Report No.497

epa Research

Understanding Ozone Levels in Ireland

Authors: Liz Coleman, Nikhil Korhale, Damien Martin, Emmanuel Chevassus, Ling Zhen, Wei Xu and Colin D. O'Dowd

Lead organisation: University of Galway

www.epa.ie

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.

National Environmental Enforcement

- 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.

epaResearch

Understanding Ozone Levels in Ireland

Authors: Liz Coleman, Nikhil Korhale, Damien Martin, Emmanuel Chevassus, Ling Zhen, Wei Xu and Colin D. O'Dowd

Lead organisation: University of Galway

What did this research aim to address?

There is still uncertainty as to what is driving ozone pollution in Ireland, and if the causes are meteorological or national or transboundary emissions. This research aims to identify the contribution of ozone pollution from various international sources and the influence of meteorology via analysis of in situ measurements and advanced modelling techniques.

Ozone is a key player in atmospheric chemistry – a reactive, heavily oxidising gas that is produced naturally in the stratosphere and produced at surface level in the presence of sunlight and precursor pollutants. Ozone acts as a double agent, playing a beneficial role in the stratosphere by filtering damaging UV rays, yet acting as a harmful pollutant at surface level, causing negative human health effects, negatively affecting vegetation growth and acting as a climate-forcing greenhouse gas.

Ozone response to emission control is non-linear, governed by complex atmospheric chemistry; hence, its regulation poses a challenge for policymakers. Using long-term measurement records and advanced modelling tools, this research offers insights into the trends and drivers of past, present and future ozone pollution in Ireland.

What did this research find?

Counter-intuitively, ozone pollution is a clean-site problem in Ireland. Coastal and rural areas show higher ozone concentrations than urban areas owing to the prevalent effect of transboundary pollution and meteorological conditions that facilitate downward transport of ozone from the stratosphere in clean conditions and along the west coast of Ireland. Over the measurement record, urban areas show rising ozone trends due to declining NO_x levels in response to emission regulations.

Most breaches of World Health Organization air quality guidelines occur in springtime in rural and coastal areas, with air advected over the North Atlantic ocean contributing significantly to peak ozone levels.

European and North American efforts to reduce NO_x and volatile organic carbon emissions have lowered extreme ozone events but caused an increase in background levels in clean areas.

Methane is the dominant reactive carbon precursor to Irish surface ozone pollution, with increasing contributions from East Asia and biogenic sources, underscoring the global nature of ozone pollution and the importance of cooperation across borders to combat air pollution.

How can the research findings be used?

This research illustrates the need to further investigate ozone pollution by developing mechanistic modelling capacity to quantify sources and sinks of ozone over Ireland at high spatial resolution. Such modelling tools would enable policymakers to investigate the effect of national emissions on Irish ozone levels, inform a targeted policy response and allow for investigation of the impacts of a changing climate on future O_3 concentrations, trends and transport. Value could be added to existing modelling infrastructure developed in the Life Emerald project by advancing the assimilation of in situ and remote observations in an integrated data system, using machine learning techniques to identify correlations and trends in O_3 production and concentrations over timescales, for both long-term trends and immediate forecasts, to provide an early warning system for air quality specific to O_3 pollution.

This study highlights the significance of transboundary pollution for Irish ozone pollution levels, indicating the need for a shared transnational commitment to ozone mitigation as air pollution policies strive towards clean-air targets. This research also makes the case for Ireland to fully commit to the international Global Methane Pledge with the aim of reducing CH_4 concentrations.

Project code: 2022-CE-1133

EPA RESEARCH PROGRAMME 2021–2030

Understanding Ozone Levels in Ireland

(2022-CE-1133)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University of Galway

Authors:

Liz Coleman, Nikhil Korhale, Damien Martin, Emmanuel Chevassus, Ling Zhen, Wei Xu and Colin D. O'Dowd

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Climate, Energy and the Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely Eoin Riordan (Department of Climate, Energy and the Environment), Pat Kenny (EPA), Sverre Solberg (Norwegian Institute for Air Research) and Roy Harrison (University of Birmingham). The authors would also like to extend their gratitude to Damien Martin, who acted as temporary principal investigator during this project, and Anne Mason (Research Project Manager on behalf of the EPA).

DISCLAIMER

This report is based on research carried out/data from January 2023 to August 2024. More recent data may have become available since the research was completed.

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

EPA RESEARCH PROGRAMME 2021–2030
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-317-1 November 2025

Price: Free Online version

Project Partners

Liz Coleman
Physics, School of Natural Sciences, and
Centre for Climate & Air Pollution Studies,
Ryan Institute
University of Galway
Galway
Ireland
Tel.: +353 91 492096
Email: liz.coleman@universityofgalway.ie

Nikhil Korhale
Physics, School of Natural Sciences, and
Centre for Climate & Air Pollution Studies,
Ryan Institute
University of Galway
Galway
Ireland
Tel.: +353 91 492496
Email: Nikhil.korhale@universityofgalway.ie

Tabish Ansari
Research Institute for Sustainability
Potsdam
Germany
Tel.: +49 331 28822 300
Email: tabish.ansari@rifs-potsdam.de

Tim Butler
Research Institute for Sustainability
Potsdam
Germany
Tel.: +49 331 28822 300
Email: tim.butler@rifs-potsdam.de

Contents

List of Figures

List of Tables

Executive Summary

Ozone (O_3) is an atmospheric double agent – playing a beneficial role in the stratosphere by filtering harmful UV rays, yet acting as a harmful pollutant at surface level, causing negative human health effects by way of increased respiratory illnesses, metabolic disorders and nervous system and reproductive issues; negatively affecting vegetation by causing leaf damage, stunting root growth and reducing crop yields; and acting as a greenhouse gas.

Tropospheric O_3 is either transported from the stratosphere or formed via complex photochemical tropospheric interactions involving precursor gases – the most important of which are nitrogen oxides (NO_x), volatile organic carbons and methane (CH_4). O_3 concentrations can decrease or increase with changes in precursor concentration, depending on the meteorological and atmospheric conditions, rendering O_3 regulation a challenge for policymakers.

This report presents a detailed analysis of O_3 measurements across Irish monitoring sites over the measurement record, with a focus on understanding trends, identifying the drivers of observed changes and assessing compliance with air quality standards. The study integrates extensive observational data with advanced modelling techniques to offer insights into the temporal and spatial dynamics of surface O_3.

Key Findings

- In Ireland, O_3 pollution is a clean-site problem, with the most elevated O_3 concentrations observed at clean rural and coastal sites. Seasonal patterns show a characteristic spring-time peak with an annual dip in summer.
- O_3 measurements at Mace Head show a declining trend in the spring-time peak over the past few decades, reflecting reductions in precursor emissions in both Europe and North America. Measurements also show a rise in winter-time concentrations, attributable to a reduction in NO_x titration events, which deplete O_3. Aviation emissions and lower-latitudinal precursor sources have a larger proportional contribution to winter-time O_3 concentrations.
- Urban sites demonstrate an increasing trend attributed to the “weekend effect”, whereby a reduction in NO_x pollution removes and reduces a mechanism for the chemical removal of O_3, ultimately causing an increase in O_3 pollution.
- Exceedances of O_3 air quality limits are disproportionately observed in rural and coastal areas because of transboundary air pollution and stratospheric intrusion.
- A third of all exceedances at Mace Head occurred when air masses were associated with clean trajectories. At Mace Head, European pollution contributes to summer-time exceedances, but most exceedances occur in March, April and May. Spring-time exceedances occur due to a build-up of O_3 sources, rather than the presence of any additional sources.
- The analysis underscores the effectiveness of North American and European regulations targeting precursor emissions but also identifies other important sources of precursors, such as South-East Asia, and the importance of CH_4 regulations in controlling surface O_3 concentrations.

Recommendations

Scientific capacity development. There is scope to develop modelling capacity to quantify sources and sinks of O_3 over Ireland in high resolution. This will inform targeted policy responses related to national emissions and allow for investigation of the impacts of a changing climate on future O_3 concentrations, trends and transport.

There is also scope to combine modelling products with *in situ* and remote observations in an integrated data system, which could use machine learning techniques to identify correlations and trends in O_3 production and concentrations and provide data for environmental services and early warning systems for air quality.

Measurement network and emissions calculation development. In line with the revised Clean Air for Europe Directive, key measurement supersites in Ireland should be equipped for continuous

measurement of O_3 and relevant precursor levels (including speciated volatile organic carbon measurements) to further understanding of the contribution of various emission sectors to O_3 pollution.

Policy development. Reaching air quality targets for protection of human health will become more challenging as legislation becomes more ambitious. CH_4 has been identified as the dominant atmospheric reactive carbon precursor influencing Irish O_3 levels. As CH_4 is a powerful greenhouse gas, CH_4 emission abatement would not only improve air quality by reducing O_3 formation but also reduce greenhouse gas concentrations. It is recommended that Ireland fully commit to the international Global Methane Pledge with the aim of reducing CH_4 concentrations. It is also suggested that Ireland address CH_4 as a precursor to O_3, as outlined in the Gothenburg Protocol of the United Nations Economic Commission for Europe's Convention on Long-range Transboundary Air Pollution.

Communication development. Mitigation efforts should include educational campaigns to raise awareness about O_3 and its sources and sinks, effect on health and contribution to climate change.

1 Introduction

Tropospheric ozone (O_3), monitored in Ireland by the Irish Environmental Protection Agency (EPA), is a pollutant hazardous to human health and ecosystems and a radiatively active gas that contributes to the greenhouse effect and has been identified by the Intergovernmental Panel on Climate Change as the third most significant greenhouse gas (GHG) after carbon dioxide and methane (CH_4) (Masson-Delmotte *et al*., 2021). Limiting O_3 pollution is a priority for policymakers at the local, national and international levels.

Despite legislation to limit precursor emissions, 94% of those living in European cities were exposed to O_3 levels exceeding the World Health Organization (WHO) air quality guideline (AQG) for the protection of human health in 2022 (EEA, 2024a; World Health Organization, 2021). More than 22,000 premature deaths in the EU were attributable to short-term exposure to O_3 in 2021 (Soares *et al*., 2023).

Over the past 150 years, modelling studies have shown that an increase in anthropogenic emissions of O_3 precursors has led to an estimated 40% increase in tropospheric O_3 burden (Archibald *et al*., 2020; Griffiths *et al*., 2021; Young *et al*., 2013). With the deleterious impact of surface O_3 on human and ecosystem health and radiative forcing, and the associated ecological and societal impacts, it is a priority to design effective mitigation strategies to limit O_3 pollution. This requires an integrated understanding of processes influencing surface O_3 concentrations at the local, national and international levels.

1.1 The Nature of Ozone

In the stratosphere, molecular oxygen (O_2) becomes disassociated by high-energy UV rays to form atomic oxygen, allowing for abundant O_3 formation. Stratospheric O_3-rich air can then undergo stratosphere–troposphere exchange (STE). when O_3-rich air is transported down into the lower atmosphere (Roelofs *et al*., 2003). STE is more significant in the northern hemisphere than in the southern hemisphere and is higher in spring than in autumn (Crutzen, 1988). O_3 is also transported from the stratosphere to the troposphere over a longer time period by Brewster–Dobson circulation – a global-scale meridional circulation mechanism whereby air rises from the troposphere to the stratosphere in the tropics and descends in the high-to-mid latitudes, redistributing O_3 from the tropics polewards (Brewer, 1949; Dobson, 1956). Brewster–Dobson circulation is subject to seasonal variation, with transport more effective in winter, which is likely to increase with a changing climate (Haklander *et al*., 2008).

In the troposphere, O_3 is formed when nitrogen dioxide (NO_2) breaks down into nitric oxide (NO) and atomic oxygen in the presence of sunlight. This process is facilitated by carbon monoxide (CO) and volatile organic carbons (VOCs) via the CH_4 oxidation chain. During this catalytic process, both nitrogen oxides (NO_x) and VOCs are in competition to react with the hydroxyl radical, and the rate of O_3 formation depends on the chemical conditions, the ratios of the precursors and the presence of sunlight. O_3 precursors are emitted from various anthropogenic sources, (traffic, combustion, industry) as well as from natural sources like vegetation, wildfires and lightning.

O_3 is removed from the atmosphere when sunlight reacts with an O_3 molecule to form O_2 and an excited singlet oxygen atom. In the presence of atmospheric water vapour, the singlet oxygen atom combines with an H_2O molecule to produce two hydroxyl radicals. In polluted areas with low insolation, O_3 can also be removed via NO_x titration, when O_3 is scavenged from the atmosphere by NO. O_3 can also be removed via dry and wet deposition, but, in the troposphere, photochemical production and destruction dominate O_3 production and loss mechanisms, respectively (Stevenson *et al*., 2006; Wang *et al*., 1998).

1.2 Current Policy Landscape

To promote health, protect global safety and safeguard vulnerable populations, WHO publishes AQGs as a non-legally binding global target for governments to achieve within their jurisdictions. The AQGs comprise

evidence-based recommendations for limit values to protect public health. The current recommended AQG for O_3 is expressed as a limit for an 8-hourly mean O_3 value of 100 µg m^{-3} and a peak-season limit of 60 µg m^{-3}. The first limit stands year round and represents short-term exposure. Longer term exposure risk is captured by the peak-season limit, which suggests that individuals should not be exposed to monthly average daily maximum 8-hour mean (MDA8) O_3 concentrations of over 60 µg m^{-3} for 6 consecutive months.

The Clean Air for Europe (CAFE) Directive (Directive (EU) 2024/2881) legislates for the protection of human health, vegetation and ecosystems from air pollution by setting air quality standards for 12 pollutants, including surface O_3. The current directive states that O_3 MDA8 should not exceed 120 µg m^{-3} at any measurement station more than 25 days per calendar year, averaged over 3 years. For the protection of vegetation (crops and forests), the CAFE Directive defines the accumulated ozone exposure over a threshold of 40 ppb (or 80 µg m^{-3}) (AOT40) calculated as the sum of hourly surface O_3 measurements exceeding 80 µg m^{-3} during daylight hours from May to July for crops, and from April to September for forests. The directive decrees that the AOT40 should not exceed 18,000 µg m^{-3} h^{-1}, averaged over 5 years, with the long-term objective of an AOT40 of 6000 µg m^{-3} h^{-1}.

NO_x and non-methane volatile organic carbons (NMVOCs) are regulated through the National Emissions reduction Commitments Directive, but CH_4 is regulated through the Climate Action and Low Carbon Development Act 2015. The Global Methane Pledge (GMP) is an international pledge to reduce CH_4 emissions by 30% from 2020 levels by 2030, launched at the 26th United Nations Framework Convention on Climate Change Conference of Parties by the EU and the United States. Policy regulation of O_3 precursor emissions under the National Emissions reduction Commitments Directive has led to a significant decrease in surface O_3 levels in western Europe (Logan *et al*., 2012), including Ireland (Tripathi *et al*., 2010), in recent decades. Despite the implementation of policy, human exposure to surface O_3 continues to pose problems, with over a million respiratory illness deaths each year attributed to tropospheric O_3 pollution worldwide (Malley *et al*., 2017).

1.3 Factors Influencing Irish Ozone Levels

Elevated O_3 levels are observed in polluted locations in spring throughout the northern hemisphere, where there is a higher emission rate of O_3 precursors than in the southern hemisphere, as well as more stratospheric influx. Remote and rural sites generally exhibit more moderate O_3 concentrations, closer to pre-industrial tropospheric O_3 levels (Seinfeld and Pandis, 2008), yet elevated surface O_3 levels are also recorded at remote and relatively unpolluted sites owing to a combination of transported O_3 and local photochemical production (Boylan *et al*., 2015; Derwent and Parrish, 2022).

The rate of O_3 photochemical formation/destruction is governed by competition between VOCs and NO_x for the hydroxyl radical. NO_x is predominantly anthropogenic in origin, whereas atmospheric VOCs can be naturally or anthropogenically produced. CH_4 is the primary VOC that exists in the chemical reservoir of the atmosphere, especially in regions removed from anthropogenic sources.

In a relatively clean, NO_x-free environment, O_3 production is said to be NO_x controlled and hence correlated with NO_x (e.g. rural areas). In polluted (e.g. urban) NO_x-rich environments, close to the NO_x source, O_3 is scavenged by NO due to hydroxyl radical competition (Bais *et al*., 2015). The retardation of O_3 formation with increasing NO_x is described as a NO_x-saturated regime, typically a temporary effect localised in time and space to the NO_x emissions that occur in times of low insolation – night-time, cloudy days and winter. Often, elevated O_3 concentrations are observed downwind of the source.

Removal of NO_x due to air quality legislation can contribute to a rise in mean O_3 concentrations, as observed in the UK (Finch and Palmer, 2020). Models have shown decreased NO_x concentrations in polluted regions leading to increased surface O_3 levels during periods of low insolation (Coleman *et al*., 2013).

Surface O_3 has an atmospheric lifetime on the scale of hours to days but can live higher up in the free troposphere (FT) for weeks. O_3 atmospheric lifetime varies with altitude, latitude and season – lifetimes being shorter in the summer due to higher solar fluxes and shorter at the surface due to higher water vapour content.

At higher latitudes there is reduced solar intensity, hence longer atmospheric lifetimes, and atmospheric lifetimes increase with vertical height (Seinfeld and Pandis, 2008), influencing O_3 transport patterns. O_3 concentrations peak downwind of major precursor sources, as the photochemical reactions involved can take several hours. Surface O_3 can undergo long-range transport, which has been shown to considerably influence O_3 levels in western Europe, including Ireland (Amann *et al*., 2008; Creilson *et al*., 2003; Hegarty *et al*., 2009). Other investigations have underscored the impact of transatlantic pollution on air quality in Europe (Li *et al*., 2002; Prather *et al*., 2003). The long-range transport of O_3 from North America to Europe is particularly effective in the middle and upper troposphere due to the longer lifespan of O_3 at higher vertical levels and the strength of the westerly winds compared with the marine boundary layer.

The North Atlantic Oscillation (NAO) has been shown to influence surface O_3 levels, with impacts across Europe (Pausata *et al*., 2012). Regional O_3 levels are also influenced by large-scale blocking systems that trap emitted precursor gases and O_3, elevating concentrations to the point of posing a health risk (Pope *et al*., 2016). These blocking systems, common in the mid-to-high latitudes, increase the chance of O_3 exceedance events by 30% (Otero *et al*., 2022).

Photochemical, physiochemical and transport processes significantly influence O_3 levels (Pancholi *et al*., 2018). Meteorological parameters like temperature, solar radiation, wind speed and atmospheric stability substantially influence O_3 levels, with maximum photochemical O_3 formation occurring in periods of high insolation and elevated temperatures (Khiem *et al*., 2010; Ordóñez *et al*., 2020; Sicard *et al*., 2016), as well as meteorological variables like relative humidity, cloud cover, wind speed, surface radiation and boundary layer height. Hence, there is an obvious diurnal and seasonal cycle associated with O_3 concentrations.

Ireland is subject to a prevailing westerly wind flow that brings clean Atlantic air. The Mace Head Atmospheric Research Station serves as a representative location for tracking background pollution flows into Europe. The geographical location of Mace Head is shown in Figure 1.1. Previous research has shown that air quality in Ireland is strongly influenced by Atlantic air masses; only a small fraction, approximately 7%, of air masses arrive from mainland Europe (Tripathi *et al*., 2010).

An early analysis of O_3 and CO concentrations at Mace Head from 1990 to 1992 identified a stable northern hemisphere baseline surface O_3 level of 30–40 ppb and recognised that the continent of Europe acts as a small but significant O_3 sink (Derwent *et al*., 1994). A subsequent study sorted Mace Head O_3 data from 1990 to 1994 using simultaneous co-located halocarbon measurements and back-trajectory

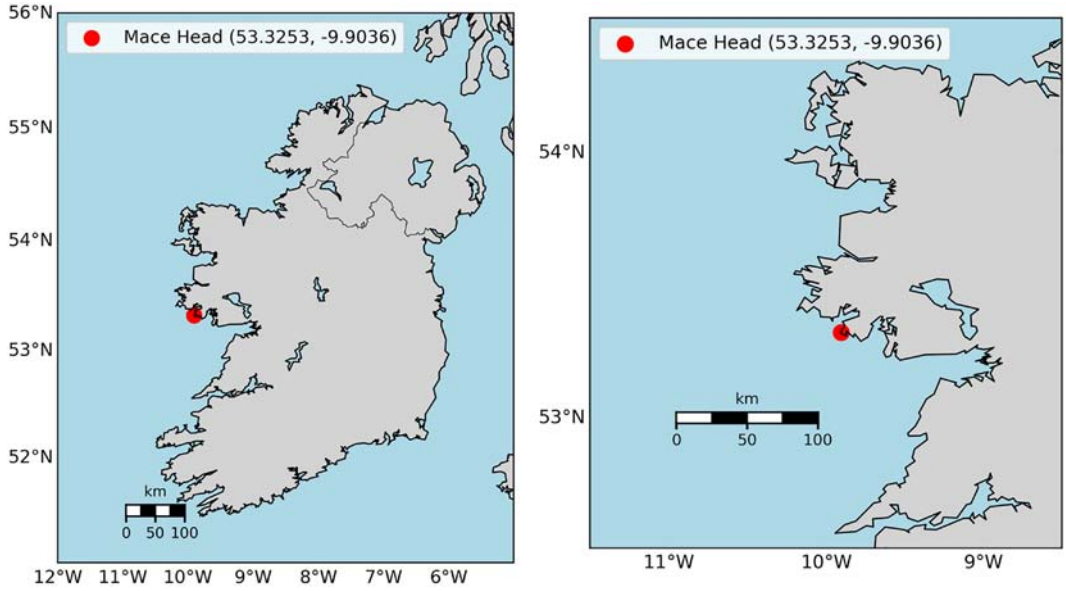

Figure 1.1. Map of Ireland (left) and local area map (right), with the red dot showing the location of the measurement station.

analysis to filter out pollution episodes, leaving stable baseline "unpolluted" values. Mean background O_3 concentrations were estimated as 35.0 ± 4.5 ppb, with a spring-time maximum and summer-time minimum (Derwent *et al*., 1998). The influence of European pollution was shown to cause a slight increase in O_3 levels at Mace Head in summertime but cause significant depletion of O_3 levels in wintertime.

The cause of the spring maximum in background O_3 levels has been the subject of considerable scientific discussion. One review study summarised the state of knowledge regarding the spring maximum (Monks, 2000), identifying a significant knowledge gap related to atmospheric chemistry and highlighting the difficulty in identifying the main drivers of the O_3 spring maximum due to the myriad of factors affecting its transport and its chemistry. Studies have highlighted the shifting seasonal pattern in the northern mid-latitudes, where the spring-time peak occurs earlier in the year than in previous decades (Parrish *et al*., 2013). This has been attributed to the increased relative importance of stratospheric O_3 and large-scale hemispheric transport and to a change in the distribution of precursor emissions (a reduction in US and EU emissions and an increase in emissions from East Asia) leading to an earlier onset of photochemical production and a more efficient rise in levels, transport and production of O_3 within the FT (Cooper *et al*., 2010, 2012; Wild and Akimoto, 2001).

The instrumental record at Mace Head has allowed the scientific community to study the trend in background O_3 levels, developing an understanding of the mechanisms influencing the O_3 pollution advected into Europe.

The most recent study by Derwent *et al*. (2024) considers the 35-year measurement record and identifies a rising trend in concentrations until the late 1990s, with more significant changes observed in the winter and spring and milder shifts in the summer, after which baseline surface O_3 was relatively stable during the 2000s, with a subsequent decline in the 2010s. However, unsorted O_3 concentration data exhibited different long-term trends compared with baseline data due to the influence of regional European NO_x and VOC emissions, which caused winter-time O_3 levels to drop below baseline levels while elevating summer-time O_3 levels above them. Episodic peak O_3 levels steadily decreased over the study period, indicating a reduction in the influence of European pollution over the analysis period, consistent with a reduction in NO_x concentrations and the shift towards an earlier spring-time peak, as observed by Parrish *et al*. (2013).

To attribute background O_3 levels to regional sources, a model study used tagged simulations and measurement comparison to determine source attribution of O_3 concentrations at Mace Head (Li *et al*., 2002). The study found that low-level westerly flows contributed an average 5 ppb to surface O_3 levels from North America at Mace Head, up to 10–20 ppb during specific transatlantic transport events. The influence of North American pollution is strongly correlated with the NAO. The study also found that 20% of exceedances of EU O_3 limits during summer 1997 would not have occurred without the influence of North American anthropogenic emissions and showed transatlantic flow patterns to be more prominent in winter.

A recent study analysed seasonal, interannual and decadal variations in tropospheric O_3 levels and attempted to determine factors contributing to changes by comparing satellite observations of tropospheric O_3 and using the Unified Model coupled with the UK Chemistry and Aerosols climate model (Russo *et al*., 2023). Observations showed an increasing trend in tropospheric O_3 levels over the North Atlantic that were not recreated in model simulation, which was attributed to the model underestimating stratospheric O_3 sources and associated transport to the troposphere. This study identified the response of stratospheric transport to large-scale North Atlantic circulation patterns, the NAO and the Arctic Oscillation, as a significant factor influencing North Atlantic tropospheric O_3 levels. The link between the Arctic Oscillation, the NAO and surface O_3 levels has been previously discussed as influencing transatlantic westerly transport (Creilson *et al*., 2003; Lamarque and Hess, 2004); its influence on downward stratospheric transport was postulated by Pausata *et al*. (2012) but not explicitly demonstrated.

The significant impact of lower-stratospheric O_3 levels on background O_3 in the FT was highlighted using surface measurements at high-altitude sites combined with sonde measurements in the lower stratosphere and stratospheric chemistry transport models, as well as a Lagrangian model in a study by Ordóñez *et al*. (2007), which indicated that the driver of change in mid-latitudinal O_3 levels in western and central Europe

was changes in lower-stratospheric O_3 concentrations, causing increased downward transport of O_3 from the stratosphere, most prominently in winter and spring. STE represents a significant source of O_3 in regions like Mace Head that are not very active in terms of photochemical O_3 production (Lelieveld and Dentener, 2000).

1.3.1 Emission of ozone precursors

European and UK emissions

Anthropogenic activities, including industrial activities, residential heating and transport, are significant contributors to the emissions of NO_x and CO, whereas atmospheric VOC concentrations are influenced by both anthropogenic emissions and biogenic emissions (Guo *et al*., 2017). CH_4 is defined as a well-mixed GHG owing to its long atmospheric lifetime and relatively even distribution across the globe, and so concentrations in the Irish domain are influenced by global emissions and trends.

Local photochemical O_3 production is influenced by incident solar radiation and atmospheric chemical conditions. A change in NO_x levels can cause either an increase or a decrease in surface O_3 production, depending on the season, meteorological conditions and the relative concentrations of the main precursors, NO_x and VOCs (Simon *et al*., 2015).

NO_x and VOC emissions have seen significant reductions in Europe (Colette *et al*., 2018; Guerreiro *et al*., 2014; Henschel *et al*., 2015). NO_x emissions in Europe have decreased by around 51% since 1990 (EEA, 2024b), facilitated by implementation of new catalytic systems in diesel engines (Selleri *et al*., 2021), but mid-latitudinal northern hemisphere O_3 concentrations have not decreased accordingly. Instead, the decrease in NO_x emissions has led to a reduction in extreme O_3 lows caused by winter-time NO_x titration and a reduction in high O_3 pollution events due to enhanced photochemical production in polluted air masses, as noted by Oltmans *et al*. (2013); therefore, the effect of air pollution abatement has been to reduce the extreme O_3 lows (or highs) in winter (or summer), as discussed by Simpson *et al*. (2014).

Mean O_3 concentrations either remained steady or even increased at rural background sites in many European countries from the 1990s to the mid-2000s (Boleti *et al*., 2020; Munir *et al*., 2013; Sicard, 2021). Urban sites have observed an increase in mean O_3 concentrations and, in some instances, both rural and urban locations have experienced upward trends, with more substantial increases observed in urban areas (Paoletti *et al*., 2014; Querol *et al*., 2016). Background mid-latitudinal O_3 levels, as represented by the measurement record at Mace Head, decreased up until the late 1990s, followed by stabilisation and then a declining trend, as reported in section 1.3.

The levels of NMVOCs derived from fossil fuel combustion and transport have decreased significantly since the late 1990s, and there has been a relative increase in NMVOCs derived from industrial and domestic solvent use (Lewis *et al*., 2020).

National emissions

The main NO_x sources in Ireland include agriculture (through the use of organic and synthetic nitrogen fertilisers, and fossil fuel combustion from power generation and traffic (petrol and diesel). Between 1990 and 2022, NO_x emissions decreased by 46% due to improvements in technologies for power generation and transport engines (EPA, 2024).

VOCs are reactive components in both continental and marine atmospheres (Lewis *et al*., 2005). Research has demonstrated that the balance between natural and anthropogenic emissions of VOCs can vary seasonally and spatially, impacting O_3 levels accordingly. The primary sources of increasing NMVOC emissions include agriculture, solvent use fugitive emissions, and the food and beverage industry, with the distillation industry doubling its contribution to NMVOC emissions between 1990 and 2022. Emissions from combustion of fossil fuels account for 10.5% of national NMVOC emissions. Reducing trends in NMVOC emissions have stabilised in recent years, and there is a growing need to mitigate emissions from the spirit production sector (EPA, 2024).

Irish CO emissions have declined, with significant reductions attributed to the use of three-way catalysts in vehicle engines in the road transport sector, along with a substantial decrease in the use of solid fuels for residential space heating. National total CO emissions

decreased by 81.6% over the period from 1990 to 2019 (EPA, 2024).

The predominant contributor to CH_4 emissions in Ireland is enteric fermentation in the agricultural sector. CH_4 emissions increased progressively throughout the 1990s, peaking in 1998 and then falling due to reductions in herd size in line with the Common Agricultural Policy, but overall maintained an increasing trend of 5% between 1990 and 2023. However, as CH_4 is a well-mixed GHG, national CH_4 concentrations are determined not by national emissions, but by the global emission burden, which has risen by 20% over the past two decades, with a consequent rise in background CH_4 levels as observed at Mace Head (Coleman *et al*., 2021; Jackson *et al*., 2024).

In Ireland, the transport sector contributes to approximately 20% of GHG emissions (EPA, 2025) and contributed 35% of NO_x emissions in 2022 (EPA, 2024). Over the past 15 years, there has been a significant increase (43%) in the number of cars in Ireland (CSO, 2017), a statistic documented in reports by the Central Statistics Office (CSO, 2017). Road transport is responsible for releasing various regulated and unregulated pollutants (Gkatzoflias *et al*., 2012). In this context, the sector is a main source of O_3 precursors in urban areas of Ireland.

1.4 Aims and Objectives

The overall aim of this study was to improve the understanding of O_3 levels and trends in Ireland, identifying the main drivers of both trends and exceedances, and to assess both the historical and potential future effects of air pollution and climate policy on Irish O_3 levels.

1.4.1 Objectives and targets

- To write an up-to-date literature review regarding the factors influencing Irish O_3 levels.
- To compile and analyse the available measurement records from EPA monitoring sites to identify trends in annual and seasonal means, relative to the WHO AQG, related to the protection of human health.
- To compare measurements against the global chemistry transport model and to identify the contribution of precursor emissions from regional sources to Irish surface O_3 levels.
- To apply machine learning methods to identify drivers of trends and O_3 pollution events at Mace Head.
- To assess the impacts of a changing climate on Irish surface O_3.

2 Methods

2.1 Measurement Sites

The EPA manages the national ambient air quality monitoring network, which carries out continuous real-time monitoring of atmospheric pollutants. O_3 is measured by UV photometry using an API M400 O_3 analyser. O_3 measurement sites and site classifications that operate under the ambient air quality network are shown in Figure 2.1. Sites were separated into three categories: coastal, rural and urban. Annual trends were assessed based on monthly mean concentrations. Seasonal trends were identified based on the meteorological seasons: spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February). O_3 exceedances were calculated based on breaching of the WHO AQGs (MDA8 should not exceed 100 µg m^{-3} and peak-season limit is 60 µg m^{-3}).

Meteorological parameters at Mace Head have been collected by Met Éireann since 2003, when an automatic weather station was installed on the site. Met Éireann data is used to determine meteorological influence on Mace Head O_3 levels.

2.2 Data Analysis

Trend analysis was performed using the openair package in R. Trends were determined using the Theil–Sen slope estimator and the Mann–Kendall test to quantify significance, in consonance with Tropospheric Ozone Assessment Report (TOAR) guidance on metrics (Lefohn *et al.*, 2018). This is a

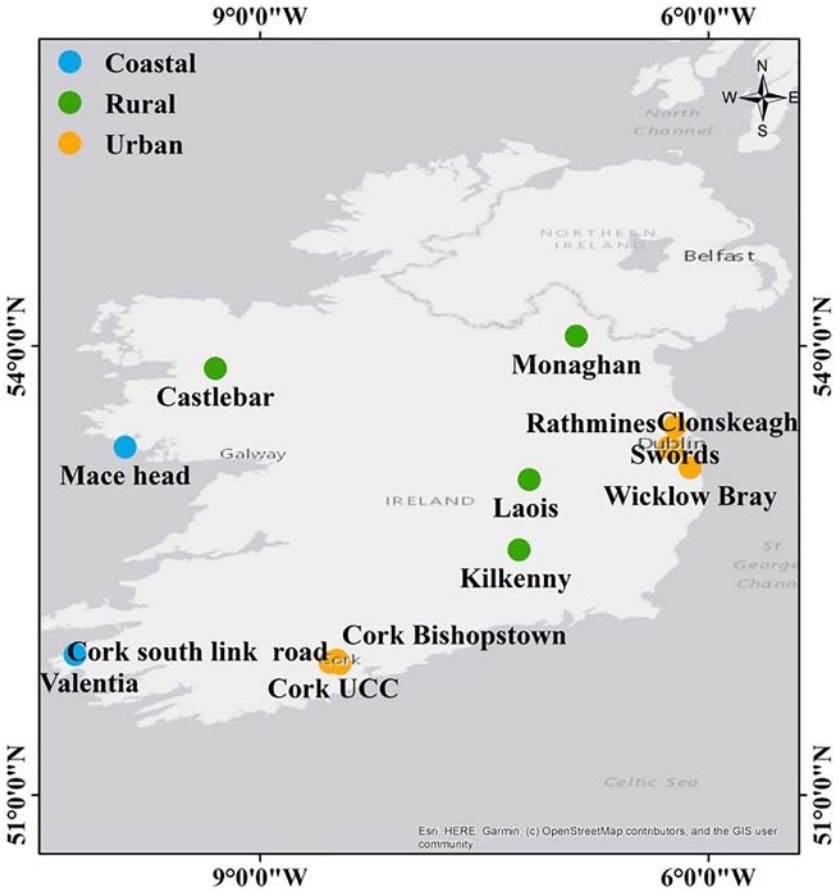

Figure 2.1. Location of O_3 measurement sites in the EPA national ambient air quality network. Blue dots represent coastal sites, green dots are for rural sites and orange dots are for urban sites. UCC, University College Cork.

robust method for estimating trend slopes in a time series that may contain outliers or irregularities. Unlike traditional least-squares regression, the Theil–Sen method calculates the median slope from all possible point pairs, providing a reliable trend. The uncertainty/reliability of the trend is calibrated according to the "probability" or *p*-value, as outlined by Chang *et al*. (2023), consistent with guidelines for best statistical practice for TOAR analysis used in the second phase of the TOAR.

2.3 Data Filtering

Filtering of data to analyse trends in background O_3 measured at Mace Head was carried out using two different methods. Firstly, data was filtered according to wind sector, whereby data taken from days when the wind direction was between 230° and 280° was classified as clean-sector data. For the identification of the clean sector, the *k*-means clustering method was used. This approach is similar to the clustering of back trajectories; however, instead of relying on back trajectories, it incorporates local wind speed, wind direction and black carbon concentration. The *k*-means clustering technique has been utilised in previous studies, such as Riley *et al*. (2023). The analysis identifies a specific cluster in the sector ranging from 230° to 280°, characterised by low concentrations of black carbon, indicating a clean sector. This filtering mechanism works efficiently but can classify continental polluted air masses that have been recirculated as coming from the clean air sector. This method was utilised in the machine learning analysis section of this study (section 5.3).

The measurement data was separated by clean or background air-mass origin using back trajectories calculated from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein *et al*., 2015). To filter out data that was free from European sources, 3-day back trajectories were computed for the trajectories for 6:00 a.m. Coordinated Universal Time, and the trajectories were segregated into those that traversed over the ocean (clean trajectories) and those that travelled over land (polluted).

The separated trajectories indicate a marked seasonality. In the summer, wind speeds are lower, so the movement of air masses arriving at Mace Head is slower, meaning that the geographical footprint of emissions influencing Mace Head is smaller. Trajectories were computed using the HYSPLIT model for 2000–2022; hence, filtered analysis was performed only from the year 2000 onwards.

2.4 Model Data

The contribution of various source regions to surface O_3 levels at Mace Head was quantified using global chemistry transport model Community Earth System Model Community Atmosphere Model version 4 (CAM4-Chem), which tags O_3 molecules in simulations relative to the origin of their NO_x and VOC precursors using two separate simulations – one to tag the VOC precursors and one to tag the NO_x precursors – the tropospheric O_3 source attribution system with tagging (Butler *et al*., 2018). The two simulations are required because, in essence, secondary O_3 formation requires two precursor "parents" – one NO_x molecule and one VOC molecule. The NO_x-tagged simulation determines the origin of the NO_x precursor and the VOC-tagged simulation determines the origin of the VOC precursor. The total simulated O_3 is equivalent in both simulations, as is the stratospheric contribution, which is set in the model as an upper boundary condition.

The tags include both natural and anthropogenic emissions, geographically separated. Results allow direct quantification of the contribution of precursors from various regions and sectors to O_3. The model is set up with a horizontal resolution of $1.9^o \times 2.5^o$ (about 150 km × 215 km) with 56 vertical levels. Anthropogenic emissions are provided from Hemispheric Transport of Air Pollution version 3 (Crippa *et al*., 2023), with aircraft emissions specified at three different vertical levels. CH_4 concentrations in the model are applied as a surface boundary condition, taken from the 2010–2018 average model flux-inversion product, where ground-based and satellite observations are assimilated into chemistry transport models – fusing together modelling and measurement techniques to get the best possible match between observed and simulated concentrations (Segers and Nanni, 2023). Within CAM4-Chem, zonally averaged monthly CH_4 values are set as a prescribed boundary condition. The simulations used for this study span the period from 2000 to 2018 (Nalam *et al*., 2024). In this current study, we analyse the simulation results for surface O_3 in the context of Irish O_3 concentrations.

2.5 Machine Learning Model

A random forest (RF) model is a versatile machine learning tool that can identify correlations and patterns in complex datasets, allowing it to make predictions with a high degree of accuracy. RF models are particularly effective in handling non-linear and complex relationships.

The RF model was applied to a daily Mace Head dataset, which included measured surface O_3 and CH_4, with CO and NO_2 concentration measurements obtained from Copernicus Atmospheric Monitoring Service reanalysis data and meteorological data from Met Éireann on rainfall, boundary layer height, temperature, wind speed and direction, and global radiation. The RF model was applied to the dataset to identify correlations among the variables. The dataset comprised 4500 daily entries, with the first 4000 days used for training the model and the remaining 500 days allocated for testing and forecasting. Hyperparameters, including the number of trees and node depths, were systematically optimised using grid search functionality. Partial dependence plots were created to illustrate the relationships between each variable and predicted O_3 concentrations, enabling the extraction of non-linear associations between specific factors and O_3 levels. Additionally, Shapley Additive exPlanations (SHAP) summary plots were generated to quantify the impact of each variable on predicted O_3 concentrations for both mean values and extremes.

3 Analysis of Ozone at Irish Measurement Sites

We examined the distribution of and trends in surface O_3 and precursor levels at the monitored locations across Ireland; the results are shown in Figure 3.1, which shows boxplots for six representative sites.

3.1 Yearly Variation

In accordance with previous studies, the highest O_3 concentrations were observed at coastal stations, followed by the rural stations, with lower O_3 levels observed at the urban stations (McHugh *et al*., 2023; Tripathi *et al*., 2010). Polluted areas have a supply of NO_x that will purge O_3 from the atmosphere, which is not present in clean areas with fewer sources of anthropogenic pollutants. *Although it is counterintuitive that areas with fewer pollution sources suffer from elevated surface O_3 concentrations, this is indicative of the non-linear nature of O_3 chemistry, as regional surface O_3 concentrations are influenced by factors other than photochemical production due to local emission sources*. Polluted land areas act as sinks of O_3, and coastal stations on the west coast of Ireland experience elevated O_3 levels due to transatlantic transport of North American pollution via lower westerly airflows and transport of O_3 and precursors in the FT and stratospheric transport, modulated by North Atlantic circulation patterns. The elevated O_3 levels decrease as O_3 becomes depleted by local pollution and deposition as it blows eastward over land. This mirrors findings from an extensive UK report (Lewis *et al*., 2021) that rural remote stations exhibit higher O_3 levels than urban and suburban stations.

3.2 Seasonal Variation

The characteristic spring-time high and summer-time low are apparent at all stations, owing to the favourable conditions in springtime for hemispheric transport, stratospheric influx and photochemical production (Figure 3.2). Summertime conditions with elevated temperatures and insolation favour photochemical destruction and lower wind speeds, leading to less transported O_3 arriving in Ireland.

The seasonal cycle is more pronounced in clean and rural stations due to a lack of influence from local emissions.

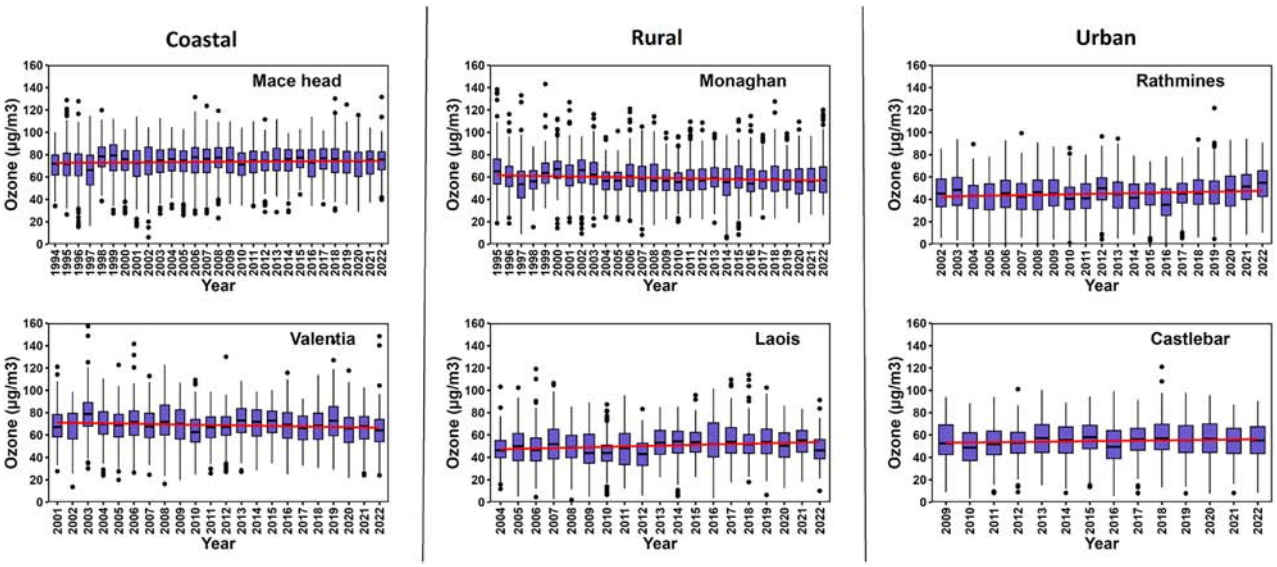

Figure 3.1. Boxplots showing annual mean surface O_3 concentrations (µg m^{-3}) over the measurement record available at each site. The lowest whisker level represents the 5th percentile, the boxes span the 25th to 75th percentiles, the horizontal line within each box represents the median 50th percentile, and the upper whisker represents the 95th percentile.

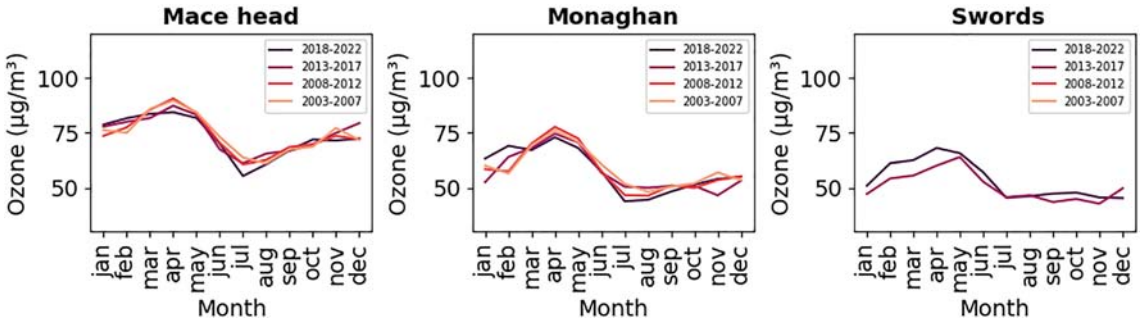

Figure 3.2. Seasonal cycle of monthly mean surface O_3 measurements (µg m^{-3}) at selected stations, represented as 5-yearly averages.

3.3 Trends in Average Ozone Measurements

These trends are mostly in agreement with previous studies, notably at the Mace Head measurement site, where there was a positive trend observed in background O_3 levels up to the mid-2000s that stabilised and began to decline in the 2010s (Derwent *et al*., 2018), although it is noted that trend analysis in Table 3.1 was performed on complete data, not data that was filtered for background conditions. Trends are variable – sometimes changing direction over the duration of the measurement record (e.g. Mace Head, Castlebar).

Analysis of the measurement record of surface O_3 levels at Valentia in this study calculated a long-term decreasing trend of –0.23 µg m^{-3} y^{-1}, consistent with a previous study by Tripathi *et al*. (2010). However, a more recent study looking at long-term trends in surface O_3 levels in Ireland identified a trend with a similar magnitude, but opposite direction, with an *increase* of 0.22 µg m^{-3} y^{-1} in surface O_3 observed at Valentia between 2010 and 2019, although this

Table 3.1. Trends in surface O_3 concentrations (in µg m^{-3} y^{-1}) calculated using the Theil–Sen slope estimator and the Mann–Kendall test to quantify significance

Site no.	Station name (classification)	Measurement record	Trend over record (µg m^{-3} y^{-1})	5-year trend, 2018–2022 (µg m^{-3} y^{-1})	10-year trend, 2013–2022 (µg m^{-3} y^{-1})	15-year trend, 2008–2022 (µg m^{-3} y^{-1})
1	Mace Head (C)	1994–2022	0.02	–0.25	–0.31**	–0.11*
2	**Valentia (C)**	**2001–2022**	**–0.23*** **	**–1.15*** **	**–0.84*** **	**–0.32** **
3	**Monaghan (R)**	**1995–2022**	**–0.19*** **	**–0.74***	**–0.35***	**–0.09***
4	**Laois (R)**	**2005–2022**	**0.39*** **	**–0.15**	**0.30***	**0.46*** **
5	Kilkenny (R)	2012–2022	0.02	–0.29	–0.01	
6	Castlebar (R)	2009–2022	0.18*	–0.71*	–0.05	
7	**Rathmines (U)**	**2002–2022**	**0.27*** **	**1.72*** **	**1.15*** **	**0.48*** **
8	**Clonskeagh (U)**	**2008–2022**	**0.33*** **	**0.97** **	**0.12**	**0.33*** **
9	**Swords (U)**	**2009–2022**	**0.60*** **	**0.07**	**0.33*** **	
10	Wicklow Bray (U)	2009–2022	0.14*	0.04		
11	Cork South Link Road (U)	2014–2022	0.51*	–0.44		
12	Cork Bishopstown (U)	2016–2022	1.05**	–1.81*		
13	Cork UCC (U)	2018–2022	–0.94	–0.94		

Trends were calculated across 13 monitoring stations in Ireland over different periods: 5 years (2018–2022), 10 years (2013–2022), 15 years (2008–2022) and the available measurement record for each station. Stations are grouped and the station name text is colour coded according to their classification as coastal (blue), rural (green) or urban (orange), correlating with the map in Figure 2.1. The *p*-value evaluates the reliability of the trend, where a lower *p*-value indicates trend certainty. Adopting the trend reliability scale defined for TOAR-II studies (Chang *et al*., 2023), * indicates trends with very high certainty, ** indicates trends with high certainty and * indicates low to medium certainty. Positive trends are denoted by orange shaded cells, and negative trends by blue shaded cells.**

C, coastal; R, rural; U, urban; UCC, University College Cork.

was without the trend being marked as having any degree of certainty/significance (McHugh *et al.*, 2023). It is noted that the measurement period was different, which explains the discrepancy between the results of this study and that of McHugh *et al*. (2023), highlighting the sensitivity of calculated trends to the timespan and the need to quantify the reliability of trends using *p*-values.

Generally, an increasing trend is observed at urban sites, with a decreasing trend at coastal and rural sites. Previous studies of surface O_3 levels at Mace Head have indicated that there is a seasonal signal to measured trends in background O_3 entering Europe from the clean marine sector. To further interrogate the seasonality of the trends, monthly trends in surface O_3 ($\mu g\,m^{-3}\,y^{-1}$) over 15-year periods were plotted (Figure 3.3). The Mace Head (coastal) and Monaghan (rural) sites predominantly show a rising trend in early spring and winter, with a decreasing trend in late spring to summer. Valentia shows a decreasing trend in every month except February, when levels are significantly impacted by long-range transport and stratospheric sources. Urban sites see a general increasing trend, but with a seasonal signal in Clonskeagh – an increase in winter/spring and a decrease in late spring/summer.

3.4 Concentrations Exceeding WHO Air Quality Guidelines

The measurement record was analysed to identify periods when measured surface O_3 concentration breached the WHO AQG of an 8-hourly average exceeding $100\,\mu g\,m^{-3}$ – the level at which surface O_3 levels could induce acute adverse health effects. For each station, the number of days in which the MDA8 exceeded $100\,\mu g\,m^{-3}$ was calculated, as depicted in Figure 3.4.

It is apparent from Figure 3.4 that exceedances occur predominantly in clean air and rural sites.

The long-term WHO AQG for peak-season MDA8 is $60\,\mu g\,m^{-3}$. The monthly mean MDA8 at each station is shown in Figure 3.5. From this figure, it is apparent that clean and rural sites experience surface O_3 levels that exceed the WHO AQGs for long-term O_3 exposure, and this can pose a health risk to the Irish population. The monthly average MDA8 at Mace Head was almost constantly in exceedance of the long-term peak-season limit between 1998 and 2020, and although not shown in this figure, the peak-season limit was similarly exceeded in Valentia. The identification of elevated O_3 levels as an issue affecting clean coastal and rural sites led us to focus

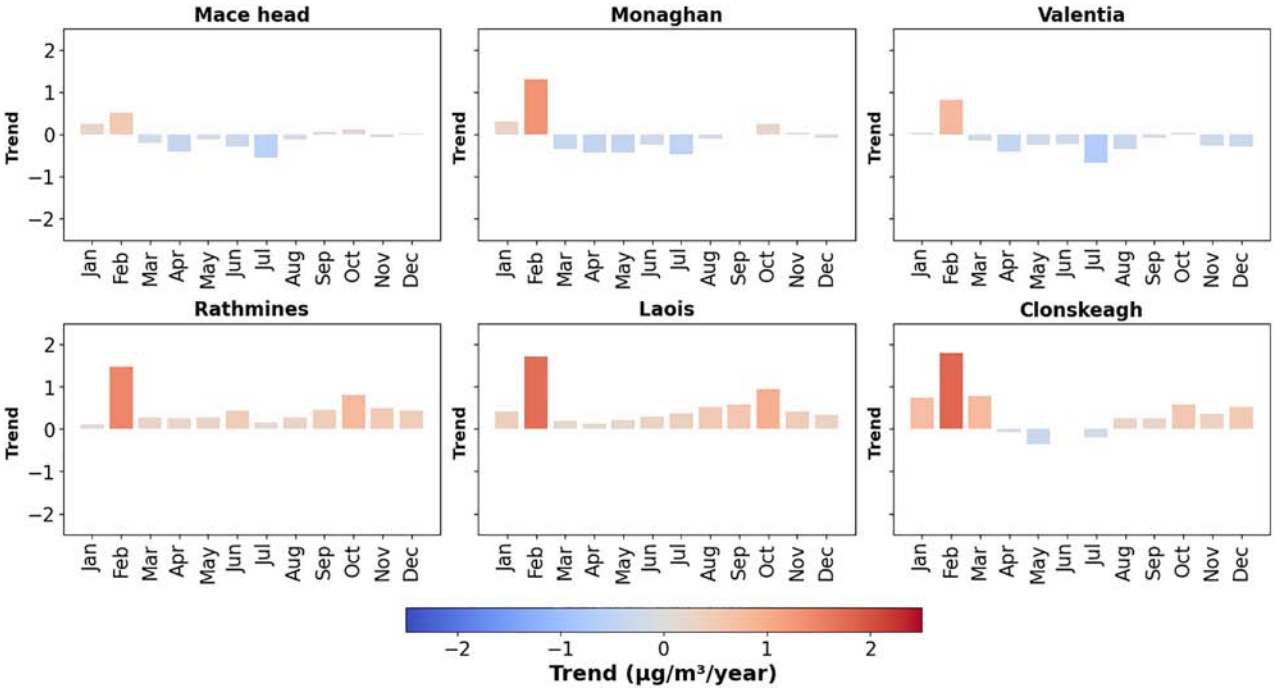

Figure 3.3. Monthly trends in surface O_3 ($\mu g\,m^{-3}\,y^{-1}$) at measurement stations that have data available for the period between 2007 and 2022. Positive trends are shown in red and negative trends in blue.

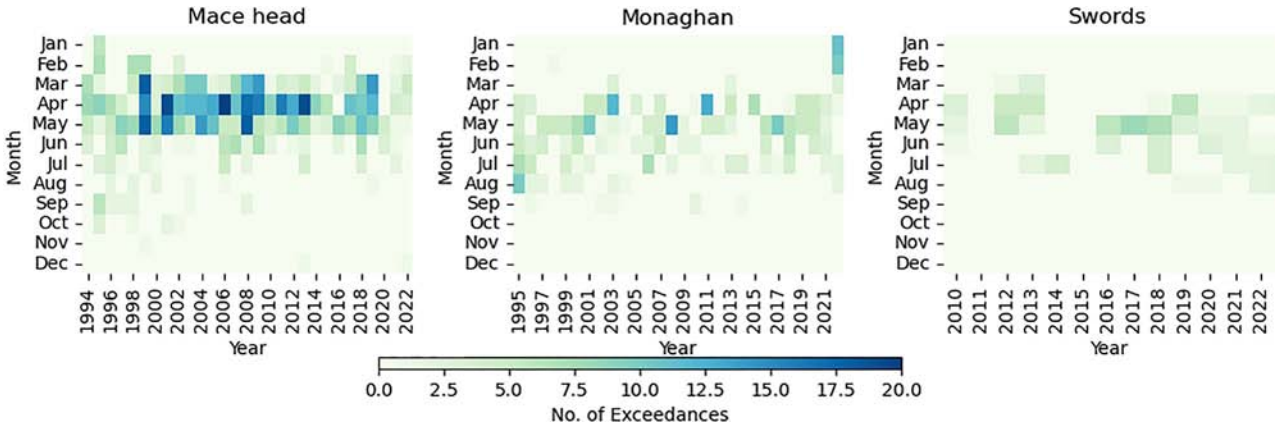

Figure 3.4. Number of days per month when surface O_3 concentration exceeded the WHO AQG of 100 µg m^{-3} for each year of the measurement record at selected sites.

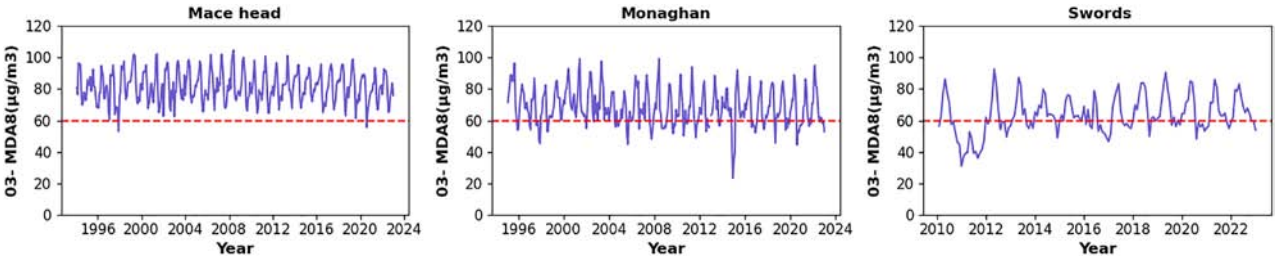

Figure 3.5. Monthly average MDA8 in surface O_3 plotted at selected measurement sites. The horizontal red line at 60 µg m^{-3} represents the long-term WHO AQG for the peak-season limit for protection of human health from long-term exposure to surface O_3.

on the identification of the factors driving O_3 levels at Mace Head. This endeavour is supported by the vast amount of scientific data, analysis and publication records on Mace Head, which can shed light on the physical, chemical and biological processes affecting O_3 pollution entering Europe from the North Atlantic.

4 Surface Ozone at Mace Head

4.1 Trends in Background and Polluted Air

Although Mace Head is classified as a global background site, quantification of the baseline pollution levels requires filtering the data to limit it to that arriving from the clean sector (see section 2.3). Measurements are deemed to be clean when the back trajectories did not traverse over a landmass in the previous 3 days. The remainder of the dataset is considered polluted.

The clean sector consistently has higher O_3 concentrations than the polluted sector – especially during the annual spring-time peak. This indicates that O_3 has a longer lifetime over the North Atlantic and that landmass emissions act as a sink for O_3 in the Irish context.

Figure 4.1 displays surface O_3 concentrations at Mace Head for each season, comparing the clean and polluted sectors, uncovering a marked discrepancy between the two sectors and a striking seasonality in trend magnitude and direction. *A decrease in spring-time levels is observed for both the clean and polluted sectors*, consistent with the decrease in precursor emissions in Europe and North America. There is a significant difference between clean and polluted sector measurements, as polluted air scavenges O_3 via NO_x titration, leading to lower O_3 levels in polluted-sector air masses. *An increasing trend is observed in wintertime in the polluted sector that is not observed in the clean sector*. This would imply a decrease in winter-time O_3 depletion events due to decreasing European emissions (from the polluted sector), consistent with previous studies of Mace Head surface O_3 levels (Derwent *et al.*, 2024). Summer-time values exhibit neither a notable trend nor a discrepancy between clean and polluted sector measurements, indicating that there is little O_3 advected into Europe from the west in the summer months. Autumn values show sectoral discrepancies, again with higher O_3 levels in the clean sector but without a significant slope.

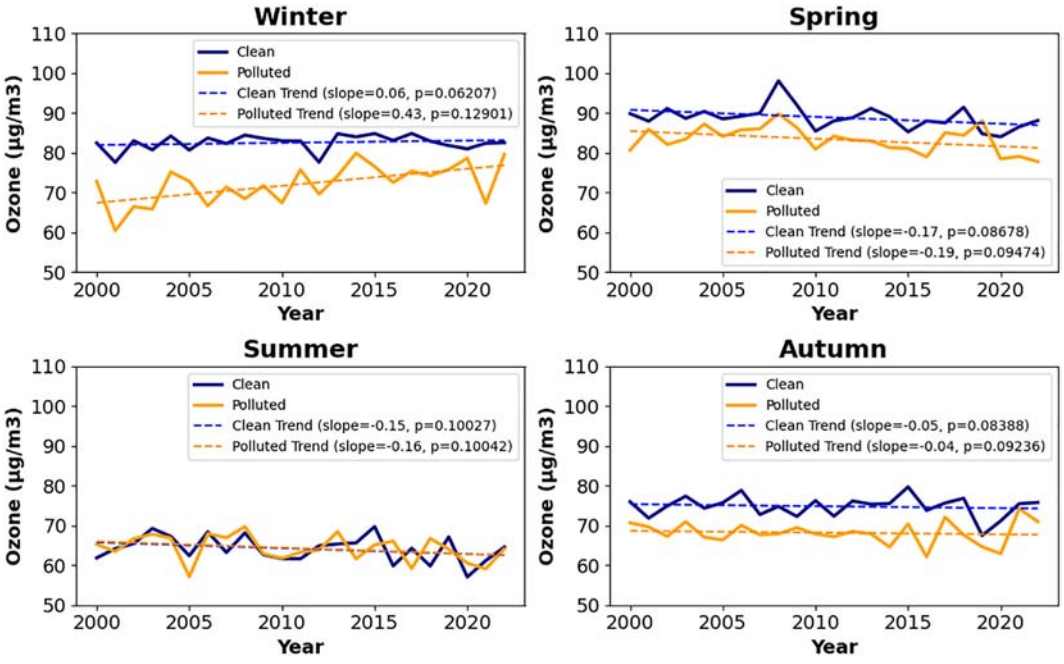

Figure 4.1. Seasonal average surface O_3 levels at Mace Head by clean (dark blue) and polluted (gold) sectors.

4.2 Exceedances at Mace Head

Focusing on Mace Head, we identified the number of short-term exceedances (days with MDA8 > 100 µg m^{-3}), as shown in Figure 4.2. *A third of all exceedances measured at Mace Head between 2000 and 2022 occurred in clean trajectory air masses.*

The remainder of the exceedances occurred when polluted air advected over landmasses, enhancing the Mace Head surface O_3 levels, which are already elevated compared with inland and urban stations.

Time series of spring-time exceedances are shown in Figure 4.3 for both the total dataset and clean-sector exceedances.

A decreasing trend in exceedances, and clean-sector spring-time exceedances, is observed, with a greater decreasing trend in the total number of exceedances. This indicates that the changes that are driving the reduction in the exceedances in Europe are coming into effect faster than the changes that are driving O_3 event reduction over the North Atlantic.

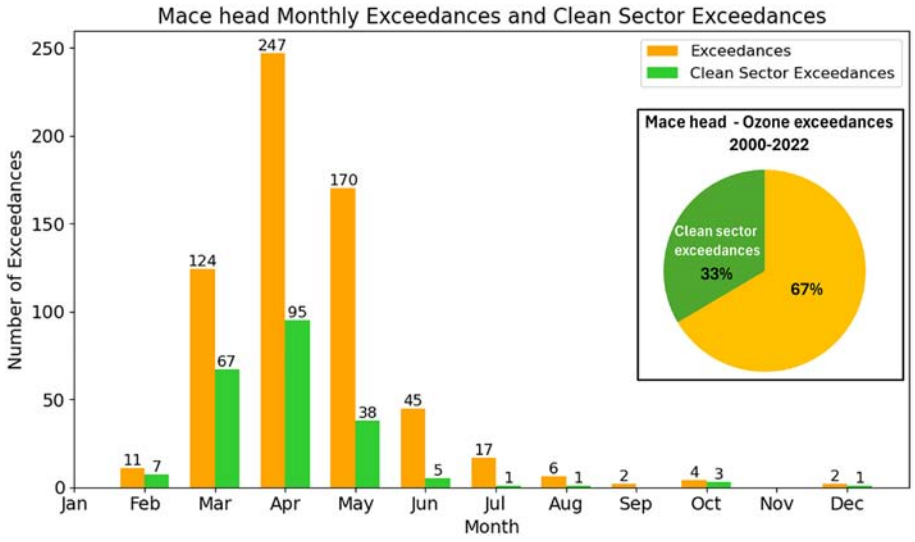

Figure 4.2. Exceedances measured at Mace Head each month from 2000 until 2022, shown as total exceedances (orange bars) and exceedances when wind was coming from the clean sector (green bars). Clean sector exceedances are shown in the inset.

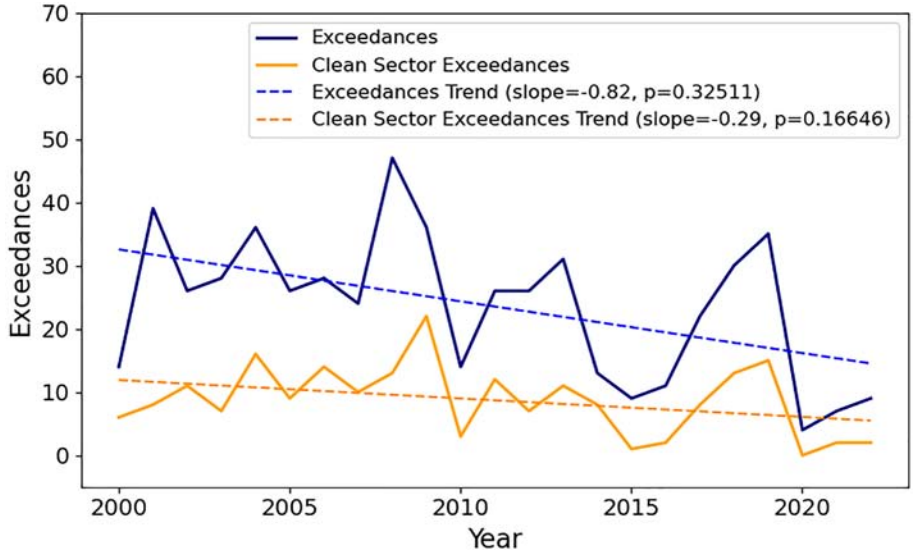

Figure 4.3. Trends in spring-time exceedances of the WHO AQG for protection of human health from short-term adverse health effects (a day is in exceedance if MDA8 > 100 µg m^{-3}), measured at Mace Head between 2000 and 2022 (dark blue line), with the clean air exceedances shown in gold.

5 Identification of Drivers

A specific aim of this project was to understand the factors driving current concentrations, trends and exceedances of surface O_3 in Ireland. The existing scientific body of knowledge on this topic is discussed in section 1.3, but, to advance our current understanding, we look at the effect of the 2021 lockdown on surface O_3 levels and use modelling results.

5.1 Relationship to Precursor Emissions and the 2020 Lockdown Effect

The two atmospheric precursors necessary for photochemical O_3 production are NO_x and reactive carbon compounds (VOCs), the latter comprising CH_4 and NMVOCs (Heald and Kroll, 2020).

To evaluate the relationship between NO_x and O_3 concentrations in an Irish context and the potential benefit of the abrupt enforcement of NO_x control measures, we consider the impact of the COVID-19 lockdown, which started in the spring of 2020.

The 2020 lockdown caused a significant decrease in precursor emissions, owing to restrictions on anthropogenic activity, particularly in the transport sector. The global reduction in precursor emissions initiated a decline in total global tropospheric O_3 levels of 6 Tg (~2%) in subsequent months (April and May 2020) (Miyazaki *et al*., 2021), but the effect of reducing precursor emissions did not universally lead to a reduction in surface O_3 levels.

Figure 5.1 shows the percentage change in measured NO_2 and measured O_3 at various measurement stations in Ireland over the 2020 lockdown period compared with average measurements for the same months in 2017–2019. The lockdown period saw a prominent relative decrease in NO_2 emissions but an increase in surface O_3 levels at most national monitoring stations, specifically those in the east of Ireland. Western sites and rural sites exhibited a small decrease in measured O_3 (Mace Head, Valentia, Cork and Castlebar). The inverse correlation between O_3 and NO_2 is indicative of a NO_x-saturated regime, normally associated with polluted urban environments and NO_x titration events – an effect noted in many different environments during lockdown (Ordóñez *et al*., 2020; Tavella and da Silva Júnior, 2021; Zhang and Stevenson, 2022). It is surprising that the significant increases in O_3 levels are observed in relatively unpolluted Irish atmosphere, where air quality is generally compliant with EU regulations and WHO guidelines, an environment not normally associated with NO_x-saturated regimes.

It is also noted that the enhancement of O_3 occurred at the inland measurement sites, despite a 2020 spring-time decrease in O_3 levels observed at background coastal sites, Mace Head and Valentia, stations that are less sensitive to changes in NO_x and O_3 transported from the continent than inland sites and more sensitive to stratospheric transport and hemispheric transport. It is also noted that there was a large stratospheric depletion event that occurred in spring 2020 (Manney *et al*., 2020), which served to reduce FT O_3 concentrations by ~4 ppb across the northern hemisphere (Steinbrecht *et al*., 2021).

5.2 Model Studies

5.2.1 CAM4-Chem model verification

In this section, we verify the global chemistry model results against Irish surface O_3 measurements to validate our use of the model results to attribute O_3 trends and concentrations to driving sources.

The model set-up is described in section 2.4. The coarse model grid shown in Figure 5.2 limits the potential of the model to correlate with *in situ* measurements; correlation between simulated values and measurements at selected sites is shown in Figure 5.3. As seen, the model performed well in recreating observed O_3 concentrations in coastal and rural areas, underestimated O_3 levels at rural and coastal sites, and overestimated O_3 levels at urban and traffic sites. The underestimation at Mace Head is likely to be due to the coarse grid resolution, which covers a large land area and so is not representative of the Mace Head conditions. The dry deposition rate over land would exceed that over the ocean, hence

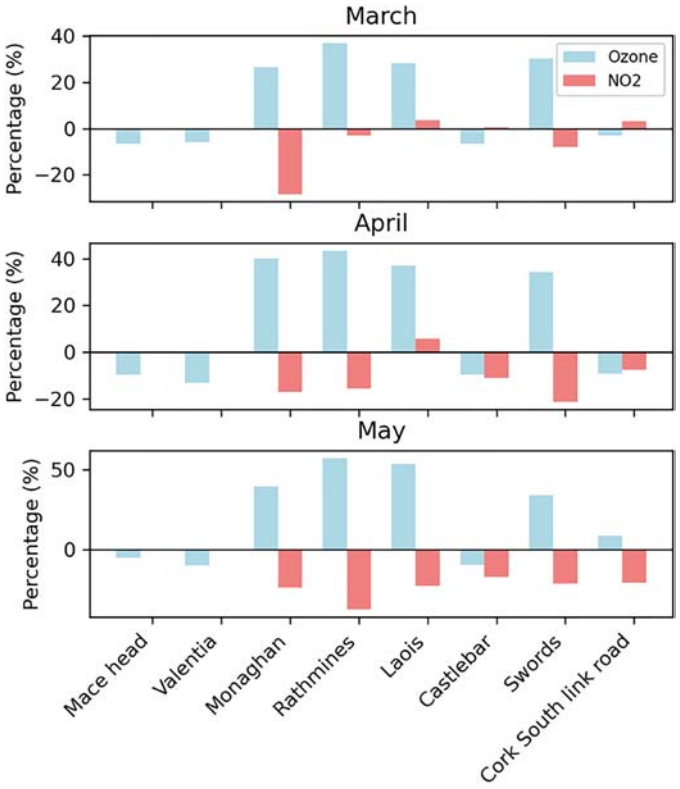

Figure 5.1. Percentage change in NO_2 (red bars) and in O_3 (blue bars) measured during the 2020 lockdown as compared with data from 2017 to 2019. Measurements taken from the Irish EPA monitoring network.

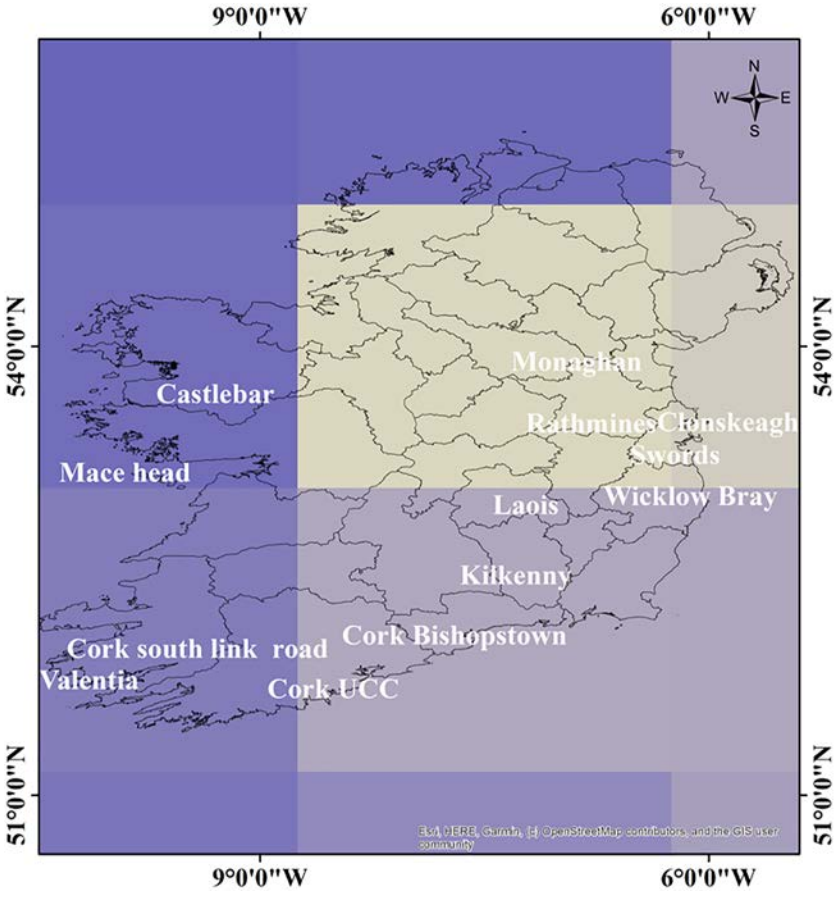

Figure 5.2. CAM4-Chem grid cells covering the Irish domain. UCC, University College Cork.

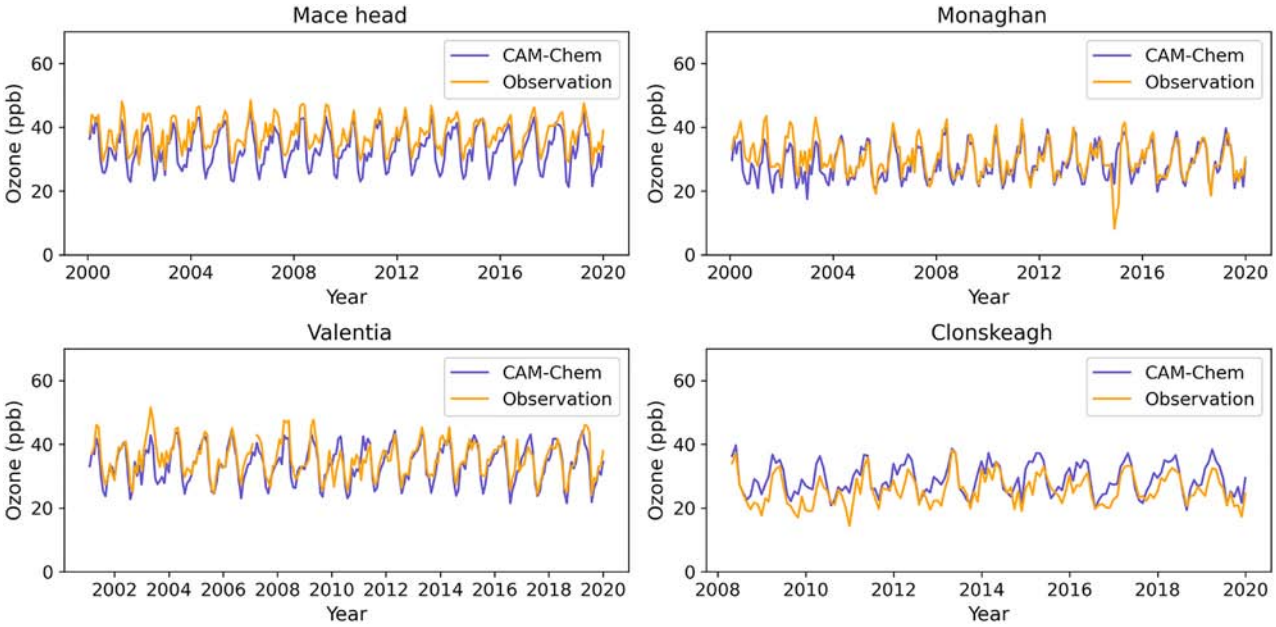

Figure 5.3. Model–measurement comparison of monthly means of surface O_3 and simulated O_3 from the CAM4-Chem simulations at the corresponding grid cells.

the lower simulated O_3 concentration for the entire grid cell. This is supported by the fact that the model–measurement discrepancy is greater in the summer months, when dry deposition to the land is enhanced by solar radiation (Pio *et al*., 2000). The overestimation of O_3 levels in Clonskeagh is likely to be due to local sources not captured by the emission dataset used by the model. A similar overestimation was observed at the Cork South Link Road measurement site, but not depicted in the figure. The model performs well in simulating the MDA8 at the measurement stations, although, in the case of the monthly means, it underestimates MDA8 at Mace Head and overestimates it at Cork South Link Road.

5.2.2 Source attribution using CAM4-Chem

The CAM4-Chem model uses the tropospheric O_3 source attribution system with a tagging method to identify the geographical and sectoral origins of precursors for O_3 for each grid cell spanning the model domain. The method requires running two tagged simulations – one to attribute the origin of the NO_x precursor for simulated O_3 and the second to attribute the origin of the VOC precursor for simulated O_3.

The simulations track the emissions category and geographical source of the precursors, subsequent atmospheric transport, and chemical transformations, eventually "tagging" the created O_3 molecule so that it can be identified by the source and sector of the precursor species. By analysing the results from both simulations, for O_3 levels in any given region, we can determine the relative contribution from precursors from different parts of the world. The identifying precursor tags are given in Table 5.1.

The month-by-month tagged precursor contribution to surface O_3 levels at the western grid cell covering Mace Head averaged over the simulation period from 2000 to 2018 is shown in Figure 5.4 indicating contributions from NO_x (left panel) and VOC (right panel). From this, we determined the following (quantitative values represent average monthly values over the entire simulation):

- The stratospheric source of O_3 dominated in winter–spring, when stratospheric transport is at its most vigorous, contributing to the spring-time maximum. The stratospheric source was present in both simulations and independent of precursor gas concentrations.
- European NO_x emissions (including national sources) contributed between 1.7 and 7.5 ppb to the western grid cell monthly concentrations, with the maximum contribution in May.
- Between 1 and 4.25 ppb surface O_3 was attributable to lightning NO_x, with contributions most significant in wintertime.

Table 5.1. List of tags used in the study identifying the source of precursor emissions, either geographical region or mechanism (lightning, shipping, biogenic, etc.)

Tag	Source of precursor emissions
AIR	Aircraft
ARC	Arctic
BIO	Biogenic
BMB	Biomass burning
BNS	Baltic and North Seas
CAS	Central Asia
EAS	East Asia
ENA	Eastern North Atlantic
EUR	Europe
HBY	Hudson Bay
IDO	Indian Ocean
INI	Initial condition O_3
LGT	Lightning
MBC	Mediterranean, Black and Caspian Seas
MCA	Mexico and Central America
MDE	Middle East
NAE	North American east coast
NAF	North Africa
NAL	North Atlantic
NAM	North America
NAW	North American west coast
NPA	North Pacific
NRW	Rest of the world (NO_x)
RBU	Russia-Belarus-Ukraine
SAS	South Asia
SEA	South-East Asia
SHO	Southern hemispheric oceans
STR	Stratospheric intrusion
XTR	Extra untagged O_3
CH_4	Methane
OCN	Oceanic sources (dimethyl sulfide)
SHP	Shipping
VRW	Rest of the world (VOC)

- North American emissions contributed between 3.5 and 5.25 ppb to western Ireland's surface O_3 levels. The relative contribution peaked in April, coinciding with the characteristic spring-time peak.
- Aviation emissions contributed between 1 and 3 ppb to simulated surface O_3 levels, with dominant contributions in winter/spring.
- Biogenic NO_x represented a significant source of simulated O_3 at Mace Head between June and October, contributing an average of 3.6 ppb to mean O_3 levels for August/September. Biogenic VOC sources contributed slightly more, over 4 ppb at the seasonal mean in late autumn, with a more sustained contribution throughout the year.
- East Asian NO_x emissions contributed significantly (up to 3.6 ppb), with the minimum contribution in July/August. This significant lower-latitudinal source of hemispheric O_3 in the context of continual emission reductions in Europe and North America was flagged in earlier model studies (Lelieveld and Dentener, 2000). This was also reinforced by the Cape Verde rising trends, which can be attributed to increasing influence from the lower latitudes because of Cape Verde's position in the North Atlantic.
- North Atlantic NO_x emissions from shipping accounted for up to 2.4 ppb of O_3 in July/August.
- NO_x emissions from Russia, Belarus and Ukraine represented a small but significant contribution to surface O_3 simulated over the Irish domain, with a contribution of, on average, 1.05 ppb to monthly means.
- CH_4 was by far the dominant reactive carbon molecule contributing to O_3 formation.
- Biogenic VOCs made a significant contribution to simulated O_3 all year round, peaking in late autumn.
- East Asian emissions represented a significant source in winter–spring, contributing to 2–3 ppb of simulated O_3 at Mace Head.
- European VOC emissions contributed 1–3 ppb to surface O_3, with the biggest contribution from March to May, coinciding with the spring-time maximum.
- Biomass burning also represented a significant source for simulated O_3 over the Irish domain, contributing 1–2 ppb, with the biggest contributions in August and September.

5.2.3 Seasonal cycle

The multiple source contributions to surface O_3 determine the seasonal cycle. The spring-time maximum occurs due to correlation with maximum stratospheric intrusion, the influence of North American, European and East Asian emissions, and lightning NO_x. The decline in O_3 concentrations in late spring occurs due to lower wind speeds, less efficient stratospheric transport and the prevalence of lightning storms. The dip in summer-time O_3 concentrations

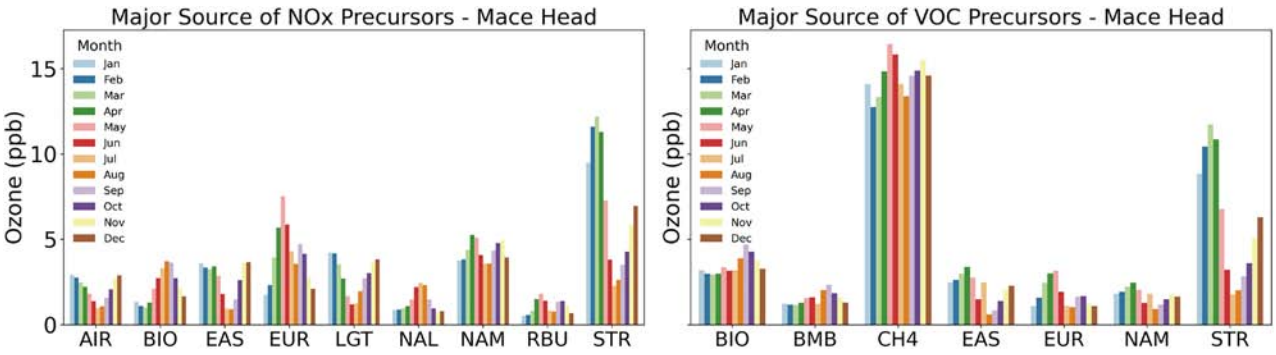

Figure 5.4. Absolute contribution of various sources from NO_x-tagged simulations (left) and VOC-tagged simulations (right) to the CAM4-Chem simulated surface O_3 levels for the grid cell covering Mace Head between 2000 and 2018, where the values are the monthly means averaged over the simulation period. Note that the stratospheric contribution to simulated surface O_3, denoted by STR, is represented in both panels.

occurs due to the peak maximum in photochemical destruction that comes with summer weather. *Higher-resolution mechanistic modelling* would be required to advance understanding of the removal processes and to further quantify the effect of national emissions on surface O_3 levels.

We now assess the monthly changes in contributions to surface O_3 levels at Mace Head over the simulation period (2000–2018) by determining the trends in contribution to surface O_3 levels in the corresponding grid cell for each month and for each tag. The results are shown in Figure 5.5. A negative (blue) trend indicates that the relative contribution of the source to simulated surface O_3 in this grid cell has declined over the simulation period, whereas a positive (red) trend indicates that the contribution to surface O_3 has risen over the simulation period. The results indicate that the amount of simulated O_3 originating from European or North American NO_x decreased during the simulation period, most likely due to EU and North American emission reductions, with more significant reductions occurring in late spring to late summer due to the decreasing EU emissions.

Conversely, there was an increase in simulated surface O_3 originating from NO_x contributions from aviation and East Asia. This rising trend was more pronounced in the winter and reduced in the summer. This seasonality can account for the reducing

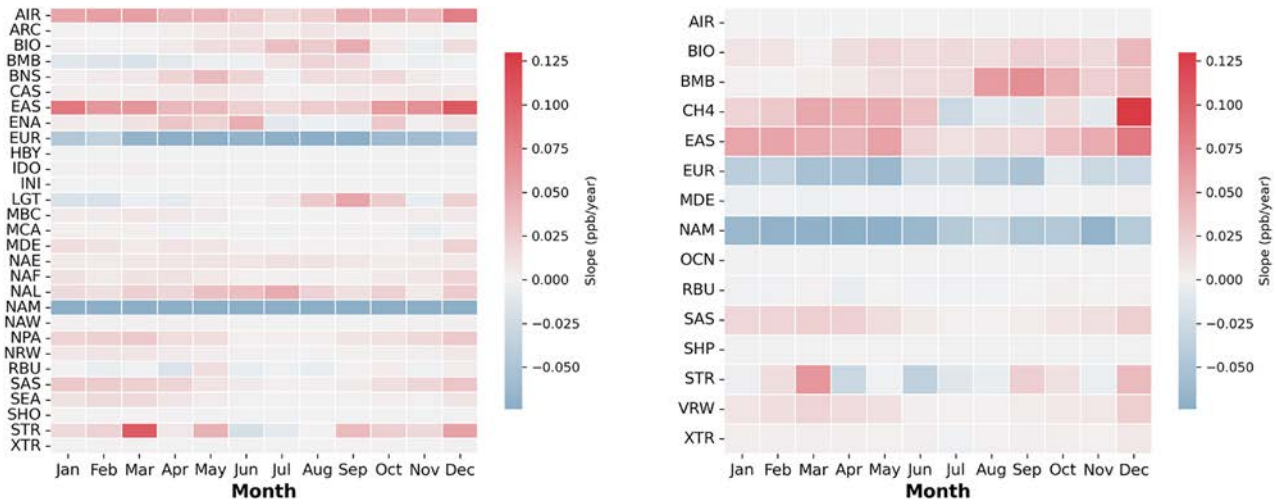

Figure 5.5. Trends in contributions to surface O_3 levels simulated by CAM4-Chem for each month of the simulation period (ppb y^{-1}) for trends in the NO_x-tagged simulation (left) and the VOC-tagged simulation (right).

spring-time high that we see in observations, and the winter-time increase. East Asian and South Asian VOCs also contributed to a rising trend in simulated O_3, with a seasonal influence in which the rise is more pronounced in winter and spring. The more pronounced winter-time increasing trend can be attributed to the reduction in winter-time NO_x titration O_3 depletion events as European and North American air quality constraints take effect; hence, there was an increase in the proportional contribution of O_3 from other sources in wintertime. The contribution of CH_4 also had a positive trend over the simulation period, but the trend only had a reliable correlation in December and spring periods, with observed trends in CH_4 contribution having low certainty (correlation coefficient, $p > 0.33$) in summer months.

To assess the contribution to O_3 events that could be harmful to health, we looked at contributions to simulated O_3 when the 8-hour concentrations exceeded the WHO AQG for protection of human health (i.e. when MDA8 > 100 µg m^{-3}). Referring to Figure 4.2, the majority of O_3 events recorded at Mace Head occurred in March, April and May, with some exceedances occurring in the summer. Figure 5.6 shows the percentage contribution of tagged precursor simulations to simulated O_3 concentrations in the Mace Head grid cell on days when measured MDA8 exceeded 100 µg m^{-3}. From this figure, it is evident that stratospheric intrusion represents the dominant source for simulated exceedance events occurring at Mace Head in early spring, with smaller contributions from European and North American NO_x. European emissions provide the majority of NO_x precursors for April emissions, with the reactive carbon precursor coming from the CH_4 reservoir. North American emissions contributed 10–12% to O_3 levels during the spring months. This aligns with the absolute contributions depicted in Figure 5.3, where the contribution to simulated O_3 from European NO_x was at a peak in May, the same time that the abundant winter-time influx of stratospheric O_3 begins its seasonal decline.

To identify the factors that drive exceedances, we interrogated the difference in percentage contribution to simulated O_3 levels at Mace Head when MDA8 exceeded 100 g m^{-3} and the percentage contribution to the monthly mean dataset; the results are shown in Figure 5.7.

Although there were small percentage increases in the contribution of North American emissions to simulated O_3 concentrations on spring-time exceedance days, there were no other significant sources of elevated O_3 spring-time exceedances caused by a sustained build-up of O_3 sources. From May to September, exceedance days were characterised by a greater contribution from European NO_x emissions and a lesser contribution from the west, indicating that summer exceedances are caused by continental outflow. The number of exceedances diminished after May, when photochemical destruction becomes the dominant removal mechanism and the winter–spring seasonal sources (stratospheric intrusion, aviation emissions, lightning NO_x) become less productive.

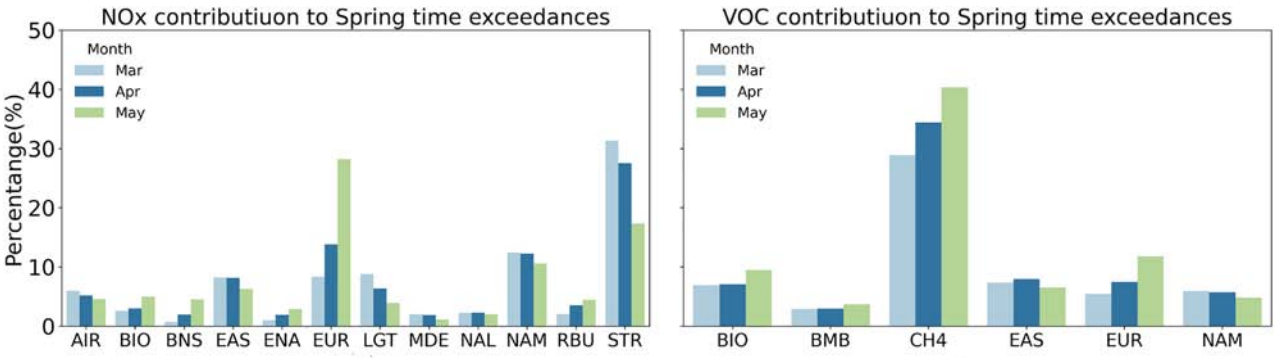

Figure 5.6. Percentage contributions from tagged simulations to surface O_3 concentrations for days when the concentration exceeded the WHO AQG of 100 µg m^{-3} during the spring-time months when exceedances occur. The contributions from major sources from the tagged NO_x simulation are depicted on the left and the contributions from major sources from the tagged VOC simulation are shown on the right. Note that the stratospheric contribution is represented in the NO_x-tagged simulation graph only.

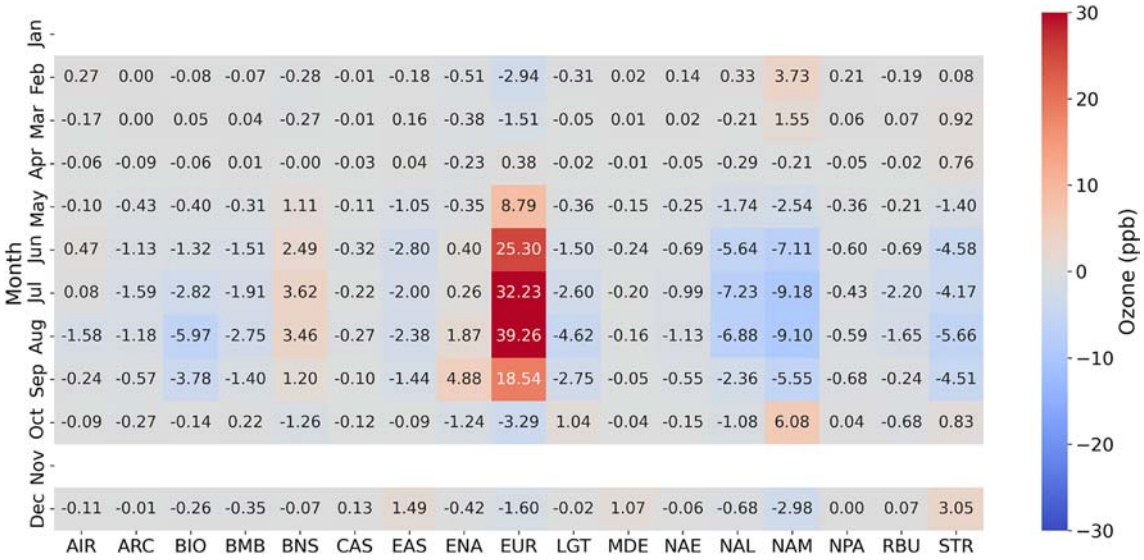

Figure 5.7. Differences between tagged NO_x precursor contribution to simulated Mace Head O_3 levels on exceedance days when MDA8 exceeded 100 µg m^{-3} and percentage contribution to the total monthly mean dataset.

5.3 Machine Learning Variability at Mace Head

Further interrogation of the drivers of trends and exceedances at Mace Head was carried out using the RF model, which was applied to a Mace Head daily dataset (for details, see section 2.5). The model performed very well, with a correlation coefficient of 0.98 and a *p*-value of $< 2 \times 10^{-16}$ for predicted versus measurement correlation plot.

The results of the algorithm, including feature importance ranking, SHAP dependence for all 11 predictors, the SHAP summary plot, distribution of predictors during both normal O_3 periods (O_3 level between 35th and 65th percentile) and during O_3 pollution episodes (O_3 level higher than its 95th percentile), are displayed in Figure 5.8. The most deterministic variable for predicting O_3 levels at Mace Head is CO concentration (Figure 5.8a). This is consistent with a similar study on the Tibetan plateau (Zhong *et al*., 2024) – a high-altitude region enclosed by mountain ranges lying between the Himalayas and the Taklamakan Desert. The region is considered remote but is subject to transboundary air pollution, as is Mace Head. Studies in more urbanised areas have identified other determining factors as more important, such as relative humidity, NO_2 level and cloud optical depth (Zhong *et al*., 2024). CO does not have a stratospheric source, has a relatively long atmospheric lifetime (weeks to months), and is formed via photochemical formation from hydrocarbons or from incomplete combustion (of fossil fuels or biomass). Therefore, it can be used as an indicator of transported pollution from combustion sources. This study indicates that CO can be used as a predictor for O_3 concentrations in remote areas subject to intercontinental FT transport and transboundary pollution (Mace Head and the Tibetan plateau), highlighting the importance of these mechanisms for O_3 levels at Mace Head.

SHAP values can be interpreted as the contribution of a specific variable to the prediction of the modelled output for an individual data point. A SHAP value is a measure of how an indicator will cause an increase (positive SHAP value) or a decrease (negative SHAP value) from the modelled parameter, relative to the average/baseline value. Scatter plots showing the relationship between the predictors and the model SHAP value are shown in Figure 5.8b. The SHAP summary plot in Figure 5.8b indicates that higher temperatures decrease the prediction of surface O_3 levels under normal conditions, but, during O_3 pollution events, high temperature and radiation are correlated with extreme O_3 pollution.

The relationship between CO and O_3 is seasonally dependent, with a positive correlation in summer and a negative correlation in winter. Considering CO as an indicator of polluted air, winter-time pollution will scavenge O_3 from the atmosphere, whereas

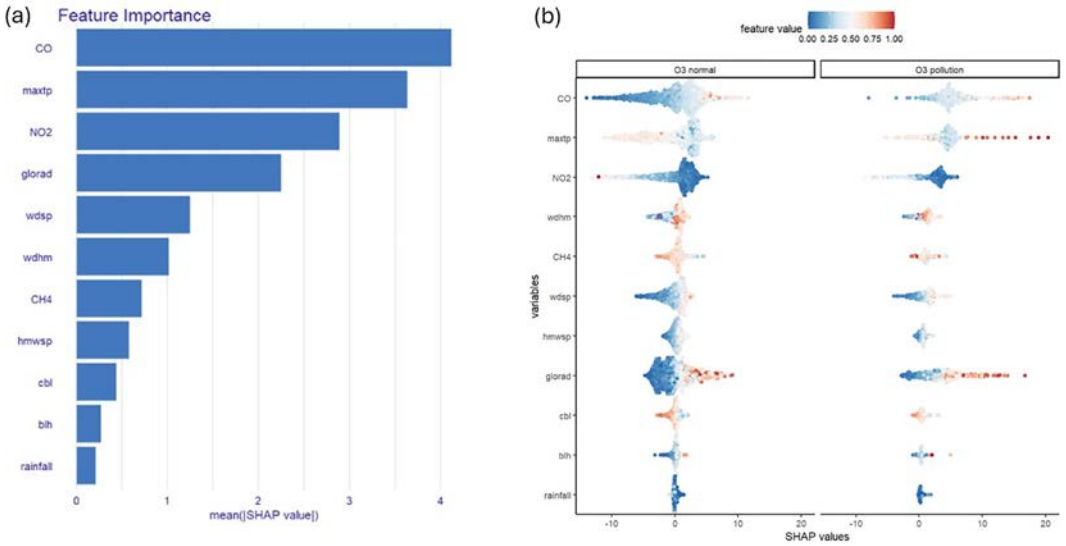

Figure 5.8. Outputs from application of the RF algorithm to the Mace Head dataset to predict surface O_3 concentration, including (a) feature importance ranking and (b) the SHAP summary plot. blh, boundary layer height; cbl, mean convective boundary layer pressure; CH_4, methane; CO, carbon monoxide; hmwsp, highest 10-minute mean wind speed; glorad, global radiation; maxtp, daily maximum temperature; NO_2, nitrogen dioxide; rainfall, daily rainfall; wdhm, wind direction at maximum 10-minute mean; wdsp, daily mean wind speed.

summer-time pollution will promote photochemical production of O_3.

When the data is separated by the clean and polluted sectors, temperature becomes the most important predictor for the clean sector, whereas radiation is the most important predictor for the polluted sector. In both the clean and polluted sectors, CO is the second most important predictor.

This provisional study highlights the possibility for machine learning techniques to elucidate correlations between various parameters and surface O_3. RF modelling has the capacity to handle complex systems, missing data and outliers, and, hence, is particularly suitable for modelling surface O_3, which is highly non-linear, reactive and variable in space and time. The use of such machine learning systems can identify complex, non-linear relationships within datasets and shed light on previously unscrutinised correlations, which can indicate suitable avenues of inquiry to determine causal drivers of patterns and trends that must be confirmed using mechanistic studies. To gain further insight, this approach could be extended to expanded spatial and temporal scales of drivers and interrogate correlations.

6 Conclusion and Recommendations

This report provides policy-relevant information on Irish O_3 levels and trends, leveraging the measurement record from instruments that contribute to the EPA air quality monitoring network. Additionally, results from advanced modelling tools are used to attribute O_3 concentrations, trends and exceedances to source regions. The report identifies seasonality in trends and exceedances and quantifies the effect of reductions in emissions and meteorological variability on O_3 formation and transport.

6.1 Key Findings

In Ireland, O_3 pollution affects clean environments. The monthly O_3 concentrations measured are higher in clean, coastal environments than in rural environments, with the lowest concentrations observed in urban areas. The elevated levels in coastal regions are due to the influence of meteorological processes, including transboundary pollution and stratospheric intrusion. Hence, the island of Ireland acts as a net sink for O_3.

There has been a statistically significant increasing trend in O_3 levels at urban sites over the past two decades but no clear annual trend at the coastal or rural sites. The increase at urban sites is likely to be due to decreasing NO_x emissions coming from Europe and North America, which leads to an increase in surface O_3 concentrations in urban areas (as observed during the COVID-19 lockdown). This indicates that the dual-regime model does not apply to all environments, and this non-linearity has also been noted in the literature. The real atmosphere is open, dissipative and hugely complex, and the relationship between O_3 and its precursors is non-linear. There is scope for employing non-linear methods to gain new insights into the relationships between O_3 and its precursors (Liu and Shi, 2021) and advancing model–measurement fusion to gain more insight into the mechanisms driving O_3 levels, and hence O_3 exposure at particular sites (Souri *et al*., 2021). This study has explored the use of an RF machine learning algorithm to model surface O_3 levels at Mace Head and found that CO is a useful predictor for modelling O_3 concentrations in areas characterised as remote and with little influence from local emissions but influenced by long-range transport and stratospheric intrusion.

Most exceedances of the WHO AQG for protection of human health and the CAFE Directive for protection of vegetation occur in the clean coastal regions; hence, our study concentrated on Mace Head, which allows data filtering by wind sector. It is noted that the years with high levels of exceedances at Mace Head are correlated with years with a higher spring maximum – exceedances can come from polluted air but occur only when baseline O_3 concentration is already above average, which in Ireland is predominantly influenced by hemispheric transport and stratospheric intrusion.

On analysis of the surface O_3 levels at Mace Head, the data was separated into data from the clean sector and data from the polluted sector. It was found that measurements made at Mace Head when the wind arrived from the clean sector revealed higher O_3 concentrations than those made when the wind arrived from the polluted sector. When the seasonality of the trends in the sectoral data was studied, it was found that there was a significant rising trend in winter surface O_3 levels when the wind was coming from the polluted sector but not when the wind was coming from the clean sector. However, there were significant decreases in the spring-time peaks observed at Mace Head when the wind was coming from both the clean and the polluted sectors. Looking at the exceedances of the WHO AQG for protection of human health, 61% of all exceedances occurred within the months of February, March and April, and one third of all exceedances occurred in a clean air trajectory, without any influence from European emissions. The trend in exceedances observed at Mace Head is decreasing at a rate of 0.8 exceedances per year, but the decreasing rate in clean-sector exceedances is less pronounced, decreasing at a rate of 0.3 exceedances per year. From this, it can be inferred that changes driving reductions in exceedances originating in Europe are acting at a faster rate than other changes in factors driving exceedances.

After verifying its ability to simulate O_3 trends and WHO AQG metrics, we used the advanced modelling capabilities of the global CAM4-Chem model to identify factors contributing to the seasonal variation in O_3 levels in Ireland with the characteristic spring-time peak and summer-time dip. This characteristic seasonal cycle is driven by seasonality in stratospheric intrusion, hemispheric transport from North America, lightning, East Asian emissions, aviation emissions and European NO_x emissions, which peak in May. The model simulates CH_4 as the dominant source of reactive carbon involved in formation of O_3, which is simulated at Mace Head at a relatively sustained level of contribution all year round. Although we had limited scope for the analysis of geographical variation in source attribution of modelled O_3, European emissions contributed more to the simulated O_3 levels in the east of Ireland than in the west; again, the landmass acted as a sink.

Model trend analysis allowed us to identify the drivers of the rising trend in wintertime such as a reduction in winter-time O_3 removal events due to NO_x titration, contributions from East Asia and aviation emissions, whereas the trend in the reduction in the spring-time peak is attributable to reductions in North American and European emissions. Reductions in total exceedances are occurring at a faster rate than reductions in clean-sector exceedances, indicating that the precursor abatement in Europe is taking effect faster than the abatement affecting clean-sector O_3 events (emissions from North America and the lower latitudes).

6.2 Recommendations

6.2.1 Scientific capacity development

This desk study uncovered many questions and potential areas for further enquiry regarding surface O_3, an atmospheric agent important for both radiative forcing and air quality. There is much scope to develop this study and capitalise on links with partners to further interrogate the Mace Head measurement record, incorporate the dataset from Valentia and employ advanced source attribution modelling tools to identify and quantify the transport and removal mechanisms of transboundary air pollution entering western Europe.

Mechanistic modelling capacity

The modelling tools applied to determine source attribution in this study were useful for identifying regional O_3 pollution drivers, but identification of drivers at the level of local authority response would require higher-resolution mechanistic models with sophisticated chemical mechanisms to determine the chemical pathways prevalent in O_3 pollution events and the effect of local and national emissions.

Development of mechanistic modelling capacity would allow for assessment of future policy interventions to reduce O_3 pollution events in Ireland across spatial and temporal scales to determine exposure and health impacts as well as effects on radiative forcing and the climate. Sophisticated handling of the chemical mechanisms and meteorology involved in atmospheric O_3 interactions is required to understand the implications of controlling precursor emissions on O_3 levels in terms of both health and climate and of the interaction between climate and future air quality.

Higher-resolution modelling would allow for quantification of various drivers, focusing on local and national emissions contributions to surface O_3 and the impact of potential/future EU and national air quality policy on Irish O_3 levels. As the policy landscape moves towards more ambitious and healthier air quality targets, such models would provide useful tools to ensure compliance with national and EU standards.

Integrated measurements, modelling, artificial intelligence and satellite observations

The use of RF methods to predict surface O_3 levels at Mace Head indicates the potential for using machine learning methods to identify influencing factors in non-linear atmospheric processes. Combined with mechanistic modelling and *in situ* and satellite measurements of atmospheric constituents, an integrated data system could be used to further identify knowledge gaps related to O_3 modelling, forecast air quality events and develop mechanistic models to assess the impact of future emission scenarios on O_3 levels, exceedances and exposure and to disseminate scientific data to end users in an accessible format. Development of an integrated system comprising satellite and *in situ* measurements and models would allow for automatic assimilated

simulations that could quantify transboundary pollution impacting Irish O_3 levels. Such tools would not be limited to simulation of O_3 levels and could be applied to other species.

6.2.2 Measurement network and emission calculation development

There is a challenge in identifying the factors contributing to O_3 levels when not all precursors are measured on site. Key sites with continuous measurement of O_3 and relevant precursors are key for understanding important formation processes. It is recommended that measurements at relevant sites are sustained and the suite of measurements is expanded to include NO_x and VOCs. Development of key sites, representative of different environments (urban, suburban, rural, coastal, remote), with continuous measurements would enable the application of machine learning techniques to identify important processes and fill knowledge gaps related to O_3 transport, formation, chemistry and pollution events. High-fidelity emission datasets are vital as input for models to assess both climate change and O_3 formation.

6.2.3 Policy development

As public awareness of air quality increases, governing bodies are striving to address air pollution by enforcing more stringent air quality regulations and lowering air pollution thresholds for the protection of human health. This study identifies CH_4 as the dominant reactive carbon parent involved in O_3 formation affecting Irish pollution levels, but, as a well-mixed GHG, a concerted, international effort is required to realise a reduction in CH_4 emissions. Global CH_4 concentrations continue to rise relentlessly, but the GMP is driving a global reduction in CH_4 emissions to limit climate forcing effects. It is recommended that Ireland's contribution to the GMP be strengthened and that the country commit fully to the ambition of the GMP, including a communication plan and a cross-sectoral CH_4 emission reduction task force made up of diverse interest-holders with the shared policy goal of reducing CH_4 emissions.

It is also recommended that international policy address the growing issue of precursor emissions from East Asia and that future policy limits for O_3 pollution be assessed in the context of the contribution to O_3 background levels from transboundary sources and from the stratosphere.

6.2.4 Communication development

It is recommended that efforts to mitigate O_3 pollution be supported by educational campaigns to raise awareness and start conversations on O_3 pollution and its impact on human and crop health and its contribution to radiative forcing. Currently, the causes and effects of O_3 pollution are relatively misunderstood in the public domain. Knowledge of the precursors and the role of human activities on O_3 formation should be communicated, as well as the health impacts of O_3 pollution.

The findings of this study underscore the importance of co-ordinated efforts across scales – local, national and international – to mitigate O_3 pollution, and it is vital that these efforts be underpinned by sustained measurement datasets and advanced modelling, satellite and dissemination products that are accessible and policy relevant.

References

Amann, M., Derwent, D., Forsberg, B., Hanninen, O., Hurley, F., Krzyzanowski, M., de Leeuw, F., Liu, S. J., Mandin, C., Schneider, J., Schwarze, P. and Simpson, D. (2008). *Health Risks of Ozone from Long-range Transboundary Air Pollution.* World Health Organization Regional Office for Europe, Copenhagen, Denmark.

Archibald, A., Neu, J., Elshorbany, Y., Cooper, O., Young, P., Akiyoshi, H., Cox, R., Coyle, M., Derwent, R. and Deushi, M. (2020). Tropospheric Ozone Assessment Report: a critical review of changes in the tropospheric ozone burden and budget from 1850 to 2100. *Elementa: Science of the Anthropocene* 8(1), 034.

Bais, A. F., McKenzie, R. L., Bernhard, G., Aucamp, P. J., Ilyas, M., Madronich, S. and Tourpali, K. (2015). Ozone depletion and climate change: impacts on UV radiation. *Photochemical and Photobiological Sciences* 14(1), 19–52. https://doi.org/10.1039/c4pp90032d

Boleti, E., Hueglin, C., Grange, S. K., Prévôt, A. S. and Takahama, S. (2020). Temporal and spatial analysis of ozone concentrations in Europe based on timescale decomposition and a multi-clustering approach. *Atmospheric Chemistry and Physics* 20(14), 9051–9066.

Boylan, P., Helmig, D. and Oltmans, S. (2015). Ozone in the Atlantic Ocean marine boundary layer. *Elementa: Science of the Anthropocene* 3, 000045.

Brewer, A. W. (1949). Evidence for a world circulation provided by the measurements of helium and water vapour distribution in the stratosphere. *Quarterly Journal of the Royal Meteorological Society* 75(326), 351–363. https://doi.org/10.1002/qj.49707532603

Butler, T., Lupascu, A., Coates, J. and Zhu, S. (2018). TOAST 1.0: tropospheric ozone attribution of sources with tagging for CESM 1.2.2. *Geoscientific Model Development* 11(7), 2825–2840.

Chang, K.-L., Schultz, M. G., Koren, G. and Selke, N. (2023). Guidance note on best statistical practices for TOAR analyses. arXiv preprint arXiv:2304.14236. https://doi.org/10.48550/arXiv.2304.14236

Coleman, L., Martin, D., Varghese, S., Jennings, S. G. and O'Dowd, C. D. (2013). Assessment of changing meteorology and emissions on air quality using a regional climate model: impact on ozone. *Atmospheric Environment* 69, 198–210. https://doi.org/10.1016/j.atmosenv.2012.11.048

Coleman, L., Mc Govern, F. M., Ovadnevaite, J., Ceburnis, D., Baroni, T., Barrie, L. and O'Dowd, C. D. (2021). Envisioning an integrated assessment system and observation network for the North Atlantic Ocean. *Atmosphere* 12(8), 955.

Colette, A., Tognet, F., Létinois, L., Lemaire, V., Couvidat, F., Alonso Del Amo, R., Gonzalez Fernandez, I., Rábago Juan-Aracil, I., Harmens, H. and Andersson, C. (2018). *Long-term Evolution of the Impacts of Ozone Air Pollution on Agricultural Yields in Europe: A Modelling Analysis for the 1990–2010 Period*. European Topic Centre on Air Pollution and Climate Change Mitigation, Bilthoven, Netherlands.

Cooper, O. R., Parrish, D., Stohl, A., Trainer, M., Nédélec, P., Thouret, V., Cammas, J.-P., Oltmans, S., Johnson, B. and Tarasick, D. (2010). Increasing springtime ozone mixing ratios in the free troposphere over western North America. *Nature* 463(7279), 344–348.

Cooper, O. R., Gao, R. S., Tarasick, D., Leblanc, T. and Sweeney, C. (2012). Long-term ozone trends at rural ozone monitoring sites across the United States, 1990–2010. *Journal of Geophysical Research: Atmospheres* 117, D22307.

Creilson, J., Fishman, J. and Wozniak, A. (2003). Intercontinental transport of tropospheric ozone: a study of its seasonal variability across the North Atlantic utilizing tropospheric ozone residuals and its relationship to the North Atlantic Oscillation. *Atmospheric Chemistry and Physics* 3(6), 2053–2066.

Crippa, M., Guizzardi, D., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S. and Morikawa, T. (2023). HTAP_v3 emission mosaic: a global effort to tackle air quality issues by quantifying global anthropogenic air pollutant sources. *Earth System Science Data Discussions* 2023, 1–34.

Crutzen, P. J. (1988). Tropospheric ozone: an overview. In Isaksen, I. S. A. (ed.), *Tropospheric Ozone: Regional and Global Scale Interactions*. Springer Nature. Dordrecht, Netherlands, pp. 3–32. https://doi.org/10.1007/978-94-009-2913-5_1

CSO (Central Statistics Office) (2017). Census of population 2016 – Profile 1 – Population and households. https://www.cso.ie/en/releasesandpublications/ep/p-cp1hii/cp1hii/bgn/ (accessed 2 June 2025).

Derwent, R. G. and Parrish, D. D. (2022). Analysis and assessment of the observed long-term changes over three decades in ground-level ozone across north-west Europe from 1989–2018. *Atmospheric Environment* 286, 119222. https://doi.org/10.1016/j.atmosenv.2022.119222

Derwent, R. G., Simmonds, P. G. and Collins, W. J. (1994). Ozone and carbon monoxide measurements at a remote maritime location, Mace Head, Ireland, from 1990 to 1992. *Atmospheric Environment* 28(16), 2623–2637. https://doi.org/10.1016/1352-2310(94)90436-7

Derwent, R. G., Simmonds, P. G., Seuring, S. and Dimmer, C. (1998). Observation and interpretation of the seasonal cycles in the surface concentrations of ozone and carbon monoxide at Mace Head, Ireland from 1990 to 1994. *Atmospheric Environment* 32(2), 145–157. https://doi.org/10.1016/S1352-2310(97)00338-5

Derwent, R. G., Manning, A. J., Simmonds, P. G., Spain, T. G. and O'Doherty, S. (2018). Long-term trends in ozone in baseline and European regionally-polluted air at Mace Head, Ireland over a 30-year period. *Atmospheric Environment* 179, 279–287. https://doi.org/10.1016/j.atmosenv.2018.02.024

Derwent, R. G., Parrish, D. D., Manning, A. J., Spain, T. G., Simmonds, P. G. and O'Doherty, S. (2024). Ozone at Mace Head, Ireland from 1987 to 2021: declining baselines, phase-out of European regional pollution, COVID-19 impacts. *Atmospheric Environment* 320, 120322. https://doi.org/10.1016/j.atmosenv.2023.120322

Dobson, G. M. B. (1956). Origin and distribution of the polyatomic molecules in the atmosphere. *Proceedings of the Royal Society of London Series A: Mathematical and Physical Sciences* 236(1205), 187–193.

EEA (European Environment Agency) (2024a). *Exceedance of Air Quality Standards in Europe*. https://www.eea.europa.eu/en/analysis/indicators/exceedance-of-air-quality-standards (accessed 10 June 2025).

EEA (European Environment Agency) (2024b). *Emissions of Air Pollutants from Transport in Europe*. EEA, Copenhagen, Denmark.

EPA (Environmental Protection Agency) (2024). *Ireland's Air Pollutant Emissions 1990–2030*. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/EPA-Air-Pollutant-Report-Final-May24.pdf (accessed 10 June 2025).

EPA (Environmental Protection Agency) (2025). *Ireland's Greenhouse Gas Emissions Projections 2024–2055*. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/07875-EPA-GHG-Projections-Report-FINAL.pdf (accessed 5 July 2025).

Finch, D. P. and Palmer, P. I. (2020). Increasing ambient surface ozone levels over the UK accompanied by fewer extreme events. *Atmospheric Environment* 237, 117627. https://doi.org/10.1016/j.atmosenv.2020.117627

Gkatzoflias, D., Kouridis, C., Mellios, G., Saliakas, V. and Katsis, P. (2012). A scenario evaluation model for the application of CO_2 and air pollutant reduction policies. *Procedia – Social and Behavioral Sciences* 48, 2859–2866.

Griffiths, P. T., Murray, L. T., Zeng, G., Shin, Y. M., Abraham, N. L., Archibald, A. T., Deushi, M., Emmons, L. K., Galbally, I. E., Hassler, B., Horowitz, L. W., Keeble, J., Liu, J., Moeini, O., Naik, V., O'Connor, F. M., Oshima, N., Tarasick, D., Tilmes, S., *et al*. (2021). Tropospheric ozone in CMIP6 simulations. *Atmospheric Chemistry and Physics* 21(5), 4187–4218. https://doi.org/10.5194/acp-21-4187-2021

Guerreiro, C. B., Foltescu, V. and De Leeuw, F. (2014). Air quality status and trends in Europe. *Atmospheric Environment* 98, 376–384.

Guo, D., Su, Y., Zhou, X., Xu, J., Shi, C., Liu, Y., Li, W. and Li, Z. (2017). Evaluation of the trend uncertainty in summer ozone valley over the Tibetan Plateau in three reanalysis datasets. *Journal of Meteorological Research* 31(2), 431–437.

Haklander, A. J., Siegmund, P. C., Sigmond, M. and Kelder, H. M. (2008). How does the northern-winter wave driving of the Brewer-Dobson circulation increase in an enhanced-CO_2 climate simulation? *Geophysical Research Letters* 35(7), L07702. https://doi.org/10.1029/2007GL033054

Heald, C. L. and Kroll, J. (2020). The fuel of atmospheric chemistry: toward a complete description of reactive organic carbon. *Science Advances* 6(6), eaay8967.

Hegarty, J., Mao, H. and Talbot, R. (2009). Synoptic influences on springtime tropospheric O_3 and CO over the North American export region observed by TES. *Atmospheric Chemistry and Physics* 9(11), 3755–3776.

Henschel, S., Le Tertre, A., Atkinson, R. W., Querol, X., Pandolfi, M., Zeka, A., Haluza, D., Analitis, A., Katsouyanni, K. and Bouland, C. (2015). Trends of nitrogen oxides in ambient air in nine European cities between 1999 and 2010. *Atmospheric Environment* 117, 234–241.

Jackson, R., Saunois, M., Martinez, A., Canadell, J., Yu, X., Li, M., Poulter, B., Raymond, P., Regnier, P. and Ciais, P. (2024). Human activities now fuel two-thirds of global methane emissions. *Environmental Research Letters* 19(10), 101002.

Khiem, M., Ooka, R., Huang, H., Hayami, H., Yoshikado, H. and Kawamoto, Y. (2010). Analysis of the relationship between changes in meteorological conditions and the variation in summer ozone levels over the Central Kanto area. *Advances in Meteorology* 2010(1), 349248.

Lamarque, J.-F. and Hess, P. G. (2004). Arctic Oscillation modulation of the Northern Hemisphere spring tropospheric ozone. *Geophysical Research Letters* 31(6), L06127. https://doi.org/10.1029/2003GL019116

Lefohn, A. S., Malley, C. S., Smith, L., Wells, B., Hazucha, M., Simon, H., Naik, V., Mills, G., Schultz, M. G., Paoletti, E., De Marco, A., Xu, X., Zhang, L., Wang, T., Neufeld, H. S., Musselman, R. C., Tarasick, D., Brauer, M., Feng, Z., *et al*. (2018). Tropospheric ozone assessment report: global ozone metrics for climate change, human health, and crop/ecosystem research. *Elementa: Science of the Anthropocene* 6, 27. https://doi.org/10.1525/elementa.279

Lelieveld, J. and Dentener, F. J. (2000). What controls tropospheric ozone? *Journal of Geophysical Research: Atmospheres* 105(D3), 3531–3551. https://doi.org/10.1029/1999JD901011

Lewis, A., Hopkins, J., Carpenter, L., Stanton, J., Read, K. and Pilling, M. (2005). Sources and sinks of acetone, methanol, and acetaldehyde in North Atlantic marine air. *Atmospheric Chemistry and Physics* 5(7), 1963–1974.

Lewis, A., Carslaw, D. and Moller, S. J. (2020). *Non-methane Volatile Organic Compounds in the UK*. UK-AIR, London, UK.

Lewis, A. C., Allan, J. D., Carruthers, D., Carslaw, D., Fuller, G. W., Harrison, R. M., Heal, M. R., Nemitz, E., Reeves, C. and Williams, M. (2021). *Ozone in the UK: Recent Trends and Future Projections*. University of Edinburgh, Edinburgh, UK.

Li, Q., Jacob, D. J., Bey, I., Palmer, P. I., Duncan, B. N., Field, B. D., Martin, R. V., Fiore, A. M., Yantosca, R. M., Parrish, D. D., Simmonds, P. G. and Oltmans, S. J. (2002). Transatlantic transport of pollution and its effects on surface ozone in Europe and North America. *Journal of Geophysical Research: Atmospheres* 107(D13), ACH 4-1–ACH 4-21. https://doi.org/10.1029/2001JD001422

Liu, C. and Shi, K. (2021). A review on methodology in O_3-NO_x-VOC sensitivity study. *Environmental Pollution* 291, 118249. https://doi.org/10.1016/j.envpol.2021.118249

Logan, J. A., Staehelin, J., Megretskaia, I. A., Cammas, J. P., Thouret, V., Claude, H., De Backer, H., Steinbacher, M., Scheel, H. E., Stübi, R., Fröhlich, M. and Derwent, R. (2012). Changes in ozone over Europe: analysis of ozone measurements from sondes, regular aircraft (MOZAIC) and Alpine surface sites. *Journal of Geophysical Research: Atmospheres* 117, D09301. https://doi.org/10.1029/2011JD016952

Malley, C. S., Henze, D. K., Kuylenstierna, J. C. I., Vallack, H. W., Davila, Y., Anenberg, S. C., Turner, M. C. and Ashmore, M. R. (2017). Updated global estimates of respiratory mortality in adults greater than or equal to 30 years of age attributable to long-term ozone exposure. *Environmental Health Perspectives* 125(8), 087021. https://doi.org/10.1289/EHP1390

Manney, G. L., Livesey, N. J., Santee, M. L., Froidevaux, L., Lambert, A., Lawrence, Z. D., Millán, L. F., Neu, J. L., Read, W. G. and Schwartz, M. J. (2020). Record-low Arctic stratospheric ozone in 2020: MLS observations of chemical processes and comparisons with previous extreme winters. *Geophysical Research Letters* 47(16), e2020GL089063.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L. and Gomis, M. (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

McHugh, K., Cummins, T. and Aherne, J. (2023). Distribution and long-term trends of tropospheric ozone concentrations in Ireland. *Atmosphere* 14(3), 569.

Miyazaki, K., Bowman, K., Sekiya, T., Takigawa, M., Neu, J. L., Sudo, K., Osterman, G. and Eskes, H. (2021). Global tropospheric ozone responses to reduced NO_x emissions linked to the COVID-19 worldwide lockdowns. *Science Advances* 7(24), eabf7460. https://doi.org/10.1126/sciadv.abf7460

Monks, P. S. (2000). A review of the observations and origins of the spring ozone maximum. *Atmospheric Environment* 34(21), 3545–3561. https://doi.org/10.1016/S1352-2310(00)00129-1

Munir, S., Chen, H. and Ropkins, K. (2013). Quantifying temporal trends in ground level ozone concentration in the UK. *Science of the Total Environment* 458, 217–227.

Nalam, A., Lupascu, A., Ansari, T. and Butler, T. (2024). Regional and sectoral contributions of NO_x and reactive carbon emission sources to global trends in tropospheric ozone during the 2000–2018 period. *EGUsphere* 2024, 1–39. https://doi.org/10.5194/egusphere-2024-432

Oltmans, S. J., Lefohn, A. S., Shadwick, D., Harris, J. M., Scheel, H. E., Galbally, I., Tarasick, D. W., Johnson, B. J., Brunke, E. G., Claude, H., Zeng, G., Nichol, S., Schmidlin, F., Davies, J., Cuevas, E., Redondas, A., Naoe, H., Nakano, T. and Kawasato, T. (2013). Recent tropospheric ozone changes – a pattern dominated by slow or no growth. *Atmospheric Environment* 67, 331–351. https://doi.org/10.1016/j.atmosenv.2012.10.057

Ordóñez, C., Brunner, D., Staehelin, J., Hadjinicolaou, P., Pyle, J., Jonas, M., Wernli, H. and Prévôt, A. S. (2007). Strong influence of lowermost stratospheric ozone on lower tropospheric background ozone changes over Europe. *Geophysical Research Letters* 34(7), L07805.

Ordóñez, C., Garrido-Perez, J. M. and García-Herrera, R. (2020). Early spring near-surface ozone in Europe during the COVID-19 shutdown: meteorological effects outweigh emission changes. *Science of the Total Environment* 747, 141322. https://doi.org/10.1016/j.scitotenv.2020.141322

Otero, N., Jurado, O. E., Butler, T. and Rust, H. W. (2022). The impact of atmospheric blocking on the compounding effect of ozone pollution and temperature: a copula-based approach. *Atmospheric Chemistry and Physics* 22(3), 1905–1919. https://doi.org/10.5194/acp-22-1905-2022

Pancholi, P., Kumar, A., Bikundia, D. S. and Chourasiya, S. (2018). An observation of seasonal and diurnal behavior of O_3–NO_x relationships and local/regional oxidant ($O_X = O_3 + NO_2$) levels at a semi-arid urban site of western India. *Sustainable Environment Research* 28(2), 79–89. https://doi.org/10.1016/j.serj.2017.11.001

Paoletti, E., De Marco, A., Beddows, D. C., Harrison, R. M. and Manning, W. J. (2014). Ozone levels in European and USA cities are increasing more than at rural sites, while peak values are decreasing. *Environmental Pollution* 192, 295–299.

Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E. and Steinbacher, M. (2013). Lower tropospheric ozone at northern midlatitudes: changing seasonal cycle. *Geophysical Research Letters* 40(8), 1631–1636.

Pausata, F. S. R., Pozzoli, L., Vignati, E. and Dentener, F. J. (2012). North Atlantic Oscillation and tropospheric ozone variability in Europe: model analysis and measurements intercomparison. *Atmospheric Chemistry and Physics* 12(14), 6357–6376. https://doi.org/10.5194/acp-12-6357-2012

Pio, C. A., Feliciano, M. S., Vermeulen, A. T. and Sousa, E. C. (2000). Seasonal variability of ozone dry deposition under southern European climate conditions, in Portugal. *Atmospheric Environment* 34(2), 195–205. https://doi.org/10.1016/S1352-2310(99)00276-9

Pope, R. J., Butt, E. W., Chipperfield, M. P., Doherty, R. M., Fenech, S., Schmidt, A., Arnold, S. R. and Savage, N. H. (2016). The impact of synoptic weather on UK surface ozone and implications for premature mortality. *Environmental Research Letters* 11(12), 124004. https://doi.org/10.1088/1748-9326/11/12/124004

Prather, M., Gauss, M., Berntsen, T., Isaksen, I., Sundet, J., Bey, I., Brasseur, G., Dentener, F., Derwent, R. and Stevenson, D. (2003). Fresh air in the 21st century? *Geophysical Research Letters* 30(2), 1100.

Querol, X., Alastuey, A., Reche, C., Orio, A., Pallares, M., Reina, F., Dieguez, J. J., Mantilla, E., Escudero, M. and Alonso, L. (2016). On the origin of the highest ozone episodes in Spain. *Science of the Total Environment* 572, 379–389.

Riley, M. L., Jiang, N., Duc, H. N. and Azzi, M. (2023). Long-term trends in inferred continental background ozone in Eastern Australia. *Atmosphere* 14(7), 1104. https://doi.org/10.3390/atmos14071104

Roelofs, G., Kentarchos, A., Trickl, T., Stohl, A., Collins, W., Crowther, R., Hauglustaine, D., Klonecki, A., Law, K. and Lawrence, M. (2003). Intercomparison of tropospheric ozone models: ozone transport in a complex tropopause folding event. *Journal of Geophysical Research: Atmospheres* 108(D12).

Russo, M. R., Kerridge, B. J., Abraham, N. L., Keeble, J., Latter, B. G., Siddans, R., Weber, J., Griffiths, P. T., Pyle, J. A. and Archibald, A. T. (2023). Seasonal, interannual and decadal variability of tropospheric ozone in the North Atlantic: comparison of UM-UKCA and remote sensing observations for 2005–2018. *Atmospheric Chemistry and Physics* 23(11), 6169–6196.

Segers, A. and Nanni, R. (2023). *Contribution to Documentation of Products and Services as Provided within the Scope of this Contract – 2023 – Part CH_4*. https://atmosphere.copernicus.eu/sites/default/files/2024-01/CAMS255_2021SC1_D55.5.2.1-2023-PartCH4_Contribution_to_documentation_of_products_and_services__v1.pdf (accessed 10 June 2025).

Seinfeld, J. and Pandis, S. (2008). *Atmospheric Chemistry and Physics*. Wiley, New York, NY.

Selleri, T., Melas, A. D., Joshi, A., Manara, D., Perujo, A. and Suarez-Bertoa, R. (2021). An overview of lean exhaust deNOx aftertreatment technologies and NOx emission regulations in the European Union. *Catalysts* 11(3), 404.

Sicard, P. (2021). Ground-level ozone over time: an observation-based global overview. *Current Opinion in Environmental Science & Health* 19, 100226.

Sicard, P., Serra, R. and Rossello, P. (2016). Spatiotemporal trends in ground-level ozone concentrations and metrics in France over the time period 1999–2012. *Environmental Research* 149, 122–144.

Simon, H., Reff, A., Wells, B., Xing, J. and Frank, N. (2015). Ozone trends across the United States over a period of decreasing NO_x and VOC emissions. *Environmental Science and Technology* 49(1), 186–195. https://doi.org/10.1021/es504514z

Simpson, D., Arneth, A., Mills, G., Solberg, S. and Uddling, J. (2014). Ozone – the persistent menace: interactions with the N cycle and climate change. *Current Opinion in Environmental Sustainability* 9–10, 9–19. https://doi.org/10.1016/j.cosust.2014.07.008

Soares, J., Plass, D., Kienzler, S., González Ortiz, A., Gsella, A. and Horálek, J. (2023). *Health Risk Assessment of Air Pollution: Assessing the Environmental Burden of Disease in Europe in 2021*. ETC/HE Report 2023/7. https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2023-7-health-risk-assessment-of-air-pollution-assessing-the-environmental-burden-of-disease-in-europe-in-2021 (accessed 10 June 2025).

Souri, A. H., Chance, K., Bak, J., Nowlan, C. R., González Abad, G., Jung, Y., Wong, D. C., Mao, J. and Liu, X. (2021). Unraveling pathways of elevated ozone induced by the 2020 lockdown in Europe by an observationally constrained regional model using TROPOMI. *Atmospheric Chemistry and Physics* 21(24), 18227–18245. https://doi.org/10.5194/acp-21-18227-2021

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J., Cohen, M. D. and Ngan, F. (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* 96(12), 2059–2077.

Steinbrecht, W., Kubistin, D., Plass-Dülmer, C., Davies, J., Tarasick, D. W., von der Gathen, P., Deckelmann, H., Jepsen, N., Kivi, R. and Lyall, N. (2021). COVID-19 crisis reduces free tropospheric ozone across the Northern Hemisphere. *Geophysical Research Letters* 48(5), e2020GL091987.

Stevenson, D. S., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C., Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., Bergmann, D. J., Bey, I., Butler, T., Cofala, J., Collins, W. J., Derwent, R. G., Doherty, R. M., Drevet, J., Eskes, H. J., *et al*. (2006). Multimodel ensemble simulations of present-day and near-future tropospheric ozone. *Journal of Geophysical Research: Atmospheres* 111, D08301. https://doi.org/10.1029/2005JD006338

Tavella, R. A. and da Silva Júnior, F. M. R. (2021). Watch out for trends: did ozone increased or decreased during the COVID-19 pandemic? *Environmental Science and Pollution Research* 28(47), 67880–67885. https://doi.org/10.1007/s11356-021-17142-w

Tripathi, O. P., Jennings, S. G., O'Dowd, C. D., Coleman, L., Leinert, S., O'Leary, B., Moran, E., O'Doherty, S. J. and Spain, T. G. (2010). Statistical analysis of eight surface ozone measurement series for various sites in Ireland. *Journal of Geophysical Research: Atmospheres* 115, D19302. https://doi.org/10.1029/2010JD014040

Wang, Y., Jacob, D. J. and Logan, J. A. (1998). Global simulation of tropospheric O_3-NO_x-hydrocarbon chemistry: 3. Origin of tropospheric ozone and effects of nonmethane hydrocarbons. *Journal of Geophysical Research: Atmospheres* 103(D9), 10757–10767. https://doi.org/10.1029/98JD00156

Wild, O. and Akimoto, H. (2001). Intercontinental transport of ozone and its precursors in a three-dimensional global CTM. *Journal of Geophysical Research: Atmospheres* 106(D21), 27729–27744.

World Health Organization (2021). *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. World Health Organization. https://iris.who.int/handle/10665/345329 (accessed 10 June 2025).

Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson, D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Horowitz, L. W., Josse, B., *et al*. (2013). Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmospheric Chemistry and Physics* 13(4), 2063–2090. https://doi.org/10.5194/acp-13-2063-2013

Zhang, C. and Stevenson, D. (2022). Characteristic changes of ozone and its precursors in London during COVID-19 lockdown and the ozone surge reason analysis. *Atmospheric Environment* 273, 118980. https://doi.org/10.1016/j.atmosenv.2022.118980

Zhong, H., Zhen, L., Yang, L., Lin, C., Yao, Q., Xiao, Y., Xu, Q., Liu, J., Chen, B., Ni, H. and Xu, W. (2024). Understanding the variability of ground-level ozone and fine particulate matter over the Tibetan plateau with data-driven approach. *Journal of Hazardous Materials* 477, 135341. https://doi.org/10.1016/j.jhazmat.2024.135341

Abbreviations

AOT40	Accumulated ozone exposure over a threshold of 40 ppb
AQG	Air quality guideline
CAFE	Clean Air for Europe
CAM4-Chem	Community Atmospheric Model version 4
EPA	Environmental Protection Agency
FT	Free troposphere
GHG	Greenhouse gas
GMP	Global Methane Pledge
MDA8	Monthly average daily maximum 8-hour mean
NAO	North Atlantic Oscillation
NMVOC	Non-methane volatile organic carbon
NO_x	Nitrogen oxides
RF	Random forest
SHAP	Shapley Additive exPlanations
STE	Stratosphere–troposphere exchange
TOAR	Tropospheric Ozone Assessment Report
VOC	Volatile organic carbon
WHO	World Health Organization

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

Webpages: www.epa.ie/our-services/research/
LinkedIn: www.linkedin.com/showcase/eparesearch/
Twitter: @EPAResearchNews
Email: research@epa.ie