

Annex 3: Global Climate Observing System (GCOS) Implementation plan

UK Report on national activities with respect to the GCOS Implementation Plan

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European Centre for Medium-Range Weather Forecasts	UK Centre for Ecology and Hydrology
Marine Biological Association	UK Environmental Observation Framework
Met Office	UK Research and Innovation
National Centre for Atmospheric Science	UK Space Agency
National Centre for Earth Observation	
Natural Environment Research Council	
National Oceanography Centre	
National Physical Laboratory	

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Annex 3:

GCOS Implementation plan

1. Introduction

This report provides an assessment of UK contributions towards the realisation of the Global Climate Observing System (GCOS) Implementation Plan. It is intended for the UNFCCC Secretariat as an input to their overall GCOS assessment. The report uses the reporting structure set out by the UNFCCC Secretariat in its Decision 11/CP.13 'Reporting on global observing systems for climate'¹.

The report includes systematic observing systems operated by or on behalf of UK public sector organisations that are relevant to the GCOS Implementation Plan. Similar to the seventh National Communication, observations made by international organisations to which the UK contributes, such as the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), are presented under the auspices of the host countries – in these two particular examples, France and Germany respectively. Similarly, the reanalysis work of the European Centre for Medium-Range Weather Forecasts (ECMWF) is included in this report because the ECMWF Headquarters are based in Reading, UK.

The structure of the report follows that requested by the UNFCCC Secretariat. In outline, this is as follows:

- Common issues
- Atmospheric Essential Climate Variables
- Oceanic Essential Climate Variables
- Terrestrial Essential Climate Variables
- Additional information

¹ Conference of the Parties on its 13th session, Bali, 3–15 December 2007, FCCC/CP/2007/6/Add.2

2. Common issues

2.1 Planning

2.1.1 Overview

Systematic observations in the UK and its overseas territories are made by a number of national agencies and organisations. Climate research and procurement of climate-related observations are sponsored by various public sector organisations in support of a range of responsibilities and policy requirements. In addition, research is increasingly being funded from a wider stakeholder base in both public and private sectors, particularly in the area of climate impacts and adaptation.

Although the UK does not have formal national plans for climate research and observations, it regularly reviews such activities through coordination functions. This coordination is facilitated through the Research and Innovation for our Dynamic Environment (RIDE) forum (see section 2.1.3 for more information). The UK Environmental Observations Framework (UKEOF) is a second way in which climate observation is coordinated (see section 2.3.1 for more information).

2.1.2 Responsible departments

Two central government departments share the majority of the responsibility for climate research and observations in the UK.

The Department for Environment, Food and Rural Affairs (Defra) is responsible for domestic adaptation to climate change and provides funds for environmental observations, including some climate observations.

The Department for Business, Energy and Industrial Strategy (BEIS) has responsibility for reporting to the UNFCCC, leads on climate change policy and provides funds for climate research and observations to advise the UK's policy and its impacts and response strategies.

BEIS is also the main or single source of funding for many of the other public sector organisations that undertake climate research and observations. These include:

- UK Research and Innovation (UKRI) and its constituent Research Councils. The Councils are responsible for maintaining the science base by providing funding for university research. Whilst funded by central government, they operate at arms length. The Research Council with the greatest direct interest in climate observations is the Natural Environment Research Council (NERC). NERC is responsible for basic research on climate prediction and processes and for some monitoring activities. NERC delivers its climate research and observing programmes through its research centres including the British Antarctic Survey (BAS), the British Geological Survey (BGS), the National Centre for Atmospheric Science (NCAS), and the National Centre for Earth Observation (NCEO); and through independent research centres including the National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML), the Scottish Association for

Marine Science (SAMS), the Marine Biological Association (MBA) and the Sea Mammal Research Unit (SMRU) . The former NERC research centre and now strategic delivery partner, the UK Centre for Ecology & Hydrology (UKCEH) also maintains major climate-science related roles.

- The climate change programme at the Met Office, the UK's national meteorological agency. This research happens primarily through the Met Office Hadley Centre. The Met Office is the lead agency for making and collecting meteorological and atmospheric observations.
- The UK Space Agency is funded via BEIS Space Directorate. It covers Earth Observation and Climate and works internationally with other satellite nations to build the GCOS system

2.1.3 Coordination processes

This section provides information on four of the main processes for coordinating UK environmental research and observations activities.

UK Environmental Observation Forum (UKEOF)

The UK Environmental Observation Forum (UKEOF) is the coordinating body across the public sector for the UK's environmental observation community. As such it plays a vital role in improving the coordination of the UK's observational evidence needed to measure, understand and manage the changing natural environment. As a partnership of public sector organisations with an interest in using and providing evidence from environmental observations, UKEOF is unique in bringing together the main organisations involved in the field. Together they generate and manage in situ and remote environmental observations across the UK. UKEOF's mission aims to achieve effective partnership working in environmental observations to maximise the benefits of observations to the UK including for science, policy and economic growth.

Research and Innovation for our Dynamic Environment (RIDE) Forum

The Research and Innovation for our Dynamic Environment (RIDE) Forum evolved from the Living with Environmental Change (LWEC) partnership in 2016.

The forum is made up of 24 public sector member organisations who hold a stake in environmental change research, innovation, training and capabilities, whether that be as funders, providers or users.

The forum's unique contribution lies in its breadth. It brings together:

- the complementary resources of the many different disciplines and publicly funded sector stakeholders needed to increase our understanding of the natural, social, economic and technological systems interacting with environmental change
- the translation of that knowledge into innovating policy and practice.

It focuses on the UK perspective and challenges, whilst placing this in the international context.

The forum aims to enhance the beneficial impact of the UK's publicly funded research and innovation by informing:

- policy and practice to support effective decision-making
- the implementation of sustainable solutions that work with our dynamic natural environment.

The forum enables members to align, leverage their resources and avoid duplication through:

- sharing and co-developing strategies
- joint priority-setting
- drawing out interdisciplinary partnership opportunities.

In doing so, members can be more efficient in their use of public funds to give decision-makers the knowledge they need to respond to the challenges and opportunities presented by environmental change.

RIDE is a mechanism that also enables the UK academic community to form independent beneficial and impactful links to the policy and practice community.

National Centre for Earth Observation (NCEO)

The National Centre for Earth Observation (NCEO) is a NERC research centre, based around core scientific units and expert staff located at leading universities and research organisations. Its scientific facilities include the Centre for Environmental Data Analysis (CEDA) hosted at the Science and Technology and Facilities Council's Rutherford Appleton Laboratory (STFC-RAL), the NEODAAS service concerned with near real-time and artificial intelligence EO data at the Plymouth Marine Laboratory and the Field Spectroscopy Facility at the University of Edinburgh. The University of Leicester hosts the NCEO Headquarters including the NCEO Director, central hub and one core science unit. Other units are based at the Universities of Reading, Edinburgh, London (King's College London, University College London and Imperial College), Leeds, Sheffield, Swansea, Oxford (incl. STFC-RAL, Centre for Ecology and Hydrology) and Plymouth Marine Laboratory.

NCEO provides research capability in Earth Observation (EO) data sets, associated merging (assimilation) techniques and model evaluation to underpin Earth System research. It aims to improve climate observations of near-term and recent decades as well as predictions of the future by exploiting EO data alongside models to examine the interactions between the atmosphere, ocean, biosphere and hydrosphere. Increasingly, NCEO is concerned with interactions at the poles including the cryosphere. NCEO research, supported by NERC, is building on the success of the UK climate-orientated satellite instruments, the ATSRs and GERBs, to derive climate data sets for surface temperature, radiative fluxes, and aerosols and clouds. NCEO also provides data on key climate variables such as methane, carbon dioxide, water vapour and ozone, along with other shorter-lived trace gases, ocean biological parameters, fire radiative power, vegetation metrics and above-ground biomass.

National Centre for Atmospheric Science (NCAS)

NCAS is a world leading research centre, funded by UKRI-NERC. The NCAS [Strategy 2020 – 2025](#) outlines its dedication to advancing atmospheric science, its goals, and its values. Research falls into three key areas: [air pollution](#), [climate and high-impact weather](#) and [long-term global changes](#) in the atmosphere. NCAS also provides the UK with state-of-the-art services for observing and modelling the atmosphere. These include a research aircraft ([FAAM](#)), advanced ground-based observational facilities ([AMOF](#)), computer modelling and support ([CMS](#)), and facilities for storing and analysing data ([CEDA](#)). The CEDA Data Centre is a node of the UKRI Environmental Data Service dedicated to the Atmospheric, Earth Observation, and Solar and space physics disciplines. In recognition of the diversity of the CEDA remit and user community the data centre has two sections: CEDA-EO and CEDA- Atmospheres, with CEDA-EO managed by NCEO and CEDA-Atmospheres managed by NCAS. CEDA is hosted at the Science and Technology and Facilities Council (STFC) and runs on the JASMIN: a globally-unique data analysis facility providing storage and compute facilities enabling data-intensive environmental science. NCAS Head office is hosted by the University of Leeds and the centre has over two hundred members of staff, embedded at eleven universities and research institutes across the UK: Universities of Leeds, Manchester, York, Oxford, Cambridge, East Anglia, Surrey, Birmingham, Reading, Cranfield and STFC – RAL Space. This ensures NCAS has close links to the national research community.

NCAS plays a significant and influential role in many international science programmes and provides advice, leadership and national capability in atmospheric science. In addition to the community accessible measurement platforms, NCAS provides capability in climate modelling (and its support), associated assimilation techniques, and model evaluation to underpin Earth System research. Through atmospheric observatories based at BT Tower ([BTTAO](#)) Chilbolton ([CAO](#)), Capel Dewi ([CDAO](#)), Cape Verde ([CVAO](#)) and Weybourne ([WAO](#)), NCAS has supported long-term measurement programmes; datasets for a range of parameters including meteorological and hydrological variables, aerosol and cloud parameters, green house gas species, and air quality parameters are archived with CEDA and contribute to interactional networks including [GAW](#), [ICOS](#) and [ACTRIS](#).

The NCAS mission is to understand our atmosphere, how it is changing, and how it impacts life on Earth. The NCAS vision is to push the frontiers of atmospheric science, and contribute to a healthy, resilient and productive global environment for the benefit of all.

2.1.4 International involvement

The UK participates in several international observations programmes and in particular activities at European level. Such activities include the following:

- **ESA:** The UK is a major contributor to a number of ESA programmes in the Earth Observation Domain. This includes the main Envelope Programme (EOEP) which is now called Future EO (FEO) the Climate Change Initiative (CCI+), Copernicus INCUBED, Global Development Assistance (GDA) and missions such as TRUTHS.

Within the ESA envelope programme (EOEP/ FEO) is the Earth Explorer Programme. This creates a platform for new and innovative science missions which have a use for society, such as for measuring the planet and therefore climate change impacts. The UK has been successful in winning many of the leading roles in these missions from the concept and science through to the industrial build and operations for missions such as:

- **Cryosat:** This mission is dedicated to measuring the thickness of polar sea ice and monitoring changes in the ice sheets that blanket Greenland and Antarctica. The UK has provided scientific leadership of Cryosat, which has generated high quality science of major public interest (with 25% of publications citing a UK author) and is providing observations which complement those undertaken by the substantial UK investment in polar research vessels.
- **EarthCare:** This mission will advance our understanding of the role that the interaction between clouds and aerosols play in climate regulation. The UK is developing and supplying the multi-spectral imager (MSI) instrument, the BroadBand Radiometer (BBR) instrument, the battery and the Instrument Control Units (ICUs) for EarthCare.
- **Aeolus:** This is the first space mission to acquire profiles of the wind on a global scale. These near-real-time observations have improved the accuracy of numerical weather and climate prediction and advanced our understanding of tropical dynamics and processes relevant to climate variability, so much so that there is now a call for Aeolus 2 to be part of the core EUMETSAT operational missions. The UK led the assembly of the Aeolus satellite. The wind profile retrieval is led by the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, UK.
- **Biomass:** This mission will provide global maps of the amount of carbon stored in the world's forests and how this changes over time, mainly through absorbing carbon dioxide, which is released from burning fossil fuels. Biomass will provide essential support to UN treaties on the reduction of emissions from deforestation and forest degradation. The UK is priming Biomass and has led the assembly of the satellite. The UK science team and others are instrumental in the global discussions of the use of the data for critical climate action and decisions on forestry.

The UK is the largest contributor to the ESA Climate Change Initiative programme (CCI+) and leads Essential Climate Variables (ECV) production activities in sea surface temperature, Antarctic ice sheets, land surface temperature and ocean colour, with substantial contributions to aerosols, clouds, ozone, greenhouse gases and cryosphere ECV data, as well as lakes. The UK has also contributed to work on fire, glaciers, Greenland ice sheets, sea level and some evaluation of land cover through the Met Office. Through NERC, the UK has funded the lake surface temperature component to the ECV work. The UK also led the ESA CCI Climate Modelling User Group (CMUG). CCI+ is run from the UK in the ESA Climate Office in Harwell. The Met Office also leads the user group for the programme.

- **EUMETSAT:** The UK contributes to EUMETSAT's polar orbiting METOP and METOP Second Generation (METOP-SG) series of satellites and the geostationary Meteosat series (MSG, MTG). The Met Office is a member of EUMETSAT's Climate Monitoring Satellite Application Facility (CMSAF). The CMSAF generates and archives datasets for specific climate application areas, derived primarily from EUMETSAT satellite data and also from US meteorological missions.

EUMETNET Composite Observing System (EUCOS): The Met Office contributes to the EUCOS network, which aims to establish, operate and evolve a European observing network under the auspices of the European Meteorological Network (EUMETNET) to deliver increased efficiency, leading to improved weather and

climate services to save lives and livelihoods across Europe and further afield. EUCOS includes a terrestrial segment (surface and upper-air observing) and a surface marine programme, both of which contribute to GCOS.

- **Copernicus:** The UK has a long history of contributing to the European Remote Sensing and Envisat satellite programmes, and continuity from these is now provided by the joint European Commission (EC) -ESA Copernicus Programme Sentinel Missions and the applications and services. The fleet of Sentinel satellites is the world's leading Earth observation constellation. Recent UK involvement includes:
 - manufacture of the Sentinel-5 Precursor satellite, launched in October 2017, bridging the data gap between Envisat and Sentinel-5 and providing measurements of greenhouse gas concentration in the atmosphere
 - Instrument contributions, including CCD detectors, radar electronics, cryo-coolers, and instrument calibration expertise and facilities
 - Platform equipment, including batteries, propulsion systems and communications equipment
 - UK scientists are leading the specification of the anticipated Sentinel-8 high spatial resolution land surface temperature instrument
 - The UK has a scientist on the CO₂ monitoring task force.

In addition to the Sentinel satellite activity, Copernicus also involves in-situ measurements and the provision of services. The European Centre for Medium-Range Weather Forecasts (ECMWF) manages the Copernicus Climate Change and Atmosphere Services from the UK. The Climate Change Service (C3S) combines observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide. Various UK institutions contribute to observational C3S services such as those recovering and providing access to historical surface meteorological observations and those providing updates forwards in time to sea-surface temperature information. The Copernicus Marine Environmental Monitoring Service, led by MERCATOR in France, also features contributions from the Met Office providing ocean reanalyses.

- **ECMWF:** The UK is a Member State of the European Centre for Medium-Range Weather Forecasts, which is based in Reading (UK), Bonn (Germany) and Bologna (Italy) (see section 2.5.9 for more information). The principal objectives of the Centre are:
 - development of numerical methods for medium-range weather forecasting
 - regular preparation of medium-range weather forecasts for distribution to the meteorological services of its Member States
 - scientific and technical research directed at the improvement of these forecasts
 - collection and storage of appropriate meteorological data.

ECMWF is a key player in Copernicus, the Earth Observation component of the European Union's Space programme, offering quality-assured information on climate change (Copernicus Climate Change Service), atmospheric composition

(Copernicus Atmosphere Monitoring Service), and flooding and fire danger (Copernicus Emergency Management Service). Through the EU's Destination Earth initiative, ECMWF is also developing prototype digital twins of the Earth.

ECMWF undertakes important reanalysis work, which is highly relevant to the GCOS Implementation Plan.

- **GEO:** The UK is a member of the international Group on Earth Observations (GEO) programme as a national delegation and also through participation in a number of the GEO committees.
- **The CEOS Committee on Earth Observing Satellites** gathers to coordinate the satellite contributions to GCOS from both technical and political aspects. Issues range from climate and methane measurement standards for data sharing, the role of the private sector and capacity building.
- **AGAGE:** The UK is involved in the international AGAGE programme through its activities at Mace Head. The Advanced Global Atmospheric Gases Experiment (AGAGE) and its predecessors (the Atmospheric Life Experiment, ALE, and the Global Atmospheric Gases Experiment, GAGE) have been measuring the composition of the global atmosphere continuously since 1978. AGAGE is distinguished by its capability to measure over the globe at high frequency almost all of the important species in the Montreal Protocol (e.g., CFCs and HCFCs) to protect the ozone layer, and almost all of the significant non-CO₂ gases in the Kyoto Protocol (e.g., CF₄, SF₆, HFCs, methane, and nitrous oxide) to mitigate climate change. The atmospheric monitoring station at Tacolneston, Norfolk, was recently accepted into the AGAGE network. This station was established in 2012 as part of the UK DECC (Deriving Emissions linked to Climate Change) Network.
- **ICOS:** The Integrated Carbon Observation System (ICOS) is a research infrastructure that combines three European monitoring networks: measurements of atmospheric composition, fluxes between the land and the atmosphere, and fluxes between the ocean and the atmosphere. The UK formally joined the ICOS-RI in June 2016. The UK currently has two ICOS-labelled sites for monitoring atmospheric composition: Ridge Hill (Herefordshire) and Weybourne (Norfolk). There are two UK-ICOS ocean sites: the Porcupine Abyssal Plain (PAP) Observatory (northeast Atlantic) and the Western Channel Observatory (near Plymouth). The Auchencorth Moss monitoring station (southeast Scotland) is an ICOS ecosystem site, measuring land-atmosphere exchange as well as the atmospheric composition for a range of key species.
- **ILTER:** The International Long Term Ecological Research (ILTER) network is a 'network of networks'; a global network of research sites located in a wide array of ecosystems that can help understand environmental change across the globe. ILTER is represented at the European scale by the LTER-Europe community who have been developing the case for a European long-term ecosystem research infrastructure (the eILTER RI). The ambition for the eILTER RI, is that coordinated and co-located measurements of biological, hydrological, geochemical and climate measurements are undertaken across Europe, and that data and models are made available through linked systems in order to contribute to global scale assessments of the effects of climate change impacts on ecosystems and ecosystem services. The UK's formal contribution to both ILTER and LTER-Europe is the Environmental Change Network (ECN), managed by the UK Centre for

Ecology & Hydrology (UKCEH). The ECN has been gathering information about the pressures on, and responses to, environmental change in physical, chemical and biological systems across a wide range of UK habitats over the past 25 years. UKCEH are currently partners in the Preparatory Phase Project (PPP) of the H2020 funded eLTER RI, formally recognised as an 'emerging infrastructure' on the EU's European Strategy Forum on Research Infrastructures (ESFRI) programme. ILTER is also a key partner in GEO, which, through its Biodiversity Observation Network (GEO BON), is developing a set of Essential Biodiversity Variables to complement the ECVs that have already been developed for GCOS.

- **FLUXNET:** FLUXNET coordinates regional and global analysis of observations from micrometeorological tower sites. The flux tower sites use eddy covariance methods to measure the exchanges of carbon dioxide (CO₂), water vapour, and energy between terrestrial ecosystems and the atmosphere. The UK has 14 contributory sites.
- **International Ocean Carbon Coordination Project:** this is the umbrella organisation to which the UK contributes to the several carbon-relevant international networks providing high quality surface and subsurface information about carbonate chemistry including CO₂ and pH. These include the BioGeoChemical Argo programme that provides subsurface ocean data; surface CO₂ sampling from commercial vessels, research ships and (SOCAT and SOCONET); subsurface BioGeoChemical profile data from ship surveys (GLODAP); and the Global Ocean Acidification Observing Network (GOA-ON).
- **OceanSITES:** OceanSITES is a worldwide coordinated network of long-term, deepwater reference stations measuring dozens of variables and monitoring the full depth of the ocean, from air-sea interactions down to 5,000 metres. The network consists of about 30 surface and 30 subsurface arrays. Satellite telemetry enables near real-time access to OceanSITES data by scientists and the public. The network complements satellite imagery and other *in-situ* observation data (like Argo floats) by extending the dimensions of time and depth. The UK contributes several sites including the Porcupine Abyssal Plain Observatory and moorings in the Drake Passage and at Rothera on the Antarctic Peninsula. The Atlantic Meridional Overturning Circulation Transport Arrays at RAPID-26N and OSNAP are also part of the OceanSites network. RAPID-26N in the subtropical north Atlantic is a collaboration between the UK (funded by NERC) and the USA (funded by NSF and NOAA) that has been measuring the Atlantic Meridional Overturning Circulation (AMOC) since 2004. OSNAP is a similar array in the subpolar North Atlantic operated by UK, US, the Netherlands, Germany and Canada since 2014. These observations have supported a number of research programs that are improving assessments of the risk and impacts of gradual or rapid climate change due to AMOC change. Significant co-funding has been obtained from related EU Framework Programmes
- **GACS:** The Global Alliance of CPR Surveys (GACS) brings together the expertise of approximately 50 plankton specialists, scientists, technicians and administrators from 12 laboratories around the world, towing a common and consistent sampling tool, the Continuous Plankton Recorder (CPR), from about 50 vessels. The Continuous Plankton Recorder Survey, based at the Marine Biological Association of the UK undertakes CPR Surveys across the Atlantic. Partnerships with other organisations have extended these surveys into the Pacific, Arctic, and also into

the Southern Ocean (via Australia CPR and also through BAS). New routes have recently started in the Gulf of Maine, Mid-Atlantic Bight, and Brazil to South Africa (run as part of the EU AtlantECO project).

- **GO-SHIP:** The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) operates reference sections to collect the highest quality observations of trans-basin and sea surface to seafloor physical oceanography variables, carbonate chemistry, and marine biogeochemistry and ecosystem variables. The coordinated network of globally sustained hydrographic sections is a fundamental part of the global ocean / climate observing system. GO-SHIP Reference Sections are coast-to-coast or coast-to-ice sections that are repeated annually or up to once a decade. The GO-SHIP sections are the primary network to provide global observations of the changing physical and biogeochemical environment in water depths greater than 2000m. The GO-SHIP data are used to calibrate and quality control data from autonomous networks including Argo floats and gliders. The UK contributes five Atlantic sections (subpolar and subtropical North Atlantic, subtropical south Atlantic, and two in the Southern Ocean).
- **RAPID-26N:** RAPID-26N is collaboration between the UK (funded by NERC) and the USA (funded by NSF and NOAA) that has been measuring the Atlantic Meridional Overturning Circulation (AMOC) since 2004. These observations have supported a number of research programs that aim to improve assessment of the risk of rapid climate change due to AMOC change, and to investigate the potential for predictions of the AMOC and its impacts on climate. Significant co-funding has also been obtained from related EU Framework Programme. In collaboration with US, Canadian and European partners the UK is also participating in the international OSNAP program to monitor the AMOC in the sub-polar North Atlantic.
- **ARGO:** The international Argo project is an international array of profiling floats that provides a continual record of the three-dimensional temperature and salinity structure of the global ocean to 2,000m depth, with a small number of newer float designs measuring down to 6,000m depth and an increasing number of floats also measuring bio-geochemical (BGC) variables (dissolved oxygen, pH, chlorophyll fluorescence, nitrate, suspended particles and irradiance). The UK's contribution to Argo is undertaken by a partnership between the Met Office and the National Oceanography Centre (NOC), which includes the British Oceanographic Data Centre (BODC). The Met Office are responsible for programme management and coordination, organizing float deployments, preparation of floats for deployment, telecommunications (costs) and international contributions. NOC has responsibility for Argo science and data management respectively, and takes the lead on deep and biogeochemical Argo. The UK presently has 133 (November 2022) active floats contributing to the Argo float array, including eight with additional biogeochemical sensors and five deep floats, this being ~3.5% of the global array of around 3,800 floats. Floats typically operate for 4 to 7 years, and over the last five years the average annual UK contribution has been around 21 core floats and seven non-standard (i.e., deep and/or with additional BGC sensors) floats, noting the number of floats deployed in the last two years has been impacted by the Covid pandemic. The UK is also a member of the Euro-Argo ERIC (European Research Infrastructure Consortium) that aims to maintain an 'infrastructure' where the European member countries have the capacity to sustain approximately one quarter of the Argo array and to develop the European contribution to the OneArgo mission that will extend Argo's

coverage beyond its original design, to span the full ocean depth, cover high latitudes and marginal seas, and add biogeochemical sensors for improved understanding of oceanic cycles of carbon, nutrients, and ecosystems.

- **OceanGliders:** OceanGliders is an internationally coordinated network of autonomous underwater vehicles, observing EOVs and physical, biogeochemical and biological ocean processes. The UK was the first country to establish sustained, continuous presence glider observations (west of the UK) in order to observe crucial boundary currents where moorings are damaged by fishing activity, and ship surveys provide additional, temporally-limited information.
- **Voluntary Ship Observations:** the GOOS Ship Observations Team coordinates voluntary sampling of ocean and atmosphere from commercial shipping, and research and military vessels. The UK Met Office has fitted 60 ships with an autonomous sampling system, and the UK has 286 registered voluntary observing ships.
- **Global Sea Level Network (GLOSS):** GLOSS measures in situ sea level, which is critical for ground-truthing observations from satellites and for accurate quantification of regional and global sea level change in the post-industrial era. The UK supports 11 tide gauges including several in small island dependencies in the South Atlantic. The Permanent Service for Mean Sea Level (PSMSL), hosted at NOC, was established in 1933 and provides a globally unique and consistent service through the collection, publication, analysis and interpretation of highest quality sea level data from the GLOSS network.

2.2 Implementation

Met Office:

The Met Office operates surface, upper air and marine observing networks that contribute to GCOS. These are mostly funded through the Public Weather Service (PWS), whose remit is to provide a coherent range of weather information and weather-related warnings to the UK public, on the basis that the GCOS commitments align well with PWS objectives. The PWS also provides UK climate and weather statistics.

The Met Office has continued the responsibility for providing the role of a full-time GCOS Network Manager, through funding from a contract with GCOS and its own internal public-weather service resources. The role of an international network manager considers all aspects of the in-situ global observing systems in meeting the Climate requirements. It links the funding from the GCOS sponsors to priority areas in developing countries, both in terms of the uniqueness of measurement (i.e., location, content) and the financial challenges for the host organisation in operating the equipment. GCOS does not own any of the observing equipment but through the GCM (GCOS Cooperation Mechanism), it aims to support National services and institutes in the design, installation and operational management of their systems.

NERC centres:

A significant portion of the UK's open ocean observations capability lies within the UK's marine research centres, funded through NERC research programmes.

The National Centre for Earth Observation (NCEO) of NERC has supported the GCOS Implementation Plan in a number of ways, including: inputs to and review of the GCOS

requirements and implementation plans, serving on the GCOS terrestrial panel, working on definitions of new Essential Climate Variables (ECV), and support for long-term data sets. Technical quality and traceability of the climate data is clearly a prerequisite for usability and NCEO is working in the UK and in European fora to underpin work on appropriate algorithms, their expressions of uncertainty in the data and in testing of the output datasets.

NCEO has also worked alongside other bodies supporting the GCOS Implementation Plan, particularly through the Committee on Earth Observation Satellites (CEOS). NCEO scientists have contributed to the Essential Climate Variable inventory maintained by the CEOS/CGMS Working Group Climate at EUMETSAT and to the CEOS Greenhouse Gas Implementation Team. There have been considerable contributions to CEOS plans through its Land Surface Imaging Virtual Constellation in support of the Global Stocktake: (i) Definition of the AFOLU Roadmap; (ii) Harmonisation of space-based maps of above-ground biomass; and (iii) Engaging with countries on use of satellite data in national reporting to UNFCCC. Importantly, NCEO provide estimates of greenhouse gas emissions through inverse modelling of atmospheric in situ ECV data to the Global Carbon Project.

International reporting of climate data has remained a priority for key climate parameters including through data portals in the UK. NCEO, NERC and the European Space Agency have continued to support climate data development including projects on above-ground biomass, land surface temperature, lake properties and water vapour. Data such as ozone, ocean colour, sea surface temperature and aerosols are provided with only small delays or is up-to-date. Much of this data is also available operationally, e.g., lake quality variables (temperature, biochemistry), which are included in the Copernicus Land Monitoring Service for 4000+ lakes. NCEO has supported state-of-the-art, long-term satellite data sets for carbon dioxide and methane, which have led to important discoveries about natural emissions and demonstrated verification of large country national contributions. NCEO continues to support Obs4MIPS and expects to do more work in this area.

2.3 Quality control

2.3.1 Efforts to ensure ECV-observing activities adhere to the GCOS climate monitoring principles

UKEOF Coordinating Climate Observations Group:

UKEOF is a partnership of public sector organisations with an interest in using and providing evidence from environmental observations. It aims:

- To achieve effective partnership working in environmental observations; and
- To maximise the benefits of observations to the UK including for science, policy and economic growth.

The UKEOF Coordinating Climate Observations Group ran from 2012-2014. The aim of the group was to oversee coordination of UK climate observing activities, advise on UK user priorities, and encourage implementation of common observing standards and methods. The group produced a report and a guidance note in 2013. Activities were then taken on by the UKEOF Management Group and Secretariat. The UKEOF holds a

catalogue of UK monitoring and observation activities². The catalogue, was last updated in 2016 enabling records to be searched in terms of Climate measurements. Future development of the catalogue is currently under review by the UKEOF Digital Advisory Group.

Met Office:

The Met Office undertakes comprehensive quality control of its GCOS stations by running a number of checks on the data held in its climate database. These include range, internal consistency and spatial checks on the observations. Faults identified are flagged for further investigation to resolve the problem promptly.

The Met Office operates a set of Change Advisory Boards (CABs) to consider and give approval to changes to its observing networks prior to implementation. Requested changes are thoroughly checked and assessed from both a technical and GCOS monitoring principles perspective. This is defined as part of the change control process within ITIL, a UK Government initiative.

The Met Office employs dedicated teams to inspect land and marine observing sites to ensure consistency of exposure according to WMO No. 8 guidelines and assess exposure using the CIMO siting classification for land observing sites. Marine sites are assessed using similar principles. Details of local conditions, instruments and exposure (metadata) are recorded using in-house developed software and archived.

The Met Office is in the process of replacing its land surface observing network, and has carried out extensive user testing and side by side comparisons of the equipment, inputs and outputs, with a programme of longer term checks being carried out. This will ensure relative performance is understood and provide documentation for future reference.

British Rainfall Standard:

The national standard for the Acquisition and Management of Meteorological Precipitation Data from a Raingauge Network - BS 7843 (2012) was reported on previously. This is currently undergoing a review and is used to minimise measurement uncertainty such as implementing change, collection of metadata, quality control and the operation of long-term monitoring sites.

National Oceanography Centre and the British Oceanographic Data Centre:

All the data sets collected by NOC undergo extensive quality control and calibration by researchers and data experts. This ensures the consistently high quality of data required for climate research, and ensures maximum value can be extracted from data sets that can be many decades long.

² <https://catalogue.ukeof.org.uk>

2.3.2 Difficulties encountered in protecting the integrity of long-term climate data records and steps being taken or required to address those difficulties

Central England Temperature:

The Met Office has earmarked a small set of observing stations to ensure the consistent maintenance of the 350-year Central England Temperature record (see section 2.5.1). These sites receive additional attention to prioritise mitigation of any potential issues at those sites that may compromise climate monitoring.

Automation of ordinary climate stations:

The Met Office continues to automate important manual climate stations at risk of closure to ensure the continuation of the climate record across the United Kingdom. The Automatic Weather Station network has exceeded targets for timeliness and quality, with figures of 98.5% and 93.8% respectively. Current challenges relate to new communication solutions and the introduction of SurfaceNet, which is replacing the MMS system.

Voluntary climate observing stations:

The Met Office supports a supplementary network of approximately 144 manual stations to support national climate monitoring activities for the UK. The MO also have access to data from over 1000 volunteer read storage gauges. It is planned to modernise the existing system for returning observations using postcards to a digital method based on the MO Weather Observations Website (WOW). WOW is also a large source of other volunteer rainfall information.

Hydrological networks:

The Met Office works closely with a number of other partner agencies in the maintenance of supplementary rain gauge networks for hydrological applications. This results in a UK network of daily and monthly rain gauges currently in excess of 2,500. An important network for capturing detailed spatial information of rainfall, particularly extreme events.

Corrections to the global record of sea-surface temperature and humidity:

The Met Office Hadley Centre and the National Oceanography Centre continue to develop corrections to the global record of sea surface temperature since 1850 to account for biases resulting from historical and ongoing changes in the composition of the data base, particularly relating to measurement platforms, methods and country of origin³. Uncertainties in these corrections are also quantified and made available together with uncertainties relating to under-sampling. A revision of the global surface marine humidity record has been produced in HadISDH, requiring careful quality control and correction of ship data to remove the impact of changes in measurement height through time⁴. The NERC National Capability programme CLASS developed a new global night marine air temperature data set for records since 1880 (CLASSnmat).

³ Kennedy, J. J., Rayner, N. A., Atkinson, C. P., and Killick, R. E. (2019) An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set. *Journal of Geophysical Research: Atmospheres*, **124**, 7719-7763, <https://doi.org/10.1029/2018JD029867>

⁴ Willett, K. M., Dunn, R. J. H., Kennedy, J. J., and Berry, D. I. (2020) Development of the HadISDH marine humidity climate monitoring dataset. *Earth System Science Data*, **12**, 2853-2880, <https://doi.org/10.5194/essd-12-2853-2020>

Improving CLIMAT data exchange:

The Met Office has occasional contacts with National Meteorological Services (NMSs) supplying CLIMAT observations with a view to improving data exchange. They also provide reports on data quality and reporting issues from the global CLIMAT network to GCOS.

Tide gauge systems can be costly to maintain, particularly if they are to be used for long-term monitoring of mm-scale trends in sea level for climate resilience, which demands $\pm 0.01\text{m}$ accuracy and labour-intensive annual levelling exercises. In recent years, the UK Tide Gauge Network (UKTGN) has been used primarily for short-term operational forecasting, with an associated accuracy tolerance that is an order of magnitude lower ($\pm 0.1\text{m}$). As a result, the ability of sea level scientists to derive robust long-term trends from UK tide gauge records has been severely compromised. In fact, the uncertainties associated with the annually-produced UK Sea Level Index have become so large in recent years that robust conclusions can no longer be drawn from UK data. The ability to estimate sea level change and variability is also dependent upon the ability to understand how rates of land motion contribute to the trends detected at tide gauge sites. This is currently a large area of uncertainty in deriving long-term sea level trends because ongoing land level monitoring systems are generally not co-located with tide gauges and even the more rudimentary annual levelling exercises have been abandoned in many cases.

A further consequence of the deteriorating accuracy of UKTGN observations is that fewer data are available for the estimation of sea level extremes and for tidal predictions. This constrains mitigation and forecasting of coastal hazards which, ironically, is the main application of the present-day network.

Additionally, the impact of the 2004 Indian Ocean Tsunami, together with technology advances in the wider sea level community, have raised the bar for tide gauge specifications. As a result, the IOC's Global Sea Level Observing System (GLOSS) programme now defines minimum standards that include high frequency sampling of 1 minute or less and the establishment of continuous GNSS receivers to monitor land levels [IOC, 2016]. Whilst other nations have upgraded their monitoring technology over the last decade, the UKTGN presently falls short of these requirements, affording sampling (15 min) and latency of observations that the IOC's North East Atlantic and Mediterranean Tsunami Warning System (NEAM-TWS) has deemed unsuitable for applications such as tsunami monitoring [ICG/NEAMTWS, 2019].

To address these issues, the NOC is developing a low operating cost (and therefore futureproof) multi-hazard sea level monitoring system that delivers the latency and sampling required for operational storm surge and tsunami monitoring, together with high accuracy sea level and land level measurements to elucidate robust long-term trends associated with climate change.

The Natural Capital Ecosystems Approach (NCEA):

The NCEA is concerned with developing a systematic evidence base and involves many elements of the environmental system. New surface water and groundwater temperature networks are being developed. For water quantity (surface water), the EA and UKECH are working together to identify a sub set of flow sites from the existing river flow network in England to form a representative sub-network and to also identify what improvements are needed to ensure the data from these sites is high quality and suitable for detecting

climate change. It is developing tools and evidence that can in the future also help improve the UK Benchmark network.

2.3.3 Efforts to ensure best practice in sampling marine biological variables

The North-East Marine Biological Analytical Quality Control Scheme (NMBAQC) provides a source of external Quality Assurance for laboratories engaged in the production of marine biological data. The Scheme is currently composed of seven components: epibiota, fish, invertebrates, particle size analysis, macroalgae, phytoplankton and zooplankton. Each component is run by a scheme administrator and technical manager (usually from a UK ALB or research institute). The scheme reports to the Healthy and Biologically Diverse Seas Evidence Group (HBDSEG) under the UK Marine Monitoring and Assessment Strategy (UKMMAS). The Scheme promotes best practice in marine biological monitoring, and is open to participants from across the EU and beyond. All UK Competent Monitoring Authority laboratories and their contractors undertaking sample analysis for statutory marine monitoring programmes are required to participate within an externally run analytical quality control scheme, and NMBAQC fulfils this role. Whilst the Scheme currently comprises the above components, part of the role of NMBAQC is to horizon-scan for future monitoring methods, and work with the wider community and stakeholders to help to produce, signpost and promote best practice. More information can be found at www.nmbaqcs.org

2.4 International data exchange and data analysis

2.4.1 National policy or guidance that has been promulgated relevant to the international exchange of ECV data

The EU Directive known as INSPIRE (Infrastructure for Spatial information in the European Union) was transposed into UK law in December 2009 and has created an EU spatial data infrastructure. This will enable the sharing of environmental spatial information among public sector organisations and better facilitate public access to spatial information across Europe.

Data specifications for the EU INSPIRE directive are currently under review. The UK contribution involves many organisations that take part in the thematic working groups (it should however be noted that although this includes UK expertise, some of the funding for these activities is via the European Framework Programme). The Centre for Environmental Data Analysis⁵ (CEDA) and the UK Met Office have representatives on the Thematic Working Group on Atmospheric Conditions and Meteorological Geographical Features. Both organisations also contribute to the MetOcean Domain Working Group of the World Meteorological Organisation (WMO) which aims to align the metadata/data models used in those communities with those being developed by INSPIRE.

The European Commission INSPIRE website⁶ has news of developments on INSPIRE and an archive of EC INSPIRE documents.

⁵ <http://ceda.ac.uk>

⁶ <http://inspire.jrc.ec.europa.eu/index.cfm>

2.4.2 Policy-level barriers to international exchange of climate data and their provision to international data centres (IDCs)

The Met Office continues to provide both real time and historical data from its network of observing stations and weather forecasts under an open licence agreement.

NERC's Data Policy details its commitment to support the long-term management of environmental data by requiring that NERC-funded scientists must make their data openly available within two years of collection and deposit it in a NERC Data Centre for long term preservation. In this way all NERC-funded data are managed and made available for the long-term for anybody to use without any restrictions.

2.5 Data centres

The section describes UK efforts to ensure that international data centres are established and strengthened for all the Essential Climate Variables.

2.5.1 Met Office Hadley Centre

The Met Office Hadley Centre receives, quality controls, and archives large amounts of observed climate data. These are used for monitoring the climate, in studies of the causes of climate change, and in climate modelling. The below sets out the datasets available from the Met Office Hadley Centre.

Datasets available:

National monitoring

Indicators of historical and present changes in climate include Central England Temperature (HadCET) and UK Precipitation (HadUKP). The HadCET mean temperature series is available at monthly resolution back to 1659, and at daily resolution back to 1772, and to date is the longest available instrumental record of temperature in the world. It is representative of a roughly triangular area of the UK enclosed by Bristol, Lancashire and London. The HadUKP (England and Wales) series is available at monthly resolution from 1766. Shorter series are available for other areas and resolutions. By using fewer, longer station records these series are designed to be more homogeneous over time.

More detailed resources for monitoring the climate in the UK are available from the MOHC National Climate Information Centre (NCIC) via its HadUK-Grid data set. It routinely creates daily and monthly series of 1 km gridded data and associated areal series using all available data. Recent work to digitise historical paper records have extended the series back to 1884 for temperature and 1836 for precipitation. All UK climate observations and NCIC products have been made openly available for any purpose, both research and commercial.

An annual assessment of the State of the UK Climate is published annually (<https://www.metoffice.gov.uk/research/climate/maps-and-data/about/state-of-climate>), which puts the year just past into its historical context.

Global monitoring

The Met Office Hadley Centre routinely publishes, on the global climate dashboard (<https://climate.metoffice.cloud/>), assessments of key global climate indicators such as global surface temperature, Arctic and Antarctic sea ice extent, sea level rise, ocean heat

content, etc. In addition, annual international assessments are significantly contributed to including the State of the Climate report published in the Bulletin of the American Meteorological Society and the WMO State of the Climate report.

Key global gridded datasets include monthly blended land surface air temperature and sea surface temperature (HadCRUT, prepared in collaboration with the Climatic Research Unit (CRU) of the University of East Anglia); sea surface temperature with sea ice (HadISST); stand-alone sea surface temperature (HadSST); night marine air temperature (HadNMAT, developed in collaboration with the National Oceanography Centre, Southampton); sub-surface ocean temperature and salinity (EN4 and HadIOD); sea level pressure (HadSLP); sub-daily station measurements of various meteorological variables (HadISD); global, gridded indices of extremes (HadEX, developed in collaboration with the University of New South Wales, Australia, and with NOAA (USA)); and worldwide gridded land daily temperatures (HadGHCND). Recently, a prototype global (land and ocean) surface humidity data set has been developed (HadISDH). Many of these data sets and analyses are provided with quantified uncertainties. These and other data holdings are fully described on the Met Office Hadley Centre Observations website⁷. Some of these data have also been made available through the Centre for Environmental Data Analysis (CEDA).

The Met Office Hadley Centre is also contributing to the development of the Copernicus Climate Change Service (C3S) global surface database service with provision of expertise on quality control and data integration.

Contribution to satellite Climate Data Record development

The Met Office Hadley Centre contributes to the ESA Climate Change Initiative SST and LST projects, leading the user requirements gathering process and interactions with climate users and climate assessment of the resultant data sets including: use in model simulations; comparison with other data sets and analyses; and the amalgamation and reporting of feedback from trial users.

As part of the EUMETSAT Climate Monitoring Satellite Application Facility, the Met Office Hadley Centre develops a Climate Data Record of Upper Tropospheric Humidity.

International Surface Temperature Initiative

The Met Office Hadley Centre contributes to the development of traceable land air temperature data sets by the International Surface Temperature Initiative through leadership of the homogenisation benchmarking working group, amongst other things.

WMO Expert Team on Climate Monitoring and Assessment

The Met Office Hadley Centre co-chairs the WMO Expert Team on Climate Monitoring and Assessment which has responsibility for both the direction of WMO's Global State of the Climate report, and influences the development of the increasing number of regional statements, developing general guidance on climate monitoring. The WMO Statement feeds into the UNFCCC process at the Conference of the Parties annually.

Reanalysis work:

The below section highlights where the Met Office is involved in reanalysis of data.

Atmospheric Circulation Reconstructions over the Earth (ACRE)

⁷ <http://www.metoffice.gov.uk/hadobs/>

The Met Office Hadley Centre leads the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative, which is an end-to-end project that facilitates both the historical global weather observational data needs of surface-observations-only climate quality reanalyses, and the seamless feeding of 3D weather products produced by these reanalyses into climate applications and impacts models. ACRE achieves this outcome by:

- linking international meteorological organisations and data rescue infrastructure to facilitate the recovery, extension, quality control and consolidation of global historical terrestrial and marine instrumental surface data covering the last 250 years;
- making these observations available to new pioneering surface-observations-only reanalyses;
- ensuring that reanalysis products can be tailored/downscaled to seamlessly flow into various climate applications and production models.

2.5.2 Global Collecting Centre for Marine Climatological Data (GCC)

Under the WMO Marine Meteorology and Oceanography Programme the Met Office runs one of two Data Assembly Centres (DAC). The aim of the Global Collecting Centre⁸ is to ensure that marine data are received from contributing members around the world and processed to an agreed standard. The data are then distributed on a quarterly basis to eight members, each with their own area of responsibility.

2.5.3 Permanent Service for Mean Sea Level (PSMSL)

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and bottom pressure recorders.

Established in 1933, the PSMSL is responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges and also provides a wider service to the sea level community. The PSMSL is embedded within the National Oceanography Centre (NOC) at Liverpool, and is funded by NOC. The PSMSL also reports to the International Association of Geodesy (IAG) and is a service of the International Association for the Physical Sciences of the Oceans (IAPSO). PSMSL also has a key role in the Intergovernmental Oceanographic Commission's (IOC's) Global Sea Level Observing System (GLOSS) and contributes to the IAG Global Geodetic Observing System (GGOS). The PSMSL is a regular member of the International Science Council – World Data System (ISC-WDS).

Datasets available:

The primary aim of the PSMSL is the provision of the global data bank for long-term sea level information from tide gauges. There are 74,759 station-years from over 2,397 stations in PSMSL. The data set and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website⁹. In addition, the PSMSL, together with the British Oceanographic Data Centre

⁸ http://www.metoffice.gov.uk/weather/marine/observations/gathering_data/gcc.html

⁹ <https://www.psmsl.org>

(BODC), is responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly or higher frequency values) from the IOC's GLOSS Core Network now carried out in collaboration with GESLA (Global Extreme Sea Level Analysis) project.

Other activities carried out by PSMSL:

PSMSL staff have continued to be active participants in the IOC Group of Experts on the Global Sea Level Observing System (GLOSS) and GGOS meetings, co-convened sea level sessions at the EGU and contributed to IOC coordination group tsunami warning system meetings. PSMSL data sets have contributed to and been acknowledged in all six Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC).

The PSMSL attempts to stimulate the development of tide gauge networks with other countries at national, regional and global level. The most important component of this work is its planning, and part-management of, the GLOSS programme. It provides, through GLOSS and via other routes, advice and training to national sea level authorities and individual sea level scientists and technologists. It organises major international meetings on the themes of sea level changes and tides. It also supplies software packages for tidal data analysis and quality control, and helps with the provision of training information and manuals. It maintains full participation with altimeter and space gravity working groups in view of the importance of those techniques to sea level research.

2.5.4 British Oceanographic Data Centre (BODC)

BODC is one of NERC's Environmental Data Centres, and part of the NOC. It is a national facility for storing and distributing data concerning the marine environment. Data holdings include biological, chemical, physical and geophysical oceanographic data, including measurements of nearly 46,000 different variables.

Datasets available:

Data can be retrieved directly from the BODC website¹⁰. Data currently available include:

- All data (including CTD profiles, current meter and wave data) held in the National Oceanographic Database
- Argo float data
- Gridded bathymetry data (General Bathymetric Chart of the Oceans)
- UK Tide Gauge Network
- Historical UK tide gauge data – scanned charts and ledgers
- International sea level data (Global Sea Level Observing System)
- Numerical model data – access to BODC's numerical model data holdings
- Historical bottom pressure recorder data
- Near real time ocean glider data

Services:

- NERC Vocabulary Server (NVS) web service - providing access to controlled vocabularies

¹⁰ https://www.bodc.ac.uk/data/online_delivery/

- Sensor Web Enablement (SWE) - developing interoperable standards to publish sensors and their data on the web
- Published Data Library (PDL) - assigning Digital Object Identifiers (DOIs) in collaboration with the British Library
- Managing real time data from platforms such as Argo floats, gliders and seal tags for operational use in the Global Telemetry System and Global Data Assembly Centres

2.5.5 Centre for Environmental Data Analysis (CEDA)

The Centre for Environmental Data Analysis (CEDA)¹¹ is part of the NERC Environmental Data Service¹², operating jointly for the National Centre for Atmospheric Sciences¹³ and the National Centre for Earth Observation¹⁴. CEDA provides data and information services for environmental science, atmospheric science and Earth observation research communities. The role of the CEDA is to assist UK researchers to locate, access, analyse and interpret data.

Datasets available:

The data held at the CEDA are of two types:

- Datasets produced by NERC-funded projects: these datasets are of high priority since the CEDA may be the only long-term archive of the data;
- Third party datasets that are required by a large section of the UK atmospheric research community and are most efficiently made available through one location (e.g. UK Met Office, ECMWF, ESA and WCRP datasets).

Some datasets of particular relevance to the UNFCCC:

- Coupled Model Intercomparison Project (CMIP): CEDA holds a copy of the core of the CMIP archive from the most recent phases (CMIP5 and CMIP6), including the projections which underpin the IPCC 5th and 6th Assessment Reports.
- ESA Climate Change Initiative (CCI): CEDA hosts data from the ESA CCI projects: cloud, aerosol, ocean colour, glaciers, sea level, fire, soil moisture, ozone, greenhouse gases, sea ice, Greenland ice sheet, land cover, Antarctic ice sheet, sea surface temperature, land surface temperature, snow, biomass, permafrost, lakes, sea surface salinity, sea state, and water vapour. High resolution land cover data, vegetation parameters and precursors for aerosols and ozone will be added when available.
- NCEO datasets: CEDA hosts the majority of the NCEO ECV datasets which are described in the Tables on satellite ECVs, alongside many other NCEO related products.

¹¹ <https://www.ceda.ac.uk/>

¹² <https://eds.ukri.org/>

¹³ <https://ncas.ac.uk/>

¹⁴ <https://www.nceo.ac.uk/>

2.5.6 The IPCC Data Distribution Centre (DDC)

The UK component of the IPCC Distribution Centre is run by MetadataWorks on behalf of the IPCC, funded by the Department for Business, Energy and Industrial Strategy. The DDC operates under the oversight of the Task Group on Data Support for Climate Change Assessments (TG-DATA)¹⁵, in close liaison with three IPCC Working Group Bureaus. The DDC is jointly managed by the Center for International Earth Science Information Network (CIESIN, USA), The German Climate Computing Centre (DKRZ, Germany), The Spanish National Research Council (CSIC-IFCA, Spain) and MetadataWorks, on behalf of the UK Department for Business, Energy and Industrial Strategy.

The UK component of the DDC hosts the main web pages¹⁶, guidance documents on the use and interpretation of climate data, and a variety of data resources. The main web pages link through to additional resources provided by the USA, German and Spanish partners.

The data resources include climatologies of observational data and simulations.

2.5.7 UK Polar Data Centre (PDC)

The UK Polar Data Centre (PDC)¹⁷ coordinates the management of data collected in the polar regions by the Natural Environment Research Council (NERC) and other UK funded scientists. The PDC is based within the British Antarctic Survey (BAS). It is the UK's National Antarctic Data Centre and a member of the SCAR Standing Committee on Antarctic Data Management (SCADM). BAS, based in Cambridge maintain extensive climate related databases which support many international initiatives including the WCRP SPARC (World Climate Research Programme - Stratosphere-troposphere Processes And their Role in Climate) activity.

2.5.8 Environmental Information Data Centre (EIDC)

The Environmental Information Data Centre (EIDC) is the NERC data centre for the terrestrial and freshwater sciences. It is an umbrella body for a number of the data activities within the UK Centre for Ecology and Hydrology (UKCEH), including the National River Flow Archive (NRFA).

National River Flow Archive (NRFA):

The NRFA is mandated by UK government (Defra) and the devolved administrations of Northern Ireland, Scotland and Wales to maintain a comprehensive data retrieval service and provide information on water resources nationally.

Datasets available:

¹⁵ <https://www.ipcc.ch/data/>

¹⁶ www.ipcc-data.org

¹⁷ <https://www.bas.ac.uk/data/uk-pdc/>

The NRFA is the UK's focal point for hydrometric data, providing stewardship of, and access to, over 61,000 years' worth of daily river flow data from 1,465 gauging stations. The NRFA also holds two further types of data – annual maxima (AMAX) and peaks over threshold (POT) for approximately 1,000 stations which forms the basis for flood risk estimation and underpin flood research in the UK. Across the UK, 1,174 gauging stations are currently operational and providing data to the national archive (November 2017). It is maintained through routine collation, quality control, and archiving of river flow data from partner organisations. Within the UK the majority of river flow monitoring is conducted by four hydrometric measuring authorities, namely, the Environment Agency (EA) in England, Natural Resources Wales, the Scottish Environment Protection Agency (SEPA), and, in Northern Ireland, the Department for Infrastructure (Rivers). The NRFA is delivered through close collaboration with these measuring authorities and the organisations work together to keep developments under review in the fields of network design, instrumentation and information technology.

As well as river flow data, the NRFA provides comprehensive user guidance information on issues such as data quality and factors affecting runoff, as well as catchment rainfall estimates and access to a variety of spatial data sets derived by UKCEH and the British Geological Survey (BGS) (e.g., rivers, landform, land cover, geology and hydrogeology). NRFA data are supplied for free to all users except for large or complex requests where a handling charge may be applied to cover the cost of supply.

Improvement of Datasets:

Efforts are made to improve data quality through rigorous quality assurance and control programmes conducted by both the NRFA and measuring authorities. Data provided to the NRFA are validated, on an annual basis, through a range of techniques, including plausibility checks and expert judgment. Data provision is covered by a Service Level Agreement which aims to monitor and drive improvements in the timeliness of data provision, completeness and data quality, and a marked increase in these areas has been witnessed since its implementation. In addition, efforts are made to improve long-term data quality through a programme of liaison between the NRFA and measuring authorities to examine the quality of data capture (in particular, examining the credibility of hydrological extremes), the homogeneity of long-term records, and accuracy of user-guidance metadata. For AMAX and POT data, and the accompanying metadata, a programme of period of record validation exists at the NRFA, whereby a proportion of the dataset is reviewed each year, which identifies any inconsistencies in the historical record with a systematic review process.

The NRFA liaises with the measuring authorities to evaluate and optimise the hydrometric monitoring network. Since 2008, all the major operators of UK hydrometric monitoring programmes have conducted detailed reviews of their current gauging station networks, including assessments of the strategic utility of networks. The quality of UK hydrometric data is advanced by the active Hydrometry Technical Committee operated by the national standards body, the British Standards Institution. Standards are maintained covering a variety of monitoring techniques and data management practices. The UK also currently chairs the Hydrometry Technical Committee of the European Committee for Standardisation and is an active contributor to the corresponding ISO Committee.

The NRFA plays a key role in hydrological research and technological and infrastructure development in the UK; its data have been used extensively by scientists, planners, engineers and students for countless water-related studies and projects. As part of its

work to detect long-term climate variability in river flow records, the NRFA established and promotes the UK Benchmark Network. This sub-set of UK gauging stations monitor near-natural catchments, making them suitable for climate applications, and provides a core capability for hydrological trend detection and appraisal. The Benchmark Network has been exploited in a wide range of national studies of river flow trends and has been utilised in the UK Climate Change Indicator programme. The original Benchmark Network (UKBN) was designated in 2003, and has since been systematically reviewed, resulting in its second iteration, UKBN2. Each of the 146 Benchmark catchments has been assigned a score base on their benchmark suitability at low, medium and high flows, recognising all stations cannot be benchmark across the full flow regime. Since 2008, the NRFA has been involved in initiatives with international collaborators, to bring together hydrological reference networks from across North America and Europe in large-scale studies of changing runoff patterns.

Data sharing:

The NRFA services many of the UK's international commitments and obligations on hydrometric data by submitting river flow data and summary information to such organisations as:

- the WMO Global Runoff Data Centre (GRDC);
- the FRIEND European Water Archive (FRIEND – Flow Regimes from International Experimental and Network Data – is a component of the International Hydrological Programme (IHP) of UNESCO);
- the European Environment Agency (EEA);
- Eurostat (the Statistical Office of the European Communities);
- the Organisation for Economic Cooperation and Development (OECD); and
- the OSPAR and PARCOM conventions.

The National River Flow Archive (NRFA) presently supplies the Global Runoff Data Centre (GRDC) with data for 225 gauging stations across the UK. Data are supplied after validation. The vast majority of these data have a complete historical record. All the data the NRFA supply is subject to GRDC T&Cs and is thus freely available to GCOS and other UN programmes. Through the GRDC, river flow records for 7 UK gauging stations are currently included in the Global Terrestrial Network for River Discharge (GTN-R). The NRFA continues to work closely with the GRDC to further improve the availability of UK river flow data to GCOS.

2.5.9 European Centre for Medium-Range Weather Forecasts (ECMWF)

The European Centre for Medium-Range Weather Forecasts (ECMWF) is based in Reading (UK), Bonn (Germany) and Bologna (Italy). Although its core mission is weather forecasting, it performs a great deal of work relevant to climate change monitoring and prediction, which is described in this section. It should be noted that ECMWF is an International Organisation supported by 35 states but is reported under the UK submission because the Headquarters are based in Reading, UK.

General climate contributions:

ECMWF's core mission is to develop its global weather forecasting system, run it operationally and distribute the results to its Member States. However, through its core activity and its role in the Copernicus Programme, ECMWF is contributing significantly to climate change studies.

The first major contribution is linked to the role that ECMWF plays as the entrusted entity implementing two environmental information services within the EU Copernicus Earth Observation Programme: the Copernicus Climate Change Service (C3S) and the Copernicus Atmospheric Composition Service (CAMS). The implementation of both services relies on contributions from many European institutions, including national meteorological services, satellite agencies and private companies. The services also make use of ECMWF's modelling and data assimilation systems for generation of global datasets in support of environmental monitoring and prediction. The scientific background of C3S is rooted in key international initiatives such as GCOS and the World Climate Research Programme (WCRP) and relies on the outcomes of several EU collaborative research projects including ERA-CLIM2, QA4ECV, UERRA, CLIP-C, and EUCLEIA, with important contributions by the Met Office. C3S provides free and open data products about past, current and future climate worldwide, with a community of more than 150,000 users. Among the most popular datasets are the global and regional atmosphere, land, ocean and sea-ice re-analyses, operational seasonal forecasts, CMIP6 climate projections and Essential Climate Variables products. Alongside these products, ECMWF invested significantly in quality assurance, user support and training, as well as in the development of public-facing products such as climate bulletins and the State of the Climate report. Sector-specific applications demonstrate the added value for specific user communities, including indicators in support of the UN SDG Goals. Finally, C3S produces the European State of the Climate.

The reanalysis was initially a by-product of the assimilation system developed for global weather forecasting, and it was aimed at:

- Studying the evolution of the observing system and evaluating the impact on the quality of the forecast.
- Testing data assimilation techniques over a long period and developing calibrations.

The quality and ease of use of the global, gridded data sets generated by reanalysis has attracted a growing interest from the climate community, as evidenced by the growing use of reanalysis data in the annual BAMS Special Supplements on the State of the Climate, and the many references to the latest ECMWF reanalysis, ERA5, in the IPCC Sixth Assessment Report (AR6) published in 2021. Recent work on homogenization of observations and improved bias correction schemes for satellite instruments has increased the credibility of climate trends deduced from reanalyses. Further improvements in reanalyses are expected in the coming years, thanks to the continuous improvement of NWP models, assimilation techniques (in particular those associated with atmospheric chemistry, oceans and continental surfaces), and advancing computing power. ECMWF's current state-of-the-art reanalysis is ERA5, which provides gapless hourly snapshots of the entire atmosphere, land surface and ocean waves from 1950 onwards at a horizontal resolution of 31 km and is continued close to present with a timeliness of 5 days. It is a very widely used dataset by a wide range of users (90,000 by October 2022) worldwide for a broad spectrum of applications. ERA5 uses a recent (2016) version of the ECMWF Integrated Forecast System. ECMWF is currently developing a new global atmospheric reanalysis, ERA6, at a horizontal resolution of at least 18 km, which will replace ERA5 when production is complete around 2026.

A second important contribution from ECMWF is in the modelling area, related to the concept of seamless systems unifying weather and climate predictions. These systems benefit from important synergies between numerical weather prediction (NWP) and climate prediction. The first synergy is that many of the key feedbacks which lead to uncertainty in climate predictions are associated with processes such as clouds, convection or boundary-layer turbulence, whose intrinsic timescales lie within the domain of NWP. Another one is that due to obvious time constraints (the need to deliver a forecast before the event), NWP has developed code optimisation and supercomputing tools that can also benefit climate prediction: this, in particular, is key to increasing the resolution of climate predictions. This contribution has been fully recognised by the international scientific community. This is not a one-way road and NWP is also benefiting from developments in climate prediction, in addressing model errors, in particular.

Thirdly, ECMWF's core activities contribute to the adaptation of our societies to climate change. The ECMWF strategy puts the early warning of severe weather at the heart of its principal goals. As severe weather events are likely to increase in frequency or magnitude with climate change, early warnings will become even more crucial for mitigating the consequences of these events.

Reanalysis work:

The below sections highlight where the ECMWF is involved in reanalysis of data.

Over the past decades, reanalyses of multi-decadal series of past observations have become an important and widely utilized resource for the study of atmospheric and oceanic processes and predictability. The first reanalysis at ECMWF was carried out in early 1980s for the First GARP Global Experiment (FGGE) year 1979, when ECMWF operations began. Four major ECMWF reanalyses have exploited the substantial advances made since then in the forecasting system, usage of observations (data assimilation), and technical infrastructure. The first project, ERA-15 (1979-1993), was completed in 1995 and the second extended reanalysis project, ERA-40 (1957-2002), in 2002. ERA-Interim was the next atmospheric reanalysis, covering the data-rich period from 1979 to 2019.

ERA5 is ECMWF's most recent atmospheric reanalysis, covering the period from 1950 (subsequently extended to 1940) to present, with daily updates with a latency of 5 days to support climate monitoring. The ERA5 reanalysis provides hourly global snapshots of the 3-dimensional atmosphere, land surface and ocean waves at a horizontal resolution of 31 km from the surface up to 80 km altitude. The system is based on a 2016 release of the IFS (Cy41r2). ERA5 data are freely available on the internet (Copernicus Climate and Atmosphere Data Store, CADS) and serves users ranging from research, (local/national/inter) governmental, policy making and commercial applications. ECMWF is preparing to replace ERA5 with a new atmospheric reanalysis at a global resolution of 18 km, based on a state-of-the-art version of the IFS.

ECMWF reanalysis has been used extensively by its Member States and the wider user community. They are also increasingly important to many core activities at ECMWF, particularly for validating long-term model simulations, for helping develop a seasonal forecasting capability and for establishing the climate of ENS (Ensemble Prediction System) forecasts needed for construction of forecaster-aids such as the Extreme Forecast Index.

2.6 Capacity building

The following section details capacity-building in least developed countries, Small Island Developing States, and countries with economies in transition, related to the collection, exchange and use of observations.

The UK supports some overseas observation sites directly through the UK/Met Office contribution to the World Meteorological Organisation (WMO) Voluntary Cooperation Programme (VCP). For over 40 years, the UK has supported significant GUAN (Global Climate Observing System – GCOS - Upper Air Network) stations at St Helena, Seychelles and in the South Pacific (the latter in partnership with the Secretariat of the Pacific Regional Environment Programme (SPREP) and New Zealand’s MetService) at Funafuti in Tuvalu, and Tarawa in Kiribati. These observations provide important data both for weather prediction and climate monitoring. Additional support is also provided to other GUAN stations where funds allow.

2.6.1 BT Tower Atmospheric Observatory (BTTAO)

The National Centre for Atmospheric Science (NCAS), in conjunction with the Centre for Ecology and Hydrology (UKCEH) and the University of Reading (UoR) operate an observatory at the top of the BT Tower (~190m) in central London. NCAS deliver measurements of AQ gas species (NO_x and O₃), UoR meteorological parameters and UKCEH fluxes of greenhouses gases. Between 2013 and 2016, measurement activities at the BT tower were supported by the NERC-funded GAUGE project (Greenhouse gAs Uk and Global Emissions) and more recently by National Capability funding.

2.6.2 Chilbolton Atmospheric Observatory (CAO)

The National Centre for Atmospheric Science (NCAS), in conjunction with UKRI Science and Technology Facilities Council (UKRI STFC), has operated an atmospheric observatory at the STFC Chilbolton Laboratory since 2013. Prior to this, the observatory was operated by STFC alone. CAO operates more than twenty major instruments including a powerful combination of dual-polarisation Doppler radars, lidars, radiometers, and supporting instruments; the continuous round-the-clock operation of lidar and cloud radar instruments at Chilbolton is unique within the UK. These are supplemented by a suite of meteorological instrumentation including rain gauges, and disdrometers. A multi-wavelength sun photometer provides continuous measurements of aerosol optical depth in clear skies, and contributes to the Aerosol Robotic Network (AERONET). The Chilbolton Advanced Meteorological Radar (CAMRa) is mounted on a 25-metre, fully steerable antenna, and is able to probe clouds and storms with unparalleled sensitivity and resolution. In addition, zenith-pointing polarimetric, Doppler 35 GHz and 94 GHz cloud radars are routinely operated for detailed microphysical studies of cloud processes and cloud climatology. The presence (since January 2016) of a Defra air quality monitoring supersite at the CAO site (providing rural background measurements as part of national and transboundary networks) offers the research community further excellent opportunities for intercomparison campaigns and instrument evaluation. In addition to AERONET, data from this site is also delivered through EUMETNET E-PROFILE, AERONET and ACRIS; by default all data is archived at CEDA.

2.6.3 Capel Dewi Atmospheric Observatory (CDAO)

The National Centre for Atmospheric Science (NCAS), in conjunction with UKRI Science and Technology Facilities Council (UKRI STFC) has operated an atmospheric observatory

at Capel Dewi near Aberystwyth since 2013; prior to this the observatory was operated by STFC alone. CDAO is the home of UK's research Mesosphere-Stratosphere-Troposphere (MST) radar, a range remote sensing capability including radar wind profilers and lidar ceilometers and supporting surface meteorological measurements. Data from the MST radar in addition to being archived on CEDA is also delivered to EUMETNET E-PROFILE.

2.6.4 Cape Verde Atmospheric Observatory (CVAO)

The National Centre for Atmospheric Science (NCAS), in conjunction with the Max-Planck-Institut für Biogeochemie, Jena, Germany (MPIB Jena), and the Leibniz-Institut für Troposphärenforschung, Leipzig, Germany (IfT), has operated a major WMO GAW station on Sao Vicente, Cape Verde since 2006. The observatory is currently supported financially by the UK and Germany and operated by the local National Meteorological and Hydrological Service, the Instituto Nacional de Meteorologia e Geofísica (INMG). The observatory contributes to a number of GAW networks and has been a key means to build people capacity associated with atmospheric composition research in the West African region.

2.6.5 Weybourne Atmospheric Observatory (WAO)

The National Centre for Atmospheric Science (NCAS), in conjunction with the University of East Anglia (UEA) has operated a major WMO GAW station and Integrated Carbon Observation System (ICOS) station at Weybourne, Norfolk since 2002; between 1992 and 2002 the site was operated by UEA alone. As well as being part of the ICOS and GAW networks and the DEFRA ozone network (AURN), Weybourne has been and remains part of the DEFRA TOMPS network (atmospheric toxic organic samplers), a DEFRA CH₄ network, the EU InGOS network (Integrated non-CO₂ Greenhouse gas Observing System), and is now contributing measurements to the NERC funded MOYA and DARE-UK projects.

2.7 Acquisition and synthesis of palaeoclimate data

The sections below provide an overview of UK activities in setting current climatic changes within a historical context using palaeoclimate data.

Palaeoclimate data relating to a range of climate variables are being acquired and synthesised by a number of groups in the UK. The UK has several world-leading laboratories for palaeoclimate research, with specialities including novel proxies for past climate conditions, palaeoclimate modelling, model-data integration, and creation of high-resolution records. In addition, much of this research into the climate of the past is only possibly due to the UK's leading role in ocean and continental drilling programmes^{18, 19}

- University of Southampton (School of Ocean and Earth Science) & National Oceanography Centre. Current research topics within the Palaeoceanography and Palaeoclimate and Geochemistry Research Groups include:
 - Climate sensitivity in the past
 - Past ocean circulation, temperature, salinity, climate and continental ice volume (sea level).

¹⁸ <https://www.bgs.ac.uk/geology-projects/seafloor-scientific-ocean-drilling/>

¹⁹ <https://www2.bgs.ac.uk/icdp/about.html>

- The history of biogeochemical cycling and global biodiversity.
- Palaeobiology and hydroclimate.
- High frequency climate change on seasonal through centennial time scales, including statistical analysis of past climate variability and sensitivity to inform future projections.
- Past changes in regional and global carbon cycling, including ocean acidity and atmospheric CO₂ levels.
- Long-term impacts of climate dynamics on past human societies (PLUS – School of Geography)
- University of Aberdeen: The School of Geosciences has a number of groups working on palaeoclimate proxies across a range of timescales, including:
 - the influence of past climate fluctuations on the behaviour of ice sheets and glaciers
 - using palaeoglaciers and palaeoecology to reconstruct, variously, past climate changes, atmospheric circulation, burning intensity, and carbon sequestration
 - evolution of terrestrial plant ecosystems and their response to periods of rapid climate change across the Cenozoic
 - exploring the effects of early land plants as drivers of palaeoenvironmental and palaeoclimatic change
 - assessing seawater chemical changes during previous periods of ocean anoxia, mass extinction and climatic change
 - reconstructing human palaeoenvironments and climate (temperatures) from European Pleistocene archaeological sites
- British Antarctic Survey (NERC), Cambridge:
 - Research to understand the behaviour of the ice-atmosphere-ocean system in Antarctica in the past, and to use this knowledge to predict future behaviour. Work is also carried out in Greenland and Svalbard.
- Bangor University:
 - Multi-proxy research on ocean-ice-climate interaction in the North East Atlantic to investigate ocean circulation, climate and ice sheet behaviour during the last 60,000 years.
- University of Cambridge:
 - Department of Earth Sciences – current research includes:
 - Understanding astronomical forcing of climate change records as recorded in oceanic sediments.
 - Multi-proxy studies of abrupt climate change in the oceans, and its impacts recorded in ice.
 - Sedimentological and geochemical tracers of past deep-sea circulation vigour and its role for changing atmospheric CO₂.
 - Use of foraminiferal metal chemistry and the stable isotopic composition of biogenic sediments in palaeochemical studies of ocean temperature and nutrient variations.
 - The stability of the Greenland and West Antarctic ice sheets, particularly during past warm periods.
 - ‘Cambridge Quaternary’ (comprised of staff and students from Archaeology, Earth Sciences, Geography, Plant Sciences and Zoology departments):
 - Research on glacial cycles over the past 2.6 million years, causing significant fluctuations in sea level, major geographical changes

and major plant and animal population migrations. Sedimentary sequences record these changes in great detail and are central to unravelling past events.

- Cardiff University:
 - The Palaeoclimate Group researches a wide variety of timescales, ranging from the causes and consequences of rapid climate change since the last ice age, to the reasons for the long-term global cooling since the age of the dinosaurs. These studies are coupled to contemporary observations of ice sheet systems that feed models on historic climate change and future earth system dynamics. Current research projects use palaeoclimate archives to investigate:
 - Ice sheet stability and rates of sea level change
 - Causes of abrupt climate change
 - Climate feedbacks including the carbon cycle
 - Greenhouse climate dynamics and impacts on life on Earth
 - Ocean acidification and impacts on marine biota
- Climatic Research Unit at the University of East Anglia, Norwich, Norfolk:
 - Quantitative climate reconstructions, climate change detection and historical documentary climatology.
- University of Edinburgh:
 - Quaternary palaeoenvironments; modelling of ancient ice sheets.
- University of Glasgow:
 - Quaternary science and polar environments.
- Liverpool John Moores University:
 - Quaternary palaeoenvironments.
- University of London, Royal Holloway and Bedford New College:
 - Quaternary research, palaeohydrology.
- Environmental Change Research Centre, University College London:
 - An interdisciplinary research centre concerned with reconstructing, monitoring and modelling environmental change, with particular emphasis on palaeolimnology, aquatic ecology and palaeoceanography. Timescales range from the past few million years to the past few hundred years and current research projects focus on Europe, China, northern and central Eurasia, the high Arctic, Amazonia, and Africa, as well as the oceans, especially the N. Atlantic.
- University of St Andrews:
 - Research on global change covers environments from forests and tropical coral reefs, to the polar ice caps and deep ocean, investigating change in climate and marine chemistry on timescales ranging from millions of years to months, and seeking to understand controls on environmental change in Earth's past, present and future. Particular foci include:
 - CO₂ reconstruction and estimates of climate sensitivity
 - Ocean CO₂ storage and release
 - Ocean circulation and rapid climate change
 - Common era temperature and hydroclimate reconstruction from tree rings
 - Impact of major volcanic eruptions on climate
- Swansea University:

- Quantifying uncertainty in isotope dendroclimatology to understand and characterise the natural variability between individual trees to maximise the potential of the tree-ring isotopic signal for palaeoclimate research.
- Durham University:
 - Research across Geography, Earth Sciences, Archaeology and Biosciences uses physical, geochemical and biological proxies to reconstruct climate change throughout geological time. Climate and ice sheet models are developed and applied. All temporal scales are represented, spanning ultra-high resolution records of tropical cyclone activity, volcanic eruptions, sea-level change, and ocean-ice sheet interactions over the last two thousand years, through the ice ages and warm intervals of the late Cenozoic, to records of the timing and extent of global glaciations more than one billion years in the past.
- University of Birmingham (School of Geography, Earth and Environmental Sciences):
 - Our research integrates sedimentologists, geographers, palaeontologists, geochemists and climate modellers to produce an integrated view of past, modern and future environmental change. Current research includes:
 - Palaeoclimate proxy data assimilation into climate models
 - Development of novel proxies for reconstructing past climates
 - Earth System and ecosystem function in warm, high CO₂ climate states
 - Climate-Ice Sheet Dynamics and Glacier-Climatic Interactions
 - Constraining climate feedbacks, sensitivity and associated uncertainties through time
- University of Exeter (Camborne School of Mines)
 - The Deep Time Global Change group seeks to understand the geological history and governing processes behind some of the major environmental changes that have affected the Earth through deep time. Using samples from cores and outcrops, work spans from lithosphere to atmosphere, and an age range from the Precambrian to the Quaternary.
- University of Bristol:
 - Research at the Cabot Institute includes:
 - Determining the drivers of environmental and climate change in the distant past and linking it to the future
 - Heavy focus on climate modelling
 - Understanding past changes in ice sheet extent in response to past climate
 - Proxies for palaeoclimate reconstruction
- University of Oxford; Department of Earth Sciences in oceanography, climate and Palaeoenvironment research group:
 - Assessment of how the climate system operates in the past using cave and marine deposits
 - Investigations into past sea level variation and ice volume change
 - Using the geological records from the Mesozoic to understand how the climate system operates when warmer than today
 - Ocean anoxia in the Mesozoic.
- University of Plymouth (Centre for Research in the Earth Sciences):

- Understanding the response of the climate system to large perturbations of the Earth system
- Ocean anoxia in the Mesozoic, mass extinctions and climate change
- Developing proxies for palaeoclimate reconstruction
- Evaluating key controlling mechanisms and quantifying rates of landscape change
- University of Nottingham (School of Geography, Geosciences Research Theme):
 - Reconstructing the past environment on a variety of scales
 - Human impacts and their intersection with climate change
 - Calibration of novel proxies.
- Northumbria University (Geography and Environmental Sciences):
 - Reconstructing climate and environmental change, palaeoseismicity and sea level at decadal, millennial and million-year timescales using a variety of biological, geochemical and geological proxies
 - Modelling climate and the palaeoenvironment (ice sheet-ocean interactions, sea-level change, abrupt climate change)
- Imperial College London (Earth Sciences and Engineering, within the MAGIC research group):
 - Long-term ocean circulation patterns and climate change
 - Monsoon dynamics in Central Asia during the Holocene
 - Stability and dynamics of the Antarctic Ice Sheet
 - Global atmospheric dust cycle - Geochemistry and Modelling
- The Open University (Environment, Earth and Ecosystem Sciences, Palaeoenvironmental Change research group):
 - Rapid global warming events
 - Sea-level change, stratigraphy and sedimentology
 - Palaeoceanography and oceanography (organic and inorganic geochemistry)
 - Palaeobiology and ecosystem dynamics
 - Monsoon dynamics
 - Climate sensitivity
- University of Leeds (School of Earth and Environment; Institute for Climate and Atmospheric Science and the Earth Surface Science Institute):
 - The use of climate models to investigate the evolution of Earth's climate systems over the full range of Earth History
 - The use of proxy data and box models to investigate the evolution of Earth's early atmosphere
 - The use of proxy data to reconstruct past carbon cycle dynamics, palaeoceanography, palaeoenvironments and the co-evolution of life and the planet
 - The use of proxy data and modelling approaches to investigate sea-level rise and ice-sheet dynamics

2.8 Guideline issues

Steps being taken to improve the availability of information:

As detailed in section 2.3.1, the UKEOF set up a coordinating Climate Observations Group which ran from 2012-2014. The aim of the group was to oversee coordination of UK climate observing activities, advise on UK user priorities, and encourage

implementation of common observing standards and methods. The group produced a report and a guidance note in 2013. Activities were then taken on by the UKEOF Management Group and Secretariat. The UKEOF holds a catalogue of UK monitoring and observation activities which was updated in 2016 so records can now be searched in terms of climate-related measurements.

3. Atmospheric Essential Climate Variables (ECVs)

The below sections describe the UK's national contributions of atmospheric ECV observations to the international community, with a focus on the requirements outlined in the GCOS implementation plan.

3.1. Contributions to the GCOS Surface Networks

Met Office Land Networks:

The Met Office climate network includes seven centennial observing stations as part of the WMO long-term observing stations initiative.

The UK's contribution to the GSN comes from the national network (for the UK itself) of 20 stations within the UK's Regional Basic Climate Network (RBCN) and the 34 stations within the UK's Reference Climate Network. The 6 UK GSN stations run by the Met Office are Lerwick (3005), Stornoway (3026), Eskdalemuir (3167), Valley (3302), Waddington (3377) and Camborne (3808). The Met Office also assists in supporting a small number of overseas stations (see section 2.6 for details).

The UK contributes to the Baseline Surface Radiation Network (BSRN) with two stations, at Lerwick and Camborne, which are in the process of being refreshed. These stations are supported by the PWS and both stations provide data to the World Radiation Monitoring Center (WRMC). There are 85 UK stations measuring downwelling global radiation, in addition to the two BSRN stations. The 85 stations are partly compliant with the GCMPs.

British Antarctic Survey:

The British Antarctic Survey (BAS) runs 4 Overseas GCOS Surface Network stations: Halley (89022), Rothera (89062), Fossil Bluff (89065) and Grytviken, South Georgia (88903). All four stations operate to GCOS standards and historic data have been supplied to the IDCs, for their operational periods where the data have been digitized.

Met Office Marine Networks:

All of the Met Office's marine observations from ships, drifting and moored buoys (and Argo floats as described earlier) contribute to the Global Ocean Observation System (GOOS), which in turn provides the ocean component of GCOS.

The Met Office contributes to the EUMETNET Surface Marine programme (ESURFMAR, managed by Meteo-France and KNMI), which deploys around 120 drifting buoys per year in the North Atlantic, Nordic Seas and Mediterranean. As of 1st April 2022, 168 drifters were operating under the E-SURFMAR Programme. This includes 96 E-SURFMAR funded Iridium SVP-Bs (including 8 ICE buoys deployed in the Arctic) and 72 purchased through the Global Drifter Programme's barometer upgrade scheme.

In addition to deploying drifting buoys for E-SURFMAR, the Met Office also funds GDP barometer upgrades and deploys these drifters in the South Atlantic/Southern Ocean in

support of the global drifter array. Typically this is around thirty drifters each year, with 61 drifters active at end October 2022.

The Met Office currently manages around 175 Voluntary Observing Ships (VOS), making manual observations. A further 50 ships host the Met Office AMOS (Autonomous Marine Observing System). These predominantly operate around the UK, however around 20% sail internationally in the polar regions, Far East and South Atlantic. AMOS are additionally installed at six land stations in the Falklands and one Met Office-Plymouth Marine Laboratory jointly operated moored buoy in the English Channel.

The Met Office is currently running a project to replace all original AMOS systems with a second generation known as AMOS2X. This is planned to be rolled out across all Met Office automated marine platforms by April 2023.

All VOS data are exchanged on the Global Telecommunication System (GTS) and available to the International Comprehensive Ocean-Atmosphere Data Set (ICOADS)²⁰. This includes contributions from BAS, NERC and other research programmes.

²⁰ <http://icoads.noaa.gov/>

Table 1a: National contributions to the surface-based atmospheric ECVs

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
GCOS Surface Network (GSN)	Air temperature	6 (Met Office) 4 (BAS)	10	10	10
	Precipitation	11	11	11	11
Full World Weather Watch/Global Observing System (WWW / GOS) surface network	Air temperature, air pressure, wind speed and direction, water vapour	20	20	20	20
	Precipitation	20	20	20	20
Baseline Surface Radiation Network (BSRN)	Surface radiation	2	2	2	2
Solar radiation and radiation balance data Ocean drifting buoys	Surface radiation	62	partly	Some	Some
	Sea surface temperature, air pressure (and position-derived surface current)	59 (Met Office)	N/A	59	59
Moored buoys	Air temperature, air pressure	None for GCOS	0	0	0
Voluntary Observing Ship Climate Project (VOSCLim)	Air temperature, air pressure, wind speed and direction, water vapour	175 (+ 50 AMOS)	175	225	225
Ocean Reference Mooring Network and sites on small isolated islands	Air temperature, wind speed and direction, air pressure	0	0	0	0
	Precipitation	0	0	0	0

Information about other sustained measurements of the surface-based atmospheric ECVs, supplementary to those activities implicit in table 1a is below.

Met Office Climate and Rainfall networks:

The entire UK land surface observing network currently comprises 280 ordinary, principle and reference climate stations (many of which have very long records) and 149 synoptic stations. There are an additional 2,482 rainfall-only stations. These stations are all compliant with GCOS standards, but are more subject to site changes or closures than those in the GSN, RBCN and the UK's Reference Climate Network. Historic time series

from a small number of the UK surface climate and rainfall stations are available in IDCs, but there has been no comprehensive activity to add all that are digitally available.

Met Office coastal moored buoy network:

The Met Office presently operates 10 moored buoys, mainly to the west of the UK and in Biscay, which contribute to the wider WWW / GOS surface network. These networks deliver data on many ECVs and there are time-series in excess of 20 years. The data are being used in marine climate studies (e.g., the Defra Charting Progress reports on the state of UK seas) and are submitted to the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

Table 1b: NCAS long-term monitoring programmes based at its atmospheric observatories deliver the following parameters

Observatory	Parameter
BTTAO	Gas species concentration: NO _x and ozone (O ₃)
CAO	<p>Meteorological parameters: Wind speed and wind direction, Temperature, Relative Humidity, Pressure, rainfall accumulation, raindrop size distribution, Broadband radiation and atmospheric stability parameters</p> <p>Profiles: Temperature, Humidity, Wind speed and direction, aerosol backscatter coefficient, aerosol optical depth, brightness temperature</p>
CDAO	<p>Meteorological parameters: Wind speed and wind direction, Temperature, Relative Humidity, Pressure, Precipitation, Downwelling short-wave radiation, tropopause altitude, cloud base altitudes, aerosol optical depth, Sky conditions and Polar Mesosphere Summer Echoes (PMSEs)</p> <p>Profiles: three-dimensional wind vector, turbulence intensity, aerosol backscatter coefficient, radar signal-to-noise ratio, temperature, ozone (O₃) and water vapour</p>
CVAO	<p>Gas species concentration: ozone (O₃), carbon monoxide (CO), methane (CH₄), carbon dioxide (CO₂), hydrocarbons (C₂-C₈), oxygenated hydrocarbons (C₁-C₃), nitric oxide (NO), nitrogen dioxide (NO₂), halocarbons, mercury (Hg) and sulphur dioxide (SO₂)</p> <p>Meteorological parameters: Wind speed and wind direction, Temperature, Relative Humidity, Pressure, Precipitation, Solar actinic flux and Solar radiation</p>
WAO	Gas species concentration: methane (CH ₄), carbon monoxide (CO), carbon dioxide (CO ₂), hydrogen (H ₂), nitrous oxide (N ₂ O), oxygen (O ₂), sulphur hexafluoride (SF ₆), CO ₂ isotopes (13C and 18O), CH ₄

isotopes (^{13}C), nitric oxide (NO), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), low level radon, volatile organic compounds (VOCs) and oxygenated volatile organic compounds (OVOCs).

Particulate matter concentration: PM1, PM2.5, PM4, PM10, and Total Suspended Particles.

Meteorological parameters: Wind speed and wind direction, Temperature, Relative Humidity, Pressure, Irradiance, Number of cloud layers and Cloud layer base height

Profiles: aerosol backscatter coefficient and Wind speed and direction (400m)

3.2 Contributions to the GCOS Upper-Air Networks

Met Office:

The Met Office Radiosonde Network is part of the Full WWW/GOS Upper Air Network and GCOS Upper-Air Network (GUAN) and provides measurements of air temperature, water vapour and wind speed and direction. The data is widely used for climate measurement and model verification. The two sites in the UK are Lerwick (03005) and Camborne (03808). In addition, the Met Office also assists with a small number of overseas stations (see section 2.6 for details).

The Shipborne radiosonde network is part of the Full WWW/GOS Upper Air Network and also monitors upper air wind speed and direction, air temperature and water vapour. The Met Office is the co-ordinating member of the EUMETNET E-ASAP programme until 2023, which manages the ship-bourne radiosonde network on behalf of members.

The Global Positioning System (GPS) Water Vapour Programme provides vertical integrated water vapour data as part of the Ground-based GPS receiver network. Data from roughly 350 stations are processed by the UK (though this varies). Most sites are run by external bodies, so data and most site choice is third party. A project to establish around 45 Met Office-owned receiving stations in the UK is planned to be rolled out over a number of years from 2022. Most sites are chosen to be of a roughly equal spatial distribution, and some are chosen to be specifically near to radiosonde stations. The Met Office also processes GPS water vapour data on behalf of a number of other National Meteorological Services and provides the data processing services on behalf of EUMETNET under the E-GVAP programme.

The Met Office operates one wind profiler at South Uist, providing observations of the vertical and horizontal velocity upper air wind speed and direction (doppler winds) and is part of the EUMETNET wind profiler network (E-PROFILE).

The Met Office manages 2,500+ AMDAR (Aircraft Meteorological Data Relay) reporting aircraft within the EUMETNET-Aircraft-Based Observations (E-ABO) Programme that generates 60,000+ high quality upper air observations of temperature, wind speed and wind direction from commercial aircraft on a daily basis. A small number (9) of aircraft in Europe also report humidity observations from water vapour sensors installed as part of an E-ABO humidity development project. E-ABO also oversees the collection of Mode-S EHS derived data across Europe, which currently produces 25+ million daily wind and

temperature observations. E-ABO is a major contributor to the World Weather Watch (WWW) of WMO, forming a regional component of the WMO ABO global Programme.

British Antarctic Survey:

The British Antarctic Survey acquires measures of air temperature, air pressure, wind speed and direction, and water vapour at Rothera and Halley (89022) stations. The upper air programme at the Halley station is fully GCOS compliant and forms part of the GUAN network. Since 2017, Halley has been closed to manned operations for most of the year due to safety concerns caused by a large crack that formed in the ice shelf that it was located on, and has since been moved. When it is unmanned it is not possible to carry out radiosonde ascents. Since 2018, Halley has carried out limited radiosonde operations in the Antarctic summer. Rothera's upper air programme is GCOS compliant in all respects except that it has flights on only 5 out of 7 days a week; it is not a GUAN station but still submits its data via GTS.

Table 1c: National contributions to the upper-air atmospheric ECVs

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
GCOS Upper Air Network (GUAN)	Upper air temperature, upper air wind speed and direction, upper air water vapour.	3 (Met Office) + 1 (BAS)	4	4	4
Full WWW / GOS Upper Air Network	Upper air temperature, upper air wind speed and direction, upper air water vapour.	2 (Met Office) + 1 (BAS)	4	4	4

Information about other sustained measurements of the upper air ECVs, supplementary to those activities implicit in table 1b are below.

NCAS Long-term observatories:

BT Tower Atmospheric Observatory (BTTO)

The BT Tower is a 190-m-tall telecommunications tower situated in central London, UK. Mean building height is 8.8 ± 3.0 m within 1–10 km of the tower and 5.6 ± 1.8 m for suburban London beyond this. The area surrounding the tower is dominated by roads and commercial residential buildings, but also includes some urban parkland. The footprint of the tower (e.g., the area from which 90% of the air measured is calculated to originate from) is 5-20 km depending on weather conditions. NCAS is not the only organisation making measurements at the BT Tower site. UKCEH operate a range of instrumentation while University of Reading provide meteorological observations. NCAS make measurements of NO_x and O₃ concentrations. The NO_x concentration measurements are made at high time resolution (5Hz) which, combined with the 3-D ultrasonic anemometer (R3-50, Gill Instruments) operated at the tower by UKCEH, allows

eddy covariance calculations of NO_x flux to be carried out. BTTAO is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme.

Chilbolton Atmospheric Observatory (CAO)

CAO is located at the STFC Chilbolton Laboratory in southern England. The site is multifunctional, serving both the atmospheric and space observation communities, and is operated through STFC. The atmospheric observational activities are lead and managed by NCAS and the main activity of the observatory is the remote sensing of clouds and aerosols using cloud radars and lidar. Co-located surface meteorological measurements including solar irradiance (relevant to the surface radiation budget) and photometric observations. Continuous monitoring of cloud profiles has allowed evaluation of biases/errors in model cloud parameterisations. Monitoring began in 1998 and is important for understanding the mechanisms by which aerosol in the atmosphere leads to the formation of different cloud types, which is important for predicting climate change. CAO has played a leading role in international collaborations on remote sensing of clouds such as CLOUDNET, and now ACTRIS. CAO is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme.

Capel Dewi Atmospheric Observatory (CDAO)

CDAO is located at Capel Dewi near Aberystwyth. The site is operated by STFC with the observational activities lead and managed by NCAS. The site is the home of the UK's only research Mesosphere-Stratosphere-Troposphere Radar, and the primary role of the observatory is to measure upper air wind speed and direction profiles with high vertical and temporal resolution. Continuous measurements started in 1997. Supporting measurements of cloud base and surface meteorological parameters are also made. CDAO is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme.

Cape Verde Atmospheric Observatory (CVAO)

CVAO situated on the Cape Verde Island of Murdeira and was established as a bilateral UK-German initiative to undertake long-term ground- and ocean-based observations in the tropical North Atlantic Ocean region. The primary role of the observatory is to measure gas species including O₃, CO, NO, NO₂, NO_y, VOCs, halocarbons, and mercury. Supporting meteorological measurements are also made. CVAO is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme. CVAO is an established GAW site.

Weybourne Atmospheric Observatory (WAO)

WAO is situated on the North Norfolk coast and is operated through a collaboration between NCAS and UEA. WAO's location means that it experiences air with a wide range of pollution levels. Predominant south-westerlies bring polluted air from the UK (including from London and the Midlands). At times, especially in anticyclonic conditions, Weybourne experiences polluted air from Europe. Weybourne can also receive clean background air in northerly airflow. This can be impacted by narrow pollution plumes from shipping in the N. Sea, and potentially gas platforms. The collaborative operation has been in place since 2002 and WAO is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme. Between 1992 and 2002 the site was operated by UEA alone. The primary role of the observatory is the measurement of greenhouse gas concentrations (CO₂, CH₄, N₂O, SF₆, and CO) on a continuous basis.

Ozone, oxygen, hydrogen and basic meteorological parameters are also measured. WAO is an established GAW and ICOS site.

3.3 Contributions to the Global Atmospheric Watch

Cape Verde Atmospheric Observatory (CVAO)

Global Station: 0-20008-0-CVO

CVAO²¹ was established in 2006 and is part of a bilateral German-UK initiative to undertake long-term ground and ocean-based observations. The Observatory measures greenhouse gases, stratospheric ozone depleting gases, short lived air pollutants, biogenic emissions, aerosols and particulates, atmospheric radiation, and precipitation, and is located in the tropical Eastern North Atlantic Ocean. It is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme.

Observations are supported by NCAS and the University of York. They are responsible for trace gas measurements at this site and the site operates as part of the WMO/GAW GCOS Global Baseline Profile Ozone Network. The gases measured are O₃, CO, NO, NO₂, NO_y, VOCs, halocarbons, and mercury. Data is archived at the World Data Centre for Greenhouse Gases (WDCGG), the World Data Centre for Reactive Gases (WDCRG) and CEDA. The Observatory has been audited by WMO GAW for ozone, carbon monoxide, greenhouse gases and VOCs, and was featured in the 2017 WMO/GAW Reactive Gases bulletin²².

Regional Station: 0-20008-0-WAO

WAO²³ was established in 1992 by Professor Stuart Penkett with funding from BP (Norway) plc and NERC. Subsequently, long term monitoring and campaigns have been supported through numerous projects funded by NERC, Department of the Environment (DoE, Defra) and the EU. NCAS has also supported the site since 2002 and it is one of NCAS's Atmospheric Observatories contributing to the NCAS long-term monitoring programme.

Observations are supported by NCAS and the University of East Anglia. They are responsible for trace gas measurements at this site and the site operates as a WMO/GAW Regional Regional Station. The gases measured are CH₄, CO, CO₂, H₂, SF₆, NO, NO₂, N₂O, O₂, O₃, VOCs, OVOCs, isotopes of CH₄, isotopes of CO₂, Ra and SO₂, and are supported by meteorological measurements compliant with ICOS standards.

Data is archived at the World Data Centre for Reactive Gases (WDCRG) and CEDA.

Long-Term Atmospheric Trace Gas Monitoring at Mace Head, Ireland:

Atmospheric composition monitoring began at Mace Head in 1987 with measurements of ozone, and a range of gases as part of GAGE (CH₄, N₂O and the CFCs), and now cover a wide range of parameters relevant to all of the atmospheric ECVs including measurements of ozone, CO, H₂, CO₂, CH₄ and other GHGs (including N₂O, SF₆, NF₃, HFCs, PFCs, halocarbons and a range of ozone depleting substances), and aerosol optical depth. Mace Head has the dual status of a WMO GAW global station and an EMEP

²¹ <https://amof.ac.uk/observatory/cape-verde-atmospheric-observatory-cvao/>

²² https://library.wmo.int/opac/doc_num.php?explnum_id=3554

²³ <https://amof.ac.uk/observatory/weybourne-atmospheric-observatory-wao/>

supersite. Mace Head is also part of AGAGE²⁴ and the “UK DECC (Deriving Emissions linked to Climate Change) Network²⁵”. The site operates as part of the GCOS-affiliated WMO/GAW Global Atmospheric N₂O, CO₂ and CH₄ Monitoring Networks (GHGs and their precursors), the WMO/GAW GCOS Global Baseline Profile Ozone Network and WMO/GAW Aerosol Network (AOD). Co-located surface meteorological measurements are taken as part of the GCOS Surface Network and Full WWW/GOS Surface Network. Mace Head also contributes to the NOAA collaborative sampling network, filling weekly flasks that are returned to NOAA/ESRL’s Global Monitoring Division.

Baseline Measurement of Stratospheric Ozone and UV:

Baseline Measurement of Stratospheric Ozone and UV is a Defra funded initiative that measures column ozone and takes place at two sites - Reading and Lerwick. The Lerwick site makes column ozone measurements with a Dobson Spectrophotometer, with measurements dating back to the 1950s. The Reading site uses a Brewer spectrophotometer with measurements dating back to the 1990s. At both sites, spectrally resolved UV measurements are also made and can be used both independently and in conjunction with the ozone measurements during both long term trend and event analysis. The sites are part of the WMO/GAW GCOS Global Baseline Total Ozone Network and WMO/GAW GCOS Global Baseline Profile Ozone Network. Ozone measurements are also made at Manchester by the University of Manchester.

Sun photometers:

Sun photometer measurements of the direct (collimated) solar radiation provide information to calculate the columnar aerosol optical depth (AOD). There are currently 20 sun photometer stations in the UK which are collecting data for the assessment of aerosol optical depth as part of the NASA AERONET project. These are listed below and they operate a CIMEL sun photometric system. Additionally there is a PREDE POM sun photometer which is operated by the Plymouth Marine Laboratory which is not part of the AERONET network.

- Bayfordbury (51N,0W)
- Camborne_MO (50N,5W)
- Capel Dewi (52N, 4W)
- Chilbolton (51N,1W)
- EastMalling_MO (51N,0E)
- Edinburgh (55N,3W)
- Glasgow_MO (55N,4W)
- Herstmonceux (51N, 0E)
- Highfield (51N 0E)
- Leicester (52N,1W)
- Lerwick_MO (60N, 1W)
- Loftus_MO (54N,0W)
- Manchester UoM (53N, 2W)
- NPL_Teddington (51.6N, 0W)
- Oxford (51N,1W)
- Portglenone_MO (54N,6W)

²⁴ <http://agage.mit.edu/>

²⁵ <http://www.bristol.ac.uk/chemistry/research/acrg/current/decc.html>

- Rame_Head (50N,4W)
- Rhyl_MO (53N,3W)
- Stornoway_MO (58N,6W)
- Watnall_MO (53N,1W)

Observations in cryospheric environments:

The British Antarctic Survey (BAS) began taking measurements of ozone at the Halley (since 1957) and Rothera stations through their Long-Term Monitoring and Survey (LTMS) programme. As stated above, Halley has been a summer only station since the Antarctic winter of 2017, with instruments operating remotely over winter. NOAA samples will be collected weekly when the station is operating during the Antarctic summer and we are automating the NOAA flask sampling to collect the samples during the winter. Halley is a GAW global station (see <https://community.wmo.int/activity-areas/gaw/research-infrastructure/gaw-stations/gaw-global-stations>).

Table 1d: National contributions to the atmospheric composition

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
World Meteorological Organisation / Global Atmosphere Watch (WMO / GAW) Global Atmospheric CO ₂ and CH ₄ Monitoring Network	Carbon Dioxide	2 (Mace Head, Halley)	2	2	2
	Methane	3 (Mace Head, Cape Verde, Halley)	3	3	3
	Other greenhouse gases	3 (Mace Head, Cape Verde, Halley)	3	3	3
WMO / GAW ozone sonde network	Ozone	4 (Mace Head, Cape Verde, Reading, Lerwick)	4	4	4
WMO / GAW column ozone network	Ozone	3 (Reading, Lerwick, Halley)	3	3	3
WMO / GAW aerosol network	Aerosol Optical Depth	3 (Mace Head, Chilbolton, Wytham Wood)	3	3	3
	Other Aerosol Properties	2 (Mace Head, Cape Verde)	2	2	2

Information about other sustained measurements of the atmospheric composition ECVs, supplementary to those activities implicit in table 1c are below.

UK DECC (Deriving Emissions linked to Climate Change) Network:

The UK DECC Network²⁶ is a network of tall tower measurement sites set up to complement the measurements that take place at Mace Head, Ireland. This is described in detail in section 2.11 of Chapter 2.

Defra funded networks monitoring air pollution: United Kingdom Eutrophying & Acidifying Network (UKEAP):

Two UK EMEP “supersites” in the UKEAP network monitor a comprehensive range of atmospheric composition parameters that are highly relevant to all of the GCOS atmospheric ECVs. The Auchencorth EMEP supersite facility in Scotland²⁷ is operated by UKCEH and supports atmospheric chemistry, climate and ecosystem measurements by Defra/EA, research organisations and SMEs. Within EMEP, the site aims to contribute as a Level II/III site. Auchencorth Moss has been contributing since 2006, and gained regional status in WMO-GAW in 2014. It became an ICOS site in 2017. Measurements of particulate mercury at Auchencorth are provided to the GAW GMOS project. A wide range of measurements relevant to all of the atmospheric composition ECVs are monitored: ozone, aerosol properties (including particulates, trace gas fluxes, emerging chemicals of concern (ECOCs)), precursors (supporting the ozone and aerosols ECVs), CO₂ and CH₄ and other long-lived GHGs. In addition, there are co-located meteorological measurements including radiation measurements, surface wetness, soil surface and below surface temperature, and water vapour fluxes. The dataset is archived on the NERC/STFC CEDA catalogue²⁸. There are significant amounts of co-located data from the past decade for Auchencorth Moss relevant to terrestrial ECVs. This includes soil, vegetation, PAR and land use (from UK and EU projects). There are also water measurements made at the stream that flows out of the site including flow, composition and GHG gas exchange information (held internally at UKCEH). The site has facility for short term intensive atmospheric measurements and for testing of prototype technologies.

3.4 Satellite atmospheric ECVs

The UK supports a number of ECVs based on Fundamental Climate Data Records (FCDRs) or their nearest equivalent dataset.

Table 2: UK contributions to satellite atmospheric ECVs

Atmosphere ECV	Types of dataset	Based on Fundamental CDR	Co-operating programmes
Temperature and humidity profiles	Global, ungridded (L2) and gridded (L3), day and night	Thermal infra-red and microwave sounders: MetOp (IASI, MHS and AMSU), S-NPP and NOAA-20 (CrIS/ATMS) (CNES/Eumetsat)	UKRI-NERC/NCEO, ESA CCI, Eumetsat
Cloud, aerosol and radiative fluxes	Global, ungridded (L2) and gridded (L3), day (aerosol, SW fluxes), day	Vis/IR imagers: ERS-2 (ATSR-2); Envisat (AATSR); Sentinel-3 (SLSTR);	UKRI-NERC/NCEO, ESA CCI, C3S

²⁶ <https://www.metoffice.gov.uk/research/monitoring/atmospheric-trends>

²⁷ <http://www.auchencorth.ceh.ac.uk/>

²⁸ <http://catalogue.ceda.ac.uk/uuid/8e6cbb111cfd41a19c92aadcb2d040fd>

	and night (cloud)	Terra/Aqua (MODIS, cloud only)	
Radiative fluxes at TOA	Approx 60S-60N, 60E-60W, native (~50 km) and HR (~10 km) outgoing longwave and reflected SW fluxes at 15 minute resolution. Ob4MIPs product (gridded 1 x 1 degree, hourly monthly mean) also available	Meteosat Second Generation (GERB)	UKRI-NERC/NCEO, ESA, Eumetsat
(Proxy) column methane	Global, gridded data	Shortwave infra-red spectrometer: GOSAT (JAXA)	ESA CCI
Height-resolved methane	Global, ungridded (L2), day and night	Thermal infra-red sounder: Metop (IASI)	UKRI-NERC/NCEO, Eumetsat
Height-resolved carbon monoxide	Global, ungridded (L2), day and night	Thermal infra-red sounder: Metop (IASI), S-NPP and NOAA-20 (CrIS)	UKRI-NERC/NCEO, Eumetsat
Height-resolved ozone	Global, ungridded (L2), day and night	uv and infra-red sounders: ERS-2 (GOME-2), Envisat (SCIA); Aura (OMI), MetOp (GOME-2, IASI); S-NPP and NOAA-20 (CrIS)	UKRI-NERC/NCEO, ESA-CCI, EU C3S.

4. Oceanic Essential Climate Variables (ECV)

The below sections describe the UK's national contributions of oceanic ECV observations to the international community, with a focus on the requirements outlined in the GCOS implementation plan. Collection of oceanographic (and marine) observations is widely distributed throughout the UK, with many government departments and laboratories, universities and commercial companies involved.

4.1 Measurements of surface oceanic ECVs

Met Office:

The Met Office routinely produce (and periodically enhance) many global ocean products (including SST, see section 2.5).

The Met Office marine meteorological observations from Voluntary Observing Ships provide measurements of sea surface temperature, sea ice and sea state (the latter two measurements being from manually observing VOS). Sub-surface observations are not made from any UK VOS.

The Drifting Buoys Programme provides sea surface temperature measurements to the Global Drifter Array, see section 3.1. Sea surface currents are derived from buoy positions.

Observations in cryospheric environments:

BAS, NERC, National Geographic and other polar sailing ships observe sea-ice type, thickness, concentration, rate of accretion, arrangement, extent and stage of development in an opportunistic manner through the VOS programme. Observations are disseminated via the WMO GTS/WWW system.

Global Sea Level Observing System:

The Global Sea Level Observing System (GLOSS) tide gauge network, which is coordinated by IOC with assistance from NOC, Liverpool, provides sea level and supporting measures of air pressure to the GLOSS Core Sea-Level Network. The UK contributes 3 tide gauges from the UK itself (Lerwick, Newlyn and Stornoway) plus Gibraltar and 8 sites in the South Atlantic, which are in different states of working or needing maintenance visits. PSMSL is providing assistance for data management for some stations situated in Africa and the Caribbean. The 3 UK stations are part of the UK Tide Gauge Network (see below).

UK National Tide Gauge Network:

The National Tidal and Sea Level Facility (NTSLF) is the UK centre of excellence for sea level measurement, computer modelling of tides and storm surges, and the statistical estimation of extreme sea levels. The core of NTSLF is based at the NOC in Liverpool and includes partners in top research universities, coastal engineering consultancies and the Met Office. The UK Environment Agency is now responsible for the operation of the 44 permanent tide gauge sites around the UK itself. However, the NTSLF is responsible for monitoring sea level in the British Overseas Territories, and at strategic sites in the south Atlantic as part of our contribution to international climate research. Sophisticated telemetry systems make the data available in real time for operational coastal flood warning.

Table 3a: National contributions to the oceanic ECVs - surface

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
Global surface drifting buoy array on 5x5 degree resolution	Sea surface temperature, sea level pressure, position-change based current	59 (Met Office)	N/A	59	59
GLOSS Core Sea-level Network	Sea level	3 UK + 1 (Gibraltar) + 8 South Atlantic (NERC/NOC)	12	12	12
Voluntary observing ships (VOS)	All feasible surface ECVs	175	175	225	225
Ship of Opportunity Programme	All feasible surface ECVs	0	0	0	0

4.2 Measurement of water column ECVs

UK Argo Programme:

The UK Argo Programme that contributes to the international Argo array of profiling floats measures temperature and salinity in the water column, as described in section 2.1.4. It is delivered by a partnership between NOC, Met Office and PML.

All UK Argo float data, irrespective of location, are processed by BODC and the data are submitted in real-time to the WMO GTS and to the Argo Global Data Assembly Centres (GDACs). All UK Argo float data are subjected to delayed-mode QC by BODC and submitted to the GDACs. As at March 2022, BODC had delivered 94,684 profiles from UK floats, of which 75,992 profiles have been submitted, representing 82% of eligible profiles.

Carbon inventory surveys:

For carbon inventory surveys, there are 2 current survey-based programmes which provide data to international data centres (CDIAC and SOCAT for CO₂ data, CLIVAR for hydrographic data):

- Atlantic Meridional Transect (AMT)²⁹ - biogeochemical surveys of N and S Atlantic. Current funding from NERC's LTSS National Capability to the Plymouth Marine Laboratory (PML) ends in 2024, with requests for future funding to be submitted during 2023.

²⁹ <http://www.amt-uk.org/default.aspx>

- GO-SHIP sections at 57°N, 24°N, 24°S, Drake Passage and Weddell Sea - coast to coast and surface to seafloor physical and biogeochemical surveys, delivered by the National Oceanography Centre (NOC) and British Antarctic Survey (BAS).

Table 3b: National contributions to the oceanic ECVs – water column

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
Global reference mooring network	All feasible surface and subsurface ECVs	1	1	1	1
Global tropical moored buoy network	All feasible surface and subsurface ECVs	0	0	0	0
Argo network	Temperature, salinity, current	148	N/A	All	Some
Carbon inventory GO-SHIP survey lines	Temperature, salinity, ocean tracers, biogeochemistry variables	5	5	5	5

4.3 Satellite surface ocean ECVs

The UK supports the following satellite ocean ECVs: sea surface temperature (led by U. Reading/NCEO), and ocean colour (led by PML/NCEO).

The sea surface temperature (SST) ECV has matured to v2.1 of the ESA CCI product, with v3.0 due imminently. The SST record is >40 years long (v3.0 will start from 1980), and progress continues towards achieving the demanding stability requirements needed. The record is used to characterise the thermal environment of endangered coral reefs and has been shown to be most useful in a variety of climate science applications.

The ocean colour CCI has just released its version 6 that covers the period 1997-2022. As always, focus is on climate-quality data and this has involved removing recent data from the NASA MODIS and NOAA VIIRS archive (from end 2019) and with the addition of Sentinel 3B OLCI (complementing S3A OLCI). OC CCI is used by many scientists including in a recent paper in *Nature* on the impact of Australian wildfires on chlorophyll-a in the Pacific (with PML/NCEO co-authorship)³⁰.

³⁰ Tang, W., et al. (2021) Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature*, **597**, 370-375. <https://doi.org/10.1038/s41586-021-03805-8>

Table 4: UK contributions to satellite surface ocean ECVs

Ocean ECV	Types of dataset	Based on Fundamental CDR	Co-operating programmes
Sea Surface temperatures	<p>Global daily gap-filled timeseries > 40 years, 5 km.</p> <p>Lower levels (L2, L3) including full resolution SSTs.</p>	<p>Thermal infra-red including: ATSRs (ESA/BEIS), SLSTRs (EC/ESA), Metop series (EUMETSAT)</p>	<p>UKRI-NERC/NCEO, ESA CCI, EUMETSAT OSI-SAF, Met Office</p>
Ocean colour	<p>Global daily sinusoidal and gridded, L3 (non gap filled), 25 years, 1 and 4 km resolution (gridded)</p>	<p>Ocean colour radiances: SeaWiFS, MODIS (NASA); VIIRS (NOAA); MERIS, Sentinel 3A and B OLCI (ESA)</p>	<p>UKRI-NERC/NCEO; ESA CCI, EU C3S, Eumetsat, Simons Foundation</p>

Information about other sustained measurements of the oceanic surface and sub-surface ECVs, supplementary to those activities implicit in tables 3a and 3b are below.

British Antarctic Survey:

Oceanographic/Biological Monitoring - Rothera Oceanographic and Biological Time Series (BAS LTMS) known as RaTS³¹, is a time series site sampled by Rothera Station personnel (since 1997) providing a comprehensive range of measurements of relevance to many of the oceanic surface and subsurface ECVs. This includes measurements relevant to the phytoplankton, salinity of the column, temperature of the column, sea ice and nutrients ECVs monitored in compliance with the GCMPs.

Oceanographic Monitoring - BAS also conducts quasi-annual autonomous underwater vehicle (ocean glider) deployments from Rothera, to extend the spatial scale of the monitoring across Marguerite Trough and the Antarctic Peninsula shelf, with measurements including ocean temperature, salinity, fluorescence and mixing. BAS holds other CTD datasets collected in consistent sampling areas over time, e.g., Drake Passage and Western Core Box, in addition to those collected at the Antarctic Peninsula.

The Western Core Box (WCB)⁴¹ is a consistent unique time series of mesoscale distribution and abundance of macrozooplankton and micronekton, and an understanding of the physical environment they are within at South Georgia, South Atlantic (1996 – current). The focus of the survey is an on/off shelf survey box (80 * 100 km) located on the northwestern shelf of South Georgia. These data are required to understand the long term variability of the marine ecosystem, in particular krill biomass, at South Georgia and the influences from climate variability, fishing pressure and predation. In addition to estimates of krill biomass, the WCB generates data and publications on pelagic community composition, ocean temperature, salinity, fluorescence and particulate organic matter. A mooring within the survey box also measures the amount of carbon flux as well as physical oceanographic variables, acoustic backscatter and whale-calls. The information provided in part fulfils UK obligations within the Commission for the Conservation of Antarctic Marine Living Resources.

SCOOBIES⁴² is a further site of sustained measurements operated by BAS in the northern Scotia Sea (site P3) to investigate the biological and biogeochemical influence of the largest persistent phytoplankton bloom in the Southern Ocean. Moored instruments collect data on deep carbon flux to the ocean interior as well as ocean temperature, salinity and fluorescence. Sensors to determine levels of ocean acidification have also been operational for some deployments and most recently, water collectors have been added to determine nutrient concentration. Whale-call listening devices have also been integrated. Furthermore, P3 has been the location of a number of focussed scientific cruises by BAS and also the COMICS⁴³ scientific programme.

³¹ <https://www.bas.ac.uk/project/rats/>

⁴¹ <https://www.bas.ac.uk/project/poets-wcb/>

⁴² <https://www.bas.ac.uk/project/scoobies/>

⁴³ <https://www.comics.ac.uk/>

BAS operate a mooring site at Rothera as part of the OceanSITES network which supplies data to the Global Reference Mooring Network as part of research programmes rather than via sustained observation budgets.

BAS will operate pCO₂ equipment on the RRS Sir David Attenborough following the long-term deployment of this equipment on the RRS James Clark Ross.

NOC – Southampton and Liverpool:

The RAPID-26N array is funded by NERC and run by NOC and became operational in April 2004. It comprises a monitoring array of deep ocean moorings and landers and contributes measurements of sub-surface temperature, salinity, oxygen, carbon, nutrients, currents and bottom pressure. It provides a globally important measure of the strength of the Atlantic Meridional Overturning Circulation, a key climate metric.

The OSNAP array is funded by NERC, and delivered by NOC and SAMS (with international partners) since 2014. It is an array with a similar design to the RAPID array, and also delivers measurements of sub-surface temperature, salinity, oxygen, carbon, nutrients and currents.

The Porcupine Abyssal Plain Sustained Observatory (PAP-SO) is a sustained, multidisciplinary observatory in the North Atlantic coordinated by the National Oceanography Centre and delivered in partnership with the Met Office. The site monitors atmospheric variables like wind speed and air pressure, and physical, biological and chemical properties of the ocean from the surface to the seafloor. The PAP mooring is part of the international OceanSITES network and a GCOS reference mooring site. There are time-series in excess of 25 years and the observing meets the GCMPs.

NOC operates 4 GO-SHIP reference sections that deliver highest quality measurements of temperature, salinity, oxygen, nutrients, carbon and pH, tracers and currents. The sections are located throughout the Atlantic Ocean (57N and Ellett Array, 24° N, 24° S and Drake Passage) and are occupied at 2-10 year intervals.

All NOC data are available through BODC and the relevant international data centres and hubs according to NERC data policies.

Plymouth Marine Laboratory:

The Atlantic Meridional Transect (AMT) provides an array of measurements of relevance to surface and sub-surface ECVs over 100° of latitude in the Atlantic Ocean. These include: ocean acidification, phytoplankton, ocean colour, partial pressure CO₂, carbon, nutrients, oxygen, greenhouse gases, temperature and salinity. AMT has provided over two decades (1995 – present); sustained observations of biogeochemical variables including named ECVs, an annual research cruise with opportunities to collaborate for the international community, access to the remote North and South Atlantic gyres, opportunities for technological development. Recent collaborations with European Space Agency have generated fiducial reference measurements to calibrate and validate Sentinel satellites including for estimation of ocean-atmosphere exchange of CO₂. The Western Channel Observatory is a NERC funded (LTSS – National Capability) oceanographic time-series and marine biodiversity reference site in the Western English Channel with an established atmospheric reference site at the Penlee Observatory. In situ measurements are undertaken weekly at the coastal station and fortnightly at the open shelf station, and comprise parameters relevant to the temperature and salinity ECVs (water column), ocean colour, phytoplankton, carbon, nutrient and oxygen ECVs. The WCO has some of the longest time-series in the world for zooplankton and

phytoplankton, and the hydrographic series dates from 1903. These long data series are complemented by hourly measurements made at moorings situated at both stations. PML also takes standard meteorological measurements at their site as part of the WCO.

Scottish Association for Marine Science (SAMS):

The Ellett line oceanographic section array in the Rockall Trough, delivered in partnership with NOC, provides a comprehensive range of measurements of relevance to many of the oceanic surface and subsurface ECVs. This includes measurements of nutrients, carbon, oxygen, salinity and temperature of the column and subsurface currents. A hydrographic section occupied every 2 years contributes to The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP). Measurement standards are maintained through long-established 'best practice' and follow protocols outlined by GO-SHIP. Data and metadata are reported and logged through the BODC. SAMS maintains a continuous occupation of the Ellett Array using full-depth moorings and using Seagliders. The gliders provide temperature and salinity profiles and depth-averaged currents.

Marine Scotland Science:

Scottish Government's Marine Scotland directorate (MS) coordinates environmental monitoring programmes covering coastal locations around Scotland and key hydrographic sections in the Northern North Sea and Faroe-Shetland Channel. Branded under the Scottish Coastal Observatory (SCOs), temperature, salinity, nutrients, chlorophyll, phytoplankton, zooplankton and ocean acidification are monitored around the Scottish coast and have been since 1997. SCOs sites provide data to fulfil the monitoring requirements of the Water Framework Directive and UK Marine Strategy, and contribute to assessments internationally (OSPAR's Quality Status Report 2023 and reporting under the International Council for the Exploration of the Seas), as well as generating the time series of data to describe variability in coastal waters and investigate the impacts of environmental change. MS also support ship-based hydrographic surveys in the Faroe-Shetland Channel and Northern North Sea, collecting temperature, salinity, nutrients, chlorophyll and oxygen measurements. An array of moorings has also been maintained in the Faroe-Shetland Channel since the early 1990s. Combining these current observations and satellite sea surface height measurements (altimetry) provide a gap-less time series of the transport of Atlantic Water. These are critical measurements of the warm-water-path of the North Atlantic Current as it enters the Nordic Sea. Changes in temperature and transport there would be strongly indicative of changing ocean circulation in response to climate change. MS surveys also provide information on many other biological components of the marine ecosystem, offering an opportunity to understand climate change impacts on commercially important fish and shellfish species, and those species and habitats of conservation interest. Measurement standards are maintained through long-established 'best practice'. Data and meta-data are reported and logged internally, as well as through the BODC and ICES data centres. MS monitoring programmes are funded through Scottish Government funding budgets, supplemented with European research programme funding.

Water Framework Directive Monitoring:

The Water Framework Directive monitoring network includes measurements in coastal areas, covering Transitional (estuaries) and Coastal waters. In England and Wales, monitoring takes place up to one nautical mile from the shore and in Scotland this is extended to 3 nautical miles. Measurements relevant to a wide range of ECVs are

monitored (hazardous substances, nutrients, dissolved oxygen, salinity, temperature, phytoplankton, benthic invertebrates, macroalgae, seagrass, saltmarsh and estuary fish).

Continuous Plankton Recorder:

The Continuous Plankton Recorder, based at the Marine Biological Association of the UK, operates the Continuous Plankton Recorder (CPR) survey. The CPR survey is the world's most geographically extensive and longest-running large-scale plankton biodiversity monitoring activity (beginning in 1931). The survey determines the abundance and distribution of microscopic plants (phytoplankton) and animals (zooplankton) in our oceans and shelf seas. Using ships from approximately 16 shipping companies, it obtains samples at monthly intervals on more than 25 routes across the oceans. The Survey has been collecting plankton with the resulting data (freely available) providing information on biogeography and ecology of the planktonic community. The results of the Survey are used by marine biologists, scientific institutes, governmental bodies and in environmental change studies across the world.

5. Terrestrial Essential Climate Variables (ECVs)

The below sections describe the UK's national contributions of terrestrial ECV observations to the international community, with a focus on the requirements outlined in the GCOS implementation plan.

Terrestrial observations are made or coordinated by the Natural Environment Research Council (NERC), the Environment Agency (EA), Natural Resources Wales (NRW), the Scottish Environment Protection Agency (SEPA), the Northern Ireland Environment Agency (NIEA), the Forestry Commission and others.

River discharge:

The UK reports river discharge measurements from seven UK gauging stations to the Global Terrestrial Network for River Discharge (GTN-R), which forms part of the Global Terrestrial Network - Hydrology (GTN-H). Data are collected by the Environment Agency (EA) in England, Scottish Environment Protection Agency (SEPA), Natural Resources Wales (NRW), Department for Infrastructure (Rivers) of Northern Ireland and the UK Centre for Ecology & Hydrology, and are provided on a UK wide basis by the National River Flow Archive via the Global Runoff Data Centre (GRDC). These sites are at: Ballathie on the River Tay (Scotland); Blairstone on the River Clyde (Scotland); Colwick on the River Trent (England); Kingston on the River Thames (England); Movinagher on the Lower River Bann (Northern Ireland); Norham on the River Tweed (Scotland), and at Redbrook on the River Wye (Wales). All seven sites operate in accordance with GCMPs. The majority of sites have a complete historical record with the GRDC. The sites represent major freshwater outflows from the UK and as such are impacted by abstractions, discharges and impoundment. Other UK sites for which data is held on the GRDC may be of higher utility for climate-monitoring assessments, for example, those in the UK's Benchmark Network (see section 2.5.8), and the NRFA is working with the GRDC regarding their inclusion in the Global Climate Sensitive Stations Dataset. Data will continue to be provided to the GTN-R for all seven sites as part of the larger UK contribution of over 200 sites to the Global Runoff Data Centre.

5.1 Satellite terrestrial ECVs

The UK supports the following satellite terrestrial ECVs:

Land surface temperature, which was first introduced as an ECV in the 2016 GCOS Implementation Plan, has matured to the first climate quality data record with a length of over 25 years. Progress continues to improve the accuracy and precision of these datasets and the first few are now starting to meet the strict stability requirements. These records are important for a variety of climate science applications, such as characterising heat waves, monitoring drought, and gap-filling the air temperature record.

The lakes ECV was extended in 2016 and now includes lake water extent, lake water level, colour, temperature, ice cover and ice thickness, with some variability in observation timespan between the thematic ECVs within the period 1992-present, and combining information from over 30 satellite instruments.

Aboveground Woody Biomass (AGB) maps have been developed for Africa (2007-2017), developed using NASA's Global Ecosystem Dynamics Investigation (GEDI), JAXA's L-band SAR ALOS-2 PALSAR-2 mosaics, and Landsat Percent Tree Cover (PTC). Further country-specific data products are being produced for Mozambique and Gabon.

NCEO has been very active in improving fire data, including data from SLSTR on Sentinel-3 (SLSTR). Also, geostationary data is available by collaboration from multiple geostationary systems, typically at spatial resolutions (1 to 4 km) plus reduced spatial resolution. The longest timeseries is from Meteosat (2004 to current).

Table 5: UK contributions to satellite atmospheric ECVs

Terrestrial ECV	Types of dataset	Based on Fundamental CDR	Co-operating programmes
Above-ground woody biomass	100 m resolution	Microwave synthetic aperture radar (L-band): ALOS-2 PALSAR-2 (JAXA) Multispectral: Landsat Optical lidar: GEDI (NASA)	UKRI-NERC/NCEO
Land surface temperature	Global daily (day and night) and monthly (day and night) 0.01deg timeseries >25 years Level-2 data also produced and available for all sensor archives	Thermal infra-red ATSRs (ESA/BEIS), SLSTR (EC/ESA), MODIS (NASA), AVHRR (NOAA), Metop AVHRR (EUMETSAT)	UKRI-NERC/NCEO, ESA CCI, EU Copernicus
Fire Disturbance	Global daily (day and night) Active Fire Detections and Fire Radiative Power. Sub-hourly, 1 to 4 km and reduced spatial resolution gridded versions.	Thermal infra-red: SLSTR (EC/ESA) Meteosat, GOES-E, GOES-W, Himawari	UKRI-NERC/NCEO, Eumetsat (LandSAF), EU Copernicus.
Lake temperature and	2000+ lakes distributed globally, provided at	Over 30 (ESA/US) instruments for	ESA CCI, EU Copernicus

biochemistry	1/120 degree grid with daily timestep. Within Copernicus, the dataset includes 4000+ lakes at 10-day timestep at full resolution (300m optical, 1km thermal)	altimetry, thermal and visible/nir optical to produce inter-consistent sub-ECVs	
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Figure: UK gauging stations for which data from the National River Flow Archive (NRFA) are provided to the Global Runoff Data Centre (GRDC). Stations shown in red also form part of the GTN-R. © NERC (UKCEH). Contains Ordnance Survey data © Crown Copyright and database right 2013.

River temperatures:

Scotland River Temperature Monitoring Network (SRTMN) was established in 2013 as collaboration between the Marine Scotland directorate of Scottish Government, local fisheries managers and the University of Birmingham. It consists of > 220 river temperature recorders and was carefully designed³² to provide reliable data to understand, predict and assess changing river temperatures. Data collected from the network are used to build statistical models which can be used to map where river

³² Jackson, F.L., et al. (2016) A novel approach for designing large-scale river temperature monitoring networks. *Hydrology Research*, **47**(3), 569-590. doi: <https://doi.org/10.2166/nh.2015.106>

temperatures are hottest, and where they will change most under climate change³³. Data are quality assured and freely available (see <https://scotland.shinyapps.io/sg-srtmn-data/>).

Snow cover:

Of the stations in the Met Office land surface network, 73 synoptic sites have automatic snow depth sensors. Some ordinary climate stations also periodically report snow depth.

³³ Jackson, F.L., et al. (2018) A spatio-temporal statistical model of maximum daily river temperatures to inform the management of Scotland's Atlantic salmon rivers under climate change. *Science of the Total Environment*, **612**, 1543-1558. <https://doi.org/10.1016/j.scitotenv.2017.09.010>

Table 6: National contributions to the terrestrial domain ECVs

Contributing networks specified in the GCOS implementation plan	ECVs	Number of stations or platforms currently operating	Number of stations or platforms operating in accordance with the GCMPs	Number of stations or platforms providing data to the international data centres	Number of stations or platforms with complete historical record available in international data centres
GCOS baseline river discharge network (GTN-R)	River discharge	7 (GCOS) 217 (GRDC)	7 217	7 217	7 217
GCOS Baseline Lake Level/Area/Temperature Network (GTN-L)	Lake level/area/temperature	0	0	0	0
WWW / GOS synoptic network	Snow cover	73	73	0	0
GCOS glacier monitoring network (GTN-G)	Glaciers mass balance and length, also ice sheet mass balance	0	0	0	0
GCOS permafrost monitoring network (GTN-P)	Permafrost Borehole temperatures and active layer thickness	0	0	0	0

Information about other sustained measurements of the terrestrial domain ECVs, supplementary to those activities implicit in table 5 are below.

Hydrometric monitoring:

Groundwater monitoring in the UK is mostly carried out by the regulatory agencies, the Environment Agency (EA), Natural Resources Wales (NRW), Scottish Environment Protection Agency (SEPA) and the Northern Ireland Environment Agency (NIEA). Groundwater levels are monitored at over 4,000 sites nationally, with the majority of wells concentrated in England and Wales. The National Groundwater Level Archive (NGLA) is maintained by the British Geological Survey (BGS), part of the Natural Environment Research Council (NERC) and operated in close collaboration with the National River Flow Archive. The NGLA brings together water level data from across the UK for a set of boreholes chosen to provide a representative national network, with boreholes in all major aquifers, which can be used to assess seasonal resource variations and long term trends. Particular attention is paid to long term data, with a number of records from the 1800s; the longest time series held dates from 1838.

Water quality monitoring is carried out in the UK by the Environment Agency (EA), Natural Resources Wales (NRW), Scottish Environment Protection Agency (SEPA), the Northern Ireland Environment Agency (NIEA) and other organisations in response to water management and regulatory activities. Particular focuses for water quality monitoring include the Water Framework Directive (WFD) Surveillance monitoring network and Upland Waters Monitoring Network. The WFD Surveillance monitoring network is a fixed monitoring network designed to measure long term environmental changes in rivers,

lakes, transitional waters (estuaries) and coastal waters, with data collection of relevance to a range of terrestrial ECVs. The requirements for WFD surveillance monitoring of groundwater is built into a wider strategic monitoring network.

Glacier monitoring:

The British Antarctic Survey (BAS) monitors and maintains networks of GPS stations and other instruments measuring the movement of key icestreams and glaciers. A network of land-based GPS stations is also maintained to assist in the determination of isostatic recovery of Antarctica. This work is a component of their long-term monitoring and survey programme (LTMS).

6. Additional information

The information below provides additional information on the UK's national climate programmes that contribute observations of the ECVs not reported elsewhere in these reports.

6.1 Contribution to satellite ECVs

The UK's main contribution to satellite based ECVs is through participation in international programmes of EUMETSAT, ESA and the EU. The UK's financial contributions to EUMETSAT, ESA and the EU may result in the UK building satellite missions or instruments but the UK does not currently have its own independent programme for building climate relevant instruments or missions. The UK contributes to the following European satellite programmes:

- EUMETSAT's polar orbiting METOP and METOP Second Generation (METOP-SG) series of satellites and the geostationary Meteosat series (MSG, MTG).
- The multi-agency JASON series of satellites.
- ESA/EU Copernicus Sentinel series of satellites which provide long term continuity of many measurements started under the ESA ERS-1, 2 and ENVISAT missions.
- ESA's Earth Observation Envelope Programme (EOEP).

EUMETSAT's polar orbiting and geostationary programmes, the JASON programme and the Copernicus Sentinels are all designed to provide long term continuity of measurements, a key requirement for climate ECVs. ESA's EOEP programme provides one-off scientific missions, which have potential to contribute to ECVs but long term continuity is not assured.

The UK has also provided instruments to international programmes. DECC (now BEIS; previously Defra and other predecessor departments) sponsored the Advanced Along Track Scanning Radiometer (AATSR) satellite instrument, which monitored sea surface temperature. It was launched in 2002 on ESA's ENVISAT satellite platform and continued to operate successfully until the end of the ENVISAT mission in 2012. The AATSR instrument extended the record of highly accurate sea surface temperature measurements obtained from its precursor instruments ATSR and ATSR-2, also funded and built in the UK, and launched in 1991 (ERS-1) and 1996 (ERS-2) respectively. Additional funding has supported the reprocessing of the ATSR-1 and ATSR-2 datasets into the format used by AATSR in order to create a consistent, long-term sea surface temperature archive. The availability of the long-term archive has led to a wealth of scientific exploitation of the ATSR data. This includes the development of several surface

temperature datasets, the latest of which is the ATSR Arctic Surface Temperature (AASST) dataset. In order to ensure that the ATSR geophysical data products are reliable, they must be validated by comparing them with *in situ* measurements. Measurements from the long-term *in situ* deployment of the Infrared sea surface temperature Autonomous Radiometer (ISAR), and also from the Scanning Infrared Sea surface Temperature Radiometer (SISTeR), have confirmed the consistency of the sea surface temperature data products. Following a break in the series with the failure of ENVISAT, similar future European capabilities have resumed with the launch of the Sea and Land Surface Temperature Radiometer (SLSTR) instrument on the Copernicus Sentinel 3A platform in 2016, to be followed by Sentinel 3B, C, and D in future years.

More recently, UK involvement in the Sentinel programme has included provision of the satellite platform for the Sentinel-5 Precursor mission, which was successfully launched in October 2017, contributions to the Jason series (Sentinel 6), and provision of many parts of the other missions

Through a bilateral Implementation Arrangement with CNES in France the UK is also contributing to:

- **SWOT:** the NASA led Surface Water and Ocean Topography (SWOT) mission. This mission, due to be launched in December 2022, will provide vital oceanographic data to help understand climate change. The UK has designed and built the Duplexer to this mission and will be involved in the calibration of the mission over the Bristol Channel.
- **IASI NG:** This mission will determine temperature and water vapour profiles in the atmosphere, record ocean surface and land temperatures, and monitor a vast range of chemical compounds and other key variables for climate research, including greenhouse gases, desert dust and cloud cover. The UK has supplied the detectors for the IASI-NG instruments flying aboard the MetOp-SG satellites, providing atmospheric temperature and composition information contributing to NWP and ECVs.
- **MicroCarb:** The UKSA is a mission partner with CNES on the MicroCarb mission. MicroCarb is a small satellite mission monitoring CO₂ sources and sinks over the whole Earth, and on a regional scale to inform climate change decision making. It is the first European mission dedicated to carbon. The UK Space Agency has agreed to fund and manage the Assembly, Integration and Test (AIT) of the satellite. The UK has also committed to providing key elements of the mission preparation activities, contributing UK scientists to the Mission Advisory group, calibration and validation activity, including UK contributions to the OGSE and development of the Payload Data Ground Segment and a pointing and calibration sub-system, as well as other platform and instrument sub-system development. MicroCarb is set to launch in 2024.

The UK also funded, designed and built the first Geostationary Earth Radiation Budget (GERB) instrument which measures solar reflected radiance and total reflected/emitted radiance. In all, a series of four GERB instruments on successive EUMETSAT geostationary satellites are planned, providing a 20 year time series from 2002 to at least 2022.

In addition to European satellite missions and instruments, the UK is involved in European programmes which develop ECVs, from satellite data, notably at present:

- The UK Met Office contributes to EUMETSAT’s Climate Monitoring Satellite Application Facility (CMSAF). The CM SAF generates and archives datasets for specific climate application areas, derived primarily from EUMETSAT satellite data and also from US meteorological missions.
- The UK contributes to the ESA Climate Change Initiative (CCI). It is the largest contributor to the second phase of CCI known as CCI+ and leads ECV production activities in sea-surface temperature and ocean colour. UK Met Office also leads the user group for the programme.

Table 7: UK participation in the ESA CCI programme

ECV	UK groups leading/participating
Aerosol	University of Oxford, Swansea University, Rutherford Appleton Laboratory
Biomass	University of Aberystwyth, NCEO: Universities of Sheffield, Edinburgh, Leicester
Cloud	NCEO: University of Oxford, Rutherford Appleton Laboratory
Fire	University of Leicester
GHG	University of Leicester (NCEO)
Glaciers	Universities of Leeds, University of Bristol
Ice sheets	Universities of Leeds
Land cover	Met Office, Hadley Centre
Land Surface Temperature	NCEO: University of Leicester, University of Reading
Ocean colour	Plymouth Marine Laboratory (lead), University of East Anglia, Telespazio-Vega
Ozone	University of Cambridge, Rutherford Appleton Laboratory
Sea ice	UCL, University of Cambridge, CGI (formerly Logica)
Sea level	CGI (formerly Logica)
Sea Salinity	Argans, National Oceanography Centre, Met Office.
Soil State	National Oceanography Centre, Plymouth Marine Laboratory, Satellite Oceanography Consultants
Sea surface temperature	University of Edinburgh, Reading (lead), University of Leicester, Met Office, Space Connexions
Water Vapour	NCEO: Rutherford Appleton Laboratory, University of Leicester, Telespazio Vega
User group	Met Office (lead)

ESA sponsors other relevant research, e.g., through its DUE (Data User Element) programme³⁴ and the STSE (Support to Science Element) programme³⁵ which develop global data sets (e.g., the DUE GLOB series of projects). Although not officially designated “ECVs” many of the activities are relevant to ECV production. A summary of current and

³⁴ <http://due.esrin.esa.int/>

³⁵ <http://due.esrin.esa.int/stse/>

recent projects relevant to ECV production with UK participants is summarised below^{36, 37}.

The ESA Climate Office is located in Harwell, UK, and from 2022 also now hosts the WMO CMIP International Project Office. Therefore the observations for climate and the models have much closer linkages.

³⁶ <http://due.esrin.esa.int/duedirectory2010.pdf> provides a complete list of all DUE projects

³⁷ http://due.esrin.esa.int/stse/files/document/STSE_report_121016.pdf provides a complete list of all STSE projects

Table 8: Other ESA sponsored projects relevant to ECV production with UK participation

ESA project	Description	UK participation
GlobAerosol	Development of a satellite data processing system to generate a standard reference multi-year global aerosol product (GAP) over land and water.	Rutherford Appleton Laboratory, University of Oxford
GlobAlbedo	Developing and delivering a multi-annual global albedo dataset that has the potential to be sustained into the future using data from operational European satellites, such as the Copernicus Sentinels.	University College London, University of Swansea
GlobColour	Demonstrated the production of a merged data set from several different satellite data streams: MERIS, SeaWiFS and Aqua / MODIS. The objective was to combine these data streams in such a way that the output product is as far as possible independent of the input data source	University of Plymouth, School of Earth, Ocean and Environmental Sciences
GlobIce	To derive information data sets over sea ice, which will improve our understanding of the role of the Arctic in global climate.	University College London, Met Office, Planetary Visions
GlobVapour	To support user requirements for a long, homogenous time series of satellite borne global water vapour measurements.	Met Office
GlobWave	To improve the uptake of satellite-derived wind-wave and swell data by the scientific, operational and commercial user community.	CGI (formerly Logica), National Oceanography Centre, SatOC Ltd
OceanFlux GHG	To improve quantitative air-sea flux estimates of CO ₂ and other greenhouse gases using EO data in synergy in the Atlantic Ocean.	North Highland College, Plymouth Marine Laboratory, National Oceanography Centre
Alanis-Methane	To investigate the potential of EO data to reduce current uncertainties in methane emissions from boreal lakes and wetlands through the synergistic use of EO-based products in a coupled land surface-atmosphere model.	UK Centre for Ecology & Hydrology

The UK is participating in a range of EU Framework 7 projects aimed at developing climate services incorporating the use of satellite data.

Internationally, the UK is a member of the Committee on Earth Observation Satellites (CEOS) and is a participating member of its Working Group on Climate (WGClimate). This is a joint group including CEOS Agencies and the Coordination Group for Meteorological Satellites (CGMS), with a remit to coordinate and encourage collaborative activities between the world's major space agencies in the area of climate monitoring, with the overarching goal of improving the systematic availability of Climate Data Records through the coordinated implementation and further development of a global architecture for climate monitoring from space.

WGClimate facilitates the implementation and exploitation of ECV time-series through coordination of the existing and substantial activities undertaken by CEOS Agencies and via strong collaboration with other CEOS Working Groups and Virtual Constellations. The UK has provided input to the CEOS Agency response to the GCOS Implementation Plan and the ECV Inventory and Gap Analysis to the UNFCCC.

The UK also participates in Global Earth Observation/Global Earth Observation System of Systems (GEO/GEOSS)³⁸ and leads the coordination of Group for High Resolution Sea

³⁸ <https://www.earthobservations.org/geoss.php>

Surface Temperature (GHRSSST, with UK funding from NERC)³⁹. NCEO hosts the UK GEO/CEOS office and the GHRSSST Project Office.

National activities also include:

- Development and use of ECVs within NERC's National Centre for Earth Observation⁴⁰, including activities which span most of the satellite related ECVs. There is close collaboration with the ESA CCI programme and the European Commission's Copernicus Climate Change Service (C3S).
- Activities within other NERC Centres and NERC delivery partners, e.g., UKCEH produce daily and monthly burnt area of the boreal forests based on MODIS-based circumpolar data (2001 onwards)⁴¹.
- Funding for national infrastructure to develop and archive ECVs through NERC's Centre for Environmental Data Analysis (CEDA) and JASMIN facility located at Rutherford Appleton Laboratory (RAL) and closely associated with the Satellite Applications Catapult. The capacity to develop and archive ECVs at the RAL facilities through NCEO has been augmented by funding from the UK Space Agency to create a "Climate data from Space Zone".
- Establishment of the Space4Climate (formerly CDSSG)⁴² initiative to coordinate the flow of data for climate. This is chaired by government but part funded by academia and industry, the group brings together all elements and people involved and aims to create a seamless supply chain of space climate data to users and customers who are non-experts in space data. There is a dedicated data processing zone and various activities of the group to respond to the challenges such a big ambition creates.

In addition, as stated in the 7th National Communication, the UK, primarily through the National Physical Laboratory (NPL), has a leading role in standards and techniques for pre- and post-launch calibration and validation to ensure that satellite datasets are consistent and reliable. NPL leads a European Commission funded project to establish a "European Meteorology Centre for Earth Observation and Climate"⁴³ which has evolved in part to become a European network of metrology institutes to support climate change⁴⁴. This is one of a number of projects within NPL's Environment program, which also includes participating in work led by the World Meteorological Organisation to look at the role of Metrology in Environmental Monitoring, and support for satellite Calibration and Validation through, CEOS, GEO, ESA and Eumetsat. Topics covered range from global monitoring of gases to satellite monitoring of land and ocean temperature, and reflectance and radiation budget. NPL conceived and provide the science lead for the TRUTHS satellite mission seeking to establish a new epoch of high accuracy SI-traceability in orbit, explicitly to serve the needs of climate monitoring and sensitivity analysis.

³⁹ <https://www.ghrsst.org/contact/ghrsst-project-office-contacts/>

⁴⁰ <http://www.nceo.ac.uk/>

⁴¹ <http://www.ceh.ac.uk/staffwebpages/drfrancegerard.html>

⁴² <http://www.the-iea.org/space4climate/>

⁴³ <http://www.emceoc.org/>

⁴⁴ <https://www.euramet.org/climate-and-ocean-observation>