner. Three linked science-based thematic policy challenge areas to be assessed by the forum are identified.

1. Understanding physical and dynamic changes; including the sea-level rise, cryosphere loss in the Arctic and Greenland, changes and trends in the major Atlantic currents with particular attention on the Atlantic Meridional Overturning Circulation (AMOC) and the regional tele-connections between weather and climate systems.
2. Human and ecosystem health, including the chemical fluxes and pathways that determine the regional atmospheric composition, e.g., atmospheric ozone concentrations, Persistent Organic Pollutants (POPs), carbonaceous species and inorganic compounds, and the influences of periodic large-scale biophysical events such Saha-

ran dust plumes from North Africa as well as biogenic emissions from natural and managed systems.

3. Constraining carbon budget ranges for global temperature increments through reducing uncertainty on 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 estimation of carbon budgets that are compatible with the temperature goal established in the Paris Agreement. However, uncertainty in estimation of carbon budgets reduces the policy effectiveness of limiting warming by curbing emissions [5]. Much of the associated uncertainty in radiative forcing is linked to the direct and indirect (cloud) effects of aerosols, the radiative properties of carbonaceous aerosols and atmosphere–surface gas exchanges that influence the carbon budget. The North Atlantic is uniquely situated to determine the impacts of a range of aerosol types on energy fluxes as well as alterations to biogeochemical cycles that influence the carbon budget. A reduction in the uncertainties surrounding these processes requires the planned development of a network of linked high-precision in situ and remote observations, tailored to integrate 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.

Advancement of these three objectives would be achieved through the establishment and maintenance of an Integrated Atmosphere/Ocean Observing/Modelling System and a forum to assess the changing state of the atmosphere. The aim of the proposed forum is to address key science-policy challenges in an integrated manner using the assets and resources that are available in the region, by building on and enhancing existing measurement and research communities, thus developing the North Atlantic region as a large-scale platform to explore and resolve key uncertainties in these areas as well as the inter-related feedbacks. This platform would assist in improving weather prediction and climate projections, including projections of sea-level rise. It would focus on the key thresholds and tipping points that are unique to this region and specifically the stability of the AMOC, the Greenland ice shelf, the seasonal loss of arctic ice cover as well as the future impact of tropical cyclones in the south of the region. A key product would be regular dissemination of findings with an emphasis on communicating outputs relevant for the generation of cross-cutting environmental policy.

The need to strengthen the in situ, sustained observational capacity of Essential Climate Variables (ECVs) has been previously highlighted [6,7]. Although there currently exists interaction and collaboration between the various measurement communities serving the North Atlantic region, geographical measurement gaps remain (See Figure 5.1 in ACE20 report [8]) which propagate to gaps in scientific understanding of environmental processes and hence the potential impacts of environmental change. Possible mitigation options are not well elucidated [9]. Furthermore, many existing sites struggle to secure sustained funding that is fundamental to the functioning of surface-based observing networks [8].

An integrated, robust observational system will require coordinated investment to fill in this observational gap and to establish the integrated analysis and assessment platform which will build on existing activities and structures that have been established under the international bodies including the conventions and their support-structures. The platform will incorporate the emerging European Research Infrastructures (ESFRIs) ICOS, ACTRIS, and IAGOS, which, respectively, monitor GHGs, atmospheric aerosols and reactive gases and a suite of aerosols and gases using commercial aircraft. These ESFRIs were developed closely in tandem, collaborate on data interoperability and are working on further integration [10], hence are well positioned to contribute to integrate assessment. The proposed platform would also work across global remote sensing programmes including the flagship Earth Observation Programme Copernicus, NOAA and NASA. Satellite measurement technology is continuously and rapidly advancing, yet in situ measurements are required not only for advanced data-fusion products, but for ground-truthing - the backbone necessary for the underpinning of space-borne remote sensing.

2. Societal and Scientific Context

Over 40% of the population live in coastal regions in both EU-27 regions and the US [11,12]. Coastal regions are major economic, societal and cultural centres which have developed and evolved over millennia, major coastal cities and population centres thrive as major economic centres, enhanced by the development of recreational and tourism facilities. These developments are contingent on access to a safe, healthy and thriving environment and the continued stability of weather and climate systems. Populations in proximity to the coast are disproportionally vulnerable to the effects of the changing Atlantic region, with significant implications for human health and well-being as well as societal and economic implications.

The North Atlantic Ocean spans an area in excess of 41 million km^2, stretching from Newfoundland to North Africa and Latin America, connecting four major continents, including two of the most developed regions in the world: the USA/Canada and Europe. It contains unique areas with major regional and global influences; dust from the Sahara Desert is advected across the Atlantic to the Amazon, replenishing the stores of phosphorous necessary to sustain the vitality of the great Rain Forests of Latin America [13,14]. The Atlantic is bound in the north by the Arctic Eurasian Basin and surrounds the massive Greenland ice sheet, the existence of which is under threat from climate change and holds enough water to cause 7.4 m of sea-level rise (SLR) [15]. The oceans are a sink for 40% of anthropogenic CO_2 emitted to the atmosphere [5,6] and they absorb over 90% of the additional energy being trapped by addition of anthropogenic GHGs. Increasing ocean temperature leads to sea-level rise and ocean acidification.

Large-scale ocean currents redistribute heat added to the surface ocean. In the North Atlantic, the AMOC is a primary driver of ocean circulation, regulating regional climate on both sides of the Atlantic, modulating carbon sequestration and interacting with atmospheric circulation patterns marked notably by the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). The AO determines the strength of the polar vortex which affects stratospheric ozone depletion [16]. The multidecadal climate variability in the North Atlantic is driven by the AMOC and the sea-surface temperature-based Atlantic Multidecadal Oscillation (AMO), the two climatic cycles interacting with each other [17,18]. The AMO has a major societal impact, influencing regional weather events, e.g., Sahel rainfall [19], European precipitation [20], North Atlantic hurricanes [21] and temperature variations [22,23]. It is influenced by the NAO [24]. These periodic circulation patterns all represent different aspects of the physical dynamical aspects of the Atlantic that influence and are influenced by climate and hence, a robust understanding of these regional climate patterns and air–sea interactions is vital in order to assess the state of our changing climate [6,25].

Many global environmental changes and trends are first evident, and in some cases, amplified in the North Atlantic region, which render the region vulnerable to further environmental change. These changes manifest over a range of timescales. Changes occurring due to elevated CO_2 emissions are essentially irreversible over century to millennial time scales [26]. Atmospheric observations and scientific assessment in recent decades have provided significant enhancement in our understanding of Earth-system processes affecting the environment. There now exists an opportunity to take advantage of existing structures to integrate atmospheric observations over the North Atlantic to advance our understanding of drivers and consequences of atmospheric change in terms of the three science-policy thematic challenges identified above.

3. Science-Policy Thematic Challenges

3.1. Physical and Dynamic Changes

In recent decades, the pace of Arctic warming has exceeded model predictions and warming observed in other regions—this is referred to as the Arctic amplification (AA) of climate change. The accelerated warming is variable over decadal timescales, strongly correlated with the AMO [27]. AA has been attributed to both atmospheric response to radiative forcing [28] and changes in seasonal sea-ice cover and thickness of sea ice [29]. The fate of sea ice is strongly coupled to dominant atmospheric circulation patterns influencing the Northern Hemisphere: the Arctic Oscillation (AO), which modulates the polar vortex, affecting weather patterns over the Northern Hemisphere, and the North Atlantic Oscillation (NAO) [30–32]. Variations of the AO and NAO strongly affect the regional climate of the North Atlantic [33] and have significant consequences for society and the environment [34]. The NAO has been shown to modulate the Atlantic Meridional Overturning Circulation (AMOC), which plays a significant role in cross-equatorial heat distribution [35–37], sequestering both heat anomalies and carbon to the deep ocean interior, thus regulating global temperature and the carbon cycle. Modifications to the AMOC would affect the AMO, which would again influence AA [27].

The AMOC has been weakening in recent years and is predicted to further decelerate in a changing climate [38,39], exacerbated by stronger Arctic warming. The weakening occurs due to freshwater inflow, which reduces the salinity gradient that drives the AMOC. Recent studies have shown that the inflow of freshwater supresses downward, mixing by forming a barrier layer that prevents surface fluxes. This leads to an anomalously warm surface layer beneath the surface cap, which becomes buoyant, further weakening the AMOC [40]. The AMOC slowdown impedes the delivery of warmer waters to the mid latitudes, leading to a decline in sea and air surface temperature in the NA region known as the "Cold Blob" or the North Atlantic Warming Hole [41]. Furthermore, a slowing AMOC has been implicated in sea-level rise (SLR) in the Mediterranean Sea [42] and on the Eastern coast of the US [43], with devastating effects on low-lying coastal communities in the mid-Atlantic region [44]. There has been major loss of the Greenland ice shelf with climate change, where observations show an increase in coastal temperatures in Greenland of 4.4° from 2009 to 2019, with each 1 °C of summer warming leading to 116×10^9 tonne mass loss from ice sheet per annum [45]. Along with thermal expansion, disintegrating ice sheets and melting glaciers have contributed to global SLR of 19 cm since 1900 [46].

Vulnerabilities of the North Atlantic

The North Atlantic is susceptible to physical and dynamical changes owing to its shared interface with the rapidly changing Arctic region and the Greenland ice shelf, which has experienced a 5-fold increase in the ice loss rate since 1992, contributing to a mean SLR of 10 mm [47]. These changes propagate to the dominant North Atlantic circulation patterns, which have profound impacts on both global and regional climate systems [48], affecting the rate of glacial retreat on the Greenland ice shelf, sea-ice melt rates, sea level and ocean salinity, biogeochemical processes and distribution of marine ecosystems [49,50], changes in terrestrial CO_2 sink [51], strength of the polar vortex and stratospheric cooling [52], and the coupling between the patterns can lead to feedbacks that could lead to tipping points, as has been identified in the Barents Sea [53]. Reaching this tipping point would greatly accelerate arctic sea-ice reduction, with implications for Atlantic circulation patterns and ecosystems, species distribution and commercial activities. It is very likely that the AMOC will weaken over the coming decades under increased radiative forcing due to the relentless rise of GHGs [54]. Modelling studies indicate that AMOC–AMO interactions are perturbed by anthropogenic forcing [55], with recent studies suggesting the AMO to be entirely caused by external anthropogenic and volcanic forcing [56].

The winter-time North Atlantic climate system is subject to mid-latitudinal westerly winds and storminess, which subject North American and European coastlines to extreme winds and associated coastal risks. The North Atlantic storm intensities and tracks are modulated by the atmospheric and oceanic modes of variability, the NAO, the AMOC and the AMO [21,57,58]. The risk of severe storms will increase in the future for the North Atlantic and northern, north-western and central Europe with considerable economic and societal impact [57].

Quantification of future sea-level rise is still uncertain. There is an upper estimate of 2.4 m rise by 2100 [58,59], posing considerable challenges for the densely populated regions on both sides of the Atlantic which will become increasingly vulnerable to coastal city flooding and environmental deterioration, with a unique 1000 km hotspot on the North American coast [60].

The observed weakening of the AMOC affects ocean-heat transport to the Atlantic and Artic [61] and carbon sequestration and ocean acidification [62], with significant implications for marine biota as well as the global carbon budget. The AMOC consumes over 70% of the dissolved organic carbon (DOC) in the entire Atlantic [63].

Perturbations to the AMOC will have compound impacts on the carbon cycle, with positive and negative feedbacks, the net effect of which are as of yet unknown [64–66]. Paleoclimatic periods defined by weakening AMOC have been shown to perturb atmospheric CO_2 from both oceanic and terrestrial sources within centuries following the AMOC perturbation [67], which will further affect radiative forcing.

3.2. Human and Ecosystem Health

Changes to the regional atmospheric composition have direct and indirect implication for human health, altering or contaminating ecosystem operations via ambient exposure and deposition of atmospheric constituents [68,69]. Seasonal loss of upper atmosphere ozone increases exposure to damaging UV radiation [70], as observed in spring 2020 [71]. Transport of hemispheric-scale pollutants such as ground-level ozone, POPs and black carbon (BC) have impacts on human health and the vitality of ecosystems. Key uncertainties exist in these biophysical and chemical systems and pathways due to changes to natural and managed terrestrial systems as well as the impacts of large-scale natural and anthropogenic emissions.

The CLRTAP has significantly contributed to formation of international legal instruments to protect the atmosphere and reduce the harmful effect of air pollution on the environment, the collective effort reducing emissions of harmful pollution by 40–80% since 1990 in Europe [72]. A reduction in sulphur-containing compounds has promoted the growth of healthy forest and soils, relevant for food security and emission reduction has reduced deposition of acidic compounds to levels below critical loads. Figure 1 shows the non-sea salt sulphate measured at Mace-Head fitted over exponential fit applied to non-sea salt sulphate measured at Valentia over a 35 year period (95% confidence band of exponential fit).

Despite the success of the CLRTAP, air pollution remains a global problem. Over 90% of the global population breathe polluted air, ambient air pollution causing an excess of 4 million deaths annually [73]. Smoke from wildfires can inject significant plumes or emissions including black carbon (BC) into the atmosphere to high altitudes, whereby it can be transported over hemispheric scales [74], affecting the radiative budget. Long-range transport of smoke has also been positively correlated with cardiopulmonary hospitalisations and deaths, the ageing that smoke particles undergo during transport increasing the oxidative capacity and hence the toxic health effects [75] and wildfire smoke has been identified as a pollution source that is highly impactful on human health, in comparison with other sources of fine particles [76]. North American wildfire emissions transported across the North Atlantic have been detected in Western Europe [77–79], and potential health effects are not elucidated, yet it has been suggested that carbonaceous aerosols are among the most toxic particulate air pollutants [80].

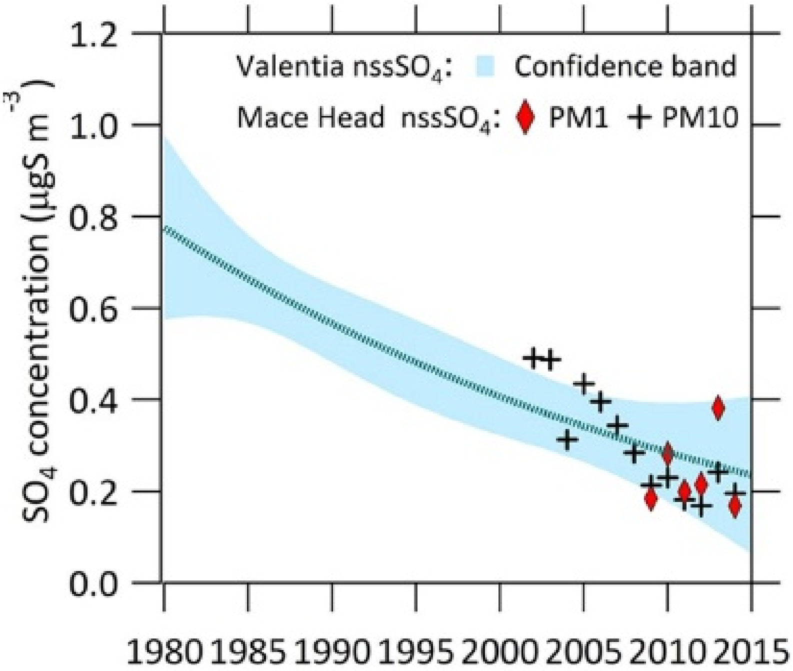

Figure 1. Sulphur air pollution trends. Non-sea salt sulphate aerosol (nss-SO_4) PM10, in the period 2001–2014, and nss-SO_4 PM1, in the period 2009–2014, (both in terms of μg S m^{-3}) observed at Mace Head with the 95% confidence bands of an exponential trend curve fitted to non-sea-salt sulphate measured at Valentia Observatory over the time period superimposed; Figure reproduced from Grigas et al., 2017 [72].

Vulnerabilities of the North Atlantic

Western Europe is subject to elevated ozone levels due to the transatlantic transport of anthropogenic ozone, contributing on average 5 ppb to background surface ozone, up to 10–20 ppb during transatlantic transport events [81]. Ozone is an atmospheric pollutant with adverse effects on vegetation and human health. In 2018, over one-third of EU citizens were exposed to ozone levels exceeding EU limits [82]. Despite ozone being a major focus of the Task Force on the Hemispheric Transport of Air Pollution (HTAP), there is major uncertainty regarding simulated surface ozone levels in global models [83]. Despite tighter controls on ozone precursors in recent decades, there has been an overall increase in ozone levels in the mid to upper troposphere of the northern hemisphere in recent decades [84], influenced by teleconnections with dynamic transport and atmospheric circulation patterns and modes of climate variability including the AO [85], the NAO [86,87] and stratospheric circulation patterns [88].

Dust clouds that are formed over deserts in conditions of strong winds can also reach high latitudes and undergo long-range transport. Dust deposition to the North Atlantic is nearly entirely of Saharan origin [68] and this deposited dust plays a huge role in nutrient cycling and hence ocean biogeochemistry [13,68] and may have significant health implications [89]. Air pollution levels observed over urban coastal areas often exceed those observed over neighbouring landmass [90]. The deposition rate of nitrogen species to the ocean in 4–5-fold higher than preindustrial levels [68] and the deposition of excess nutrient loadings to the ocean compromises water quality and has a negative impact on ocean physiochemical and biogeochemical processes, leading to eutrophication, toxic agal blooms. This in turn has devastating consequences for ocean biodiversity, aquatic life and ecosystems [91–95], with considerable societal and economic impact. As the planetary boundary for nitrogen and biodiversity have already been breached, nitrogen deposition represents a significant vulnerability for the North Atlantic region [1].

3.3. Reduce Knowledge Gaps on the Global Carbon Budget and the Earth's Energy Balance

As outlined in Section 3.1, the North Atlantic is a fundamental component of the Earth system, a stage on which many key processes are played out that affect ocean circulation, ecosystem health, climate of the surrounding continents and the global carbon budget. It is important, therefore, to understand the energy budget of the North Atlantic which is a fundamental component of the Earth system. Much attention has been given to the Arctic region because of dramatic changes in the Arctic Ocean ice implications for North Atlantic circulation patterns and the connection to global climate change.

The energy balance in the North Atlantic region is affected by the GHG levels over the Atlantic Ocean, and despite concerted political efforts to curb emissions since the establishment of the UNFCCC in the 1990s, Figure 2 (Left) shows the relentless rise of CO_2 sampled at observation stations surrounding the North Atlantic taken from NOAA's Carbon Cycle Greenhouse Gas network of surface flasks measurements. Figure 2 (Right) shows the trends for both CO_2 and CH_4 taken at Mace Head Global GAW supersite. Global CH_4 emissions have come under scrutiny owing to sharp rise in methane levels since 2007 [96–98] after stabilising somewhat in the 1990s and the early 2000s, reasons for which are not yet well understood [99] but stabilisation of methane levels in the late 20th century prior to a sharp rise may be attributable to changes in methane emissions from fossil fuels extraction and combustion [100]. The current observed CH_4 mixing ratios surpass those in the IPCC's Representative Concentration Pathway(RCP) 4.5, which projects global temperatures up to 2.6 °C by 2100 [101], posing a challenge for the realisation of the Paris Agreement goals to limit the impacts of irreversible climate change due to anthropogenic radiative forcing [99].

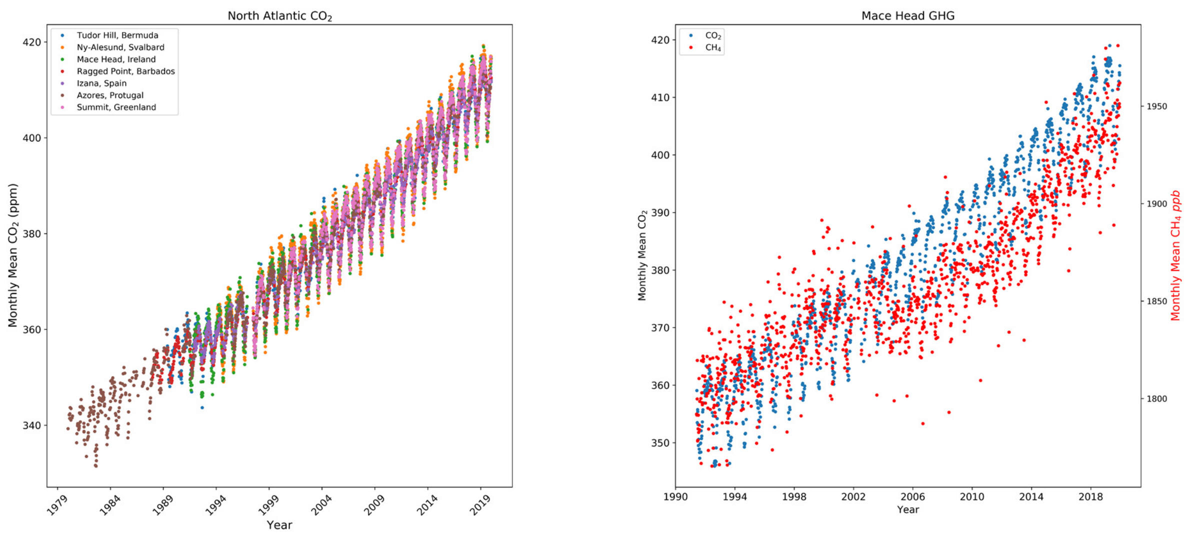

Figure 2. (**Left**) CO_2 trends from 1979 onwards taken from sites surrounding the Atlantic Ocean. Data taken from the Carbon Cycle Greenhouse Gas cooperative air sampling network, which began in Colorado, 1967 and resampled to monthly mean values. The data here are sampled in each station using flask containers and sent back to NOAA's Global Monitoring Division. (**Right**) CO_2 and CH_4 record taken at Mace Head, Ireland. The data are filtered to display only samples representative of a remote, well-mixed troposphere and data are available from the Global Monitoring Laboratory of the National Oceanic and Atmospheric Administration. Data available at the NOAA Global Monitoring Laboratory.

Atmospheric carbon is the key player instrumental in anthropogenic radiative forcing, as shown in Figure 3. Recent ocean flux measurements suggest that the oceanic carbon sink has been underestimated and there is a need for revision of the global carbon budget [102].

The Arctic region is very sensitive to aerosol forcing from remote sources, with a particularly large Arctic response to BC perturbations [103–107]. Estimating the effect of BC on radiative forcing represents a major challenge. The radiative properties of BC are strongly influenced by the ageing state and mixing state of the compound, which can be highly heterogenous and the uncertainty regarding the influence of BC on RF is large [108], with large empirical scaling factors being applied to BC emissions in global models in order to match observed aerosol absorption optical depth absorption [109]. This uncertainty will only be reduced by way of coordinated synoptic measurements with adequate spatial and temporal resolution. Owing to the sensitivity of the Arctic to BC, observations should include isotope measurements of elemental carbon and organic carbon should be made using thermal or thermal-optical analysis to enable the determination of reactive light absorption coefficients (AAC) of reported BC [110] and verification and validation of sources [111]. The current models used to estimate the radiative absorption properties of BC are in need of refinement [112] and a reduction in the current uncertainty in the size distribution of emitted BC is essential to evaluate the radiative effects of BC [113,114]. The deposition of BC on snow also causes positive radiative forcing, accelerating snowmelt and contributes to Arctic warming [115,116]. The spatial distributions of BC concentrations in the Artic are highly sensitive to the anthropogenic emission flux. Estimation of the warming impact of BC on the Arctic requires a comprehensive understanding of the emission, transport, size distribution and ageing of BC that only be achieved by integrated measurement networks comprising remote and advanced in situ measurements.

The indirect effect is still a major unknown in climate models [117], and the role of marine bioaerosols in cloud formation remains a large uncertainty [118]. The role of marine aerosols in cloud formation is dependent on aerosol composition and size, and hence a robust understanding of aerosol formation processes is necessary to quantify radiative changes in the marine environment.

Vulnerabilities of the North Atlantic

The relentless rise in GHGs around the North Atlantic as shown in Figure 2 will continue to perturb the radiation budget in the region. Furthermore, the North Atlantic is home to one of the most productive seasonal phytoplankton blooms in the world [119–122]. The North Atlantic is subject to deposition of Saharan dust, as mentioned above, which interacts with ocean primary productivity and hence biogeochemical cycling, influencing atmospheric CO_2 and radiative forcing, with studies implicating dust deposition in the suppression of atmospheric CO_2 and, in turn, influencing atmospheric radiative forcing at a regional scale [123–125]. The magnitude of this feedback is not yet known, as model estimates of dust deposition to the ocean vary by an order of magnitude, and so the fraction of iron dust involved in ocean fertilisation is highly uncertain [126].

Marine aerosols play a significant role in aerosol load and hence albedo and climate, with phytoplankton blooms playing a key role in the aerosol–cloud–climate feedback system [127,128]. The presence of organic matter in aerosols significantly alters CCN properties [129,130], applying a seasonality to the marine CCN budget. CCN in the pristine environment can be affected by long-range transport of pollutants, which may have significant enhancing effect on dimming [131]. Hence, decreasing levels in background aerosol levels would lead to brightening [132], but the interactions between aerosols, clouds and the energy budget are complex and non-linear. For example, the presence of sea spray in CCN can disproportionately affect cloud albedo compared to the presence of sulphate, yet the magnitude of the effect depends on the ratio of sulphate to sea spray aerosol and meteorological conditions [133].

A recent review of aerosol indirect forcing effects on North Atlantic Sea Surface Temperature (NASST) concludes that at least two-thirds of the NASST response in an Earth system model is associated with aerosol–cloud interactions, highlighting the need to better understand them [134]. Additionally, a dynamical response of the fully coupled atmosphere–ocean system to changes in the aerosol pattern was evident. This result is consistent with CMIP6 Climate Models [135]. Results from this study suggest that the continued decrease in anthropogenic aerosol emissions in the interest of air quality will reinforce GHG-induced AMOC weakening in recent decades. The aerosol indirect effect in the North Atlantic especially needs further investigation for more complete understanding of our climate system and the knowledge gap will be closed only by continued study of interactions and feedbacks between the ocean and the atmosphere that are facilitated by sustained measurements with advanced atmospheric probing instrumentation for aerosols, clouds, and short-lived gas-phase species, including in situ and remote sensing measurements at key strategic sites. The Arctic region is susceptible to rapid changes in response to changes to the radiative properties in the atmosphere, which will lead to physical and biogeochemical changes in the North Atlantic, with major consequences.

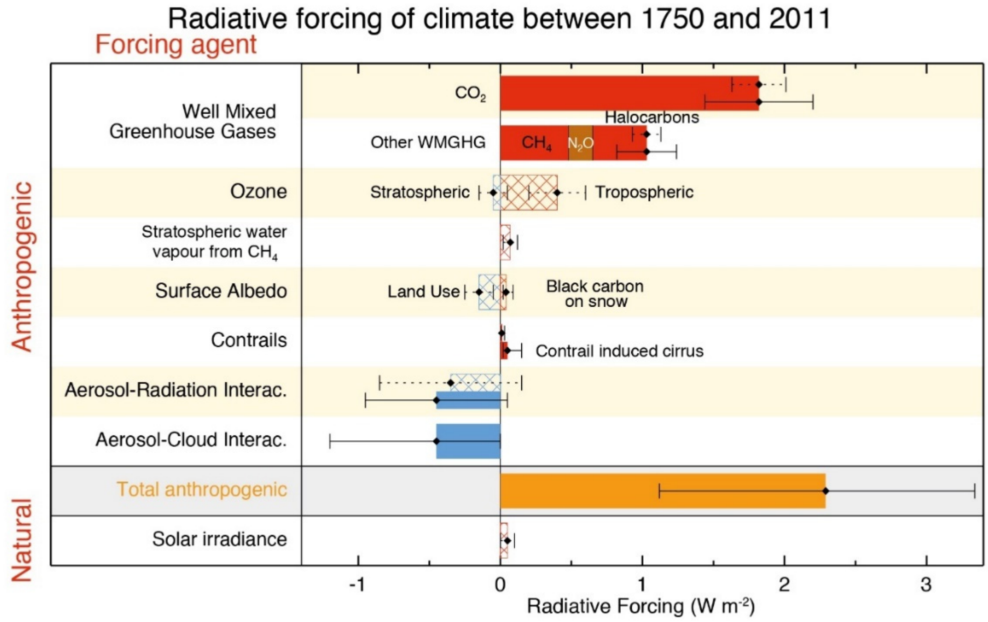

Figure 3. Figure reproduced from Figure 8.15, Chapter 8 of the AR5, IPCC [136].

4. Potential Cross-Thematic Benefits of Integrated Assessment System and Monitoring Network

The three science-policy issues pertaining to atmospheric composition can be viewed as distinct environmental challenges facing the North Atlantic region, an integrated assessment of the atmospheric composition and changes would enable an aggregated, co-beneficial policy response addressing each thematic challenge. 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.

Air–sea–ice interactions play a key role in regulation of circulation patterns which may profoundly influence climate, regional weather patterns and pollution, as well as the carbon cycle. Quantification of uncertain and poorly constrained Earth system feedback processes have been recognised as an important uncertainty in determining the carbon budget [5]. Monitoring of atmosphere–ocean interactions via an integrated network would allow for improved quantification of these feedbacks, which would lead to better constraint of carbon budgets, enabling more effective policy to reach the goals of the UNFCCC Paris Agreement. Further, changes to the energy balance that are influenced by the carbon budget are intrinsically linked to the physical and dynamic changes observed in the North Atlantic region, and so assessment of changes to the radiative balance will provide insight into potential changes to the North Atlantic system, changes to the radiative properties of the atmosphere serving as early-warning indicators for impending physical and biogeochemical changes to the region and subsequent societal and economic impacts.

Monitoring of the radiation anomalies has been shown to offer a potential means to improve the prediction of interannual Arctic sea ice variability [137], which influences the dominant circulation patterns regulating the North Atlantic. The rapid timescales of the AA response to anthropogenic forcing indicates potential of near-term climate mitigation. The success of the Arctic council and the AMAP highlights the potential of targeted intergovernmental fora to address regional environmental protection and reduce mortality caused by atmospheric pollution by catalysing air pollution abatement regulation underpinned by robust, scientific analysis and comprehensive long-term datasets.

Owing to the sensitivity of the Arctic region to BC forcing, prediction of significant changes in the Arctic and the Atlantic Ocean requires better understanding of emission and transport of aerosols. Better quantification of BC transport will allow for improved estimates of radiative forcing, with knock-on effects for sea-ice cover and North Atlantic circulations, but also determination of positive health effects associated with targeted BC policy [138]. Improved monitoring of BC transport can be facilitated by combined use of in situ measurements as well as satellite- and ground-based remote sensing measurements. Such integrated systems are complementary and can be used to elucidate vertical and spatial aerosol and cloud distribution [139–141]. The role of ground-based instruments serves not only to calibrate spaceborne data, but the fused data products comprising satellite and ground-based information can allow identification of aerosol type and enable tracking of long-range transport [142–146]. Such a system can be realised with investment in the four existing Arctic sites that boast long-term time series of BC for maintenance and upgrades [110]. the economic and social importance of such a system was demonstrated with the Eyjafjallajökull Icelandic volcano eruption in April 2010, which caused the cancellation of more than 100,000 flights, affecting 10 million passengers and incurring economic loss exceeding €5 billion [147,148].

Atmospheric composition contributes to physical changes in the multidecadal climate variability of the North Atlantic [23]; sea surface temperatures, and hence North Atlantic climate variability, is influenced by changes to atmospheric composition from both natural and anthropogenic sources [149,150]. Atmospheric aerosol cooling supresses tropical cyclone activity [151], and significant anti-correlation between Saharan dust and tropical cyclone activity in the North Atlantic [152], where studies have shown Saharan dust plumes to affect environmental stability [153,154], yet causality has not been firmly established.

Regional climatic patterns also modulate dust export [155,156], which in turn affects health, ecosystem, biogeochemistry, and radiative forcing in the North Atlantic region. Currently, global models cannot adequately simulate the dust cycle, so dust impacts represent an uncertainty in development of future scenarios. Model capacity is limited by the lack of simultaneous, high-quality measurements of characterised aerosols necessary for verification and development of model parameterisations [126,157]. There is a need for more robust understanding of aerosol–cloud–radiation feedbacks to allow for decadal-scale regional climate forcing and subsequent feedbacks [158–160], which could be facilitated by the integrated monitoring and assessment of atmospheric constituents as proposed here [134].

Tropospheric ozone is both a powerful GHG and a health, ecological and economic concern as it is an agent of crop and vegetation damage. North Atlantic surface ozone levels can be modulated by ocean productivity [161–163]. The current generation of chemical transport models still exhibit strong inter-model differences in simulated ozone mixing ratios, especially prevalent in spring time [83]. Owing to the vital role that ozone plays in atmospheric chemistry, radiative forcing, 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 US will approach $7 ($10) billion by 2050 and $18 ($26) billion by 2090 under RCP4.5 (RCP8.5) projections [164]), it is vital that global models have the capacity to accurately simulate ozone mixing ratios. The large range in surface atmospheric ozone concentrations between current models indicate the need for better representation of ozone-regulating transport, atmospheric chemistry and removal processes in our models. Improvement of the performance of atmospheric chemical transport models in simulating ozone concentrations and budgets in the North Atlantic requires more comprehensive vertical measurements of ozone and its precursors. Atmospheric circulation patterns significantly affect surface ozone levels in the North

Atlantic [86,165], where transport of elevated ozone levels in the marine boundary layer has been previously observed [166–168].

As local air pollution sources have declined owing to the success of the unified global effort of the CLRTAP, the contribution of long-range transported precursors to ozone levels in Europe and North America has increased [169–171]. Models will not have the capacity to accurately simulate intercontinental ozone transport without a clear understanding of the processes that affect ozone formation and destruction in the marine boundary layer. This understanding necessitates co-ordinated high-precision measurements in and around the region [172].

5. Conclusions

The North Atlantic region is undergoing unprecedented changes which may have major implications for the surrounding areas. It has been identified that while major networks do serve the North Atlantic region (EMEP, GAW, IAGOS, AGAGE, ACTRIS, ICOS, CAMS, NOAA, and NASA), key gaps exist in observation and analysis systems. To address these issues, an international initiative to establish a North Atlantic multidisciplinary scientific assessment system and observation network is proposed. This initiative envisages formation of a North Atlantic Atmospheric community, building on existing research activities and observational networks and infrastructures, development of this network would necessitate sustained investment in existing measurement sites. Long-term, high-quality in-situ measurements provide the gateway to understanding of large-scale atmospheric processes, laying the scientific foundation for effective policy required to meet grand societal and environmental challenges. The need to sustain sites with core measurement capabilities has been recognised in previous publications on both sides of the Atlantic [8,173] and we reiterate the need here.

The objective of the proposed initiative is to address key science-policy challenges that cross a range of thematic areas to better inform policy responses. One of the major challenges in responding to pressure applied to planetary boundaries is in outlining regional or national responses to global-scale problems [2]. The creation of this North Atlantic atmospheric community would greatly enhance the capacity to respond to multiscale, cross-thematic environmental challenges. Atmospheric protection is enshrined in international policy via three very successful but separate Multilateral Environmental Agreements (MEAs)—the UN Framework Convention on Climate Change (UNFCCC), which addresses climate response to radiative forcing; the UN-ECE Convention of transboundary air pollution (CLRTAP), which addresses the issue of transboundary air pollution; and the Vienna Convention for Protection of the Ozone Layer, which addresses stratospheric ozone depletion.

In this paper, the environmental issues/challenges highlighted for the North Atlantic atmospheric region are described separately, whereas in the natural world, no such separations exist. Analysis of comprehensive datasets comprising advanced aerosol measurements, vertical profiling lidar capabilities, remote sensing data, GHGs, ozone precursor measurements and air–surface fluxes would allow scientists to identify linked processes and feedback loops [171], cross-cutting all three thematic science-policy challenges. We have seen how policy targeting air pollution inadvertently led to an increase in solar radiation reaching the Earth's surface, i.e., solar brightening [132], and how aerosol reduction can unmask warming events potentially harmful to ecosystems and human health [174]. Effective mitigation policy, simultaneously co-benefitting the range of environmental challenges in the North Atlantic can be delivered if supported by integrated assessment systems of comprehensive, synoptic, high-quality measurements spanning the breadth of the region. The proposed integrated observation network will envelop existing measurement communities, providing a forum to monitor changes that are occurring in the North Atlantic atmosphere, assess the potential impacts of these changes and produce regularly disseminated reports with tailored policy-relevant output to inform cost-effective measures of environmental protection.

Scientific output and a knowledge of best practice do not in themselves stimulate the large-scale behavioural change that is necessary to achieve the UN Sustainable Development Goals. Exploration of environmental issues via artistic media can illicit emotion in a range of audiences powerful enough to evoke motivation for behavioural change [175]. It is recommended that the forum will engage with stakeholders across the scientific, social scientific, artistic and policy communities to explore the subject of the boundaries of the atmosphere.

This initiative may possibly be developed from a political institutional level, as was the Arctic Council, which has achieved considerable success in the identification of emerging issues pertaining to the protection of the Artic environment and framing them with a view to policy response [176]. The atmospheric initiative can be developed by coupling to the coordinated Atlantic efforts of ocean community. The political will to support transatlantic research efforts for ocean observation and protection was galvanised in the 2013 Galway Statement, which has catalysed transatlantic research integration via the Atlantic Ocean Research Alliance (AORA). Another option is establishment of an alliance for North Atlantic integrated atmospheric research to complement the Ocean effort, but existing as an independent framework with close coupling to AORA. This North Atlantic atmospheric alliance could have an international membership of major research organisations supported by a Secretariat in a prominent North Atlantic atmospheric-oriented country, following the successful blueprint of the AMAP, whose Secretariat was hosted by Norway, who offered to host the Secretariat, with combined institutional funding from North American and European agencies.

The Copernicus Air Monitoring Service (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. It is strongly connected with European Research Infrastructures focused on atmospheric observations (ICOS, IAGOS, and ACTRIS). In addition, this could potentially be supported by joint invitations to tender from CAMS, C3S and the Marine Monitoring Service.

Environmental stability has been compromised by anthropogenic activity from the industrial revolution, to the globalist era of today. As globalisation has advanced, countries are intimately connected, no longer separated by geography. Globalisation has evoked a shared responsibility for environmental protection, as reflected by existing MEAs, yet we are increasingly in danger of breaching the planetary boundaries which could result in non-linear abrupt environmental change that would threaten the capacity of the Earth to support life. Formulation of effective policy to prevent further transgression of planetary boundaries requires increased understanding of Earth-system processes to predict the multidisciplinary feedbacks and interactions that affect environmental stability. The North Atlantic provides a unique stage to increase this understanding owing to its key role in global climate regulation, the unique vulnerabilities of the region, the high level of seasonal biological activity, and the existing capacity and infrastructure that could be leveraged and developed into the proposed co-ordinated measurement network and multidisciplinary assessment system to form a transatlantic alliance for the protection of the North Atlantic atmosphere. An immediate next step towards the realisation of such an alliance is to further engage with stakeholders, with a specific focus on policy and decision makers from national agencies and governments on both sides of the Atlantic. Already, there has been engagement from major networks listed above during a science strategy meeting. The next step is to outline a two-year communications plan to engage key actors up to 2024.

Author Contributions: Conceptualisation, L.C. and F.M.M.G.; writing—original draft preparation, L.C.; writing—review and editing, F.M.M.G., J.O., T.B., D.C., and L.B.; supervision, C.D.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Irish EPA, grant number 2019-CCRP-DS.22.

Acknowledgments: Data in Figure 2 from NOAA Global Monitoring Laboratory. Thank you to Springer Nature for allowing the reproduction of material from Nature Scientific Reports in accordance with Creative Commons copyright licence.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *Nature* **2009**, *461*, 472–475. [CrossRef]
2. Biermann, F.; Kim, R.E. The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity. *Annu. Rev. Environ. Resour.* **2020**, *45*, 497–521. [CrossRef]
3. Lovelock, J.; Lovelock, J.E. *Gaia: A New Look at Life on Earth*; Oxford University Press: Oxford, UK, 2000.
4. Hari, P.; Petäjä, T.; Bäck, J.; Kerminen, V.-M.; Lappalainen, H.; Vihma, T.; Laurila, T.; Viisanen, Y.; Vesala, T.; Kulmala, M. Conceptual design of a measurement network of the global change. *Atmos. Chem. Phys. Discuss.* **2016**, *16*, 1017–1028. [CrossRef]
5. Rogelj, J.; Forster, P.; Kriegler, E.; Smith, C.J.; Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nat. Cell Biol.* **2019**, *571*, 335–342. [CrossRef]
6. IPCC. *Climate Change 2014: Synthesis Report Summary for Policy Makers. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014.
7. Skinner, I.; Farmer, A.; Kuik, O. *The Thematic Strategy on Air Pollution*; Policy Brief for the EP Environment Committee; IEEP: Brussels, Belgium, 2006.
8. Barrie, L.; McGovern, F.M. Protecting the North Atlantic atmosphere: A report on the outcome of an international meeting on the twentieth anniversary of the second aerosol characterisation experiment (ACE2). In *EPA Research Report*; EPA: Tenerife, Spain, 2017.
9. WMO. *GCOS/IPCC/UNCCC Workshop on Enhancing Observations to Support Preparedness and Adaptation in a Changing Climate—Learning from the IPCC 5th Assessment Report*; WMO: Bonn, Germany, 2015.
10. ATMO-ACCESS. 2021. Available online: https://www.imk-aaf.kit.edu/1361.php (accessed on 12 July 2021).
11. European Union. *Eurostat Regional Yearbook 2011*; European Union: Brussels, Belgium, 2011.
12. NOAA. *National Coastal Population Report*; NOAA: Washington, DC, USA, 2013.
13. Yu, H.; Chin, M.; Yuan, T.; Bian, H.; Remer, L.A.; Prospero, J.M.; Omar, A.; Winker, D.; Yang, Y.; Zhang, Y.; et al. The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. *Geophys. Res. Lett.* **2015**, *42*, 1984–1991. [CrossRef]
14. Prospero, J.M.; Barkley, A.E.; Gaston, C.J.; Gatineau, A.; Sansano, A.C.Y.; Panechou, K. Characterizing and Quantifying African Dust Transport and Deposition to South America: Implications for the Phosphorus Budget in the Amazon Basin. *Glob. Biogeochem. Cycles* **2020**, *34*, 6536. [CrossRef]
15. Morlighem, M.; Williams, C.; Rignot, E.; An, L.; Arndt, J.E.; Bamber, J.L.; Catania, G.; Chauché, N.; Dowdeswell, J.; Dorschel, B.; et al. BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. *Geophys. Res. Lett.* **2017**, *44*, 11. [CrossRef]
16. Waugh, D.W.; Polvani, L.M.; Sobel, A.H. Stratospheric polar vortices. *Extreme Events* **2010**, *190*, 43–57.
17. Kim, H.; An, S.; Kim, D. Timescale-dependent AMOC–AMO relationship in an earth system model of intermediate complexity. *Int. J. Clim.* **2021**, *41*, 3298. [CrossRef]
18. Zhang, L.; Wang, C. Multidecadal North Atlantic sea surface temperature and Atlantic meridional overturning circulation variability in CMIP5 historical simulations. *J. Geophys. Res. Oceans* **2013**, *118*, 5772–5791. [CrossRef]
19. Zhang, R.; Delworth, T. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophys. Res. Lett.* **2006**, *33*. [CrossRef]
20. Sutton, R.; Dong, B. Atlantic Ocean influence on a shift in European climate in the 1990s. *Nat. Geosci.* **2012**, *5*, 788–792. [CrossRef]
21. Goldenberg, S.B.; Landsea, C.W.; Mestas-Nunez, A.; Gray, W.M. The Recent Increase in Atlantic Hurricane Activity: Causes and Implications. *Science* **2001**, *293*, 474–479. [CrossRef]
22. Chen, X.; Tung, K.-K. Varying planetary heat sink led to global-warming slowdown and acceleration. *Science* **2014**, *345*, 897–903. [CrossRef]
23. Wang, C.; Dong, S.; Evan, A.T.; Foltz, G.; Lee, S.-K. Multidecadal Covariability of North Atlantic Sea Surface Temperature, African Dust, Sahel Rainfall, and Atlantic Hurricanes. *J. Clim.* **2012**, *25*, 5404–5415. [CrossRef]
24. McCarthy, G.D.; Haigh, I.D.; Hirschi, J.J.-M.; Grist, J.; Smeed, D. Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nat. Cell Biol.* **2015**, *521*, 508–510. [CrossRef]
25. Laffoley, D.; Baxter, J.M. *Explaining Ocean Warming: Causes, Scale, Effects and Consequences*; IUCN: Gland, Switzerland, 2016.
26. Solomon, S.; Plattner, G.-K.; Knutti, R.; Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 1704–1709. [CrossRef]
27. Chylek, P.; Folland, C.K.; Lesins, G.; Dubey, M.K.; Wang, M. Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.* **2009**, *36*. [CrossRef]

28. Previdi, M.; Janoski, T.P.; Chiodo, G.; Smith, K.L.; Polvani, L.M. Arctic Amplification: A Rapid Response to Radiative Forcing. *Geophys. Res. Lett.* **2020**, *47*, e2020GL089933. [CrossRef]
29. Dai, A.; Luo, D.; Song, M.; Liu, J. Arctic amplification is caused by sea-ice loss under increasing CO_2. *Nat. Commun.* **2019**, *10*, 1–13. [CrossRef]
30. Flis, A. Winter Breaking Point. North Atlantic Oscillation and Arctic Oscillation Reach Near-Record Values, Affecting Both Sides of the Atlantic. One Gets Spring, and One Gets Cold. Which Side Are You On? 2020. Available online: https://www.severe-weather.eu/global-weather/winter-breaking-point-arctic-atlantic-oscillation-february-fa/ (accessed on 12 July 2021).
31. Rigor, I.G.; Wallace, J.M.; Colony, R.L. Response of Sea Ice to the Arctic Oscillation. *J. Clim.* **2002**, *15*, 2648–2663. [CrossRef]
32. Stroeve, J.C.; Maslanik, J.; Serreze, M.C.; Rigor, I.; Meier, W.; Fowler, C. Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010. *Geophys. Res. Lett.* **2011**, *38*. [CrossRef]
33. Visbeck, M.; Hurrell, J.W.; Polvani, L.; Cullen, H.M. The North Atlantic Oscillation: Past, present, and future. *Proc. Natl. Acad. Sci. USA* **2001**, *98*, 12876–12877. [CrossRef]
34. Hurrell, J.W.; Kushnir, Y.; Ottersen, G.; Visbeck, M. An overview of the North Atlantic Oscillation. In *Large Igneous Provinces*; American Geophysical Union (AGU): Washington, DC, USA, 2003; Volume 134, pp. 1–35.
35. Bryden, H.L.; Hall, M.M. Heat Transport by Currents Across 25 N Latitude in the Atlantic Ocean. *Science* **1980**, *207*, 884–886. [CrossRef] [PubMed]
36. Johns, W.E.; Baringer, M.; Beal, L.M.; Cunningham, S.A.; Kanzow, T.; Bryden, H.; Hirschi, J.J.M.; Marotzke, J.; Meinen, C.S.; Shaw, B.; et al. Continuous, Array-Based Estimates of Atlantic Ocean Heat Transport at 26.5 °N. *J. Clim.* **2011**, *24*, 2429–2449. [CrossRef]
37. Wells, N.C. *The Atmosphere and Ocean*; Wiley: Hoboken, NJ, USA, 2011.
38. Srokosz, M.; Bryden, H. Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises. *Science* **2015**, *348*, 1255575. [CrossRef] [PubMed]
39. IPCC. Technical Summary. In *Climate Change 2013: The Physical Science Basis*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; IPCC: Geneva, Switzerland, 2013; pp. 33–115.
40. Haskins, R.K.; Oliver, K.I.C.; Jackson, L.C.; Wood, R.A.; Drijfhout, S.S. Temperature domination of AMOC weakening due to freshwater hosing in two GCMs. *Clim. Dyn.* **2019**, *54*, 273–286. [CrossRef]
41. Keil, P.; Mauritsen, T.; Jungclaus, J.; Hedemann, C.; Olonscheck, D.; Ghosh, R. Multiple drivers of the North Atlantic warming hole. *Nat. Clim. Chang.* **2020**, *10*, 667–671. [CrossRef]
42. Volkov, D.L.; Baringer, M.; Smeed, D.; Johns, W.; Landerer, F.W. Teleconnection between the Atlantic Meridional Overturning Circulation and Sea Level in the Mediterranean Sea. *J. Clim.* **2019**, *32*, 935–955. [CrossRef]
43. Ezer, T.; Atkinson, L.P.; Corlett, W.B.; Blanco, J.L. Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *J. Geophys. Res. Ocean.* **2013**, *118*, 685–697. [CrossRef]
44. Mitchell, M.; Hershner, C.; Herman, J.; Schatt, D.E.; Eggington, E. *Recurrent flooding study for Tidewater Virginia*; William&Mary: Williamsburg, VA, USA, 2013.
45. Hanna, E.; Cappelen, J.; Fettweis, X.; Mernild, S.H.; Mote, T.L.; Mottram, R.; Steffen, K.; Ballinger, T.J.; Hall, R.J. Greenland surface air temperature changes from 1981 to 2019 and implications for ice-sheet melt and mass-balance change. *Int. J. Clim.* **2021**, *41*. [CrossRef]
46. Dangendorf, S.; Hay, C.; Calafat, F.M.; Marcos, M.; Piecuch, C.G.; Berk, K.; Jensen, J. Persistent acceleration in global sea-level rise since the 1960s. *Nat. Clim. Chang.* **2019**, *9*, 705–710. [CrossRef]
47. Shepherd, A.; Ivins, E.; Rignot, E.; Smith, B.; van den Broeke, M.; Velicogna, I.; Whitehouse, P.; Briggs, K.; Joughin, I.; Krinner, G.; et al. Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* **2020**, *579*, 233–239.
48. Jackson, L.C.; Kahana, R.; Graham, T.; Ringer, M.; Woollings, T.; Mecking, J.V.; Wood, R.A. Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Clim. Dyn.* **2015**, *45*, 3299–3316. [CrossRef]
49. Fromentin, J.; Planque, B. Calanus and environment in the eastern North Atlantic. II. Influence of the North Atlantic Oscillation on C. finmarchicus and C. helgolandicus. *Mar. Ecol. Prog. Ser.* **1996**, *134*, 111–118. [CrossRef]
50. Melero-Jiménez, I.J.; Salvo, A.E.; Báez, J.C.; Bañares-España, E.; Reul, A.; Flores-Moya, A. North Atlantic Oscillation drives the annual occurrence of an isolated, peripheral population of the brown seaweedFucus guiryiin the Western Mediterranean Sea. *PeerJ* **2017**, *5*, e4048. [CrossRef] [PubMed]
51. Bastos, A.; Janssens, I.; Gouveia, C.; Trigo, R.; Ciais, P.; Chevallier, F.; Penuelas, J.; Rödenbeck, C.; Piao, S.; Friedlingstein, P.; et al. European land CO_2 sink influenced by NAO and East-Atlantic Pattern coupling. *Nat. Commun.* **2016**, *7*, 10315. [CrossRef]
52. Randel, W.J.; Wu, F. Cooling of the Arctic and Antarctic Polar Stratospheres due to Ozone Depletion. *J. Clim.* **1999**, *12*, 1467–1479. [CrossRef]
53. Lind, S.; Ingvaldsen, R.B.; Furevik, T. Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. *Nat. Clim. Chang.* **2018**, *8*, 634–639. [CrossRef]
54. IPCC. *Impacts of 1.5 C Global Warming on Natural and Human Systems. Global Warming of 1.5 C. An IPCC Special Report*; IPCC: Geneva, Switzerland, 2018.
55. Tandon, N.F.; Kushner, P.J. Does External Forcing Interfere with the AMOC's Influence on North Atlantic Sea Surface Temperature? *J. Clim.* **2015**, *28*, 6309–6323. [CrossRef]

56. Mann, M.E.; Steinman, B.A.; Brouillette, D.J.; Miller, S.K. Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science* **2021**, *371*, 1014–1019. [CrossRef]
57. EEA. *Climate Change, Impacts and Vulnerability in Europe 2016: An Indicator-Based Report*; EEA: Copenhagen, Denmark, 2017.
58. Bamber, J.L.; Oppenheimer, M.; Kopp, R.E.; Aspinall, W.P.; Cooke, R.M. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 11195. [CrossRef]
59. Kopp, R.E.; DeConto, R.M.; Bader, D.A.; Hay, C.C.; Horton, R.M.; Kulp, S.; Oppenheimer, M.; Pollard, D.; Strauss, B.H. Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. *Earth's Future* **2017**, *5*, 1217–1233. [CrossRef]
60. Sallenger, A.H.; Doran, K.; Howd, P.A. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nat. Clim. Chang.* **2012**, *2*, 884–888. [CrossRef]
61. Delworth, T.L.; Zeng, F.; Vecchi, G.A.; Yang, X.; Zhang, L.; Zhang, R. The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. *Nat. Geosci.* **2016**, *9*, 509–512. [CrossRef]
62. Perez, F.F.; Fontela, M.; García-Ibáñez, M.I.; Mercier, H.; Velo, A.; Lherminier, P.; Zunino, P.; De La Paz, M.; Alonso-Pérez, F.; Guallart, E.F.; et al. Meridional overturning circulation conveys fast acidification to the deep Atlantic Ocean. *Nat. Cell Biol.* **2018**, *554*, 515–518. [CrossRef] [PubMed]
63. Fontela, M.; García-Ibáñez, M.I.; Hansell, D.A.; Mercier, H.; Perez, F.F. Dissolved Organic Carbon in the North Atlantic Meridional Overturning Circulation. *Sci. Rep.* **2016**, *6*, 26931. [CrossRef]
64. Zickfeld, K.; Eby, M.; Weaver, A.J. Carbon-cycle feedbacks of changes in the Atlantic meridional overturning circulation under future atmospheric CO_2. *Glob. Biogeochem. Cycles* **2008**, *22*. [CrossRef]
65. Shen, Y.; Benner, R. Mixing it up in the ocean carbon cycle and the removal of refractory dissolved organic carbon. *Sci. Rep.* **2018**, *8*, 2542. [CrossRef]
66. Brown, P. Feedbacks between the AMOC and the carbon cycle: A present and future perspective. In *2018 International AMOC Science Meeting*; US-CLIVAR: Washington, DC, USA, 2018.
67. Nielsen, S.B.; Jochum, M.; Pedro, J.B.; Eden, C.; Nuterman, R. Two-Timescale Carbon Cycle Response to an AMOC Collapse. *Paleoceanogr. Paleoclimatol.* **2019**, *34*, 511–523. [CrossRef]
68. Prospero, J.M.; Barrett, K.; Church, T.; Dentener, F.; Duce, R.A.; Galloway, J.N.; Levy, H.; Moody, J.; Quinn, P. Atmospheric deposition of nutrients to the North Atlantic Basin. *Nitrogen Cycl. N. Atl. Ocean. Watersheds* **1996**, *35*, 27–73.
69. Zamora, L.M.; Prospero, J.; Hansell, D.; Trapp, J.M. Atmospheric P deposition to the subtropical North Atlantic: Sources, properties, and relationship to N deposition. *J. Geophys. Res. Atmos.* **2013**, *118*, 1546–1562. [CrossRef]
70. Dugo, M.A.; Han, F.; Tchounwou, P.B. Persistent polar depletion of stratospheric ozone and emergent mechanisms of ultraviolet radiation-mediated health dysregulation. *Rev. Environ. Health* **2012**, *27*, 103–116. [CrossRef] [PubMed]
71. WMO. *Arctic Ozone Depletion Reached Record Level*; WMO: Geneva, Switzerland, 2020.
72. Grigas, T.; Ovadnevaite, J.; Ceburnis, D.; Moran, E.; McGovern, F.M.; Jennings, S.G.; O'Dowd, C.; Grigas, T.; Ovadnevaite, J.; Ceburnis, D.; et al. Sophisticated Clean Air Strategies Required to Mitigate Against Particulate Organic Pollution. *Sci. Rep.* **2017**, *7*, srep44737. [CrossRef]
73. WHO. *9 out of 10 People Worldwide Breathe Polluted Air, but More Countries are Taking Action*; WHO: Geneva, Switzerland, 2018.
74. Jumelet, J.; Klekociuk, A.R.; Alexander, S.P.; Bekki, S.; Hauchecorne, A.; Vernier, J.P.; Fromm, M.; Keckhut, P. Detection of Aerosols in Antarctica From Long-Range Transport of the 2009 Australian Wildfires. *J. Geophys. Res. Atmos.* **2020**, *125*, 032542. [CrossRef]
75. Magzamen, S.; Gan, R.W.; Liu, J.; O'Dell, K.; Ford, B.; Berg, K.; Bol, K.; Wilson, A.; Fischer, E.V.; Pierce, J.R. Differential Cardiopulmonary Health Impacts of Local and Long-Range Transport of Wildfire Smoke. *GeoHealth* **2021**, *5*, 000330. [CrossRef]
76. Aguilera, R.; Corringham, T.; Gershunov, A.; Benmarhnia, T. Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nat. Commun.* **2021**, *12*, 1–8. [CrossRef]
77. Martin, M.V.; Honrath, R.E.; Owen, R.C.; Pfister, G.; Fialho, P.; Barata, F. Significant enhancements of nitrogen oxides, black carbon, and ozone in the North Atlantic lower free troposphere resulting from North American boreal wildfires. *J. Geophys. Res. Space Phys.* **2006**, *111*, 23.
78. Baroni, T.; Ceburnis, D.; O'Dowd, C.D. Classification of Pollution Types Degree of Severity Encountered Over the NE Atlantic—A Decadalscale Perspective From Remote Sensing Techniques. in preparation. 2021.
79. Forster, C.; Wandinger, U.; Wotawa, G.; James, P.; Mattis, I.; Althausen, D.; Simmonds, P.; O'Doherty, S.; Jennings, S.G.; Kleefeld, C.; et al. Transport of boreal forest fire emissions from Canada to Europe. *J. Geophys. Res. Space Phys.* **2001**, *106*, 22887–22906. [CrossRef]
80. Sandstrom, T.; Nowak, D.; Van Bree, L. Health effects of coarse particles in ambient air: Messages for research and decision-making. *Eur. Respir. J.* **2005**, *26*, 187–188. [CrossRef] [PubMed]
81. Li, Q.; Jacob, D.J.; Bey, I.; Palmer, P.I.; Duncan, B.N.; Field, B.D.; Martin, R.; Fiore, A.; Yantosca, R.M.; Parrish, D.D.; et al. Transatlantic transport of pollution and its effects on surface ozone in Europe and North America. *J. Geophys. Res. Space Phys.* **2002**, *107*, ACH 4-1–ACH 4-21. [CrossRef]
82. EEA. Indicator Assessment. In *Exceedance of Air Quality Standards in Europe*; EEA: Geneva, Switzerland, 2020.
83. Butler, T.; Lupascu, A.; Nalam, A. Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model. *Atmos. Chem. Phys. Discuss.* **2020**, *20*, 10707–10731. [CrossRef]

84. Gaudel, A.; Cooper, O.R.; Chang, K.-L.; Bourgeois, I.; Ziemke, J.R.; Strode, S.A.; Oman, L.D.; Sellitto, P.; Nédélec, P.; Blot, R.; et al. Aircraft observations since the 1990s reveal increases of tropospheric ozone at multiple locations across the Northern Hemisphere. *Sci. Adv.* **2020**, *6*, eaba8272. [PubMed]
85. Zhang, J.; Tian, W.; Xie, F.; Sang, W.; Guo, N.; Chipperfield, M.; Feng, W.; Hu, D. Zonally asymmetric trends of winter total column ozone in the northern middle latitudes. *Clim. Dyn.* **2018**, *52*, 4483–4500. [CrossRef]
86. Pausata, F.S.R.; Pozzoli, L.; Vignati, E.; Dentener, F.J. North Atlantic Oscillation and tropospheric ozone variability in Europe: Model analysis and measurements intercomparison. *Atmos. Chem. Phys. Discuss.* **2012**, *12*, 6357–6376. [CrossRef]
87. Lin, M.; Fiore, A.; Horowitz, L.W.; Langford, A.; Oltmans, S.J.; Tarasick, D.; Rieder, H.E. Climate variability modulates western US ozone air quality in spring via deep stratospheric intrusions. *Nat. Commun.* **2015**, *6*, 710. [CrossRef] [PubMed]
88. Neu, J.L.; Flury, T.; Manney, G.L.; Santee, M.L.; Livesey, N.J.; Worden, J. Tropospheric ozone variations governed by changes in stratospheric circulation. *Nat. Geosci.* **2014**, *7*, 340–344. [CrossRef]
89. Karanasiou, A.; Moreno, N.; Moreno, T.; Viana, M.; de Leeuw, F.; Querol, X. Health effects from Sahara dust episodes in Europe: Literature review and research gaps. *Environ. Int.* **2012**, *47*, 107–114. [CrossRef]
90. Goldberg, D.L.; Loughner, C.P.; Tzortziou, M.; Stehr, J.W.; Pickering, K.E.; Marufu, L.T.; Dickerson, R. Higher surface ozone concentrations over the Chesapeake Bay than over the adjacent land: Observations and models from the DISCOVER-AQ and CBODAQ campaigns. *Atmos. Environ.* **2014**, *84*, 9–19. [CrossRef]
91. Moffat, A.S. Ecology: Global Nitrogen Overload Problem Grows Critical. *Science* **1998**, *279*, 988–989. [CrossRef]
92. Morgan, C.; Owens, N. Benefits of water quality policies: The Chesapeake Bay. *Ecol. Econ.* **2001**, *39*, 271–284. [CrossRef]
93. Galloway, J.N.; Aber, J.D.; Erisman, J.W.; Seitzinger, S.P.; Howarth, R.; Cowling, E.B.; Cosby, B.J. The Nitrogen Cascade. *Bioscience* **2003**, *53*, 341–356. [CrossRef]
94. Desbonnet, A.; Costa-Pierce, B.A. *Science of Ecosystem-Based Management: Narragansett Bay in the 21st Century*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2008.
95. Loughner, C.P.; Tzortziou, M.; Shroder, S.; Pickering, K.E. Enhanced dry deposition of nitrogen pollution near coastlines: A case study covering the Chesapeake Bay estuary and Atlantic Ocean coastline. *J. Geophys. Res. Atmos.* **2016**, *121*, 221. [CrossRef]
96. Nisbet, E.G.; Dlugokencky, E.J.; Bousquet, P. Methane on the Rise–Again. *Science* **2014**, *343*, 493–495. [CrossRef]
97. Nisbet, E.G.; Dlugokencky, E.J.; Manning, M.R.; Lowry, D.; Fisher, R.; France, J.; Michel, S.E.; Miller, J.; White, J.W.; Vaughn, B.; et al. Rising atmospheric methane: 2007–2014 growth and isotopic shift. *Glob. Biogeochem. Cycles* **2016**, *30*, 1356–1370. [CrossRef]
98. Nisbet, E.G.; Manning, M.R.; Dlugokencky, E.J.; Fisher, R.E.; Lowry, D.; Michel, S.E.; Myhre, C.L.; Platt, S.; Allen, G.; Bousquet, P.; et al. Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement. *Glob. Biogeochem. Cycles* **2019**, *33*, 318–342. [CrossRef]
99. Nisbet, E.G.; Fisher, R.E.; Lowry, D.; France, J.; Allen, G.; Bakkaloglu, S.; Broderick, T.J.; Cain, M.; Coleman, M.; Fernandez, J.; et al. Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement. *Rev. Geophys.* **2020**, *58*, e2019RG000675. [CrossRef]
100. Aydin, M.; Verhulst, K.R.; Saltzman, E.S.; Battle, M.O.; Montzka, S.; Blake, D.R.; Tang, Q.; Prather, M.J. Recent decreases in fossil-fuel emissions of ethane and methane derived from firn air. *Nat. Cell Biol.* **2011**, *476*, 198–201. [CrossRef] [PubMed]
101. IPCC. Summary for policymakers. In *Climate Change 2013: The Physical Science Basis*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; IPCC: Geneva, Switzerland, 2013.
102. Watson, A.J.; Schuster, U.; Shutler, J.D.; Holding, T.; Ashton, I.G.C.; Landschützer, P.; Woolf, D.K.; Goddijn-Murphy, L. Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory. *Nat. Commun.* **2020**, *11*, 1–6. [CrossRef] [PubMed]
103. Jacobson, M.Z. Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *J. Geophys. Res. Atmos.* **2010**, *115*. [CrossRef]
104. Stjern, C.W.; Samset, B.H.; Myhre, G.; Forster, P.M.; Hodnebrog, Ø.; Andrews, T.; Boucher, O.; Faluvegi, G.; Iversen, T.; Kasoar, M.; et al. Rapid adjustments cause weak surface temperature response to increased black carbon concentrations. *J. Geophys. Res. Atmos.* **2017**, *122*, 462. [CrossRef]
105. Westervelt, D.M.; Conley, A.J.; Fiore, A.M.; Lamarque, J.; Shindell, D.; Previdi, M.; Faluvegi, G.; Correa, G.; Horowitz, L.W. Multimodel precipitation responses to removal of U.S. sulfur dioxide emissions. *J. Geophys. Res. Atmos.* **2017**, *122*, 5024–5038. [CrossRef] [PubMed]
106. Sand, M.; Berntsen, T.K.; Kay, J.E.; Lamarque, J.F.; Seland, Ø.; Kirkevåg, A. The Arctic response to remote and local forcing of black carbon. *Atmos. Chem. Phys.* **2013**, *13*, 211–224. [CrossRef]
107. Oshima, N.; Yukimoto, S.; Deushi, M.; Koshiro, T.; Kawai, H.; Tanaka, T.Y.; Yoshida, K. Global and Arctic effective radiative forcing of anthropogenic gases and aerosols in MRI-ESM2.0. *Prog. Earth Planet. Sci.* **2020**, *7*, 1–21. [CrossRef]
108. Wang, R.; Balkanski, Y.; Boucher, O.; Ciais, P.; Schuster, G.L.; Chevallier, F.; Samset, B.H.; Liu, J.; Piao, S.; Valari, M.; et al. Estimation of global black carbon direct radiative forcing and its uncertainty constrained by observations. *J. Geophys. Res. Atmos.* **2016**, *121*, 5948–5971. [CrossRef]
109. Bond, T.C.; Streets, D.; Yarber, K.F.; Nelson, S.M.; Woo, J.; Klimont, Z. A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res. Space Phys.* **2004**, *109*. [CrossRef]

110. Tørseth, K.; Andrews, E.; Asmi, E.; Eleftheriadis, K.; Fiebig, M.; Herber, A.; Huang, L.; Kylling, A.; Lupi, A.; Massling, A.; et al. *Review of Observation Capacities and Data Availability for Black Carbon in the Arctic Region: EU Action on Black Carbon in the Arctic—Technical Report 1*; Balmer, J., Ed.; AMAP: Tromso, Norway, 2019.
111. Ceburnis, D.; Garbaras, A.; Szidat, S.; Rinaldi, M.; Fahrni, S.; Perron, N.; Wacker, L.; Leinert, S.; Remeikis, V.; Facchini, M.C.; et al. Quantification of the carbonaceous matter origin in submicron marine aerosol by 13C and 14C isotope analysis. *Atmos. Chem. Phys. Discuss.* **2011**, *11*, 8593–8606. [CrossRef]
112. Liu, F.; Yon, J.; Fuentes, A.; Lobo, P.; Smallwood, G.J.; Corbin, J.C. Review of recent literature on the light absorption properties of black carbon: Refractive index, mass absorption cross section, and absorption function. *Aerosol Sci. Technol.* **2020**, *54*, 33–51. [CrossRef]
113. Matsui, H.; Hamilton, D.S.; Mahowald, N.M. Black carbon radiative effects highly sensitive to emitted particle size when resolving mixing-state diversity. *Nat. Commun.* **2018**, *9*, 1–11. [CrossRef]
114. Zhao, G.; Tao, J.; Kuang, Y.; Shen, C.; Yu, Y.; Zhao, C. Role of black carbon mass size distribution in the direct aerosol radiative forcing. *Atmos. Chem. Phys. Discuss.* **2019**, *19*, 13175–13188. [CrossRef]
115. McKenzie Skiles, S.; Painter, T.H. Assessment of Radiative Forcing by Light-Absorbing Particles in Snow from In Situ Observations with Radiative Transfer Modeling. *J. Hydrometeorol.* **2018**, *19*, 1397–1409. [CrossRef]
116. Mori, T.; Goto-Azuma, K.; Kondo, Y.; Ogawa-Tsukagawa, Y.; Miura, K.; Hirabayashi, M.; Oshima, N.; Koike, M.; Kupiainen, K.; Moteki, N.; et al. Black Carbon and Inorganic Aerosols in Arctic Snowpack. *J. Geophys. Res. Atmos.* **2019**, *124*, 13325–13356. [CrossRef]
117. Zhang, S.; Wang, M.; Ghan, S.J.; Ding, A.; Wang, H.; Zhang, K.; Neubauer, D.; Lohmann, U.; Ferrachat, S.; Takeamura, T.; et al. On the characteristics of aerosol indirect effect based on dynamic regimes in global climate models. *Atmos. Chem. Phys. Discuss.* **2016**, *16*, 2765–2783. [CrossRef]
118. Brooks, S.D.; Thornton, D.C. Marine Aerosols and Clouds. *Annu. Rev. Mar. Sci.* **2018**, *10*, 289–313. [CrossRef]
119. Boyce, D.G.; Lewis, M.R.; Worm, B. Global phytoplankton decline over the past century. *Nat. Cell Biol.* **2010**, *466*, 591–596. [CrossRef]
120. Behrenfeld, M.J.; Falkowski, P.G. Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnol. Oceanogr.* **1997**, *42*, 1–20. [CrossRef]
121. Sverdrup, H.U. On Conditions for the Vernal Blooming of Phytoplankton. *ICES J. Mar. Sci.* **1953**, *18*, 287–295. [CrossRef]
122. Behrenfeld, M.J.; Boss, E. Resurrecting the Ecological Underpinnings of Ocean Plankton Blooms. *Annu. Rev. Mar. Sci.* **2014**, *6*, 167–194. [CrossRef]
123. Martin, J.H.; Gordon, R.M. Northeast Pacific iron distributions in relation to phytoplankton productivity. *Deep. Sea Res. Part A Oceanogr. Res. Pap.* **1988**, *35*, 177–196. [CrossRef]
124. Bopp, L.; Kohfeld, K.; Le Quéré, C.; Aumont, O. Dust impact on marine biota and atmospheric CO_2 during glacial periods. *Paleoceanogr. Paleoclimatolog* **2003**, *18*. [CrossRef]
125. Röthlisberger, R.; Bigler, M.; Wolff, E.W.; Joos, F.; Monnin, E.; Hutterli, M.A. Ice core evidence for the extent of past atmospheric CO_2 change due to iron fertilisation. *Geophys. Res. Lett.* **2004**, *31*. [CrossRef]
126. Schulz, M.; Prospero, J.; Baker, A.R.; Dentener, F.; Ickes, L.; Liss, P.S.; Mahowald, N.M.; Nickovic, S.; García-Pando, C.P.; Rodríguez, S.; et al. Atmospheric Transport and Deposition of Mineral Dust to the Ocean: Implications for Research Needs. *Environ. Sci. Technol.* **2012**, *46*, 10390–10404. [CrossRef]
127. O'Dowd, C.; Facchini, M.C.; Cavalli, F.; Ceburnis, D.; Mircea, M.; Decesari, S.; Fuzzi, S.; Yoon, Y.J.; Putaud, J.-P. Biogenically driven organic contribution to marine aerosol. *Nat. Cell Biol.* **2004**, *431*, 676–680. [CrossRef]
128. O'Dowd, C.; Ceburnis, D.; Ovadnevaite, J.; Vaishya, A.; Rinaldi, M.; Facchini, M.C. Do anthropogenic, continental or coastal aerosol sources impact on a marine aerosol signature at Mace Head? *Atmos. Chem. Phys. Discuss.* **2014**, *14*, 10687–10704. [CrossRef]
129. Sanchez, K.J.; Chen, C.-L.; Russell, L.M.; Betha, R.; Liu, J.; Price, D.J.; Massoli, P.; Ziemba, L.D.; Crosbie, E.C.; Moore, R.H.; et al. Substantial Seasonal Contribution of Observed Biogenic Sulfate Particles to Cloud Condensation Nuclei. *Sci. Rep.* **2018**, *8*, 1–14. [CrossRef] [PubMed]
130. Ovadnevaite, J.; Zuend, A.; Laaksonen, A.; Sanchez, K.J.; Roberts, G.; Ceburnis, D.; Decesari, S.; Rinaldi, M.; Hodas, N.; Facchini, M.C.; et al. Surface tension prevails over solute effect in organic-influenced cloud droplet activation. *Nat. Cell Biol.* **2017**, *546*, 637–641. [CrossRef]
131. Wild, M. Enlightening Global Dimming and Brightening. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 27–37. [CrossRef]
132. O'Dowd, C.; Ceburnis, D.; Vaishya, A.; Jennings, S.G.; Moran, E. Cleaner air: Brightening the pollution perspective? *AIP Conf. Proc.* **2013**, *1527*, 579–582.
133. Fossum, K.N.; Ovadnevaite, J.; Ceburnis, D.; Preißler, J.; Snider, J.R.; Huang, R.-J.; Zuend, A.; O'Dowd, C. Sea-spray regulates sulfate cloud droplet activation over oceans. *NPJ Clim. Atmos. Sci.* **2020**, *3*, 1–6. [CrossRef]
134. Fiedler, S.; Putrasahan, D. How Does the North Atlantic SST Pattern Respond to Anthropogenic Aerosols in the 1970s and 2000s? *Geophys. Res. Lett.* **2021**, *48*, e2020GL092142. [CrossRef]
135. Hassan, T.; Allen, R.J.; Liu, W.; Randles, C.A. Anthropogenic aerosol forcing of the Atlantic meridional overturning circulation and the associated mechanisms in CMIP6 models. *Atmos. Chem. Phys. Discuss.* **2021**, *21*, 5821–5846. [CrossRef]

136. Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; et al. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; IPCC: Geneva, Switzerland, 2013.
137. Huang, Y.; Chou, G.; Xie, Y.; Soulard, N. Radiative Control of the Interannual Variability of Arctic Sea Ice. *Geophys. Res. Lett.* **2019**, *46*, 9899–9908. [CrossRef]
138. Kühn, T.; Kupiainen, K.; Miinalainen, T.; Kokkola, H.; Paunu, V.-V.; Laakso, A.; Tonttila, J.; Van Dingenen, R.; Kulovesi, K.; Karvosenoja, N.; et al. Effects of black carbon mitigation on Arctic climate. *Atmos. Chem. Phys. Discuss.* **2020**, *20*, 5527–5546. [CrossRef]
139. Sugimoto, N.; Nishizawa, T.; Shimizu, A.; Jin, Y. The Asian Dust and Aerosol Lidar Observation Network (AD-Net). In *Optics and Photonics for Energy and the Environment*; Optical Society of America: Washington, DC, USA, 2016.
140. Liu, B.; Ma, Y.; Gong, W.; Zhang, M.; Yang, J. Study of continuous air pollution in winter over Wuhan based on ground-based and satellite observations. *Atmos. Pollut. Res.* **2018**, *9*, 156–165. [CrossRef]
141. Kim, S.-W.; Berthier, S.; Raut, J.-C.; Chazette, P.; Dulac, F.; Yoon, S.-C. Validation of aerosol and cloud layer structures from the space-borne lidar CALIOP using a ground-based lidar in Seoul, Korea. *Atmos. Chem. Phys. Discuss.* **2008**, *8*, 3705–3720. [CrossRef]
142. Engel-Cox, J.; Holloman, C.H.; Coutant, B.W.; Hoff, R.M. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmos. Environ.* **2004**, *38*, 2495–2509. [CrossRef]
143. Vijayakumar, K.; Safai, P.; Devara, P.; Rao, S.V.B.; Jayasankar, C. Effects of agriculture crop residue burning on aerosol properties and long-range transport over northern India: A study using satellite data and model simulations. *Atmos. Res.* **2016**, *178–179*, 155–163. [CrossRef]
144. Marchese, F.; Sannazzaro, F.; Falconieri, A.; Filizzola, C.; Pergola, N.; Tramutoli, V. An Enhanced Satellite-Based Algorithm for Detecting and Tracking Dust Outbreaks by Means of SEVIRI Data. *Remote. Sens.* **2017**, *9*, 537. [CrossRef]
145. Winker, D.M.; Liu, Z.; Omar, A.H.; Tackett, J.; Fairlie, D. CALIOP observations of the transport of ash from the Eyjafjallajökull volcano in April 2010. *J. Geophys. Res. Space Phys.* **2012**, *117*, 20. [CrossRef]
146. Duncan, B.N.; Prados, A.; Lamsal, L.N.; Liu, Y.; Streets, D.G.; Gupta, P.; Hilsenrath, E.; Kahn, R.A.; Nielsen, J.E.; Beyersdorf, A.J.; et al. Satellite data of atmospheric pollution for U.S. air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. *Atmos. Environ.* **2014**, *94*, 647–662. [CrossRef]
147. Flentje, H.; Claude, H.; Elste, T.; Gilge, S.; Kohler, U.; Plass-Dülmer, C.; Steinbrecht, W.; Thomas, W.; Werner, A.; Fricke, W. The Eyjafjallajökull eruption in April 2010—detection of volcanic plume using in-situ measurements, ozone sondes and lidar-ceilometer profiles. *Atmos. Chem. Phys. Discuss.* **2010**, *10*, 10085–10092. [CrossRef]
148. O'Dowd, C.; Ceburnis, D.; Ovadnevaite, J.; Martucci, G.; Bialek, J.; Monahan, C.; Berresheim, H.; Vaishya, A.; Grigas, T.; Jennings, S.G.; et al. The Eyjafjallajökull ash plume—Part I: Physical, chemical and optical characteristics. *Atmos. Environ.* **2012**, *48*, 129–142. [CrossRef]
149. Evan, A.T.; Vimont, D.J.; Heidinger, A.K.; Kossin, J.P.; Bennartz, R. The Role of Aerosols in the Evolution of Tropical North Atlantic Ocean Temperature Anomalies. *Science* **2009**, *324*, 778–781. [CrossRef] [PubMed]
150. Birkel, S.D.; Mayewski, P.A.; Maasch, K.A.; Kurbatov, A.V.; Lyon, B. Evidence for a volcanic underpinning of the Atlantic multidecadal oscillation. *NPJ Clim. Atmos. Sci.* **2018**, *1*, 24. [CrossRef]
151. Mann, M.E.; Emanuel, K.A. Atlantic hurricane trends linked to climate change. *Eos* **2006**, *87*, 233–241. [CrossRef]
152. Evan, A.T.; Dunion, J.; Foley, J.A.; Heidinger, A.K.; Velden, C.S. New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks. *Geophys. Res. Lett.* **2006**, *33*, 33. [CrossRef]
153. Wang, K.Y.; Liu, C.H.; Wan, K.-Y. Transport of the Saharan dust air plumes over the tropical North Atlantic from FORMOSAT–3/COSMIC observation. *Atmos. Pollut. Res.* **2014**, *5*, 539–553. [CrossRef]
154. Carlson, T.N.; Prospero, J. The Large-Scale Movement of Saharan Air Outbreaks over the Northern Equatorial Atlantic. *J. Appl. Meteorol.* **1972**, *11*, 283–297. [CrossRef]
155. Moulin, C.; Lambert, C.E.; Dulac, F.; Dayan, U. Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation. *Nat. Cell Biol.* **1997**, *387*, 691–694. [CrossRef]
156. Újvári, G.; Stevens, T.; Molnár, M.; Demény, A.; Lambert, F.; Varga, G.; Jull, A.J.T.; Páll-Gergely, B.; Buylaert, J.-P.; Kovács, J. Coupled European and Greenland last glacial dust activity driven by North Atlantic climate. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, E10632–E10638. [CrossRef]
157. Adebiyi, A.A.; Kok, J.F. Climate models miss most of the coarse dust in the atmosphere. *Sci. Adv.* **2020**, *6*, eaaz9507. [CrossRef]
158. Booth, B.B.B.; Dunstone, N.; Halloran, P.; Andrews, T.; Bellouin, N. Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nat. Cell Biol.* **2012**, *484*, 228–232. [CrossRef]
159. Bellucci, A.; Mariotti, A.; Gualdi, S. The Role of Forcings in the Twentieth-Century North Atlantic Multidecadal Variability: The 1940–75 North Atlantic Cooling Case Study. *J. Clim.* **2017**, *30*, 7317–7337. [CrossRef]
160. Robson, J.; Aksenov, Y.; Bracegirdle, T.J.; Dimdore-Miles, O.; Griffiths, P.T.; Grosvenor, D.P.; Hodson, D.L.R.; Keeble, J.; MacIntosh, C.; Megann, A.; et al. The Evaluation of the North Atlantic Climate System in UKESM1 Historical Simulations for CMIP6. *J. Adv. Model. Earth Syst.* **2020**, *12*, 002126. [CrossRef]
161. Coleman, L. *Regional Scale Modelling of Boundary Layer Ozone and Influences of Climate Change*; National University of Ireland: Galway, Ireland, 2012.

162. Coleman, L.; Martin, D.; Varghese, S.; Jennings, S.; O'Dowd, C. Assessment of changing meteorology and emissions on air quality using a regional climate model: Impact on ozone. *Atmos. Environ.* **2013**, *69*, 198–210. [CrossRef]
163. Coleman, L.; McVeigh, P.; Berresheim, H.; Martino, M.; O'Dowd, C.D. Photochemical Impact on Ozone Fluxes in Coastal Waters. *Adv. Meteorol.* **2012**, *2012*, 1–6. [CrossRef]
164. USEPA. *Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment*; US Environmental Protection Agency: Washington, DC, USA, 2017.
165. Parrish, D.D.; Law, K.; Staehelin, J.; Derwent, R.; Cooper, O.R.; Tanimoto, H.; Volz-Thomas, A.; Gilge, S.; Scheel, H.-E.; Steinbacher, M.; et al. Lower tropospheric ozone at northern midlatitudes: Changing seasonal cycle. *Geophys. Res. Lett.* **2013**, *40*, 1631–1636. [CrossRef]
166. Simmonds, P.; Derwent, R. Measurements of ozone and other radiatively active gases at Mace Head in the Republic of Ireland. *Atmos. Environ. Part A Gen. Top.* **1991**, *25*, 1795–1808. [CrossRef]
167. Derwent, R.; Manning, A.J.; Simmonds, P.G.; Spain, G.; O'Doherty, S. Analysis and interpretation of 25 years of ozone observations at the Mace Head Atmospheric Research Station on the Atlantic Ocean coast of Ireland from 1987 to 2012. *Atmos. Environ.* **2013**, *80*, 361–368. [CrossRef]
168. Rodríguez, S.; Torres, C.; Guerra, J.-C.; Cuevas, E. Transport pathways of ozone to marine and free-troposphere sites in Tenerife, Canary Islands. *Atmos. Environ.* **2004**, *38*, 4733–4747. [CrossRef]
169. Parrish, D.D.; Trainer, M.; Holloway, J.S.; Yee, J.E.; Warshawsky, M.S.; Fehsenfeld, F.C.; Forbes, G.L.; Moody, J.L. Relationships between ozone and carbon monoxide at surface sites in the North Atlantic region. *J. Geophys. Res. Space Phys.* **1998**, *103*, 13357–13376. [CrossRef]
170. Oltmans, S.J.; Levy, H. Surface ozone measurements from a global network. *Atmos. Environ.* **1994**, *28*, 9–24. [CrossRef]
171. Lelieveld, J.; Van Aardenne, J.; Fischer, H.; De Reus, M.; Williams, J.; Winkler, P. Increasing Ozone over the Atlantic Ocean. *Science* **2004**, *304*, 1483–1487. [CrossRef]
172. Boylan, P.; Helmig, D.; Oltmans, S.J. Ozone in the Atlantic Ocean marine boundary layer. *Elem. Sci. Anth.* **2015**, *3*, 000045. [CrossRef]
173. National Academies of Sciences and Medicine. *The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow*; National Academies Press: Washington, DC, USA, 2016.
174. Unger, N. Global Climate Forcing by Criteria Air Pollutants. *Annu. Rev. Environ. Resour.* **2012**, *37*, 1–24. [CrossRef]
175. Paterson, S.K.; Le Tissier, M.; Whyte, H.; Robinson, L.B.; Thielking, K.; Ingram, M.; Mccord, J. Examining the Potential of Art-Science Collaborations in the Anthropocene: A Case Study of Catching a Wave. *Front. Mar. Sci.* **2020**, *7*. [CrossRef]
176. Kankaanpää, P.; Young, O.R. The effectiveness of the Arctic Council. *Polar Res.* **2012**, *31*, 31. [CrossRef]