



Observing the Earth

Expert views on environmental
observation for the UK

July 2015

**This project was commissioned by
the Government Office for Science.**

*Observing the Earth – Expert views on
environmental observation of the UK*
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Cover image

The UK as photographed by the UK-DMC2
satellite, the only UK built and operated commercial
environmental observation satellite.

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Foreword



Our thirst for information about our surroundings and the environment in which we live is driving the creation of new highly capable observing systems. As the science progresses and observations become a growing part of our everyday lives, there are opportunities to utilize these systems better for informing Government priorities, policy-making and in progressing the UK growth agenda. In this context, a summary of the state of play of environmental observations and potential future trends to help inform Government Departments is timely.

Environmental observation technologies are developing rapidly to collect more data from more places over shorter periods of time. The datasets they generate can increasingly be combined and analyzed to gain new insights. These advances are set to continue as new technologies, like unmanned vehicles and small satellites, are brought into wider use. We should be aware of these growing capabilities for their potential application to policy priority areas.

The expert papers prepared for this report highlight a need to think strategically about how to create an integrated system for environmental observation – one that manages the increasing volume of observation data in a way that serves the breadth of uses and users, and allows data to be accessed and processed in a way that creates knowledge to inform policy and action. Key to this capability is a stable, long-term funding commitment and an adequately skilled workforce to ensure that environmental observations are used to their full potential.

This work was commissioned by the Government Office for Science. It was intended to be a short and intensive piece of work over just six months in order to be useful, first to inform and then to shape UK views and policy using this powerful new tool. We look forward to the work the Government Office for Science will be doing in this area and hope that this report helps support conversations about how to optimise the use of environmental observation technologies across departments, academia and industry across the UK.

I would like to express my grateful thanks and appreciation to the authors of the expert papers who have all committed significant time and effort to make this report possible, often in the face of demanding deadlines, overseen by the Core Group who guided the report's development with their expertise and wisdom, and to the Society's staff for their support. I would also like to thank the many people who contributed throughout the project and have helped focus this report on the most pressing issues.

A handwritten signature in black ink that reads 'Martin Sweeting'. The signature is written in a cursive style and is underlined with a single horizontal line.

Professor Sir Martin Sweeting OBE FRS FREng
Chair of Core Group

Executive summary

Observations of the physical and built environment are of critical importance to the UK, since the environment is directly tied to our national well-being, prosperity and security. Robust observing systems are vital for understanding, managing and forecasting environmental change. It is important that we capitalise on such observations to support decision making in Government with accurate and timely scientific evidence for the greatest public benefit.

Knowledge of the consequences of urban and rural development on quality of life, as well as the efficiency of business, can only be gained through comprehensive, continuous and fresh observational data derived from a wide variety of sources. The nature of environmental systems is such that observations should not be constrained within national borders but must address local, regional and global phenomena. Comprehensive environmental observation also requires systems that can be applied to various timescales, from short-lived events that need to be monitored on an hourly or daily basis to long-term climate and geological changes.

Our need to adapt to the changing environment necessitates the monitoring of a growing range of parameters that feed into increasingly sophisticated models. Information derived from observation data and models provides a more comprehensive picture on which Government departments can base strategic, policy and tactical decisions. These decisions can have significant impact on the UK economy as well as the health and safety of its citizens.

There are many opportunities for the UK to engage with environmental observation. Some examples include deploying constellations and/or networks of sensors, developing data processing and storage capability, developing research infrastructure and the skills base, and engaging with technologies on the horizon. As opposed to making recommendations for engagement, the purpose of this report is to present the state of the art and the art of the possible for environmental observations.

Environmental observations have been used for reducing the impact of natural hazards, which can cost billions of pounds a year. At the same time, they can be used for improving agricultural production, urban planning, business analytics and a wide range of other applications. To inform Government departments as to the scope, value and applied uses of observations, an expert overview is provided in this report. This overview is based on the priority areas for environmental observation in the UK and has been drawn up in individual chapters covering:

- Climate
- Air
- Oceans and ice
- Land and freshwater
- Natural hazards
- International

1. *In situ* means 'in place' or 'in location' and *in situ* sensors are those that measure the immediate environment of the instrument. For example, a mercury-in-glass thermometer measuring the temperature of the air.

Each area addresses the strengths, opportunities and challenges for the technology in the next 5 to 10 years and provides examples of how the observations can help meet UK priorities. For readers who are less familiar with environmental observation and who wish to dig deeper into the background technology, a technical primer is provided in the appendices.

Each of the topic areas requires a range of measurements derived from a variety of platforms that can be satellite, airborne and *in situ*.¹ Finally, the value of environmental observations, and their international context, is introduced.

Examples of technologies on the horizon

- Cloud computing for processing, storing and disseminating observation data.
- Crowd sourcing/citizen science combined with authoritative data sources for evidence of environmental impact.
- Wider use of opportunistic data from systems not originally designed for environmental observation (e.g. hand held devices, cars, aircraft).
- Automated sensors connected to the internet for real-time data as part of the Internet of Things.
- Wider use of autonomous underwater vehicles for marine observation.
- New models integrating data from the novel data sources listed above.
- Proposed very large constellations of small satellites (e.g. Google, Facebook).

Climate

As emphasised by the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change (IPCC), changes in the world's climate and the influence of human activity are important issues that must be addressed. World leaders and decision-makers are increasingly faced with important decisions that rely on accurate observations of the global environment. This places demands on the accuracy and traceability of measurements and the ability to interpret small changes over the long-term.

Robust, continuous and accurate data are required to help Government make evidence-based decisions about the effects of climate change and their possible mitigation. These observations need to be assured over the long-term so that they can provide information on trends such as the regional effects of the global rise in sea level, the contribution of greenhouse gases, and the effect of air traffic on the solar radiation budget.²

There are a number of challenges in capitalising on the data. Growing databases need to be stored, processed and transformed into information products useful for knowledge-based decision making. As climate observations are global and long-term, there is a need to define international standards of interoperability so data can be shared and used globally.

Sensor and instrument technologies are developing fast, along with the platforms to carry them. To take best advantage there is an urgent need to build an integrated and sustained international climate observing system. This is an area where the UK can play a leading role.

Examples of policy relevant information

- Trend data, e.g. to track sea level rise, and the shrinking of polar icecaps and forests.
- Regional data to identify specific regional problems and to enable tailored solutions.
- Data on whether mitigation or adaptation policies are having the desired effect.
- Compliance data to monitor progress in support of an agreement.
- Planning data to provide consistent and timely information to governmental and commercial planners to reduce uncertainty.

2. The solar radiation budget is the difference between the amount of solar radiation absorbed by the Earth system and the amount of thermal radiation emitted back out into space.

Air

Observations of the air provide a key contribution to national quality of life and economic prosperity, so air quality measurements are critical to the development of national policies, infrastructure planning and environmental services. Government policy requires strong evidence from air observations for major policy actions, whether it is in response to volcanic clouds, urban pollution and traffic management or weather forecasting. There is significant research competence in the UK which complements the operational Met Office programme.

Greater integration of atmospheric and air quality observing systems will provide a better evidence base for decision making, whilst easier access to data, supported by processing facilities, will enable better information to be delivered to those who need it across Government and industry. Consideration needs to be given to the design and implementation of systems which combine observations from multiple sources and provide insights that support monitoring and forecasting in the future.

International cooperation is necessary for implementing cost-effective systems. Cooperation is imperative for prioritising and maintaining long-term observing systems, developing new systems and cost sharing.

Examples of policy relevant information

- Forecasts that support planning in multiple sectors e.g. transport, agriculture, insurance, energy, healthcare.
- Air quality data with high spatial and temporal resolution e.g. to attribute the source of air pollution.
- Compliance data to monitor progress e.g. treaties on climate, stratospheric ozone depletion, air quality and pollution transport.
- Rainfall and wind measurements to provide early warning and response to disruptive events e.g. storms and flooding.

Oceans and ice

As an important source of food, means of access to the UK and a major climate driver, the marine environment is critical for national security and economic opportunity. Environmental observations from all types of platforms are critical for addressing the policy and regulatory priorities related to oceans and ice. They allow us to monitor coastal seas, sea level height, ice sheet changes, ocean biology and more.

Together with advanced data analysis and modelling these observations are useful for extracting information. However, current spaceborne measurements are limited largely to the sea and ice surfaces and need to be complemented by *in situ* subsurface measurements. In general, both the oceans and ice are under-sampled because of the wide range of spatio-temporal scales that need to be observed (i.e. millimetres to thousands of kilometres and seconds to centuries), which underlines the need for improved observations.

There are also a number of challenges to capitalising on environmental observations of oceans and ice. ‘Value chains’ need to be developed to ensure that relevant information reaches the key users and stakeholders. The responsibility and funding for sustaining ocean and ice observations is not clear at present. To ensure the best use of the data, the skills base will need to be developed so that appropriate data is collected, and ‘translated’ into outputs that are useful and accessible for policy makers.

Examples of policy relevant information

- Ocean forecasting.
- Measuring salinity and temperature to assess ocean circulation, which can be used to assess the impacts of climate change.
- Real-time tracking of ship locations e.g. monitoring of national fishing fleet activities, piracy.
- Ocean colour monitoring to assess ocean biology e.g. detection of harmful algal blooms.
- Measuring sea level, wave height and wind speed in coastal regions which can be used to improve coastal flood prediction.

Land

Intelligent rural and urban policies, if framed correctly, can optimise the use of finite land and freshwater resources in the UK. This relies on land observing systems that accommodate users across a wide range of areas, including resource management, urban planning, agriculture, forestry, waterways, terrain mapping, land tenure and monitoring international areas.

Common barriers in realising the full potential of land observing systems include: disparate national and international approaches to observational technologies that hinder interoperability and data-sharing; limited uptake and integration of increasingly sophisticated observation technologies; limited data-sharing between Government departments; lack of data-handling expertise for extracting information and sharing that information with decision makers in an accessible way.

Five steps for strengthening land observing systems in the future are identified in this report. Current observations could be better integrated into operational systems alongside planning for data continuity. The benefits of the European Copernicus programme should be fully exploited for UK national priorities. New technologies could be used to integrate systems and build in redundancy (e.g. deploying combinations of low cost sensors and creating sensor networks). New data-handling approaches could be developed and exploited. National resources and capabilities in environmental observation could be better joined up and used to meet UK observing needs.

Examples of policy relevant information

- Optical imaging to provide crop condition assessments.
- Soil moisture measurements can show how soil moisture and temperature varies with soil type, climate and vegetation.
- Satellite and aerial imagery with ground surveys to track forest changes in wooded areas.
- Stereo and multiple viewing angle aerial imaging, together with LiDAR, to map and re-map cities and urban areas, and construct of 3D city models.
- Vehicle-based ground penetrating radar and LiDAR technologies to assess road surfaces for managing re-surfacing operations.

Natural hazards

Natural hazards can have profound environmental and economic impacts that compromise human health, public safety, critical national infrastructure and environmental services. For example, the severe weather of winter 2013/14 affected more than 13,000 households and businesses³ and caused severe damage to roads, railway lines and flood defences. The costs of flood damage could exceed £27 billion annually by 2080.⁴

Environmental observations are critical for forecasting, monitoring, responding to and assessing recovery from natural disasters. The UK challenge is to broaden the focus of natural hazards risk management from an early warning system to a more holistic and integrated approach, with greater emphasis on risk reduction and prevention. A critical element of the success of this vision will be for the UK to measure related environmental factors. It is vital to have an effective means of monitoring natural hazard events and impacts, making observations and reports available in real time for forecasting, as well as providing advice and information to the communities and Government decision makers.

Both domestic and international hazards that could impact UK policy priorities need to be addressed with environmental observations. There is significant scope for the UK to take a leading role in demonstrating the ability to respond to natural hazards in a coordinated way. Government support is important for the development of future research leaders in environmental observation, so that the UK remains at the forefront of development and exploitation of environmental data for high-impact natural hazard research.

Examples of policy relevant information

- Meteorological data, soil moisture and ground water status are used to measure river level and flow data which can help with flood forecasting.
- Precipitation measurements by C-band weather radar or rain gauges.
- Space-borne radar altimeters to map ocean-surface topography, the hills and valleys of the sea surface.
- Satellite imagery for monitoring wildfires and mapping flood extent.
- Satellite radar interferometry to monitor tectonic and volcanic processes.

3. Winter 2013/14 severe weather recovery progress report - An overview of the Government's recovery support, Department of Communities and Local Government, November 2014

4. Flood defense spending in England, Standard note: SN/SC/5755, House of Commons Library, 19 November 2014

International

Access to geospatial data and services intersects with a wide variety of economic and policy objectives. Environmental observations are also crucial for implementing management regimes related to land tenure; international aid; food security; refugees; disaster risk reduction and relief; and climate change and adaptation. The UK has a major role in many of these and is well positioned to make a significant contribution to how global observing systems are used to help resolve environmental policy issues internationally.

International cooperation is also crucial for gaining access to comprehensive datasets and the science that allows us to exploit environmental observations. The UK must continue to work collaboratively to build new capacity and ensure interoperability of systems and methods in order to realise the benefits of environmental observations for policy, science, innovation, and commerce in the UK and beyond. Access to international datasets also relies on the UK being able to make valuable contributions through national environmental observations capability.

In situations where data critical to UK interests need to be collected overseas and is not addressed by current programmes, these should be developed. In such situations, efforts should be made to share resources, expertise and capacity for the benefit of the international community in the same way that the UK actively participates alongside international partners in the International Charter 'Space and Major Disasters'. The UK also has an opportunity to take a leading position in the commercial provision of services for informing both policy and commercial activities. There is significant export and economic growth potential for the UK in providing end-to-end services for customers in all sectors.

Key considerations for environmental observation:

- Planning for the future is based on understanding the past, present and environmental trends.
 - Extensive observing systems are the basis of our current understanding of the physical and built environment.
 - The UK has strong heritage and capability in both gathering and exploiting observation data.
 - Opportunities and means for observations are growing rapidly as a result of fast-advancing technologies and data-handling techniques.
 - Maintaining and expanding data gathering capabilities, alongside better exploitation of the datasets across Government departments should be a priority for ensuring national well-being, prosperity and security.
-

Relevance of the international context

- Many rich data sources relevant to UK interests are generated and coordinated on an international basis.
- Potential policy and economic benefits of observing systems are often tied to national interests and the international political context.
- Some policy and legal aspects of environmental observing systems can only be addressed in an international context.
- Many international agreements and undertakings depend on high quality, fresh, geospatial data.

Conclusions

Rapidly advancing technology and data availability are transforming environmental observation, creating an opportunity for the UK to take advantage of improving environmental observational capabilities. With the right observation infrastructure, skills base, and international partnerships the information gathered from these systems can drive social policy and the growth agenda.

Better access to data and assurances of data continuity are essential for entrepreneurs and small to medium-sized enterprises (SMEs) to commit to developing information products and services. Sustaining services and research and making the necessary advances in monitoring and forecasting in the future requires stable long-term funding, accompanied by wise policies governing observation methods. Our improved understanding of the natural environment, together with enhanced predictive capability in weather, climate and related hazards, create an opportunity for UK industry to secure a strong position in this developing global market.

The papers produced for this report expose a number of common factors that are crucial to successful utilisation of environmental observing systems:

- Comprehensive systems that integrate various observational capabilities and modelling.
- Transitioning new technologies from research to operational deployment.
- Sharing public and private observational data between departments, institutions and commercial entities.
- Improving data-analysis techniques and access to derived information for better data exploitation yielding actionable knowledge, especially across Government departments.
- Increasing the skills of the workforce to utilise data and develop new sensors that extend or reduce the costs of environmental observations.
- International collaboration for securing geospatial data that can be applied to national and international priorities.

To ensure that these critical issues are addressed and the best use of environmental observations is made for UK national interests, there is a clear need for ongoing dialogue between Government stakeholders and the expert community. This dialogue should address the need for effective, efficient exploitation of existing systems (e.g. Copernicus) and evaluate opportunities for acquiring UK sovereign capabilities for environmental monitoring. It is important that we capitalise on environmental observations to support decision making in Government with accurate and timely scientific evidence for the greatest public benefit.

Introduction

This report contains the considered thoughts of a select group of experts informed by consultation with key stakeholders to give an overview of environmental observation in the UK.

Six commissioned expert papers form the basis for the chapters of the report and divide environmental observation across six domains – climate, air, oceans and ice, land and freshwater, natural hazards and international – although inevitably due to the nature of the subjects, there are overlaps between the chapters. Each chapter provides an overview of the issues as seen from a select group of experts and is not intended to represent the consensus of the community.

For each domain the current use of platforms and sensor technologies is described, as well as the strengths, opportunities and challenges, where the technologies are going in the next 5 to 10 years and how the UK stakeholders can use these to best advantage.

Technical primer

There are many different technologies that apply to environmental observation. To support the information provided in the chapters, a technical primer describing each of the technologies and what they are used for is provided in the appendices.

Acronyms

A full list of the acronyms used in the report is provided in the appendices.



Chapter one

Climate

Alan O'Neill, University of Reading

Left

Epic supercell storm cloud.

© petesphotography.

Climate

1.1 Introduction

Changes in the world's climate⁵ and the influence of human activity on our planet are of key concern. The importance of climate change has been recognised in recent reports from the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change, which has again reaffirmed the overwhelming scientific case that human activities are affecting climate. The significant economic consequences of not taking action are set out in the Stern Review on the Economics of Climate Change.

World leaders and decision makers are increasingly faced with important decisions on environmental matters, which often have vast economic implications, and they wish to rely on the most accurate scientific observations of the state of the global environment. This need for scientific observations of ever increasing accuracy and complexity is placing stringent demands on the accuracy of global observing systems and on the traceability of measurement results to internationally agreed units of measurement and standards. Moreover, the need to interpret accurately small changes in long-term environmental data series requires measurement standards with well-characterized uncertainties and well-monitored and maintained stabilities.

1.2 Current use

1.2.1 Space-based instruments

The following examples serve to illustrate the ability of spaceborne instruments to make critically important measurements of changes in the climate system and of their effects. They have been selected, from the many examples that could have been chosen, to highlight topical areas where new technologies are allowing climate science to make considerable strides, providing more robust evidence for policy decisions. The UK has considerable expertise in each of these areas.

1.2.2 Sea level rise

Sea level is one of the 50 Essential Climate Variables (ECVs) listed by the international Global Climate Observing System (GCOS) programme for climate change monitoring.

Over half the world's population lives within 60 km of the ocean shoreline, and numbers are increasing. This trend makes increasing numbers of people vulnerable to one of the most obvious effects of Earth's changing climate – sea level rise. The sea level is also a crucial parameter for marine ecosystems and associated food chains.

Satellites measure sea level rise globally in regional detail. Such detail is important, first, because sea level rise is not uniform over the world's oceans; and secondly, because the patterns of sea level rise represent a 'fingerprint' of climate change, allowing the different causes of sea level rise to be determined.

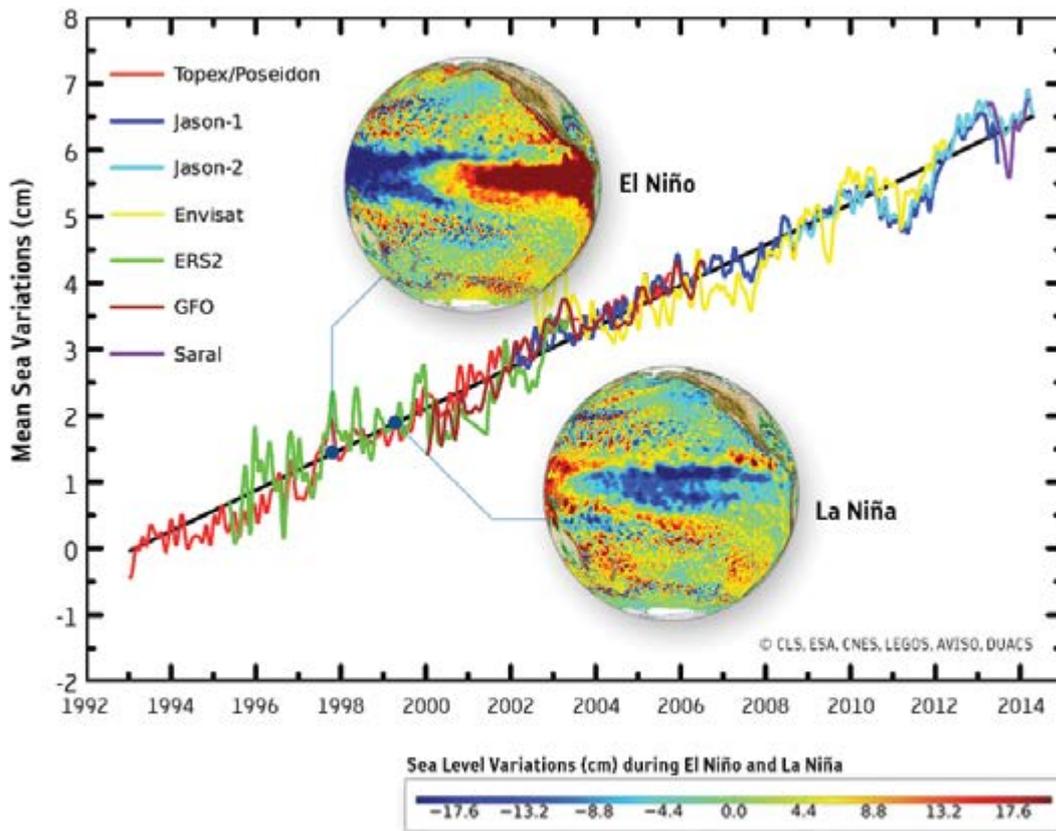
Radar altimeters on Earth orbiting satellites, which have now been operating for over two decades, provide very accurate measurements (cm accuracy) of sea level rise over the world's oceans. Radar altimeters on a sequence of satellites – Topex/Poseidon (1992 – 2005), ERS-1 (1991 – 2000), ERS-2 (1995 – 2011), Jason-1 (2001 – 2013), Jason-2 (2008 – present) – have together provided a consistent and compelling record of sea level rise, amounting to a globally-averaged value of about 3mm per year over recent decade. About half of this is due to thermal expansion of the oceans and the rest to melting of ice on land (see Figure 1). Jason-3, scheduled for launch in 2015, will continue the data record, along with planned Jason-CS satellites and the Sentinel-3 satellite of Europe's operational satellite system, Copernicus.

5. Climate change refers to a change in the state of air, sea, or land environment that can be identified (e.g. by using statistical tests) by changes in the mean or variability (generally both) of its properties, with the change persisting for an extended period, typically decades or longer. The detection and attribution of climate change demand long records of carefully cross-calibrated data.

FIGURE 1

The illustration shows the global trend in mean sea level as derived from a series of altimeters on various satellites. Sustained observations are essential to understand the processes that can lead to long-term trends in the Earth system and to discriminate between long-term trends induced by human activities and shorter-term natural variability (e.g. El Niño, La Niña).

Sustained observations are also vital to turn scientific advances into sustainable services for the benefit of society.



Used with permission from Earth Observation Science Strategy for ESA: a new era for scientific advances and for societal benefits, 2015.

Altimeters in space are now so accurate that they can measure ice thickness (freeboard⁶). The altimeter on the European Space Agency's (ESA's) Cryosat-2 has confirmed that the long-term decline in the areal extent of sea ice over the north polar cap, witnessed by radiometers on operational satellites, is not due simply to a piling up of ice in one region at the expense of another. Rather it is due to a significant downward trend in recent decades in sea-ice volume. Satellites will play a crucial role in monitoring the situation in coming decades, for example in guiding ship routing through ice-free passages that could increasingly develop in summer months if the downward trend in ice cover and volume continues.

1.2.3 Monitoring greenhouse gases from space and identifying sources and sinks

Monitoring and verifying greenhouse gas (GHG) emissions is of particular importance. Reduction and regulation of GHG emissions are part of most discussions on how to manage climate change. Reaching an agreement to reduce GHG emissions is complicated, however, because of scientific uncertainty and incomplete understanding of Earth's carbon cycle and its response to global warming. There are also significant gaps in the observations.

Currently, identifying trends in GHG emissions relies on weaving together data collected from the relatively sparse ground-based networks and the few GHG-measuring spaceborne instruments. This limited observational system needs improvement to attribute⁷ GHG sources and sinks accurately to individual countries and to individual regions.

Deployment of a constellation of GHG-measuring satellites would be a significant advance. Because satellites can make many thousands of observations each day, sources and sinks of GHGs can be delineated in regional detail, allowing scientists to disentangle anthropogenic and natural sources and sinks down to the local scale.

It is essential, however, to augment the satellite measurements with ground-based measurements in order to calibrate the satellite measurements accurately. In addition, current measurement techniques by satellite, which are based on the detection of solar radiation reflected from the Earth's surface, can measure reliably only the total amount of carbon dioxide or methane in a column above a point on the Earth's surface, not the detailed vertical distribution of the GHGs. The near-surface information provided by ground-based sites is a valuable augmentation in order to track back measured concentrations of a gas to their emission locations at the surface.

Important progress in GHG monitoring has occurred recently with the launch (2010) of the Jaxa GOSAT mission and the US National Aeronautics and Space Administration (NASA) OCO-2 mission. In Europe, a candidate ESA mission, CarbonSat, will improve (if selected) the technology of GHG measurements by sampling the world with both high precision and with much higher spatial resolution than has been obtained previously. The Sentinel-5 satellite of the European Copernicus system will represent a sustained operational capability for carbon dioxide and methane measurements (though the former is expected to be of limited quality).

6. Freeboard is the distance between normal water level and the top of a structure or mass that rises out of the water, such as a buoy, dam, or ice floe.

7. The attribution can be attempted in principle by computing backward trajectories of air samples containing GHGs by using atmospheric wind data until the air meets the surface.

What is still missing is an optimally designed carbon and GHG observing system, combining the advantages of both ground-based and space-based systems. Without such a system, accurate independent measurements of anthropogenic GHG emissions on the scale of individual countries (and better) will remain a challenge, limiting their use in formulating and policing climate policies.

1.2.4 Earth's radiation budget

The whole climate system of the Earth is driven, at root, by the difference between the amount of solar radiation absorbed by the Earth system and the amount of thermal radiation emitted back out into space. Accurate measurements of this radiation budget are of central importance to understanding climate change. The ability of climate prediction models to replicate essential features of the measured budget is a stringent test of the models.

Earth orbit is the only location from which to measure the (top-of-the-atmosphere) radiation budget and its variability around the globe. Key findings using measurements from NASA's Earth Radiation Budget Experiment satellite showed that clouds double the Earth's reflectivity of solar radiation (a cooling effect) but also reduce the amount of thermal radiation emitted to space (a warming effect). Measuring accurately and simulating this fine balance between opposing effects is central to climate science and to the trust we can place in the predictions of climate models.

These days, instruments to measure the radiation budget are not just for research but are carried on operational weather satellites, such as the Geostationary Earth Radiation Budget (GERB) instrument⁸ on weather satellites operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

More advanced technologies, involving not just spectrometers but lasers and radars, are needed to understand in detail the complex interactions between radiation, clouds and aerosols within the atmosphere itself. ESA's EarthCare satellite, scheduled for launch in 2016, will incorporate such technology, and is expected to advance significantly our understanding of the complex feedbacks between clouds and radiation in the climate system.

1.2.4 Ground-based and ocean-based observing systems

Satellites are not always the best platforms to make observations relevant to climate change. Ground-based radar and LiDAR are powerful tools to measure cloud properties with resolution in space and time that cannot typically be matched by a satellite. Aircraft can measure cloud properties remotely and directly, and Unmanned Aerial Vehicles (UAVs) augmented by high-tech, low cost Argo float, robotic ocean gliders and other autonomous underwater vehicles (AUVs) are expected to transform this and other areas of environmental measurements.

Satellites cannot measure very far below the surface of the ocean, and *in situ* measurements are therefore essential. The network of ocean buoys, using satellite telemetry to communicate information, is of vital importance for climate research and prediction. This system is now being augmented by high-tech, low-cost robotic gliders, which are expected to transform the discipline of oceanography and reduce the need for expensive research vessels.

8. GERB measurements are "broadband": radiometers designed simply to measure total radiation in broad spectral bands in the solar and thermal regions.

The land surface is highly heterogenous, with varying physical properties, soil moisture and vegetation types on a wide range of space and time scales. Many important processes relevant to how this system interacts with climate change are sub-surface. Although radars on satellites can achieve some ground penetration, the sub-surface to a large extent is hidden from space. New technology is introducing low-cost, miniaturized instruments and modern telecommunications (including the internet and telecommunication satellites) allow them to be increasingly interconnected. The concept of a planetary web of instruments is now feasible for climate and environmental monitoring.

1.3 Strengths and opportunities

1.3.1 Key attributes of Earth-orbiting satellites for climate change

Observations from space, integrated with ground-based networks (on land, in the sea and on aircraft), provide unique information, which greatly assists the successful understanding, forecasting and management of climate change. Besides revealing trends in regional temperature, satellite data:

- improve our ability to monitor and understand atmospheric accumulations of GHGs in the atmosphere;
- measure sea level rise with great accuracy;
- allow changes in the amounts of ice on land and sea to be quantified;
- measure the radiation balance of the Earth (radiation from the sun and emitted thermal radiation from the Earth);
- quantify changes in carbon emissions through land-use change (e.g. deforestation) to support emissions trading programmes; and
- enable changes in risks and hazards associated with climate change to be detected (e.g. frequencies of flooding, droughts, high-impact weather, forest fires).

In the 1970s, only a handful of satellites were in orbit. Today, more than 60 are continuously monitoring the state of the Earth. Over approximately the next 15 years, 150 Earth-orbiting satellites, with over 300 different instruments will be in orbit. Information derived from space has a number of distinct advantages over conventional, ground-based measurements for climate change purposes:

- Satellite-derived information is comparable. The same instrument takes measurements over the whole globe, allowing data to be compared between different geographic areas and different times of acquisition.
- Satellite measurements are taken remotely, yielding a global picture of interconnected variability and change. In addition, satellite operators do not need the consent of a country or a party to monitor a particular area.
- Satellite measurements are verifiable. Raw satellite data can be reprocessed by independent parties from commonly accessible data archives.
- Satellite measurements are continuous (during their operational lifetime). Their global nature and long-term operation help close measurement gaps in space and time.
- Satellites can measure a number of ECVs simultaneously, providing a more integrated picture of the Earth's environment.
- Satellite measurements can be accessed and collated rapidly, allowing near-real time forecasts to be made with weather and climate prediction models by setting the initial conditions.
- Satellite measurements, by being global and multi-variable, enable stringent testing of climate prediction models.

Yet of this array of growing numbers of Earth observation (EO) satellites, there are relatively few that, at present, could be termed “climate satellites,” ones that incorporate advanced technologies that make measurements of direct interest (when suitably reprocessed) to climate science and policy makers. Of those in orbit, many are well passed their planned service life. And although more than 50 nations operate or plan to operate EO satellites, most of these are basic electro-optical satellites, essentially orbiting digital cameras that lack the necessary sensors for precise climate modelling. While general-purpose weather satellites provide important data for climate studies (when suitably processed and cross-calibrated), they cannot fully meet the needs for climate information.

1.3.2 The current lack of a co-ordinated, sustained climate observing system

While it is increasingly clear that observations from Earth-orbiting satellites are critical, there is not yet a co-ordinated, sustained climate observing system in space. This shortcoming contrasts with the situation in operational weather forecasting, for which an internationally sustained satellite observing system and data processing capability exist, to the enormous benefit of science, society and the economy. Only a co-ordinated, international programme of investment, including revised prioritisation for spending on civil space programmes, can change this. In this regard, two international bodies are playing important roles. The GCOS is defining the essential climate observations that are needed (with their desired accuracies), and the Committee on Earth Observation Satellites (CEOS) is encouraging co-ordination between space agencies in responding to the observational needs.

1.3.3 The data and information challenge

Having the right technology providing the right kinds of data is only part of the challenge. The usefulness of the data depends on the fidelity of climate models and the available computer power for data processing. It also depends crucially on our ability to disseminate the data and to transform them into useable information by decision makers. The focus of climate data gathering to date has been on fulfilling the needs of the scientific community, rather than on directly meeting the needs of decision makers, who must determine how to adapt and respond to changing climate. (The science has itself been a fundamental input to decision making, however.)

Managing climate-related risks requires accurate, robust, sustained and wide-ranging climate information. Sustained and continuous observations are needed for researchers to evaluate and test climate model accuracy, and to identify causes of particular elements of climate change (the problem of attribution).

While a great deal of data are already collected for the atmospheric, oceanic and terrestrial phenomena, and are shared among the research community through various international data centres, provision for the direct informational needs of policy makers requires improvement. The kind of information needed by policy makers will include:

- trend data, e.g. to track sea level rise, and the shrinking of polar icecaps and forests;
- regional data to identify specific regional problems and to enable tailored solutions;
- data on whether mitigation or adaptation policies are having the desired effect;
- compliance data to monitor progress in support of an agreement; and
- planning data to provide consistent and timely information to governmental and commercial planners to reduce uncertainty.

1.4 Challenges

1.4.1 The challenge

Climate change is governed by a combination of processes taking place on a range of space-time scales. The complexity of the system, and the many, but as yet poorly understood interdependent feedbacks, make reliable prediction difficult. This also makes problematic unambiguous attribution of climate change to substantiate global mitigation action.

Globally sampled measurements on multi-decadal time scales of a wide variety of climate-sensitive parameters – in particular, the ECVs of GCOS – are needed to provide the information to help understand and thus better describe and model important climate processes e.g. carbon cycle.

To detect the small climate trends from a background of natural variability, and the vagaries of localised climatic anomalies, particularly those due to mankind's direct impacts, requires that the data include many parameters simultaneously; are as accurate as possible and are geographically homogenous over long time scales. This emphasises the need for:

- continuity in the observing system;
- an integrated (“systems engineered”) approach to its design;
- international cooperation to achieve this; and
- accurate instruments that are robustly tied to invariant references (no one instrument can be relied upon for anything close to the multi-decadal period needed).

Localised *in situ* measurements are a highly valuable component of any climate observing system. One of their primary functions is to help in understanding processes and to provide a means of validating and/or calibrating the critical assets, Earth-orbiting satellites. The latter are the only means to get truly global coverage, and sufficient sampling to avoid biases from geographical environmental anomalies.

Since any individual satellite sensor will typically have a life that is short compared to a trend in climate (one detectable above the “noise” of natural climate variability), it is paramount that a robust linkage of the datasets can be established. The current ideal – derived from meteorological best practices and adopted by GCOS as one of its climate observing principles – is to ensure sufficient time overlap of satellite sensors to guarantee data continuity and comparability.

This strategy, while sound in principle, is costly for the number of variables needed for climate, since spares are required in case of in-orbit failure. A failed or delayed launch, such as between ESA's Envisat and the Sentinels of the European Union's (EU) Copernicus programme, can easily lead to data gaps. Even without such data gaps the smallness of climate trends over a few years can lead to unreliable conclusions given the additional likelihood of undetected small drifts in properties of satellite instruments themselves. *In situ* data, if sufficiently accurate, can play a role in helping to bridge these gaps, at least for some parameters however, the accuracy and limited sampling limits its capabilities.

To date, most climate data records are built from observations from research missions and those designed and built for weather. The maturity and societal dependence on the latter means that strong reliance can be put on the continuity of their observations – the necessary ‘spare’ is always ready if needed. Observations for weather forecasting have been the starting point for many climate data records. But the primary emphasis for such sensors is short-to-medium term weather forecasting, where sensitivity and relative accuracy is more important than the long-term accuracy needed for climate.

For example, the widely used satellite-based measure of atmospheric temperature is derived from the microwave sounding unit and advanced microwave sounding unit instruments on National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. But the data need a great deal more work to render them “climate quality”. Over the years, the time series of derived temperatures has been adjusted numerous times to account for differences between instruments on different satellites, degradation of instruments with time and slow changes in orbit. It is very challenging to make adjustments accurately enough to obtain reliable long-term climate trends.

In a similar way, the Sentinels of Copernicus are focused on operationally collected data for a wide range of environmental monitoring applications. These provide data for studies of important processes for climate, but the earliest detection of small long-term decadal trends exhibited by climate is not the first priority. There is therefore an urgent need to design and build a dedicated climate observing system, which is capable of meeting the needs of policy makers in a timely fashion.

Such a climate observing system will ultimately need to be built as a global partnership, with full data-sharing and planning to ensure all the key variables are continuously monitored into the long-term, and archived indefinitely. It will need to make measurements of the Earth/Sun system spectrally resolved across the full electromagnetic spectrum, through active and passive sensors from space by both geostationary and orbiting satellites. The focus of such sensors for climate change monitoring will be high accuracy. It may not necessarily demand the high spatial resolution needed to understand climate processes or for other environmental applications (e.g. weather and ocean forecasting). The system will be complemented by data from other sensors used for such purposes (including *in situ* data, aircraft and UAVs). A sensor or system designed for climate can also meet other environmental needs. Indeed there would be significant benefits from synergy.

1.4.2 Responding to the challenge: four pillars of a climate observing system

Although the full realisation of this climate observing system, through a dedicated concerted action of the international community, may still be some time away, it is possible already to make significant steps towards its establishment, at least in prototype form, through relatively small investments now, even at a national level (see Figure 2).

FIGURE 2

The construction of a virtual constellation of satellites from different space agencies. International collaboration is needed for the cost-effective and optimal design of a global integrated observing system. Such a system could involve virtual constellations, as illustrated here, or formation flying and convoys. International collaboration should extend to open access to data (from publicly funded satellite missions and projects at least), data-sharing, data quality assessment and interoperable data processing systems.



Used with permission from Earth Observation Science Strategy for ESA: a new era for scientific advances and for societal benefits, 2015.

The first pillar of any climate observing system is a commitment to make long-term global observations of the Earth/Sun across a broad range of the electromagnetic spectrum, along with the facilities to provide ground-truthing in a manner that is globally distributed and internationally accepted. From a European perspective the Copernicus and EUMETSAT satellite programs go a long way towards meeting this goal. The GCOS programme will continue to play a vital role in defining requirements for climate observations in space (the previous and current chairs are both from the UK). With appropriate coordination, through organizations like CEOS, this can be complemented with international partnerships and virtual constellations of satellites. While efforts are being made to ensure that these sensors are accurate and traceable to international standards, these efforts are largely targeted at needs other than those of climate change.

The second pillar of a climate observing system is accuracy and ‘traceability to invariant reference standards’ (international SI units). More effort needs to be focused here, and new approaches are needed. Instead of seeking to improve the post-launch calibration accuracy of every individual satellite to a level that meets the needs of climate observations on a case-by-case basis, climate requirements could be met in a more holistic manner through a common, optimised in-orbit calibration system. Flying ‘calibration satellites’ in space could facilitate the upgrade in performance of other sensors, where they were limited by accuracy and traceability (for optical sensors this is the majority of cases).

In the UK, such a concept has been developed for a climate calibration mission involving a small satellite. The proposed TRUTHS satellite (Traceable Radiometry Underpinning Terrestrial and Helio Studies) can measure incoming and reflected solar radiation at an accuracy of 0.3%. This is around 10 times more accurate than comparable current and planned sensors, such as those on Sentinel-2 and 3, allowing changes in key climate feedback parameters (involving clouds, albedo and land cover) to be detected and the radiation balance in climate models to be tested. Its orbit can be chosen to transfer its high-accuracy calibration to some of the sensors on the Sentinel satellites, and it would be a calibration anchor for *in situ* monitoring systems and networks. Full benefit would come from a continuous (or at least regular) flight of a series of such sensors, since a detectable change in the climate state will still be beyond the life of a single satellite.

A third pillar of a climate observing system is advanced computing, data processing, visualisation and data dissemination tools – the “ground segment” of a climate observing system. The vast amounts of data already received from space are set to increase dramatically in the future. Data-handling technologies will be every bit as important as data measurement technologies. Interoperability of data-processing systems at international level will be essential.

In the area of data processing, so-called re-analysis of observational data (both satellite and *in situ*) is of great importance for understanding climate change and for detecting and attributing trends in climate variables. Re-analysis involves the synthesis of diverse observational datasets into a self-consistent estimate of the global climate by assimilating data into a global numerical model. The goal is to provide long, stable time series of global data. Currently, the most well-developed re-analyses are for the atmosphere and ocean, but eventually it is expected that the methodology will be widened to include other components of the climate system, e.g. the land. The European Centre for Medium Range Weather Forecasts (based in Shinfield, near Reading, UK) is a world leader in this endeavour.

A fourth pillar of a climate observing system will be long-term (indefinite) archiving of data, along with ancillary information on data characteristics (including errors, and significant events in data capture or processing) – so-called metadata. For some applications, an environmental measurement has its greatest value at or near the time it was taken. For climate data, the value of a measurement generally increases with time into the future, as the data record gets longer. Climate-relevant measurements taken today will be a highly valuable legacy of today's investment in observation programmes for future generations. Since the cost of storing the huge amounts of data to come from satellites and ground-based systems would be prohibitively expensive with today's technology, judgements will have to be made about which subsets of the available data are to be stored for posterity.

1.5 Future trends

There are clear trends in technology, international cooperation and programmatic activities that will significantly enhance the value of climate observations for scientists, policy makers and business people.

On the technology front, the range and accuracy of parameters that are now being measured from space will continue to increase. The days are long passed when Earth observation (EO) from space simply involved optical cameras. Sensors now cover a wide range of wavelengths of the electromagnetic spectrum; they will have increasing sensitivity and spectral resolution; and they will increasingly involve not just passive sensing (detecting natural radiation) but active sensing with advanced radars and LiDARs.

Miniaturisation is revolutionising space technology, leading to a whole new business model for EO involving small satellites. Their relatively low cost means that constellations involving many satellites can be deployed carrying (passive) optical and (active) radar sensors giving all-weather capability, with every point on Earth being viewed at least once a day. Such small satellites, including in-orbit calibration satellites such as the proposed TRUTHS satellite, can be interspersed with larger, more capable (and much more expensive) satellite systems such as the Sentinels to develop an integrated climate observation system in synergy with investments for other environmental information needs.

Continuing rapid improvement in computer power and novel architectures such as the computing "Cloud" will transform the way we process and disseminate data, allowing diverse data from around the world to be synthesised and processed very efficiently in a seamless way. Modern telecommunications and powerful hand-held devices will enable climate information to be packaged, tailored to user need and disseminated quickly. Besides the value of this technology for traditional users of climate information, it will allow the wider public to be engaged in the whole process of monitoring climate information ("crowdsourcing"), bringing wide-ranging practical benefits as well as a much deeper understanding of climate change and of the decisions made on behalf of society by policy makers.

On the international front, it is now widely recognised that international cooperation will be essential to establish an optimally-designed, cost-effective climate and environmental monitoring system. The Climate Working Group of the Committee on Earth Observation Satellites is providing international co-ordination on the climate side. A “systems engineering” approach will be necessary to build a well-designed, fully-integrated climate monitoring system in space, integrated with tailored ocean and ground-based systems. Building virtual constellations of satellites – whereby individual nations prioritise and deploy their own contributions to the system in recognition of the investments of other nations – will reduce some of the risks inherent in collaborative space programmes, and will allow individual nations, if they wish, to prioritise investment in particular capabilities and technologies.

On the programmatic front, there are now significant moves internationally to “operationalise” environmental and climate information and to develop services. In Europe, the deployment of a sustained Earth observing system by Sentinel satellites is a landmark.

Sustained observations are essential not just for scientific detection and attribution of climate change but also for the development of climate-related services – e.g. quantitative measures of changing risks in various sectors of society and the economy associated with changing climate. Without sustained observations, business is reluctant to make investments and design services that exploit space data if they are only short-lived. This has been a major impediment to the exploitation of EO of space in the past, with the exception of weather forecasting, the whole practice of which now depends hugely on the sustained provision of satellite observations. On the strength of the Copernicus system, the European Commission has now instituted a large programme to fund the development of climate services, and the ESA Climate Change Initiative, in which UK scientists are heavily involved, should be an ongoing, vital element to ensure that that data are processed and calibrated to the high levels of accuracy and precision needed for climate science, policy and services.

National investments in facilities such as the Centre for Climate and Environmental Monitoring from Space, involving a partnership between academia and industry, as well as in high-performance computing and data processing technologies, are putting the UK in a strong position to exploit the benefits of the wealth of climate-relevant data we can expect.

1.6 Summary

Climate change presents decision makers with difficult decisions, and environmental observations will provide important evidence for the progress of climate change as well the success of any mitigation mechanisms that are employed.

The data supporting these decisions need to be robust and accurate and this can be assured through long-term planning to ensure the continuity of environmental observations which should then be appropriately stored, processed and transformed into products for the benefit of society and decision makers. As the observations need to be global and long-term this will rely on agreed standards for interoperability at an international level. As the technology evolves, a greater range and accuracy of environmental observations will be possible. The greatest benefit from these will accrue through an integrated and coordinated international system that provides sustained climate observations for social and economic benefit.

At present, we lack an integrated and sustained climate observing system. There is an urgent need to build one, a challenge that will have to be met through international collaboration. This is an endeavour in which the UK can play a leading role.



Chapter two

Air

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Polluted city. © RapidEye.

Air

2.1 Introduction

Air is a fundamental requirement for human existence, and its physical and chemical properties are essential to human health and well-being. Air supports human life by providing oxygen, cycling carbon dioxide and forming the atmosphere which moderates temperature and humidity. It also produces the weather and protects us through the ozone layer filtering dangerous solar radiation.

This section concentrates on the air, its physical and chemical properties and contributions to the understanding of weather and air quality whilst acknowledging that there are many other aspects of air that cannot be addressed here, such as indoor air, toxicology of air, and radioactive effects.

Air is ubiquitous, global and dynamic and this has inherent consequences for how we treat it and as a driver of many environmental impacts – both those that are dealt with as part of everyday life and those that are especially hazardous and require overt mitigation. Particular conditions, such as urban infrastructure and rural development, can cause changes to the local environment which mean that, although air is still related to the wider environmental atmosphere, it has distinctive characteristics.

These changes in the physical and chemical composition of air locally may be transported from region to region or across the globe in processes which span from hours to years, depending on horizontal and vertical structures of the atmosphere. Air also interacts with the land, oceans and ice which can transform and disrupt it, changing its movement, direction and composition. This is important as it means that air is not restricted to national borders and globalises environmental changes as physical and chemical changes are carried with it as it travels around the world.

A consequence of these considerations is that observations of air must cover relevant cycles of air on similar timescales to the physical motions and chemical transformations, which can range from a few seconds to decades. Prediction beyond a day ahead requires measurements from half the globe; and beyond three days ahead requires a full global view stretching further up into the atmosphere as the timescales lengthen to months and years.

The nature of air means that the observations are necessarily implicated in other domains identified in this report. For example, the atmospheric transport of volcanic ash after an eruption (covered in the Natural hazards chapter) relies on an understanding of the atmosphere. Equally, the importance of climate was covered in the previous chapter. It is the long-term measurements of the physical and chemical properties of the atmosphere which are fundamental to understanding Earth's climate, past and future.

2.1.1 Drivers for air measurements

Each of us conducts a daily assessment of the atmosphere as we make judgements about what the weather today will mean for us. The need for knowledge about the weather is both a pragmatic consideration but also a cultural pre-occupation in the UK. This UK (and global) societal need for weather information has strongly driven the need for more scientific, regular observations of the dynamics of air and its properties, such that the weather forecast system, for example, is an integral service in modern day life. It has also expanded the need for atmospheric measurements to cover all aspects of the air around us.

Multiple systems of operational instruments are required as part of the public infrastructure, and underpin many services from policy regulation for health to responses to major environmental hazards. Models of the atmosphere use these air measurements as the foundation for predictions of the future, whether for estimating tomorrow's weather, levels of air pollution, or in the long-term changes, e.g. climate change.

Integrated systems (of data and models, brought together through data assimilation) are the foundation of Met Office weather forecasts. Improved historical and current data series inform large-scale policy and industrial developments in the climate change arena and such data is increasingly used to constrain climate predictions. Observations of the properties of air are therefore an essential part of the UK landscape.

Based on these well-developed systems there are a diverse range of applications and services, of which the Public Weather Service of the Met Office (meteorology-based numerical weather prediction (NWP)) is the best-known. Its principal objective is to produce accurate and timely weather forecasts for the general public (for example, through extensive bulletins and time slots) and to protect life and infrastructure; there are also large benefits in cost effectiveness and efficiency savings through wider support of Government. Academic research, through Natural Environment Research Council (NERC), is a significant source of advances; the Met Office and NERC co-operate in valuable joint programmes.

The applications of weather services reflect the diversity of impacts on individuals, and on market sectors from transport, construction and farming to insurance and energy industries. These impacts are significant, for example, flooding from storms and extreme precipitation affects hundreds of thousands of households directly through flood insurance; major UK events have resulted in up to £3 billion in insurance claims. The influence of weather information continues to grow as environmental awareness increases and atmospheric inputs become increasingly woven into national economic and social infrastructures such as energy, transport, agriculture and healthcare.

Much of the immediate use of air information is for activities which require short timescale information and the range and diversity of applications continue to grow. Rapid investment in wind energy infrastructure (more than £30 billion since 2010) has resulted in an atmospheric dependant infrastructure that can supply around 10% of UK electricity. The successful integration of this variable source into the wider grid requires excellent forecasting over a range of timescales.

In the urban environment air pollution is now a significant driver. Air pollution can have a significant impact on local front-line healthcare services and accurate forecasting allows for provision to be made. The total cost of air pollution to the UK is estimated to be as high as £16 billion per annum; globally, air pollution is responsible for substantial premature death and is projected to be the largest environmental cause of mortality. NERC science and its Centres, such as the National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO) and the Centre for Ecology and Hydrology (CEH), contribute observations and new science of direct relevance to Government, local authorities and people.

Changes in the average state of the atmosphere and short-term fluctuations mean that planning for the long-term is increasingly difficult, particularly requirements for climate information with respect to adaptation, e.g. statistics of atmosphere mean state and its extremes.

There are important issues of Government policy which require information on the status of air over long timescales. Relevant treaties requiring air observations include those on climate, stratospheric ozone depletion, air quality and pollution transport. Reporting requirements for these treaties are often supported by atmospheric research, through NERC, to explore characteristics of the air, understand the relevant processes, develop operational systems to characterise them and then working with Government to disseminate the findings and inform responses to events. Direct activities include re-analyses of meteorological information (i.e. backwards in time), reconstruction of climate records, and future climate analyses.

Finally, responses to disruptive events such as storms and flooding (extreme rainfall; high winds), drought (lack of rainfall; high temperatures), explosions, high pollution events and volcanic eruptions (ash) benefit from both continuous monitoring and from the ability to re-deploy research assets. Rapid response air observations are of value in these situations from underpinning warning systems to characterisation of events and consequences. These type of events and their observations are described more fully in the chapter on natural hazards.

2.2 Current use

The economic impact and quality of life impacts of air observations are such that formalised operational and bespoke research systems exist for acquiring relevant data; the operational systems are there to provide robust delivery systems for essential data in stable, long-term systems. Research systems collect data by innovative means or for discrete events or bespoke purposes.

This section divides the main types of air observation systems into three categories related to the observation platform. However, this is just for ease of discussion as it is the combination of observations from the different platforms, into integrated observing systems, which provides the knowledge of air characteristics sought by atmospheric science and services.

For each of these types of air observation system both the established uses are described as well as those that are primarily for research. These research systems are used for academic and strategic research, as well as allowing translation of science into monitoring for policy and new observation methods for companies. Research systems can provide innovative observations not available before, understanding of physical and chemical processes and long-term observations of the atmosphere which are critical to scientific deductions, such as those regarding climate change.

The UK has world-class instrumentation for measuring the atmosphere, which is well used for weather forecasting and could be better used for other purposes, such as air quality monitoring or pollution tracking. Maintaining current capabilities and securing investment in new technology remains a challenge.

2.2.1 Fixed site networks

Fixed site networks provide *in situ* and remote sensing observations of local and regional conditions (systems based at local fixed sites for observation or launch of small balloons or sondes). Such measurements may be used directly, incorporated into models to improve forecasts or used to demonstrate compliance with legally prescribed standards.

Examples of fixed site operational systems in the UK:

- Meteorological surface reference sites (SYNOP and AWS networks).
- A UK-wide precipitation radar network.
- Vertical profile measurement systems such as radiosondes for temperature and humidity, ozonesondes for ozone.
- Local Authority and Department for Environment, Food and Rural Affairs (DEFRA) air quality stations (AURN and related sensors).
- Department of Energy and Climate Change (DECC) GHG measurement tall-towers.

The main UK research systems for fixed site air observations are run by NERC through its Centres and through universities.

9. Limb sounding is similar to vertical sounding, which measures the physical properties of the atmospheric columns (e.g. pressure, temperature, wind speed) indirectly by taking readings of emissions and absorption. The limb is a 'slice' across the edge of the atmosphere and limb sounding measures emitted or scattered radiation by looking across the atmosphere into space or at an object (e.g. sun, moon, star).

2.2.2 Satellite-based sensors

Systems which are satellite-based deliver near real-time and delayed information on key atmospheric variables from local to global scale.

Operational satellite systems which the UK is subscribed to and receive data from are particularly based around the EUMETSAT-operated satellite systems for meteorology (Metop and Meteosat) and the EC Copernicus Sentinel series of satellites for chemical properties of air. These have built on the successes of the ESA European Remote Sensing and Envisat satellites, although there is a notable future gap in the lack of provision of limb sounding⁹ observation for vertical profiling of many atmospheric gases.

The research systems for satellite-based sensors are conducted through projects with the ESA. The ESA deploy research and pre-operational demonstration satellites, which have contributed operational-type information for specific cases. The ESA operates research satellites for EO on behalf of the UK, through dual-key support from the UK Space Agency and NERC, and there are upcoming mission launches (ADM Aeolus; Earthcare) concerned with innovative atmospheric physics in which the UK can play a leading role. NCEO is charged with supporting these activities on behalf of NERC. In the past the UK obtained substantial gearing and capability for world-class atmosphere research through bilaterals with NASA, contributing small instruments to larger missions. There remain major scientific drivers for undertaking such work.

2.2.3 Aircraft and balloons

The last category is dynamic aircraft and balloon observations. These platforms complement fixed site and satellite measurements as they provide greater vertical or horizontal resolution than satellites and have a larger coverage than fixed site systems. The use of these is not as prevalent as fixed site or satellite and consists mostly of using research aircraft to monitor specific areas, e.g. for emergency response.

The major UK mobile asset is the Facility for Airborne Atmospheric Measurements aircraft, operated by NCAS on behalf of NERC in collaboration with the Met Office, which provide an excellent platform for atmospheric research and allows flexibility in deployment. There are also small aircraft operated by Universities, alongside involvements in European aircraft and balloon systems. NERC has invested some money into small deployable instruments for UAVs, such as the NASA GlobalHawk, and small instruments for balloons. NERC, its Centres, and also universities have small deployable systems which are funded on a case-by-case basis for specific campaigns. Indeed, this third category of mobile measurement capability is very important for atmospheric research science as it provides flexibility of focus.

2.2.4 Integration of observations

Integration of these observations has been achieved strikingly well in NWP. This has been driven by the rapid increase in satellite observations in the past 25 years, providing a major source of observations of the atmosphere at regional and global scales, whilst location-specific *in situ* measurements remain key contributors of observations in the human-occupied zone near the surface and with very high vertical reach for certain systems. In other areas of atmosphere research and services, this integration is more *ad hoc*, on a project-by-project basis, but is nonetheless invaluable and it is clear that more substantive effort is required to build both co-ordination of programmes and integrated systems.

Where observations have been performed over long timescales, the systems described here can and do provide climate observations. This requires the careful calibration (a challenge) and data rescue for historical data. Considerable efforts are being made to improve the climate datasets, requiring archiving and reprocessing of large quantities of data and advances in scientific techniques. The science community in the UK plays a leading role in the construction and interpretation of climate datasets for the atmosphere.

2.3 Strengths and opportunities

2.3.1 Strengths

The UK is strong in developing observation technologies for studying the atmosphere, leading the development of instruments and methodologies for both the UK and the global community. The development of observation technologies requires skills in physics, engineering, chemistry, mathematics and computing.

The UK is particularly strong in the instrument technology, data techniques and system design. The ability to combine (often mathematically) observations with analysis tools, such as models, has been developed in the UK over decades and is core to the ability to generate outstanding science and knowledge of use to society.

There are significant opportunities to capitalise on this scientific and technological leadership. It is possible to build on current capability to develop new systems that directly inform policy and contribute to areas of public benefit. These new systems could also be used for research to generate new academic insights into the atmosphere which can also be used for policy and public benefit.

The development of observation systems and their expansion from research tools into large-scale operational networks has been a major achievement of atmospheric observation research and a UK-led strength for the future. Immediate information on air characteristics is of value to weather services and to natural hazards response, as well as to scientific monitoring of the critical regions of the atmosphere. The long-term nature of some key satellite systems indicates both the strength of air observations and also an opportunity to grow UK strengths in climate data, which is one of the agendas of the Innovation and Growth Strategy for Space. The development of climate services will increase the re-use of atmosphere observations for economic impact and growth.

2.3.2 Opportunities

There are trends in observation technologies that could be capitalised on in developing the UK's capability to observe the atmosphere, in both the way the data is collected and how it is processed.

2.3.2.1 Developments in air observation sensors and platforms

Developments in sensors, platforms and their distribution are allowing for more data to be collected from more places with more detail.

These developments include:

- new sensors with greater resolution;
- more *in situ* systems deployed locally – smaller, lower-cost sensors leading to greater resolution and coverage of wider areas;
- ubiquitous use of sensors in devices (e.g. cars and smart phones) which can communicate data and positions in real time; and
- remote sensing systems increasingly offering wide coverage through scanning instruments, e.g. in future providing datasets across cities using radar.

2.3.2.2 Developments in models and forecasting

The UK has a strength in combining data with models to analyse the atmosphere in real time, exemplified by the world-leading work of the Met Office in weather forecasting. Future models and forecasting could be expanded to address air quality concerns through the inclusion of chemical composition data.

Developments in weather forecasting have seen further improvements due to the increased use of observations from satellites and improved models for UK and global weather forecasting. These improvements have been further supported by inclusion of the historically collected atmospheric observational data by developing methods to reliably use and analyse it, which has provided a new resource for research and strategic planning.

The strength in weather forecasting could be extended by building better models for air quality and to improve climate models. This could be done by incorporating data on the physical and chemical atmospheric properties into models, as has begun with local air quality forecasts which are improved through the inclusion of *in situ* data. Methods of including atmospheric chemical composition data are already being used in research and being investigated at the European level to improve air quality information. There are opportunities to embed these new developing observations into policy and regulatory requirements where they can deliver significant improvements to understanding of public health. Models are also being developed for other new uses such as determining where GHGs and chemical emissions occur using global observations through model inversion techniques.

In chemical terms, continued sensitivity and specificity improvements have driven observation science forward. The ability to observe new species locally, and also globally from satellites, provides new capabilities for understanding air composition as well as direct observations of key emissions. These developments potentially provide innovative new insights into the science of air and hence into chemistry-related societal and economic problems.

2.3.2.3 Connecting established and innovative new systems

Historically, and continuing into the foreseeable future, there will be a need for both operational and research systems for atmospheric observations as they support one another. The operational systems deploy largely proven technology for systematic monitoring and provision of data to operational analysis systems. The research systems are intended to be innovative and for specific research purposes, and hence will always be valuable additions to current capacity, enabling future operational system evolution.

As the availability of both types of systems has grown, the advantage of improving the connectedness between the systems is becoming increasingly apparent, a point noted by the World Meteorological Organization (WMO) in its ten year vision for integrated observing systems. Operational systems offer long-term observations which could be available continuously for research. Complementing operational systems, research instruments and platforms deliver rapid response capability to intermittent events and research datasets provide new explanations of processes, observations of greater sensitivity and insight into uncertainties in operational observations and models.

Data-sharing with common facilities for processing and application would allow more discoveries and services, increasing the ability of observations to provide knowledge and information to society.

2.4 Challenges

The challenges for air observation systems are:

- the availability and long-term maintenance of specific observation systems fulfilling particular roles in measurements of the atmosphere;
- improving spatial and temporal resolution of observations;
- maintaining long-term records to track for climate and environmental changes;
- increasingly efficient exploitation of datasets; and
- growing uses by individuals beyond weather forecasting.

There are a number of significant issues surrounding air observation systems which have major impacts on the integrated observing system.

2.4.1 Maintaining existing systems

The need to ensure availability of existing observation systems, particularly for fixed site *in situ* systems such as the radiosonde network, weather and air quality stations, radars and premier composition research sites. The quality and quantity of these sites directly impacts the quality of services and research characterising the weather and environment of the UK. This includes the ability to monitor locally relevant conditions, e.g. the effect of wind farms on radar observations.

Satellite programmes also play a key role in UK capabilities for science and services. Although there is ongoing support for the meteorological series of satellites, there are key issues in maintaining capability: protecting the electromagnetic (EM) spectrum and ensuring continued financial support. The use of the EM spectrum is governed by international agreements and national regulation. As it is also used for such things as telecommunications and wifi, it is important to ensure the parts of the EM spectrum used for environmental observation are protected to prevent loss of capability, e.g. degradation of microwave instrument measurements used for weather forecasting due to interference. The other ongoing challenge is to ensure continued financial support for key operational and research satellite programmes with EUMETSAT, the EC and ESA.

2.4.2 Improving resolution of measurements

Particular regions of the atmosphere are not as well observed as they should be. The region of atmosphere close to the surface (boundary layer) is a specific concern where required systems include:

- observations throughout the atmospheric boundary layer to record physical quantities such as temperature, wind, water vapour and dynamical flow;
- *in situ* observations of the atmosphere above the oceans, including coastal seas;
- fixed site *in situ* measurements in the human-occupied zone near the ground particularly for pollutants, for freezing or frozen precipitation, and for fog;¹⁰ and
- profiles of physical and chemical properties of the air in urban areas, which could be collected using instruments on buildings and instrument towers above buildings.

10. Observations of pollutant concentrations are often inadequate for meeting policy requirements. In many air pollution and GHG applications it is the emission rate of a pollutant that can be most informative to determine underlying processes. Models and measurements need to be brought together to give estimates of fluxes.

Observation and prediction of extreme and dangerous atmospheric conditions represent major challenges. Uncertainties in observation and in prediction are greatest in conditions that greatly differ from average, while dangerous conditions may destroy the sensor. Extreme conditions often have highly varying impacts and genesis, so that low-coverage observation networks, which are typical of many operational *in situ* systems, are unlikely to capture the worst conditions and their underlying initiators. A priority needs to be placed on underpinning observations that efficiently match the space and timescales of the maximal impact.

There is a strong need for fine scale observations of the atmosphere commensurate with the grid size of the high spatial resolution models for weather and air quality that can now be implemented for the UK (close to 1 km or higher resolution), and the need to understand climate impacts. High temporal resolution is also desirable through satellites in geostationary orbit as well as *in situ* systems.

At higher altitudes, the free troposphere (above the boundary layer) and lower stratosphere are not well observed in terms of winds, clouds, precipitation and chemistry, yet these are very important regions for forcing of climate and the hemispheric transport of air. There is currently a lack of planned satellite measurements internationally in this part of the atmosphere, despite the opportunities and needs, and this is a major concern.

Alternative approaches through mobile *in situ* sensors are also required as part of the integrated observing system since they provide the high vertical resolution not obtainable with satellites and access regions where satellite data may have limited sensitivity. In addition to research aircraft, instrumented commercial aircraft have provided new insight into free troposphere chemical composition and offer an excellent platform for long-term measurements.

2.4.3 Long-term records

As described in the previous chapter, climate observations, both physical and chemical in the atmosphere, represent a challenge. For completeness, some additional points are noted here. The timescales for systematic change in the atmosphere can be very long and signals small compared to natural variability. Nonetheless, records of the atmosphere are sufficiently long and detailed to enable trends to be diagnosed, at least in near surface weather for which more than 100 years of data is available, and to some extent in the upper atmosphere for which more than 50 years of data is available in some parts of the world.

Chemical observations exist over a shorter time period, with the modern *in situ* instrumental records for most species beginning in the 1960s and 1970s, and satellite records beginning (for ozone) in the 1980s. However, there are otherwise only a small number of dedicated systems for climate or other long-term environmental changes in the atmosphere. For the atmosphere, operational observation systems can and will contribute to long-term climate records but this capability must be recognised and promoted. The challenge with these systems is to maintain quantity (numbers of instruments; data streams; rescue of historical data) and quality (traceable calibration to SI units, unifying of disparate sources of data) over the long-term, to utilise systems efficiently and to exploit data across all systems (e.g. through assimilation into climate models). The application of atmosphere data to long-term environmental change must be a priority.

2.4.4 Exploiting datasets

There is a challenge in sharing, archiving and processing the rapidly growing large datasets of atmosphere observations. There is a good existing UK infrastructure for many physical atmospheric observations, particularly in meteorology. This has been supported by the Met Office, international agreements that enable co-design of systems with other countries, notably the US, and the WMO has been able to facilitate sharing of *in situ* observations from across many countries. More could be done to enable access to datasets to all public science organisations and to realise efficiencies in value-for-money, productivity and optimised co-investment. There is a great deal of significant information that could be mined from existing atmosphere datasets.

For chemical composition, this data-sharing infrastructure does not exist in the same way, although networks exist for bringing together air quality observations at fixed sites across Europe. The users and providers of chemical information are often different and are highly dispersed. For example DEFRA has legal responsibilities for meeting binding EU air quality targets, but it commissions monitoring services from the private sector. Local Authorities have legal responsibilities for implementing air quality strategies locally and take a wide range of different approaches to their observation systems (from in house to fully outsourced).

The landscape is similarly complex in other areas, for example, GHGs, eutrophying chemicals and ozone depleting substances. International developments through Copernicus and WMO Global Atmosphere Watch (GAW) mean that this situation is beginning to change, but there are clear challenges to include UK expertise and capabilities within these systems, and to take advantage of UK knowledge of the complexity of chemical systems. Clear remits and responsibilities are needed for appropriate datasets to ensure they are easily accessible and exploitable.

2.4.5 Uses beyond weather forecasting

Much improved access to data, with appropriate signposting and Government support, is likely to make a considerable difference to the impact of air observational data to UK society. There is strong recognition in public life of the role of the Met Office and of its importance, particularly for physical weather forecasting and climate modelling. In contrast, for both the public and for Government, the importance of chemical air systems is only partially recognised and there is less recognition of the new powers offered by *in situ* instrumentation and new satellite systems.

The chemical composition of air is likely to become increasingly significant due to its connection to health, for example, the World Health Organization predicts that air pollution will be the largest global cause of preventable death by 2030. The observational power that is becoming available in the chemical domain will only realise its full value when the data can be easily put in the hands of end-users in a digestible and usable form. These might include integrated advice on transport and commuting patterns, recommendations on physical activity, home ventilation or medical interventions. The challenge is to increase attention on chemical observations and to enable the data to be easily accessible so everyday use can be made of information on air quality so that it can become as widely used in society as weather information.

2.4.6 International collaboration: air is a global quantity

The general considerations for international collaboration are summarised in the International section. Here we emphasise some key points to provide context to air observations. In particular, it is important to emphasise that the UK needs to know about the air over the UK but also the characteristics of air globally. In addition, knowledge of air globally is needed to support UK interests across the world, including climate hot spots.

Fortunately, there are some areas of excellent international cooperation and exchange of weather-related air observations, particularly at the larger scales and for the free atmosphere. The main Western country-based satellite operators exchange their data freely with each other, and hence with the national weather services. International formats have been agreed for the exchange of observations of the physical properties of the atmosphere. The UK's support for EUMETSAT and ESA is critical in this regard.

Although there is good availability of satellite data for chemical composition, the same ability to share data does not exist formally as for physical observations. For *in situ* chemical observations in the background atmosphere, the WMO GAW programme provides a framework for ensuring data quality and data-sharing. GAW, however, probably reflects only a small fraction of total global observation effort and explicitly excludes urban observations. There has been some progress at regional levels in integrating datasets on air pollutants in Europe via the European Environment Agency (EEA) and EMEP and in Asia via EA-NET. There are also many delivery systems which make data-sharing and consistent practice much harder to achieve. For the Copernicus satellite systems, the UK route is through liaison with ESA and the EC Copernicus Core Services. Considerable work is required internationally to deliver data efficiently with effective quality control.

2.5 Future trends

2.5.1 Trends

Due to population growth, wealth growth, urbanisation and climate change, the sensitivity of human life to atmospheric disturbances will grow. The related demand for monitoring and prediction will also increase as a result, both for hazard management and for forward planning, particularly on the monthly to seasonal timescale. Indeed there is some urgency to supporting innovative developments in air observations to meet priority societal and economic demands.

Integrated, multi-platform observing systems are required to improve both operational services and our understanding of atmospheric processes. Not only are they much more powerful than the individual components alone, but the ability to sense different dimensions of the atmosphere simultaneously provides a complete picture of the atmosphere that would be difficult to achieve by other methods. This is particularly important for modelling and incorporating data into models. New research observations need to demonstrate their uniqueness and ability to contribute to the overall observing system.

Operational systems and research systems should complement one another. There is an increasing trend towards co-design of systems, recognising that there are key air properties that need new sensors (e.g. wind, precipitation, clouds, chemical speciation and aerosols), that data incorporated into models should provide consistent information, and where improvements in temporal and spatial resolution (both horizontal and vertical) will have profound impacts, for example:

- increasingly high spatial resolutions of regional weather and chemical models;
- coverage at fine spatial resolution across cities;
- new strategic *in situ* observations and supersites; and
- advanced capabilities in geostationary orbits.

In terms of satellite systems, the emphasis will remain on large international programmes. However, there will be an increasing pressure for bespoke EO space missions for research, demonstration of new technologies or particular applications for scientific and societal benefit. There will also be a potential trend towards networks of fixed site or mobile sensors, or wide coverage, fixed site remote sensing instruments.

Further use of the electromagnetic spectrum, especially by microwave instruments and active optical lasers, for remote atmospheric sounding offers further benefits, but also cautions as signals can only be detected if noise is low enough, and interference is already becoming a major threat to existing capability. Spectrum sharing is a critical issue where the internationally agreed access to frequencies for observations needs to be protected; otherwise there could be a significant loss of capability with direct impact on the public.

2.5.2 Disruptive air measurement technologies

The demands for new techniques and technologies for observing the atmosphere are such that potentially disruptive technologies are always evolving. Three technologies with the potential to make large impacts are:

- geostationary sounding instruments on satellites;
- Global Positioning System (GPS) satellite constellations and ground-based receivers enabling much wider coverage of air networks of physical and chemical sensors; and
- UAVs.

Another area which could have a significant impact is the use of the lower quality data available from citizen observations or other non-professional sources (e.g. sensors in cars and smart phones). Currently these networks have coarse resolution and lack a breadth of measurements; however, if different organisations shared their data and good use was made of smaller sensors combined with GPS in real-time, these limitations could be overcome. This presents additional technical and legal challenges, however, coping with the large volumes of data generated, sustaining the networks, quality assuring the data and dealing with privacy considerations for individual users. If successful, these networks could play an important role in smart cities and hazard monitoring and warning.

In seeking new methods to access the atmosphere in critical, hard-to-reach areas, UAVs may yet have a substantial role to play although the route for research progress is clearer than for operational implementation. Certainly there is a trend towards increased programmes testing the utility of UAVs for atmospheric measurements, e.g. the NASA GlobalHawk system. Limitations include understanding the range of UAVs, their mass and power restrictions, and legal constraints on their use. Efforts in the UK are disconnected and diverse, and would most likely benefit from coherence across environmental observations.

2.5.3 Capitalising on future systems and usage

A big challenge in air observations is the development of efficient systems which maximise the return on investments in the instrument technologies. Greater sharing of data between central and local government and between different agencies in Government would help – possibly to the extent that one such agency acts on behalf of others in the collection and dissemination of the raw data in some areas. Research Councils, such as NERC, Science & Technology Facilities Council, and others, have very good expertise in data storage and data access which could be utilised and complemented by experience in the Met Office and business.

Ownership and protection of sensing data could be a major obstacle to improved sensing of the atmosphere and its impacts. Further work needs to be done to understand the likely growth in sensor and satellite networks and the access routes to data.

2.6 Summary

Observations of air are a key contribution to national public life and to economic prosperity. The economic value of air observations and their use in weather forecasting, natural hazards work and urban living is indisputable and strong. Government policy requires a strong evidence base from air observations for major policy actions and continued work is necessary to encourage Government departments to make best use of all observation data for the atmosphere. The Met Office, NERC and its Centres (NCAS, NCEO, CEH) play substantive and continuing roles for the UK working with the academic community and specialised small companies.

There is a strong base for long-term air observations existing in operational national networks and international programmes, and in complementary long-term observations in strategic research programmes. These long-term measurements are valuable for weather forecasting and for pollution monitoring but also have considerable benefit for the research community (including climate scientists).

Continued attention needs to be given to the design and implementation of the multi-platform integrated observations systems that are needed to sustain services and research and to make the necessary advances in monitoring and forecasting the atmosphere in the future. This involves prioritisation with respect to sustainability of key systems, implementation of next generation sensors, and international collaboration with the cost sharing and gearing that this brings.

Spectrum sharing is an area where frequencies for observations must be protected. The benefits to the UK from effective use of these systems are substantial with respect to the investments, and support efficiency and effectiveness of the national infrastructure for air observations.

It is clear that there is a significant research observation strength in the UK which is fundamental and complements the operational programme. In the research world, two key areas are research satellite missions for air observations building on UK strengths, and operational and research networks of sensors, particularly in cities. The needs are for fine scale observations targeting critical regions of the atmosphere at street level, in the boundary layer and in the climate-forcing, transport-dominated regions of the free atmosphere above. Where fine scale observations can be combined with models to estimate emission fluxes of pollutants, both short and long lived, these are likely to be of high value in validating policy and Government interventions. Research satellites and sustainable networks of miniaturised sensors will provide major progress, especially where such investments can be targeted in a cost-effective manner in critical areas of science.

International cooperation is central to implementation at a reasonable cost for many of the UK's requirements for air observations and providing information both over the UK and across the globe with its influence on the UK. Small, strategic investments in satellite instruments could leverage some large benefits and this is an important consideration. Hence whilst the investment in large programmes is paramount, cost-effective bilateral arrangements (e.g. with USA, China, France) would allow for substantial gearing of investments in EO instruments for atmosphere science.

Finally, observations of air are critical to national policies, public benefits and environmental services. Further integration of air observation systems will provide a better evidence base for governments, whilst easier access to data, supported by processing facilities, will enable better information to be delivered to those who need it across Government and industry.



Chapter three

Oceans and ice

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Iceburg. © Tingitania.

Oceans and ice

3.1 Introduction

This chapter covers the key issues that arise when considering how environmental observations provide policy relevant information concerning oceans and ice.

An important point that is also highlighted in other chapters is that continuity of observations is a key issue if the observations are to be useful in a policy context. The reasons for this are:

- to provide a baseline (mean, seasonal changes, variability) against which any change or unusual event may be assessed (for example, increase in sea level or coastal flooding)
- investment in any end-to-end system providing policy relevant information is pointless if the observational input is not guaranteed (this is an issue of data security and one well recognised by operational agencies such as the Met Office), and
- to ensure that the ongoing requirements for information to satisfy UK and EU environmental regulation and legislation continue to be met.

Of course, the corollary of the need for continuity (sustained observations) is the need for continuity of funding for the observations. For many of the environmental observations discussed below uncertainty regarding continuity of funding is a major issue. The recent degradation of the Global Tropical Moored Buoy Array shows the vulnerability of environmental observations (in this case *in situ* ones) to budgetary pressures.

A key point to note for the ocean is that, as one stakeholder phrased it, “the under sampling problem cannot be overstated”. Oceanic variability exists across a very broad spatio-temporal range (seconds to centuries, millimetres to thousands of kilometres), so even with modern technologies the ocean is seriously under-sampled. Therefore, any technologies that can improve spatio-temporal sampling will enhance environmental observations.

Before proceeding it should be noted that, with regard to the oceans, a distinction can be made between coastal seas and the open ocean, as the former are subject to much more UK and EU environmental regulation and legislation, and, with regard to ice, it is convenient to distinguish between land (such as on Greenland and Antarctica) and sea ice (such as in the Arctic and “Southern Ocean”). These distinctions are implicit in what follows.

3.2 Current use

Currently environmental ocean and ice observations are gathered by many means, both in terms of the platforms from which the observations are made and the sensors that measure specific parameters of environmental interest. Three areas are briefly touched on here: satellite, airborne and *in situ* observations.

3.2.1 Satellite observations

Satellite data now provide a wealth of ocean and ice observations, for example:

- sea level, wave height, wind speed (radar altimetry);
- ice sheet volume and sea ice thickness plus extent (radar altimetry);
- ice sheet mass (gravity measurements);
- sea ice extent (passive microwave);
- ocean biology (chlorophyll from ocean colour);
- sea surface temperature (SST, infrared and passive microwave);
- sea surface salinity (SSS, passive microwave);
- wind speed and direction (scatterometry);
- wave spectra (synthetic aperture radar (SAR)); and
- ocean bottom pressure (gravity measurements).

Such observations enable a global picture of environmental changes to be painted but are largely restricted to the sea or ice surface (as electromagnetic radiation cannot penetrate far in to water). Nevertheless, the observations have shown the global sea level to be rising (radar altimetry) and detected changes in the Arctic sea ice (passive microwave) and the Greenland and Antarctic ice sheets (radar altimetry). Likewise changes in the ocean biosphere have been seen, but the satellite record is too short at present to determine whether these are indicative of climate change. Environmental observations from satellites are generally undertaken by space agencies (ESA, NASA) and operational agencies (EUMETSAT, NOAA), who have in place systems for processing and distributing the data.

Satellite technologies also allow real-time tracking of ships on which Automated Identification System (AIS) transceivers are now required. The resulting ship tracks are useful for cargo tracking, maritime surveillance in coastal waters, collision avoidance, search and rescue and accident investigations at sea. In terms of environmental observations, the AIS has proven most useful for monitoring of national fishing fleet activities, particularly where they fish, when and for how long.

3.2.2 Airborne observations

Airborne systems have generally been used for environmental observations in coastal seas and over land ice, due to limitations on the operational range of the aircraft systems used. Common uses of such systems are for applications like oil spill monitoring and tracking, detection of harmful algal blooms, mapping bathymetry and water quality assessment. In the land ice case, airborne radars and lasers have been used to map ice sheets. The distribution of data from such systems is more *ad hoc* than that from satellites.

3.2.3 *In situ* observations

Traditionally, *in situ* observations of oceans and ice have been made on board ocean research vessels. This chapter primarily concerns new technologies that are able to sample the ocean cost effectively, more rapidly in time and more densely in space than is possible using by ships. But there is still important use for shipboard observations in making highest quality environmental surveys that include the deepest parts of the ocean where satellite, airborne and new technologies cannot penetrate. Of particular note for open ocean observations is the CLIVAR GOSHIP programme to survey the global ocean's physical and biogeochemical properties with great accuracy from top-to-bottom on a decadal timescale in order to detect subtle climate changes in the ocean. For coastal waters, shipboard surveys remain the principal method for assessing environmental water quality and fish stocks to meet national and international regulations.

Modern *in situ* observation systems for the global ocean are many and varied. They include the global tide gauge network, ship-based sensors on commercial ships such as the towed Continuous Plankton Recorder, floats (for example, surface buoys and drifters and Argo floats, with the latter making measurements of temperature and salinity down to 2000m), moorings (such as the RAPID array at 26.5°N in the Atlantic monitoring the meridional overturning circulation (MOC), which carries heat northwards); or the TAO and PIRATA arrays for monitoring air–sea interactions in the tropical Pacific and Atlantic, respectively) and more recently ocean sub-surface gliders and other AUVs. Argo floats have shown the changes occurring in ocean heat content, which in the Atlantic are related to change in the MOC and possibly to the hiatus in the rise in global air temperature (more heat entering the ocean). Tide gauges have demonstrated that the sea level is rising. In many cases (for example, tide gauges, Argo, RAPID array) systems are in place for distributing quality-controlled observations.

For coastal waters, countries typically build a network for national monitoring and assessment of environmental variables. For example, around the UK, the UK Integrated Marine Observing Network¹¹ which is part of the UK Marine Monitoring and Assessment Strategy (UKMMAS), details the operating *in situ* monitoring sites including meteorological buoys, wave buoys, bottom trawl surveys for fisheries assessment, isolated buoys in Tíree Passage, Liverpool Bay and the Western Channel, as well as regional networks for Scotland and Northern Ireland. Further information is available on UK-DMOS,¹² a meta-data database, which includes physical measurements as well as contaminants and various biological parameters. These are covered by various evidence gathering groups overseen by the Marine Assessment Reporting Group (MARG).¹³ A practical use for the wind and wave buoys of great societal value is to use the real-time observations with coastal storm surge and wave models to make predictions for local coastal areas prone to flooding.

3.3 Strengths and opportunities

3.3.1 Using the data

While the systems described in Section 2 produce environmental observations, they generally only lead to policy relevant information through further analysis and/or use with models. The Met Office is perhaps the best-known example of the latter approach, through its use of environmental observations to validate and verify models (weather, wave, seasonal and ocean forecasting, and climate projections), and assimilation of the observations to improve forecasts. The assimilation of data into models is a key way to synthesise observations of different types from diverse sources. For example, ocean forecasting assimilates observations from Argo floats, surface drifters, satellite infrared and passive microwave sea surface temperature (SST) and altimetric sea surface height, among others. Note that there is now a move towards coupled predictions at all timescales, including

weather forecasting. This simply underlines the needs for environmental observations at all timescales (and associated space scales) for assimilation, validation and verification. Results from observations and models feed into policy in various ways, one example being the AVOID programme¹⁴ in the case of climate.

3.3.2 Technological opportunities

The following examples illustrate some of the new technological opportunities in these areas. They have been selected, from the many examples that could have been chosen, to highlight topical areas where new technologies could be used to advance knowledge about oceans and ice.

1. Surface oil spill monitoring

currently this is carried out by sensors flown on aircraft, but it could be carried out by miniaturised sensors on drones. The technology exists or is being developed and could reduce the cost of monitoring significantly. However, there are issues with flying drones in UK coastal airspace that might prove a barrier to adopting such technology. The drone measurements could be complemented by in-water measurements from gliders.

2. Subsurface oil spill plumes

the Gulf of Mexico oil spill had a substantial subsurface component, as did the Braer spill off Shetland. AUVs including gliders with suitable sensors can be used to monitor the 'hidden' spill and to track its trajectory to help quantify the true extent of the pollution.

3. Deep ocean circulation observations for climate

so-called deep-Argo floats capable of measuring temperature and salinity over the full ocean depth could be deployed as they become available. Here the barrier is probably one of cost as, initially at least, one would want to maintain the existing Argo float network (currently depth capable to 2000m).

11. <http://www.uk-imon.info/>

12. <http://www.ukdmos.org/>

13. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263756/MSCC-v10-WEB.pdf

14. <http://www.avoid.uk.net/>

4. Improved monitoring of ocean winds and waves

(feeding into weather and wave prediction modelling) the use of constellations of small satellites taking advantage of GPS signals of opportunity to measure wind and wave conditions (GNSS-R).

5. **Advances in radar altimetry**, including higher spatial resolution and better accuracy allowing improved measurements of sea level, wave height and wind speed, particularly in coastal regions to within a few kilometres of land. Examples of the benefits of this improvement would be: better linking of open ocean sea level rise to coastal tide gauge observations; and better near coast wave measurements leading to better wave predictions by assimilation of data into wave models, which would benefit coastal flooding prediction.

6. **UK-led NovaSAR S-band system** has established a way forward for low-cost SAR technology with many potential environmental monitoring applications, such as flooding, shipping and oil spills, and ice.

3.3.3 Maritime surveillance

In addition to observation from space and *in situ* sensors, the recent development of ocean (sub-surface) gliders and associated sensor technologies is revolutionising observational capabilities for scientific experiments, commercial applications, military operations and environmental monitoring. For example, it is now possible to contemplate sending a fleet of gliders to comprehensively survey the coastal seas around the UK. Similarly, gliders could be sent to operate in military hotspots, to observe pollutant plumes or harmful algal blooms, and in the near future to make observations under the Arctic sea ice. Currently, gliders have restricted depth capability (down to 1000m), but this is not a major limitation for many applications. Full depth (approximately 6000m) ocean gliders are under development. Presently gliders are used optimally for monitoring a special event or phenomenon or region rather than for large-scale, long-term monitoring. For the first time in-water maritime surveillance is economically feasible with a short lead time anywhere in the world.

3.3.4 UK leadership

The UK is an international leader in many areas of environmental observations, both technologically and scientifically. Examples include: measurements of land and sea ice (particularly through Cryosat), the development of small satellite technologies (such as the use of GPS signals of opportunity to measure winds and waves), the production of long-term validated climate records (such as SST), and the development of the RAPID monitoring of the Atlantic meridional overturning circulation. The UK is also an international leader in specific geographical regions such as the North Atlantic (with RAPID), and in the Antarctic through the strength and depth of the British Antarctic Survey's logistics, exploration and scientific achievements.

However, the UK does not always benefit from its leadership, as there is often insufficient or too slow investment. For example, the UK has been at the forefront, both in terms of technology and scientific understanding, of developing low cost systems for using GPS signals of opportunity to measure ocean winds and waves. Despite this, it is NASA that will fly the first constellation of small satellites that exploit these UK-led developments.

3.4 Challenges

3.4.1 The most important challenges

The most important environmental challenges facing policy makers related to oceans and ice are:

- Impacts of climate change. For example, the opening up of the Arctic Ocean both to shipping and oil exploration due to the faster-than-anticipated reduction in sea ice. Both this opening up and the decline in Arctic sea ice itself will impact Arctic ecosystems. Another example would be sea level rise combined with storm surges and large waves leading to coastal flooding. A final example could be change in the ocean biology (including the effect of ocean acidification due to CO₂ absorption) affecting biodiversity, ecosystem services and fisheries. Sustained observations are required to assess the magnitude and pattern of climate changes.

- UK and EU environmental regulation and legislation. These apply predominantly to the coastal sea and include issues such as water quality, pollution, harmful algal blooms, and so on. Again sustained observations are needed in coastal waters to provide the continuous assessments to satisfy environmental regulations.

With regard to challenges to developing and using environmental observation technologies in the UK context, these vary from area to area. For example, a specific challenge in the satellite area is the gap between technological developments and environmental applications. Thus, ESA and UK Space will fund the development of new technologies (largely engineering) and NERC will fund the use of new environmental observations (largely science), but no one seems to have a clear responsibility for ensuring that the satellite observations can be translated from engineering units to environmental parameters, and then validated – key steps to ensuring the usefulness of the data, whether for scientific or policy relevant applications.

With regard to *in situ* observations, at present for many such observational systems the funding is either through research channels (as for RAPID) or in an *ad hoc* fashion (as for Argo). If such systems are to provide ongoing policy relevant environmental observations, the barrier to be overcome is how they can be sustained in the long-term. If policy decisions are to rely on environmental observations, then the issue of data continuity (data security) must be addressed.

One perennial issue in terms of acquiring environmental observations is the question of how they should be funded, and how decisions should be made regarding funding priorities. There is no single source of funding for the ongoing sustained observations, whether satellite or *in situ*, that are necessary to provide policy relevant information. To take the satellite example, the Met Office is responsible for the UK contribution to EUMETSAT, while UK Space is responsible for the UK's contribution to the ESA, and the Copernicus system is part funded through the UK's contribution to the EU. In addition, in an era of generally declining budgets (with the odd exception, such as Government investment in robotics, which has benefited the development of the use of AUVs), there is the tension between funding new technologies versus continuing to fund existing environmental observations – who decides?

3.4.2 End-to-end value chain

With regard to climate change the existence of the IPCC to a large extent provides the integration of information that is required for policy makers (specifically through its Summary for policymakers), but this is at a fairly high level and at a global scale. For UK specific policy issues (which might be global or local) it is necessary to provide the means to integrate the environmental observations in relevant ways. Often this is through specifically funded projects such as AVOID rather than in an ongoing consistent way. The Met Office climate programme funded by DECC and DEFRA may be seen as an example of ongoing work to provide policy relevant information from both environmental observations and models.

In the case of coastal seas, DEFRA works with a variety of organisations (such as the Centre for Environment, Fisheries and Aquaculture Science, the Environment Agency, the Marine Management Organisation and various organisations across the Devolved Administrations, e.g. Marine Scotland, Department of Environment Northern Ireland, Natural Resources Wales) to ensure that UK and EU legislation and regulation are being adhered to.

3.4.3 The need for real-time data

The meaning of 'real-time' varies significantly from application to application and from environmental observation to environmental observation. For example, for weather prediction oceanic wind observations are required within a few hours, while for seasonal and longer-term predictions of ocean circulation, temperature and salinity observations within a few days are probably adequate.

3.4.4 Translation of new technology

In the area of satellite-based (and possibly other) environmental observations, one barrier in the UK is the lack of a mechanism to identify opportunities for technological pull-through and then support the transition from proof-of-concept technology to validated environmental observations that can be both scientifically and policy relevant.

3.4.5 Skilled workforce

A well-acknowledged barrier to the development and use of new technologies for environmental observations is the difficulty of recruiting people with the requisite mathematical and computing skills into the environmental sciences. This is a long-standing problem and unlikely to have a simple solution.

3.5 Future trends

3.5.1 Technological advances

Looking ahead, bearing in mind that predicting the future is a difficult art, some of the technological advances that will benefit the area of environmental observations are:

- miniaturisation of sensors (*in situ*, airborne, satellite; for measuring both physical and biogeochemical parameters);
- better use of existing platforms (e.g. met buoys, SMART buoys);
- new platforms on which to deploy sensors (e.g. gliders, drones, small satellites, tagged seals); and
- moving from individual platforms to groups (e.g. fleets of gliders, constellations of small satellites) and associated 'command and control' systems to optimise their observations.

All these will need to be tested against existing observational systems to ensure their ability to maintain continuity of observations as well as provide enhanced observations (either of new environmental parameters or increased numbers of observations of currently observed parameters).

Although citizen science is a less likely development for ocean and ice environmental observations (for obvious reasons) there are aspects of coastal observations that could be developed. For example, combining ongoing sea level observations (tide gauges and radar altimetry) with observations and photographs taken by people living in coastal areas during incidents of coastal flooding could allow improved characterisations of such events and eventually improved predictions.

3.5.2 Gaps in environmental observations

Some of the gaps in environmental observations that might be addressed in the next decade through technological developments include (not in any order of priority):

- deep ocean circulation by deep-Argo or full ocean depth capable gliders;
- biogeochemical ocean parameters by bio-Argo;
- improved coastal ocean surveillance deploying high frequency (HF) radar stations on offshore platforms and shore stations supplemented with fleets of ocean gliders and airborne drones;
- improved sampling of ocean winds using GPS signals of opportunity (GNSS-R); and
- global ocean currents at the sub-mesoscale (<10km) by new developments in satellite altimetry (SAR altimetry, interferometric altimetry).

Some of these gaps are closer to being closed, such as the use of fleets of gliders in coastal waters (currently being trialled), whereas new satellite systems usually have a timescale of the order of a decade from conception to launch. A gap in land and sea ice observations will occur when the Cryosat mission ends as no follow-on mission is currently envisaged.

3.5.3 Continuity versus novelty

A key issue with all the new developments is how to balance continuity of existing policy relevant environmental observations against the opportunity to gain new ones. At base this comes back to the issue of how to fund long-term strategic environmental observation programmes and how to transition observations that have been developed with research funds to operational status, once the need for their continuity has been acknowledged.

In the UK, there is no operational agency with responsibility for maintaining sustained observations of the oceans and ice. In the USA, the NOAA is tasked with this responsibility (e.g. maintaining the US contribution to the global Argo network and satellite measurements of SST).

While, in principle, in the UK this could be done via coordination between agencies, in an era of declining budgets this is difficult to achieve in practice as each agency's priorities differ and there is no ultimate arbiter for any decisions that need to be made. Two options suggest themselves:

1. responsibility (and budget) for sustained ocean and ice observations is given to one agency (for example, NERC);
2. the office of the Chief Scientific Adviser acts as arbiter, with power to redistribute budgets for sustained observations accordingly.

Note that setting up a new agency to take responsibility for sustained observations seems to be overly bureaucratic and not a good way forward.

One final point to be made is that novel technologies for making environmental observations are being developed all the time and may provide more cost effective solutions for obtaining the observations. However, for many applications, such as climate studies, it is vital to overlap observing systems using old technology with ones using new technologies to ensure the continuity and calibration (new against old technology) of critical environmental observations. This applies to both satellite observations, such as sea level or SST, and to *in situ* ones, such as sea level from tide gauges. The corollary of this is that in the short-term both old and new technologies may need to operate in parallel, which may lead to a corresponding short-term increase in cost (but with savings in the longer-term).

3.5.4 Continuing environmental observation challenges

To make best use of environmental observations, the following will be continuing challenges:

- The question of uncertainty in the observations needs to be considered. Are they good enough for the purposes for which they are to be used?
- Re-processing and re-analysis of historical observations (whether made *in situ* or by satellite) is a critical task for continually improving the climate record.
- There is a continuing need for scientists to be involved in the acquisition and analysis of environmental observations that are being used for policy purposes. This is to ensure the scientific validity of the observations.
- A danger to be avoided is the view that improved environmental observations will enable the narrowing of uncertainties in predictions, but the reality is that improved observations may broaden the range of uncertainty. For example, the recent 2009/10 event observed in the Atlantic meridional overturning circulation lay well outside the range of interannual variability seen in the climate models used in the latest IPCC report.

3.6 Summary

Environmental ocean and ice observations depend on a range of platforms – satellite, airborne and *in situ* – and a multitude of sensors, but some common themes emerge from this.

- Environmental observations *per se* do not usually provide policy relevant information. Therefore, the UK needs to define what it sees as the key ocean and ice policy relevant environmental observations that it wants to invest in (taking account of international programmes that it is already involved with to gather such observations). Then it needs to ensure that the so-called value chain is in place to ensure that the information reaches the relevant users and stakeholders.
- The responsibility for sustaining environmental observations (or the UK contribution to such), and so for funding them, needs to be clearly defined along with a separate budget. Without data security (sustained observations) there is no point in investing in systems that depend on them, whether for policy, commercial or other purposes.
- The UK needs to develop its current skills base to make environmental observations, to ‘translate’ them into policy relevant form, and to make them readily available. Then when anomalous events or longer-term changes occur they can be assessed and interpreted against the known background conditions.

The UK is well placed to make and make use of many different types of ocean and ice environmental observations that are policy relevant, but the issues raised here need to be addressed if the UK is to fully benefit from its investments in this area.



Chapter four

Land and freshwater

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Left

Ariel view of a river.

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Land and freshwater

4.1 Introduction

Observations over land areas come from imagery or measurements collected by satellite, aircraft or other airborne platforms, complemented by data from vehicles, ground-based surveys and instruments, and including direct field work by in-sector experts or anonymous citizen scientists. These form sources of information for mapping landscape features and their changes, for tracking sudden events like the impacts of a natural disaster, or for objective measurements (biophysical or geophysical variables) of the land surface (and sub-surface) and its water bodies, to support scientific models and to track the impact of policy.

The user community for land observation applications is very diverse, and includes (directly or indirectly):

- the science and research community;
- policy users / evidence-based decision makers at national level;
- regional policy users, local government and city administrations;
- commercial users; and
- the public, through internet-based tools like Google Earth or through the broader quality-of-life benefits brought about through environmental management.

UK-based users may also have interests outside of the UK, which include DECC, DfID and DEFRA. Internationally, other users may be national governments, non-governmental organisations (NGOs), EU institutions or international agencies such as the UN or World Bank.

Land observing systems have not been operationally integrated with the same degree of success as weather observing systems. This situation may begin to change with upcoming large scale observing systems and services like that offered through the EC Copernicus programme. The Copernicus Land Service encompasses a global component, a pan-European component (covering the full EU territory) and a local component (currently for Europe's principal urban areas), reflecting different geographic coverage scenarios, mapping scales and themes. The continental component has been preparing a suite of five 'high resolution layers' of cartography from satellite imagery, describing urban/built-up areas, forestry/ woodland, grassland, wetlands and water bodies.

4.1.1 Environmental Issues related to Land

National or EU policy forms a framework for understanding and tracking landscape status and change, underpinning an 'evidence-based' policy approach which geographically-referenced data or observations support. The European Environment Agency provides a series of regularly updated themed reports on land issues across the EU,¹⁵ based on inputs from Member States which provide a useful reference.

Many of the concerns covered by different policies overlap, in terms of the landscape phenomena that require monitoring. For example, habitats and their related biodiversity will be affected by both climate change and agricultural practice. In turn, agricultural practice may impact on water quality in adjacent river networks or reservoirs, which may affect aquatic biodiversity. In turn, data acquired to support one policy area has the potential to be re-used in support of another.

15. Available at <http://www.eea.europa.eu/themes>

UK agricultural policy is concerned with agricultural scheme compliance monitoring, tracking and assessing the impacts of the Common Agricultural Policy on the agricultural landscape, improving farmland biodiversity, and safeguarding animal and plant health. Annualised information is required for statistical summaries, for agricultural census purposes and policy implementation. At field/farm level, there is ongoing interest by farmers in the concept of precision agriculture, using ground-based and airborne instruments for detailed within-field information on crop status and condition.

The management of agricultural land has a profound impact on the quality, quantity and speed with which drainage waters reach surface waters and groundwaters. Required annual information to support Catchment Management focusses on high-level agricultural land cover and land management criteria which may influence areas vulnerable to soil or fertiliser loss, in relation to topography and proximity to water courses. Water bodies themselves show problems of algal blooming and consequent eutrophication. Upland landscapes form another dimension to catchment management, as well as for nature conservation policy where concerns are related to changes in vegetation cover and type and in moorland wetness, together with indicators for peat exposure and erosion risk.

Habitats have been affected in recent decades by both land use conversion and well as changing land management practices, and where the impacts of invasive non-native species and the complex effects of climate change on habitat condition are increasingly a factor.

Coastal zone issues also form a specific policy sector within the UK, where policy must reconcile and manage potentially competing activities and interests. Accordingly, the concept of Integrated Coastal Zone Management has been in development since the 1990's to address these issues in a holistic manner, both nationally as well as in response to European policy.

In the UK, the majority of managed forests are plantations of known composition, under management plans and where average stand sizes are small. Less is known about wooded areas less than 0.5 hectare in extent, but also playing a valuable ecosystem role in both rural and urban settings.

Land use changes in and surrounding the urbanised environment form some of the most persistent and dynamic land changes happening anywhere. In the UK, urban creep is a recognised issue affecting loss of permeable urban garden space, 'greenbelt' and green field areas, contributing to the phenomenon of 'urban heat islands', urban drainage and flood risk. Other issues concern building energy efficiency, urban climate and land stability.

Monitoring of infrastructure relates to roads, railways, ports, airports, power lines and pipelines. These assets are monitored to assess their relative condition, safety, efficiency and security. Waste disposal sites (e.g. landfills) represent risks of methane leakage, subsurface fires, or risk of leachate plumes reaching the groundwater.

The sustainable future use of the geological subsurface — for groundwater, energy and waste disposal — will require much greater understanding of subsurface characteristics and processes, together with existing knowledge of historic resource extraction.

Further to the environmental issues identified above, there are a range of international environmental issues relevant to the UK. These include tropical deforestation, mapping for land ownership and tenure, and damage assessments from natural disasters.

4.2 Current use

4.2.1 Data Sources

A range of observational technologies are in current use from various platforms, from orbiting satellites through to airborne, vehicle-based, and ground-based. Instruments may be categorised into ‘passive’ and ‘active’ technologies.

4.2.1.1 Satellites

Satellites provide repetitive coverage according to the orbital pattern, with overpasses over the same location (typically at the same local crossover time) measured in days.

4.2.1.2 Aircraft, UAVs and HAPs

Aircraft offer the flexibility of focussing operations for when data campaigns are required at specific times, according to clear weather breaks. Aircraft are also used to host geophysical instruments for sub-surface observation. UAVs, also known as ‘drones’, are just entering tentative usage as aviation regulatory controls adapt, and are currently best suited for local areas of inspection with (typically) quite simple instrumentation on board small airframes. High-altitude, long endurance solar-powered High Altitude Platforms (HAPs) are very much at the research and development stage with a range of theoretical operational profiles.

4.2.1.3 *In situ*

In situ ground-based passive instruments and sensors for recording environmental parameters (e.g. temperature, moisture) at specific locations are expanding in sophistication, but currently tend to form their own observation networks but with a vision for them to contribute towards a holistic observing system. Their role concerns continuous time-based measurements or observations, primarily in support of scientific models rather than mapping. Ground-based active instruments are typically more purposive in how they are used. Examples include the tripod-mounted or handheld terrestrial LiDAR instruments, or vehicle-mounted or towed ground penetrating radar.

Passive *in situ* instruments are applied particularly for measuring local soil/vegetation conditions, climatology, weather-related parameters, and the hydrographic network of streams and rivers. For example, the land surface observing network operated by the Met Office is primarily for recording the current status of the atmosphere but includes land-related measurement profiles of soil temperature, depth of lying snow, amount of received rainfall, and concrete minimum temperature measurements at some locations, mainly relevant to the incidence of ice on runways or roads.

Wireless sensor usage, particularly in rural settings, partially remains in the research and development domain and examples of networks have been quite local in coverage, though with the promise of ‘smarter’ observation strategies. Examples of wireless trials (not necessarily in the UK) have included:

- Cattle monitoring: the position of livestock over time through GPS collars, together with soil moisture at various locations as an indicator of pasture vigour, and with video cameras at water troughs.
- Ground water quality: measurements of salinity, water table and water extraction rate in boreholes.
- Lake water quality: vertical temperature profiles providing information about water mixing, using anchored floats with a high-gain antenna and solar cell on the float.
- Micro-climate sensing (rather than ‘land’ *per se*): suites of instruments per location for wind direction, wind speed, soil moisture, humidity, air temperature and leaf wetness, e.g. for vineyard management.

4.2.1.4 Citizen science and crowdsourcing

Citizen science or ‘crowdsourcing’ forms an expanding area of data gathering, increasingly using hand-held devices, either on a tasked basis or anonymised. For land observations, examples exist of a crowd-based approach for ‘volunteered geographic information’, such as traditional cartography (e.g. OpenStreetMap), or for field-checking of land cover maps (e.g. Geo-Wiki).

4.2.2 Temporal and Spatial Aspects

The temporal and spatial context behind an observational requirement will constrain what technologies and data strategies are appropriate, for example, how frequently a phenomenon should be observed, at what degree of detail, and how quickly the data or derived products need to be delivered to the end application. These temporal contexts are:

- Continuous time series or multi-temporal (i.e. regular repetitive measurements, e.g. for climate-related observations, seasonal vegetation changes or agricultural cropping patterns).
- Periodic (e.g. every 1- 5 years, based on policy or funding cycles, typically for ‘static’ mapping or inventory updating).
- Event or purpose-driven (one-off phases of data acquisition in response to a short-term requirement, such as a natural disaster).

Equally, the geographic extent of interest is an important factor in data selection. This could be as area-based coverages:

- local/site-based (e.g. farms, conservation sites);
- catchment/county;
- national;
- continental/global; and
- additional geographic criteria concern linear features or ‘corridors’ (roads, railways, powerlines, urban ‘greenways’), or collecting information at discrete geographic points (e.g. video cameras, *in situ* sensors). Trade-offs thus exist between local, point-based detail versus wider area, spatially contiguous data coverages, which can form parallel strands of an integrated monitoring approach (e.g. the Countryside Survey in the UK).

4.3 Strengths and opportunities

Overall, the observation technology contribution for land applications revolves around five high-level roles:

- land cover/ land use mapping or updating (LCLU) to various nomenclatures, scales and policy fit – a role provided primarily (though not exclusively) by optical imagery from satellites and aircraft, supplemented by field work;
- the ability to objectively detect and assess landscape ‘change’ to help target field inspection, be it through incoming fresh data acquisitions over a time period of interest, or retrospectively through analysing image archives;
- a more quantitative generic role through biophysical parameters (e.g. vegetation-related, hydrographic features or climate-related variables), largely derived from satellite instruments (for global scales) or diverse *in situ* instruments, in support of science models;
- the provision of land surface and object height information over both rural and urban areas, extending 2-dimensional mapping into the 3rd dimension together with measures of terrain stability; and
- the provision of ‘background’ or contextual information for other geographic data analyses, for visual or computer-based assessment.

These technologies can fulfil both a primary and a supplementary data role, depending on the usage context and other ways of working. The applications areas presented below highlight some key activities for land observations.

4.3.1 Agriculture

Compliance with the Common Agricultural Policy is operationally supported by a high spatial resolution optical satellite approach (supplemented by SAR) for a confidential sample of farms within each Member State, under the coordination of the European Commission’s Joint Research Centre in Italy. Existing land parcel maps (ownership-based) are able to provide a spatial framework for analysis.

Routine crop mapping for wide-area inventories and statistics is tentative, depending on how fine a distinction is required between crop categories and the timing of image data relative to the crop calendar. Nevertheless, case studies have been in development for many years from optical imagery where outcomes are encouraging and functional methodologies exist. The enhanced temporal revisit of upcoming satellites (notably Sentinel-2) and to what degree these optical datasets could be supplemented by SAR imagery (notably from Sentinel-1), will go some way in mitigating cloud cover issues.

For precision agriculture, satellite, airborne or UAV-based optical imaging can provide crop condition assessments at within-field/per plant scales, allowing farmers to micro control the application of fertilisers or pesticides, with positional support from GPS. The more sophisticated optical instruments allow derivation of biophysical observations (leaf chlorophyll, nitrogen, other pigments, senescence) which may correlate with sources of crop stress, such as disease or soil moisture deficit. However, precision approaches are still in development, both technically and in terms of business case.

With respect to animal disease, temporally current land use/land cover data informs on areas that could act as barriers or conduits for disease propagation, where ‘vectors’ may be located, and where grazing pastures and water bodies are located in the landscape – at farm-scale detail. Data sources and methodologies exist but wide-area land cover maps with sufficient thematic detail are currently not refreshed frequently enough. Time series of optical satellite imagery (albeit currently at coarse spatial resolutions) can support the tracking of vegetation phenology patterns as surrogates to indicate climate-related influences on disease outbreak. ‘Land’ observations could thus act as inputs to predictive epidemiological models which may include other observations, such as land surface temperature or air temperature. Some case studies have already been developed along these lines.

FIGURE 3

Agricultural land use from multi-temporal optical satellite imagery

Multi-temporal Satellite Imagery Stack



Derived Land Cover Classification



KEY

- Oilseed Rape
- Maize
- Winter Wheat
- Spring and Winter Barley
- Grass Ley
- Woodland
- Urban

Image courtesy of DMCii

4.3.2 Soil moisture

Soil moisture levels at different depths in the soil profile is measured by *in situ* probes, as 'point' measurements. Remote methods with the greatest operational potential include both active and passive microwave techniques, which provide contiguous areal estimates.

CEH is establishing the first UK large area soil moisture network with *in situ* instrumentation, termed Cosmic Ray Soil Moisture Observing System (COSMOS). Recorded data shows how soil moisture and temperature varies across the country with soil type, climate and vegetation. These include soil moisture measurements from neutron detecting probes, with results representative of a 350m radius and to a depth of 0.5m. Other soil sensors measure moisture, conductivity and temperature at different depths within the top 1m of the soil profile. COSMOS stations also measure the weather and

other environmental variables. The network has great potential to transform hydro-meteorological modelling by providing real-time data for assimilation and model validation, underpinning a wide range of science needs in agronomy, ecology, land-atmosphere processes, hydrology, flood forecasting, drought monitoring and climate science in general.

To potentially complement COSMOS, there is expectation of soil moisture observations being operationally feasible from SAR instruments from aircraft or satellite. A number of prototype soil retrieval algorithms have been in development for ESA's (C-band) Sentinel-1 SAR mission. This holds some potential for estimating soil moisture for less vegetated areas with the goal of a 1km spatial resolution product, though will largely reflect soil moisture at the surface with limited depth penetration (as the technique is radar wavelength dependent).

4.3.3 Catchment Management

Catchment management concerns land management practices that may impact on surface or subsurface drainage waters, as well as the water bodies themselves.

Optical imagery from aircraft, satellite or UAV can inform on the degree of bare versus vegetated land at different times of the year, high-level principal crop types (winter cereals, oil seed rape, spring/summer crops), tillage style and direction, location of grazing pastures and their proximity to water bodies, and features that mitigate soil erosion such as hedgerows and uncultivated buffer strips. These aspects can be addressed by multi-temporal satellite optical imagery for agricultural land use inventory across wide areas, addressing the land cover dynamics aspect with very high resolution (VHR) imagery (airborne or satellite) recording field boundary features and other seasonally static farm aspects related to land management practices. Sentinel-2 (as for agriculture in general) is expected to provide the 'workhorse' tool for the temporally dynamic role for land cover/land use and 'change', ideally supported by land parcel boundary mapping to provide the spatial framework.

However, there is a current tension between the need for farm detail (very high resolution but local coverage per acquired scene area) and wide area, potentially catchment-wide coverage. VHR satellites provide levels of terrain detail competitive with areal imagery though individual scene coverage is limited

to 20km x 20km. Aircraft can provide wider area contiguous coverage but surveys are undertaken years apart. Thus, although the instruments are fit for purpose, the issue (as for agriculture in general) is to be able to acquire such information systematically at desired times of the year, rather than any inherent limitation in the data themselves. As cloud cover issues affect the utility of optical imagery, there is merit in evaluating SAR alternatives that could sustain temporal sequences through the winter period, when agricultural land can be at its most vulnerable, though with some uncertainty on what it is able to consistently map compared to optical methods.

Case studies have been carried out for the mapping and monitoring of moorland, using VHR optical satellite or aerial imagery to map upland vegetation patterns, evidence of ditching, degree of peat exposure or burn histories. The intricate vegetation patterns and the required detail of geomorphology require very high spatial resolution (e.g. in the range 0.5 – 5m, depending on the task), and deliverable from airborne or satellite imagery. SAR imagery is as yet under-explored. High temporal repeat within a given year (as needed for agriculture) is not a requirement though obtaining data from different seasons is helpful in resolving vegetation categories. Most issues relate to operational data supply rather than methodology, though there is not yet a systematic solution for determining moorland wetness.

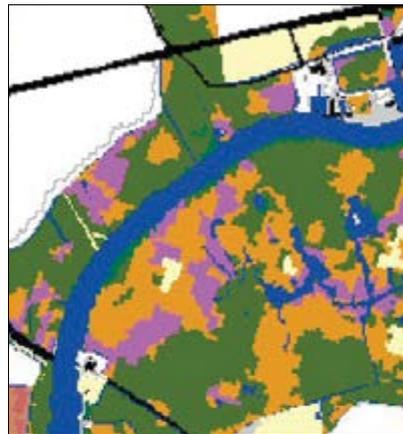
FIGURE 4

Detailed habitat mapping with a combination of aerial, satellite imagery, Ordnance Survey mapping and digital terrain data.

RGB aerial photography



Landscape classification



SPOT imagery



KEY

- | | |
|------------------------|---------------------------------------|
| ○ Arable | ● Grazing marsh (high productivity) |
| ● Urban | ● Grazing marsh (low productivity) |
| ● Bare ground | ● Grazing marsh (medium productivity) |
| ● Gardens | ⊘ Improved grassland |
| ● Coniferous woodland | ● Semi-improved grassland |
| ● Broadleaved woodland | ● Water |
| ● Woodland scrub | ● Wet grassland |
| ● Fens | |

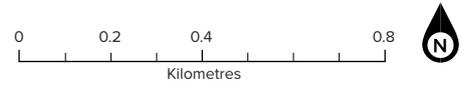


Image courtesy of Joint Nature Conservation Committee

Satellite or airborne optical imagery is able to detect plankton blooms in water bodies. Functional methodologies exist, still largely research and development based and more useful when a time series of optical observations is achievable, rather than on a one-off basis. This has latterly only been possible at coarser spatial resolutions (300 – 500m pixels) and thus for larger-scale lakes, though once again cloud cover can interrupt the sequence. At UK landscape scales, there is some potential to test this application from Sentinel-2.

The National River Flow Archive (NRFA) is the UK's focal point for river flow data, for near-continuous flow monitoring. The NRFA collates, quality controls, and archives hydrometric data from gauging station networks across the UK including the extensive networks operated by the Environment Agency (England), Natural Resources Wales, the Scottish Environment Protection Agency (SEPA) and the Rivers Agency (Northern Ireland). The instrumentation provides information on water levels, flow rates and water chemistry.

4.3.4 Habitats and Ecosystems

Habitat surveillance requirements have a strong focus on land cover mapping and changes – to various nomenclatures and mapping scales – though over longer timescales (up to decadal) than year-to-year cropping patterns. The conservation agencies in the UK have been particularly proactive in testing satellite, airborne or (latterly) UAV solutions to mapping, as a complement to traditional field work. Mapping is of a periodic nature and there is potential to benefit from improved temporal resolutions to exploit seasonal change, and SAR-based methods for inferring vegetation differences (in the sense of habitat 'condition') based on changes of plant shape and structure.

Similar to the ECVs introduced in the climate chapter, the land domain is developing a set of Essential Biodiversity Variables (EBVs) under the leadership of the Group on Earth Observations (GEO) Biodiversity Observation Network. The purpose of EBVs is to track progress towards the 2020 targets of the Convention on Biological Diversity. The Copernicus land cover/land use products are complemented by coarser spatial resolution, time series-based biophysical observations that underpin the global component, that act as inputs to some of the land-related ECVs and EBVs. Together with field work, remote sensing methodologies are expected to be a primary source of input data to the EBVs. Land cover and water body mapping and their changes over time are integral to proposed land-related EBVs such as habitat type, distribution, extent and fragmentation, in complement with time-series based biophysical observations of vegetation condition and soil moisture.

At national level, 'Land Cover Map' (LCM) is a land cover mapping programme forming a component of the Countryside Survey, led by the CEH and with the goal of a 6-year repeat. This dataset provides land cover information for the entire UK based on the Biodiversity Action Plan Broad Habitats which are widely used in monitoring and reporting. LCM and the Countryside Survey thus form operational programmes though are able to revise their specifications with each update cycle, according to new data opportunities or resources.

Wales has developed its own approach for a Phase 1 habitat map based on satellite and aerial imagery, to a more detailed specification (both spatially and thematically) and more regionally tuned than LCM. A similar methodology has been tested by Joint Nature Conservation Committee and partners for Norfolk through the Making Earth Observation Work project, and is now being extended to the North York Moors and Northumberland.

FIGURE 5

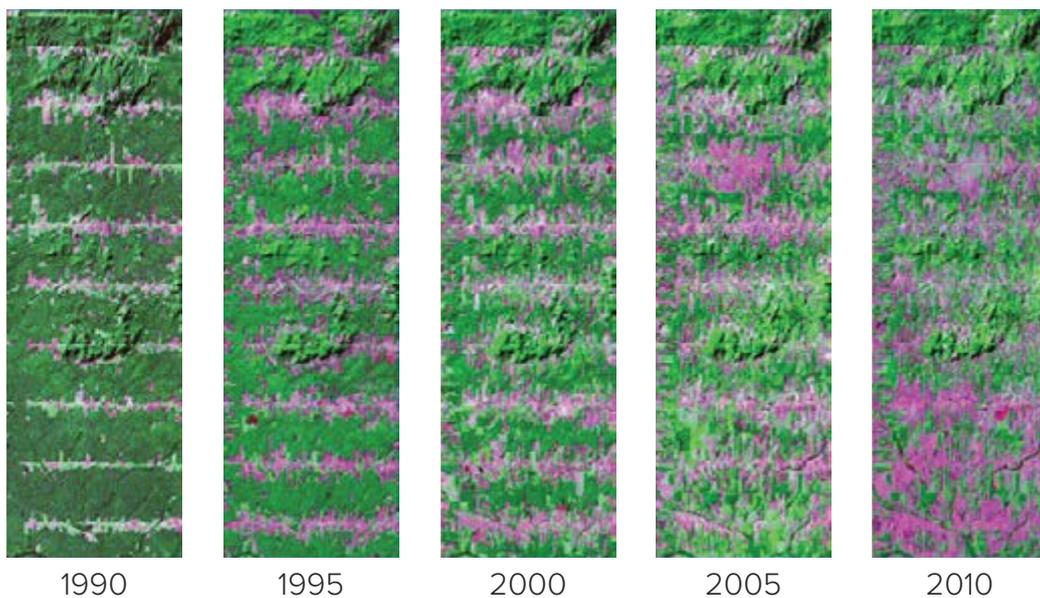
Identifying small areas of woodland (<0.5 hectare) as green polygons and isolated trees in yellow



Imagery courtesy of GeoPerspectives

FIGURE 6

Progressive deforestation over a 20-year period, Rondonia, Brasil, as recorded by Landsat-5 as the loss of green-coloured areas



Courtesy of Airbus Defence and Space

The UK Environmental Change Network (ECN) of observation sites is led by the CEH and represents the UK's long term ecosystem research network. There are currently 12 terrestrial and 45 freshwater sites, covering a wide range of upland and lowland habitats. Observations include the chemistry of water, soils and air; weather and climate; habitats, plants and selected invertebrates and vertebrates. The ECN also provides the UK contribution to the International Long-Term Ecological Research Network (ILTER) and LTER-Europe.

The conservation community also includes a significant 'volunteer' component, tasked with field observations. Volunteers report what they observe in a standardised way, to ensure consistency and maximum utility of the information. This can work very well through partnerships between Government and NGOs, which coordinate a huge volunteer effort very efficiently. Examples are the National Plant Monitoring Scheme and the Breeding Birds Survey.

4.3.5 Coastal Zone

Routine LiDAR and optical aerial imagery campaigns are flown by the Environment Agency, with specific focus on the coastal zone and river floodplains, operationally flown on a periodic update basis and recently in partnership with Natural England. Applications include flood risk modelling, assessing areas of coastal erosion or accretion, changes in morphology of shingle ridges, or sand dune movements.

Tracking of coastal subsidence through the technique of SAR interferometry has been the subject of recent research and development work (the EC project 'SUBCOAST') for selected zones of the European coastline and also for directly monitoring the integrity of coastal barrier systems and infrastructure. A consistent long-term SAR data supply is required for this application, with expectations for Sentinel-1.

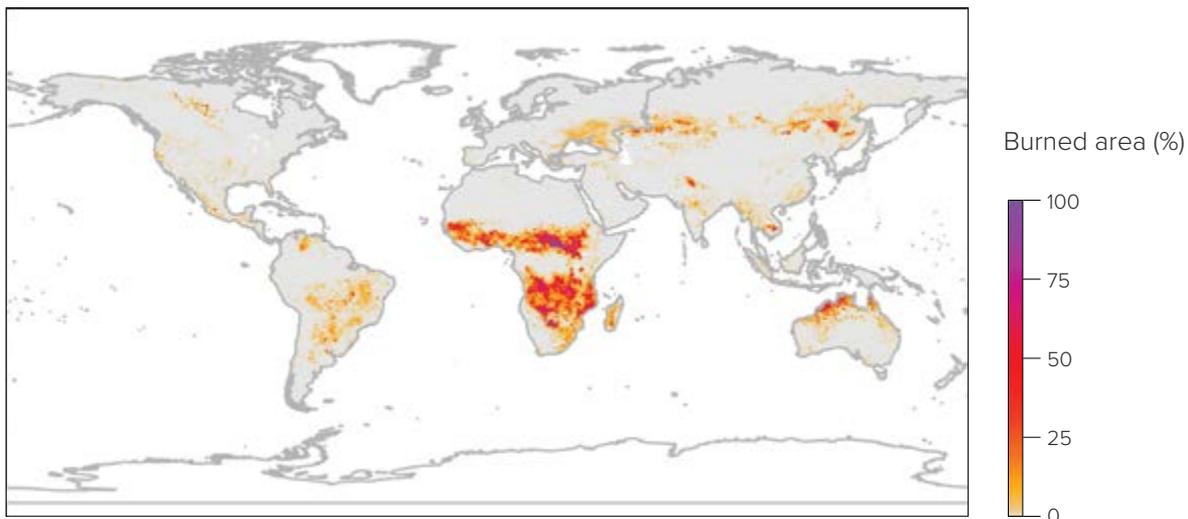
4.3.6 Forestry and Woodland

The Forestry Commission's National Forest Inventory is a current operational programme, which incorporates satellite and aerial imagery with ground survey to track forest changes in wooded areas greater than 0.5 hectare in extent. This supports ongoing forest management activities as well as providing an input to national GHG emission estimations. Tree species is typically not sought beyond a simple coniferous/broadleaf/mixed categorisation, unless already known from plantation management information or specific project-based, field survey.

There is time series potential from the newer generation of higher spectral resolution optical satellites (notably Sentinel-2) to detect spectral anomalies within forest stands that may correlate with stress or disease indicators and their temporal evolution across a landscape, versus a 'normal' background condition. However, optical methods are weak in addressing specific forest parameters such as tree height or stem diameter, whereas LiDAR approaches (both airborne and terrestrial) have been shown to be effective for this.

FIGURE 7

An example of a global scale land-related ECV, expressing the mean annual area burned in 2008 as the fraction of each 0.5° map grid cell. The product is derived from the third-generation Global Fire Emissions Database (GFED3), itself derived from MODIS satellite imagery. The purpose is to help elucidate the role of biomass burning in the global carbon cycle



Courtesy of University of Leicester

For rural or urban areas of small woodland, a combination of high spatial resolution (2m or better) optical imagery and matching airborne LiDAR has been demonstrated though it remains difficult to pinpoint and characterise individual tree types. Problems are encountered of a high degree of between-species confusion and within-species variability which challenge classification algorithms – as there is no singular spectral signature per tree species, coupled with issues of the seasonal timing of observations. Nevertheless, a similar data approach is also pertinent for assessing tree condition/risk along infrastructure corridors such as railways, where condition assessments are related to a proximity index. Some promising trials have also been performed for tree species discrimination with more sophisticated hyperspectral optical instruments from aircraft or UAV, which offer more spectral bands. With respect to tropical deforestation, the UN-REDD

programme is supporting countries to develop cost-effective, robust and compatible national monitoring and ‘Measurement, Reporting and Verification’ systems – providing tools, methodologies, training and knowledge sharing that help countries to strengthen their technical and institutional capacities. Though land cover reference mapping is more effectively done by optical imagery, data sources and analysis methodologies may differ, and the persistently cloudy nature of the tropics can make mapping to any specific reference year problematic. SAR has potential as an all-weather change alert tool for land cover/land use change though is not yet established in this role.

4.3.7 Urban Environment

The 3rd dimension is a key requirement in urban applications. Stereo and multiple viewing angle aerial imaging, together with LiDAR, play operational roles in the mapping and re-mapping of cities and urban areas, including the construction of 3D city models. Vehicle mounted cameras and LiDAR collect pictorial and surface morphological detail of building and street facades, to add realism and detail to the 3D models. City models may be used to calculate building ‘footprint’ areas, height, roof type and orientation, dominant roofing material, building density per unit area, degree of impervious surfaces and degree of urban vegetation cover. Such information can be available for city planners and supports the concept of ‘smart cities’. Nocturnal thermal imagery from aircraft has been used to inform on the heat loss performance of the building stock. This is perhaps more effectively done by thermal camera from vehicles traversing the road network, as heat is mostly lost from windows and doorways.

At city-wide scales, the phenomenon of urban heat islands can be recorded by satellite thermal instruments though it is not possible to record multiple observations within the same 24-hour diurnal period from a single satellite. Spatial resolution is currently too coarse to resolve city block detail, further complicated by a lack of knowledge of local emissivity factors and thermal variations due to local urban micro-climates, which makes quantitative modelling still challenging. Air temperature also needs to be measured as the relationship with underlying surface temperature is complex.

Industrial facilities and waste disposal sites fit a site-based monitoring approach. Radioactive contamination can be detected by airborne geophysical instruments able to record gamma ray emissions. Thermal systems will inform on heat loss, pollution risk, near-surface concealed fires or surrogates for methane leakage, and have been demonstrated from both *in situ* and airborne systems.

In urban settings, the concept of ‘smart cities’ has a heavy reliance on sensor networks. Examples (largely of what could be) may include:

- monitoring of parking spaces through video cameras and object-counting algorithms;
- structural integrity of buildings or structures (e.g. motion sensors);
- urban noise maps;
- electromagnetic field strength;
- traffic congestion (both vehicles and pedestrian);
- smart lighting;
- waste management (levels of waste in disposal containers or sites);
- smart roads (warning messages, diversions according to weather or traffic conditions) through sensors embedded in the road surface or on vehicles; and
- air pollution.

4.3.8 Infrastructure

Infrastructure corridors are routinely monitored to ensure high levels of safety, asset condition, efficiency and security. For instance road surface condition is monitored using vehicle-based ground penetrating radar and LiDAR technologies to highlight deterioration and to prioritise re-surfacing operations. The UK power line network is monitored with aerial imagery and LiDAR to assess the risk posed by adjacent vegetation and to action accordingly. The UK rail network is exhaustively monitored using aerial and train-based sensors. For instance, the threat of vegetation encroaching on rail lines is assessed by using aerial LiDAR to model tree fall potential, while train-mounted video is used to assess line sighting compliance.

4.3.9 Terrain surface, subsurface and stability

Aerial LiDAR, optical stereo imagery aircraft and satellites, and SAR interferometry are useful for modelling terrain surface, subsurface and stability. Digital elevation models derived from these data and a space shuttle flight are used for characterising the land and a wide variety of land applications including mining, surface geology, soils, earthquakes, volcanoes landslides and rising/falling coastal zones.

4.3.10 Land Tenure

For the development of administration systems for land tenure in developing countries the World Bank has recently been acting as a source of financial loans for applicant countries together with other development banks, to support programmes to refresh the mapping of urban (and to a lesser extent – rural) areas, funding both newly acquired airborne and satellite data as a mapping base. This fresh data then forms a platform for the construction of dedicated Geographic Information System (GIS) tools and a land tenure information system. Digital aerial imagery at 15-50cm spatial resolution is typically proposed for these new in-country programmes, though due to the rapidity of urban expansion, regular updating would be anticipated and the current proposed approach is to suggest VHR optical satellites to provide this, rather than a further phase of new airborne surveys.

4.3.11 Global Monitoring

For global land monitoring, coarse resolution satellite data (250m – 1km or coarser) is a primary source of data to monitor land surface parameters at continental-to-global scales, utilising a range of optical, thermal and microwave technologies. For example, satellite optical observations of land surface albedo and vegetation are central to developing models of radiation interaction with the terrestrial land surface, for quantifying terrestrial ecosystem dynamics. Globally-consistent 10m resolution optical data could also be useful for linking *in situ* meteorological sites to land classes (such as ‘urban low-rise’, ‘grassland’, ‘barren’) to aid interpretation of the meteorological observations.

Global observations of burnt areas are of key relevance for estimating carbon cycle feedbacks to the climate system. Estimation of soil moisture has relevance for hydrology, meteorology, climatology and agronomy, with high potential to ingest soil moisture information into NWP, climate studies and flood forecasting. The development of these (and other) biophysical observations and their incorporation into models is increasingly undertaken within the framework of the ECVs programme.

The development of a subset of 14 ECVs from all three ECV domains forms the basis of ESA's Climate Change Initiative programme introduced in the Climate chapter. The programme is driven by the needs of the climate science community, who guide activities and validate results. The Land-related ECVs under development within the CCI comprise Land Cover, Fire, Soil Moisture, Ice Sheets (Greenland and Antarctica), and Glaciers. Remaining ‘Terrestrial’ ECVs are river discharge, water use, groundwater, lakes, snow cover, permafrost, albedo, fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), soil carbon, and above-ground biomass.

With respect to the direct assessment of above-ground biomass (AGB) in forested/wooded terrains, airborne LiDAR is able to measure forest structure from which woody biomass can be inferred, and is being used in some tropical countries as part of their MRV system. The use of ground-based terrestrial LiDAR instruments to estimate biomass is a current area of research and development. Longer wavelength SAR systems (L-band and P-band) possess canopy penetration capabilities and are anticipated to provide a valuable and consistent source of AGB estimations. Satellite P-band SAR will be tested through ESA's BIOMASS science mission (which is UK-led), aimed at providing global maps of biomass and biomass change every 6 months during its 4-year lifetime. L-band SAR systems are expected to be only effective in lower biomass tropical forests, and operational data sources are currently limited.

4.4 Challenges

4.4.1 Common barriers

There are a number of common barriers for land observations:

- common approaches nationally, across Europe and globally that still meet local needs;
- uptake of observational technologies to their full potential;
- data-sharing between Government departments;
- lack of expertise in using and integrating various data types; and
- providing data in appropriate and usable forms for end-users.

Most monitoring is for regulatory compliance rather than a systematic understanding and attribution of change which leaves important gaps in our knowledge – stronger links could be established with monitoring action plans, for example. However, uptake of observational technologies at their current level of sophistication has been patchy – due to a number of issues including financial, technical, licensing, cultural and political. Although aerial imagery is well established as a mapping tool, the use of satellite imagery outside of the UK Land Cover Map and Welsh habitat mapping programme has been limited and *ad hoc*. Nevertheless, when feasibility studies have engaged with the user community, the response has been generally positive.

Overall, the usage of observational technologies across the national, European and global dimensions will increasingly require a common approach to improve cross-border or inter-regional consistency. This process is already underway for land cover mapping in Europe, through the work of the EEA-coordinated EAGLE group, to address the issue of European-level land use/land cover mapping in its current form being thematically unsuitable for national re-use (e.g. the EEA-led CORINE dataset is generally less effective for some research applications than datasets derived for national or regional coverage).

There is a lack of data-sharing between Government departments and an insufficiently ‘open’ approach to geographically referenced spatial data. The ‘Defra-1’ initiative is intended to address this for the DEFRA ‘family’. Overall, national resources and capabilities in environmental observation have yet to be joined up and maximised, despite this being well articulated in the medium to long term Government strategy for spatial data called ‘Place Matters: the Location Strategy for the United Kingdom’.

There remains a lack of expertise or familiarity in using and integrating the various data types. Although the use of aerial (digital) photography falls within a comfort zone within user communities, satellite data typically does not, due to the perceived data processing barriers. This will be exacerbated by expanded operational SAR data streams, even less familiar to users than working with optical imagery.

Although EO-methods play both primary and supplemental roles in monitoring the wider landscapes, mechanisms to feed such EO-based information into the user community are not well developed. Little existing data infrastructure exists thus far to support coordinated (comprehensive, sustainable) environmental observations and data-sharing. Thus, the emerging UK Sentinel collaborative Ground Segment concept to manage and exploit the satellite data streams from the European Copernicus programme (European Commission and ESA) is pertinent to improving this situation, at least for public satellite data streams.

4.4.2 Data-related issues

There are a number of issues which arise from the data:

- EO data has an inherent degree of uncertainty.
- The different computational methods used mean it is hard to standardise and therefore ‘accredit’ data sources.
- The interference of clouds in optical methods, which can be overcome with more frequent collection of observations or different methods.
- UAV use will be limited until regulations regarding privacy and public safety concerns are addressed adequately.
- No national system to calibrate satellite, air-borne and ground-based observations.
- Ensuring the accuracy of *in situ* manual observations (field work).
- Costs of accessing data from commercial systems.
- Potential of ‘crowdsourcing’ data limited until quality assurance and legal concerns addressed.
- Building large sensor networks is attractive, but their use is still limited by cost, robustness and data processing and storage issues.

Environmental observation data carries with it an inherent degree of uncertainty. Maps are interpretations or abstractions of the real world, rather than direct representations of what we see. Descriptions pertinent for one geographic area may not be pertinent for another.

There are basic issues with regard to knowing what data or products are available, how it can be accessed and the method by which it was produced (important for common standards and protocols). The availability of different datasets measuring the same phenomena seems to be an increasing issue. This can be an advantage for validation purposes but also can act as a limitation where common standards are sought for monitoring and reporting. This, perhaps part-explains why EO and other observational data sources may not yet qualify as ‘accredited’ or robust in relation to more traditional methods of data collection, encouraging the status quo to remain.

For areas of the world such as the UK and Europe, access to good quality imagery, at a high-resolution, is not necessarily a limiting factor for research and monitoring. Expectations for the utility of optical satellite imagery are tempered by our typical cloudy weather conditions over the UK, which make it difficult to ensure frequent or timely acquisition, hindering translation into routine working procedures. More frequent satellite coverage from newer-generation systems, e.g. from once every 16 days to daily (potentially) is one way to address this, as is an expansion of SAR-based approaches. The same cloud cover issues affect airborne or UAV operations but at least the operator can be selective about where to fly and when, depending on weather forecasts. However, satellite data are often essential for mapping and monitoring in developing countries due to a lack of suitable alternative data.

Regarding UAVs, the main obstacles to wider uptake concern CAA regulations, public safety and privacy concerns, the risk of mid-air collisions or crashes into urban areas or important infrastructure, such as powerlines. Nevertheless, there is great community interest in developing the usage of these technologies.

We have no formal national calibration/validation sites in the UK to directly compare satellite or airborne-derived measurements against ground instrumentation.

In situ manual observation (i.e. field work) remains hugely relevant but accuracy may be difficult to assess, as field-based mapping can be very subjective and lacking cartographic control. Furthermore, the scale of field observation may not be commensurate with remotely sensed imagery, and ancillary data is often interpolated and lacking in uncertainty information.

Commercial satellites operating on a bespoke basis offer higher spatial resolution specifications (down to sub-1 m) than public systems and are thus technically better suited for site/local based applications. However, data costs can be an issue and this also mitigates against a time series approach being attempted (even though it might be technically feasible and justified on science grounds).

Crowdsourcing of observational data is an interesting and novel growth area, though it brings with it some challenges, mostly relating to data quality/assurance and various legal aspects. Boundaries are blurred between the otherwise distinct roles of producer, service provider and user/consumer.

With respect to sensor networks, there has been a vision for approximately ten years for large-scale pervasive environmental *in situ* sensing, though this has yet to be realised. For example, wireless sensor networks remain typically small in size (less than 30 nodes) or only deployed over short time periods (days to months). Installation and maintenance costs can be high, and improvements to robustness are needed through the data chain. Scaling up to larger networks (conceptually 1000's) brings physical and logistical issues, together with potentially large data volumes – and would represent significant investments.

4.5 Future trends

No single observational technology can do everything, thus we need to develop data strategies which provide a mixed sensor approach. We should also be aware of which technologies are one-off and experimental in character, versus those which offer long-term continuity as platforms for routine operations. So it is important to consider the balance between data continuity to ensure time series remain possible over the longer term with backward compatibility, as well as support for novel science-driven demonstrators to test new instrument concepts or observational requirements.

Trends for the Land domain:

- increased data volumes;
- easier access to imagery for multi-scale applications;
- exploitation of time series approaches at higher spatial resolutions (e.g. for vegetation phenology patterns at district-level mapping scales);
- expanding use of UAV technology;
- maturing of SAR techniques for land applications;
- maturing of packaged information services;
- more powerful data visualisation tools;
- integrated applications using multiple sensors;
- joined-up methodologies and data-sharing for national environmental monitoring using linkages and overlaps between different policy sectors ('collect-once/use-often'); and
- progress towards a 'system of systems' approach underpinned by open data policies, powerful computing facilities and pan-government licensing.

4.5.1 Building a solid foundation using key principles

There are four key principles to the future of environmental observation for land in the UK:

- use current technologies better and plan for data continuity
- ensure UK benefit from the Copernicus programme
- use new technologies to build richer, more diverse options for environmental monitoring
- exploit new approaches for land applications.

4.5.1.1 Current technologies and data continuity

We must make better use of current technologies and prepare plans for data continuity. We should be using new tools for finding the data, such as the upcoming Satellite Applications Catapult Data Discovery Hub. Optical imagery can be sourced from various, often similar satellites. However, their data formats and degrees of preparation differ. Algorithms should be routinely available (e.g. in a data services setting) to inter-calibrate and reformat image data, to simplify the input data streams to downstream processes and to facilitate a ‘virtual constellation’ approach across a mix of satellites. This would help EO-sourced products achieve ‘accreditation’ alongside more established data sources.

LiDAR has become a mainstream environmental dataset, in complement to optical or SAR imagery. However, there is no UK-wide LiDAR-quality terrain model. Many rural areas have no accurate, new generation models of terrain which impacts on the quality of (for example) run-off models in river catchments. Indeed, there is a case for including LiDAR as a standard data element of a future Countryside Survey approach. Some gap-filling opportunities arise from using elevation models from SAR interferometry (NextMAP, WorldDEM).

UK land applications would benefit by working to a common, open, exchangeable spatial framework derived from existing national cartography. To an extent, this happens already with the availability of the Ordnance Survey Vector Map District products, and LCM2007 was built on a generalised version of Ordnance Survey MasterMap – but agricultural field parcels, national park boundaries, river catchment boundaries also offer valid spatial units for analysis and attribution.

4.5.1.2 Copernicus programme

We must ensure UK benefit from the Copernicus programme. This includes the mapping products but should focus on the source data itself and how best to exploit it within national systems. Refresh of knowledge and skills are therefore of high pertinence (and indeed some urgency) alongside some case study development for working with Copernicus data.

Although the ‘continental’ products from the Copernicus Land service are probably too coarse to be used directly for national purposes, they do provide full territorial coverage and have some merit if top-down and bottom-up monitoring approaches can be combined. They also might have a role in supporting a simple land cover change ‘alert’ system.

The ESA and planned national infrastructure behind the Sentinel program (through the UKSA-led concept of a UK Sentinel collaborative Ground Segment) will act as a central point of access, handling archive services and a ‘TBD’ level of pre-processing and data preparation, to ease uptake by the user community.

4.5.1.3 Richer more diverse options

There will be a richer and more diverse set of technology options for environmental monitoring, including platforms, instruments and integrated systems. We should expect a degree of redundancy to be built into the system (e.g. if one satellite went down, there should be alternatives). Indeed, today's simpler lower-cost instrumentation coupled with the advent of microsatellite platforms and reducing launch costs has resulted in constellation-based approaches becoming increasingly routine, comprised of numerous cost-effective deployments of the same observational capability.

Other longer-term, potentially game-changing technologies or approaches could be:

- Low-cost SAR with flexible options for custom orbits (to bias coverage/revisit towards specific geographic areas).
- 'Convoy' approaches to satellite operations, i.e. the formation flying of closely spaced platforms to geographically expand concurrent coverage, or to bring complementary instruments into closer synergy. Such arrangements could be on a bi-lateral or multi-lateral collaborative basis.
- Geostationary satellites with very high spatial resolution 'zoom in' capability.

Apart from the obvious security or military-related applications, small UAVs are increasingly being trialled in environmental applications for agriculture and habitat surveillance, as well as for more timely interventionist examples such as illegal forestry or poaching. An operational advantage over satellite or aircraft is the ability to collect data beneath cloud cover, as and when it is needed, together with even higher spatial resolution (to millimetric if needed). Small UAVs fill a unique observational role for local-scales but further regulatory approvals and operating protocols are necessary concerning safety, privacy and legalities.

HAPs offer a unique 'pseudo satellite' capability for persistent local or regional observation, temporally more efficient than aircraft or satellites and also made possible by novel, miniaturised instrumentation. Prototype platforms already exist (currently with a military interest) but the business and usage cases need refinement for civilian or commercial operations. Operational scenarios have been considered for forest fires, border security and maritime surveillance but other specific land applications are less obvious. Nevertheless, usage cases will continue to develop as instrument options (singly or in combination) expand in capability.

With regard to instruments, there is an opportunity to capitalise on the Copernicus Sentinel-1 SAR mission alongside other SAR missions, as SAR is relatively under-investigated for UK land applications. An airborne test-bed facility now exists in the UK to help develop SAR applications, though funding is a constraint.

The ongoing miniaturisation and sophistication of low-power consumption instruments will expand the range of observational opportunities achievable from UAV platforms, as for HAPs. It is conceivable that farmers could operate their own small UAV as a regular item of farm equipment. Apart from direct very high spatial resolution mapping, an additional role could be for underpinning measurements to calibrate corresponding satellite instruments.

Optical systems on satellites and UAVs are acquiring more spectral bands which should imply 'better' or additional applications. Nevertheless, the role of visual and computer-based assessment from 'simple' imagery will continue to have a place, particularly with respect to change detection and business intelligence.

In situ sensor networks will become more spatially dense, as they become cheaper and robust, more power-efficient and easier to deploy, though are not likely to offer a pervasive solution in the near future. Nevertheless, they represent a compelling growth area and are fundamental to holistic environmental observation strategies. The UK is already very active in this field. *In situ* approaches will mature and extend in the future to the concept of sensor webs. NASA has a programme for sensor web development, on the basis of there being a high degree of synergy between a diverse suite of observational platforms. The long-term vision is for automated science data collection and mission operations with real time collaborative information being shared between sensors, spacecraft, or investigators.

The UK Environmental Observation Framework (UKEOF) recognises the need for a holistic observational framework for environmental monitoring, and forms a key component of the NERC-coordinated 'Living With Environmental Change' (LWEC) programme. The potential is recognised for combining wireless sensor networks with satellite data to create a network of networks. This would bring the UK closer to a "full model of the environment", working in partnership with industry and Government. Internationally, this trend towards a 'system of systems' approach as introduced in the international chapter is coordinated by GEO.

4.5.1.4 Exploit new approaches for land applications

Improved data, technology and systems approaches will foster new applications in the land domain. The big near-term EO opportunity is to exploit multi-temporal/time-series approaches for UK land issues at higher spatial and temporal resolutions than has been possible in the past, rather than *ad hoc*'get-what-you-can' data scenarios. This is specifically the case for land use/land cover applications (agriculture, habitats, catchment monitoring, forestry, water quality), where data requirements and opportunities are quite similar. Sentinel-2 (optical) data could be supplemented by targeted VHR optical acquisitions for specific sites of interest – which provide options (for example) on the future design of the Countryside Survey.

Both optical and SAR technologies show potential to work together synergistically. Though optical Sentinel-2 would be a primary choice for land cover/land use mapping, cloud cover issues will still interfere with an acquisition strategy, thus Sentinel-1 (SAR) or any other radar system can be explored for gap-filling.

An increasing challenge will be our ability to interpret that imagery in an intelligent manner to detect and identify features and characteristics of importance (e.g. field drains, crop disease, crop yield). To do this requires a combination of sophisticated image processing skills, data integration and solid, timely and large-scale ground-based observations.

Land motion and sub-surface sensing will increase in importance as the UK considers its new-generation energy sources (fracking for shale gas, coal bed methane) or waste disposal requirements. District/county-scale services will be routinely possible from Copernicus Sentinel-1 data, with commercial SAR systems able to support higher spatial resolution, more local scenarios.

There is expanding need for modernised and sustainable cadastral land administration systems in developing countries, where the technical component provides the observation data upon which to build upgraded systems. This is already of interest to UK Government (e.g. programmes in Rwanda and Ethiopia) and is a high-impact activity in terms of support for national development.

One of the biggest global land-related issues is tropical deforestation, where satellite and other technologies provide the only objective and consistent basis for mapping, inventory and change detection across biomes and between continents. Future developments could include a SAR satellite placed in near equatorial, with several overpasses per day to track process and change, as a complement to the biomass assessment capabilities of the ESA BIOMASS mission. The UK offers a world-class science capability in this field, which also can be deployed in capacity building in tropical countries, as well as through our membership to GEO.

4.5.2 Final Thoughts

Although many user organisations or agencies realise the potential offered by environmental observation technologies, expertise in understanding how to access and exploit the data may be lacking. Consideration should be given to training programmes, as (for example) a component of a Copernicus national preparatory programme, which could involve both industry and academia.

Regarding early career EO specialists, more scientific depth is typically needed compared to, for example, the needs of the GIS industry. There are recent or current examples of initiatives to complement and extend undergraduate programmes. The University of Leicester has recently led an EC-funded Marie Curie Initial Training Network, structured around a portfolio of EO-based PhD projects termed GIONET, with industry sharing the hosting of early career researchers. Also, the University of Reading has led since 2013 the Space Intern Network (SpIN), which places science undergraduates into summer placements in commercial company settings, to encourage follow-on interest in Space for careers.

Further to the need for training, increasingly decentralised and devolved governmental structures are not necessarily a good thing for environmental observation where a more coordinated approach has been recognised to encourage cost effectiveness, skills sharing, best use of budget resources, capturing data opportunities, and to follow the 'collect once, use many times' data paradigm.

For example, a consistent portfolio of intermediate data products is needed from EO imagery but is best manufactured centrally, to ease the final stage of information extraction by in-sector service providers or directly by users. Furthermore, as data sources and volumes expand, together with the sophistication in what information may be extracted from them, there is a clear need and opportunity for large-scale data management and data preparation tasks to also be handled centrally. This fits the Sentinel collaborative Ground Segment model being developed by UKSA and partners, and is fully in line with DEFRA's recognition in recent years of the merits of a 'hub-and-spoke' model for observational data.

Innovative data licensing may need to be negotiated with data suppliers to support a more joined up and collaborative way of working. Amended data licensing arrangements could be explored (though varying in detail according to the data provider) that would allow central purchase and bulk discounts, but 'free' at point of usage within a defined user community, along lines similar to the Pan Government Agreement followed in recent years for aerial imagery and LiDAR data.

4.6 Summary

Land observing systems have a diverse user community who have interests in a range of application areas both within the UK and outside the UK, which includes agriculture, forestry, waterways, terrain, land tenure and global monitoring.

This diverse user community faces some common barriers in deploying land observing systems to their full potential, including the need for common approaches nationally, across Europe and globally; exploiting the technologies to their full potential; and obtaining the greatest value from the data by sharing of data between users, including between Government departments, having sufficient expertise to integrate various data types and translating it into an accessible and usable form for end-users.

The four keys for the future development of environmental observation for land include making better use of current system and planning for data continuity; ensuring UK benefit from the Copernicus programme; using new technologies to build richer, more diverse options for environmental monitoring; and exploiting new approaches for land applications.

Overall, national resources and capabilities in environmental observation have yet to be joined up and maximised. Environmental observations are crucial for a number of the land applications areas – we should individually and collectively work toward taking full advantage of these capabilities and driving future mission to meet UK observing needs.



Chapter five

Natural hazards

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Forest fire, California.

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Natural hazards

5.1 Introduction

The aim of this section is to report on the current state of environmental observations related to natural hazards and identify the future requirements.

Natural hazards can result in harm to human health and loss of life. They can also destroy livelihoods and cause significant environmental and economic damage, particularly to infrastructure. Hazards include floods, storm waves, coastal erosion, drought, heat waves, cold weather, windstorms, wildfires, pests and diseases, air quality, ground instability (e.g. landslides and subsidence), ash, gas and aerosols from overseas volcanic eruptions and space weather.

The UK challenge is to broaden the focus of natural hazards risk management from what has been predominantly an early warning system towards a more holistic and integrated approach, placing more emphasis on risk reduction and prevention. A critical element for success in this vision will be for the UK to be able to measure key environmental factors that can support, where possible, the forecasting of these events. As a result it will be vital to have an effective means of monitoring natural hazard events and impacts and making these observations and reports available in real time to those dealing with the forecasting of the event and its impacts, as well as providing advice and information to the responder community who are dealing with the incident on the ground. This may in some cases also include hazard events overseas which have the potential to impact the UK.

The Natural Hazards Partnership (NHP), established in 2011, provides information, research and analysis on natural hazards for the development of more effective and better coordinated policies, communications and services for civil contingencies, governments and the responder community across the UK.

The NHP is already gaining international recognition as world leading and as a model “other nations may wish to adopt”.¹⁶ A collaboration between UK technical research institutions and Government partners, the NHP aims to:

- establish a forum for the exchange of knowledge, ideas, expertise, intelligence and best practice in relation to natural hazards;
- provide a timely and consistent source of advice to Government and emergency responders for civil contingencies and disaster response; and
- create an environment for the development of new services to assist in disaster response.

The gathering of environmental observations and reports is highly dependent on partnerships and collaborations between Government departments and on international agreements. Natural hazards cut across natural scientific disciplines and hence there is a need for a collaborative approach to tackle the major challenges of preparedness and disaster risk reduction. There is a wealth of data being gathered across the UK and overseas that could be harvested for the benefit of the entire UK economy and we should seek to develop and enhance these partnerships and facilitate the use of the data in improving the UK’s resilience to natural hazards.

Natural hazards cost the UK economy billions of pounds a year. Whether it is volcanic ash restricting airspace, flooding and inundation, severe storms or space weather, the impacts can be great. Enhanced observations of the environment will improve the UK’s ability to forecast and monitor natural hazards and deal with their impacts. The UK is regarded as world leading in many of these areas but continued investment and development is required to maintain this position.

16. United Nations Office for Disaster Risk Reduction review of UK Approach to Resilience. <http://www.unisdr.org/we/inform/publications/32996>

5.2 The natural hazards risk landscape

In this chapter the current state of the art and future requirements for observations related to some of these hazards are identified. The following list of natural hazards are covered:

- severe weather – rain, wind, snow, ice, fog;
- flooding – river, coast, surface water, groundwater and drought;
- storm waves;
- volcanic ash;
- space weather;
- natural ground instability (landslides and subsidence);
- wildfires;
- air quality;
- earthquakes, volcanoes and tectonics; and
- invasive species and disease.

A table providing the agencies responsible for monitoring and detection, forecasts and advice and mandated or legislated warnings, for each natural hazard recognised by the NHP, is provided in the appendices.

5.3 Severe weather: Wind, snow, ice, fog and temperature (hot or cold)

5.3.1 Environmental Observation Technologies

The observation and forecasting of severe weather related to wind, snow, ice, fog and temperature are the responsibility of the Met Office. The Met Office maintains a robust observations network of its own but is also reliant on partnerships, both national and international, to secure the data necessary for its forecast operations. NWP is extremely data intensive. The Met Office receives around 95,000 Megabytes per day of satellite data from a combination of around 60 instruments. In addition to this around 50,000 Megabytes per day of data from surface systems and upper air instrumentation is received.

The prediction of severe weather and its impact is an output of standard Numerical Weather Prediction. Here we will limit the discussion to some key areas of observation related to severe weather events which we consider worth highlighting.

Observation of temperature, water vapour and wind through the total depth of the atmosphere is absolutely critical to NWP. Satellite data offer global measurements of temperature and water vapour using infrared and passive microwave sounding data. However, satellite data do not typically capture fine vertical structure in the atmosphere, particularly in the boundary layer near the surface, and they generally have spatial resolutions in the order of approximately 10km at UK latitudes.

The requirement still exists for vertical measurements from radiosonde balloons, wind profilers and aircraft to supplement the satellite data. Surface observations of standard meteorological parameters are also required from land and oceanic sites with the highest density achievable. Enhanced observations from radiosonde balloons especially during severe weather events would be highly beneficial. Commercial aircraft are routinely able to measure temperature and wind. The measurement of water vapour from commercial aircraft is a growth area and investment is required to develop this capability. Overnight, commercial passenger aircraft tend to fly less and this leaves a significant gap in temperature and water vapour measurement. There is an urgent need to fill this gap in order to improve prediction of fog – for which understanding the overnight development of the boundary layer is critical. An improved understanding of the structure of the boundary layer would also benefit air quality predictions which are very sensitive to boundary layer depth.

Future environmental models will run at higher and higher spatial resolutions and have the capability to resolve fine features. Such models will require increasing densities of observations for initialisation and verification. In addition to supporting this requirement for high density observations the promotion of a network of environmental sensors within schools, all connected to the internet and providing data in real time, would also provide an excellent source of data for schools to use in teaching science, mathematics and environment science to the next generation.

5.3.2 Challenges and Opportunities

5.3.2.1 Wind

Wind storms represent the dominant cause of damage and fatalities within the UK. The current NWP capability is well placed to deal with this natural hazard and planned enhancements in high performance computing will deliver enhanced skill in prediction of impacts. This high performance computing investment needs to be secured into the future and the observations to support it need to be developed to match this capability. In particular a denser network of radiosondes would be beneficial. For cost reasons the density of observations should remain flexible such that they can be initiated by forecasters as desired.

The dominant cause of fatalities and disruption is trees, then lorries and temporary structures (including mobile homes). The NHP recognises gathering data on these factors as very important but equally problematic. The fire and rescue services have access to this information soon after the event but it is not currently available for use in national hazard prediction and warning.

5.3.2.2 Snow/ice

Snow depth is highly variable due to local sheltering and wind accumulation effects. Snow depth can be measured at Met Office surface sites using laser range finding techniques.

A fundamental parameter is surface adhesion which is difficult to measure except with *in situ* vehicle tests. Some research in the USA has looked at how data from computers on modern private cars can be used to gather environmental data. In addition to the obvious measurement of temperature seen as a display in modern cars, the computers monitor the traction control system and anti-lock braking systems, wiper blades and light levels, all of which can provide information on the state of the roads. Collaboration between motor manufacturers, the highways agency and NHP could see roadside interrogation of car computers for these environmental related data allowing real time monitoring and prediction of road state when combined with satellite navigation information. Car satellite navigation systems could be developed to receive road status and weather forecast data allowing the presentation of these data to drivers, in a similar way that congestion data is done currently on some systems, to allow drivers greater awareness of this hazard and present the option of taking action to reduce the impacts.

5.3.2.3 Fog

Fog poses a hazard to motorists and airlines where the significant reduction in visibility is both a risk to life but also affects efficiency of these transport systems causing costly delays and inconvenience to the public.

17. The study of the physical geography of mountains and mountain ranges.

Fog is inherently difficult to forecast as its formation and dissipation is related to a very sensitive balance of available water vapour, surface moisture, atmospheric turbulence, orography¹⁷ and the presence of cloud in the atmosphere at higher levels. It is a shallow feature often only a few tens of metres thick. It therefore poses significant challenges to current forecast models.

Visibility can be measured using visimeters which monitor the scattering of a laser source by droplets in the atmosphere. This is a proven method of detecting poor visibility, including fog, but does not significantly aid the forecasting process. Satellite thermal imagery is used to monitor fog but the small thermal contrast in fog temperature to the background land surface temperature makes measurement challenging.

The prediction of fog could be enhanced with the greater use of wind profilers to determine the boundary layer structure and atmospheric turbulence. The distribution of water vapour in the atmosphere could be better understood in critical areas (e.g. airports) through more radiosonde ascents and potentially through the use of UAVs instrumented to measure temperature and water vapour profiles.

5.4 Flooding (river, coast, surface water and groundwater) and drought

Sources of flood risk can be defined as: Coastal, Fluvial, Surface Water (Pluvial) and Groundwater. Monitoring and forecasting techniques are at a different level of maturity, depending on the 'source', and authority/agency responsible for warning communities.

A coordinated approach to the gathering of data to facilitate flood forecasting and to monitor flooding events and their impacts is required.

The creation of the Flood Forecasting Centre (FFC) in 2009 (a partnership between the Environment Agency and Met Office) has transformed the way flood forecasting is managed within England and Wales. An outcome of the Pitt Review into the summer 2007 floods, the FFC combines the Environment Agency's expertise in flood risk management and the Met Office's expertise in weather forecasting for the first time. Similar combined hydrological, coastal and meteorological expertise was established in the form of the Scottish Flood Forecasting Service (SFFS) which has been operating since 2011 (a partnership of the SEPA and the Met Office).

Storm waves are also a hazard in their own right, as well as an important contributor to coastal flooding, since they present a particular risk to public safety, property and infrastructure damage from subsequent erosion of the coast. A coordinated approach to the gathering of data, through such initiatives as the Regional Coastal Monitoring Programmes, provides real time and archive data that supports developments and enhancements in risk modelling, facilitates flood forecasting, and aids the monitoring of coastal flood events and their impacts.

The winter of 2013/14 demonstrated the impact that flooding can have on the UK with the combined effects of river flooding, ground water flooding and coastal flooding. The UK Environmental Prediction System is a new model of the UK environment being developed by a partnership of the Met Office, CEH and the National Oceanography Centre. It aims to bring together a range of models that deal with the atmosphere, river flow, and coastal shelf flow into a unified coupled system to improve the prediction of natural hazards, including flooding and algal blooms.

To enable better flooding and drought forecasts a complete understanding of the water in the entire environmental system is required, including the water in the atmosphere stored as water vapour and within clouds. How much of this falls out of the atmosphere as precipitation is the next factor to be better captured. Once the precipitation rate is known an understanding of evapotranspiration, soil moisture and status of ground water levels is required. Meteorological data, soil moisture and ground water status are all important precursors to measuring river level and flow data. Ultimately an understanding of the state of the oceans in the coastal regions which not only determine the flow of river water out to sea but also knowledge of the wave height and period is required to allow prediction of impacts on coastal infrastructure and the probability of wave inundation.

5.4.1 Observing Water in the Atmosphere

5.4.1.1 Environmental Observation Technologies

Critical measurements are temperature and water vapour content in the atmosphere. This allows determination of the relative humidity and hence the generation of cloud. The prime mechanism for measuring water vapour is through satellites measuring in the microwave and infrared regions of the electromagnetic spectrum. In addition ground based and satellite borne Global Navigation Satellite System (GNSS) receiver signals are impacted by the presence of water vapour in the atmosphere. These remote sensing techniques are critical as they provide the necessary global coverage. However, their vertical resolution is limited so they need to be complemented with high-quality high-vertical-resolution data from radiosonde balloons. Such systems provide high accuracy but are expensive to run and hence the density of such systems in the UK has been in decline for many years. The EUMETNET-Aircraft Meteorological Data Relay (E-AMDAR) programme aims to deliver temperature and water vapour data from bespoke scientific grade instrument systems fitted to European commercial airlines. Whilst temperature measurement from aircraft is fairly straight forward and common the measurement of water vapour is a significant challenge. New

instrumentation like the Water Vapour Sensing System (WVSS-II) sensor has performed very well in trials and a few systems are now being installed on commercial aircraft. Operational weather forecasting would benefit significantly from investment in the installation of such sensors on more aircraft across the commercial fleet.

The measurement of precipitation is achieved with C band weather radar. The Met Office has developed, in partnership with the Environment Agency, a C-band radar system that shows superior performance to any other system on the market. The UK network could be enhanced to include two or three new installations along the west coast of the UK providing enhanced monitoring of precipitation and, through their Doppler and dual polarised capability, data on humidity and winds that would be ingested into forecast models. Positioning new systems on the west coast would provide greater knowledge of approaching weather systems.

5.4.1.2 Challenges and Opportunities

Research is ongoing to measure refractivity in the atmosphere using weather radar systems which could provide additional data on boundary layer water vapour. Digital radio reception is sensitive to near surface water vapour and research into the signal attenuation of digital radios could deliver useful measurements of boundary layer refractivity. Mobile phone reception is sensitive to rainfall rate and access to mobile phone network data could provide useful environmental data for free.

C-band weather radars are large installations and expensive to run. The network is therefore designed carefully to provide total UK coverage but the local orography can mean that rainfall in some river catchments is not well measured. Filling in the gaps can be achieved in primarily one of two ways. The use of smaller, cheaper X-band radars has the potential to provide more detailed precipitation measurements in particularly sensitive catchment areas where the large UK network sensitivity is reduced due to orography, or where finer detail is required in support of critical UK assets or interests. These could be permanent

installations or mobile systems brought to particular regions during periods of enhanced risk. Research would be required to determine the optimum siting and cost benefits of such a deployment. There are varied opinions amongst scientists as to the sensitivity, accuracy and hence value of X-band radar systems.

An alternative way of measuring the precipitation at the surface is by rain gauge. The UK has a rain gauge network of around 3400 sites operated by the Environment Agency, Met Office, SEPA and other agencies. Around 2500 of these provide monthly reports often requiring examination by humans. Others use tipping bucket technology to measure precipitation rate. The data from these can be polled more frequently remotely. Whilst the manually inspected rain gauges provide extremely useful information on precipitation totals, which are used to understand water availability and climatology, the data are received too slowly to be useful in short term meteorological and hydrological models. Tipping bucket rain gauges have difficulties in snow events where they don't respond until the snow on the instrument actually melts which can be some time after it fell. Commercially available rain gauges that weigh the precipitation continuously are available and are installed at a small number of sites. Since these systems report the incremental changes in weight of the precipitation they are able to cope with snow.

Of the total network around 1000 report data within twenty four hours but only a few hundred are able to provide data within one hour. A significant effort to deploy a larger number of weighing rain gauges with real-time telemetry to the modelling community would have great benefit in improving accuracy of river flow modelling and flood forecasting. It is not possible to cover the UK with the density of rain gauges required to understand the catchment area of all main river systems. The merging of weather radar data with high quality rain gauge data in real-time does however have the potential to significantly enhance the ability to monitor and predict flooding and investment in both systems is highly desirable to facilitate an enhanced and more accurate flood warning system. Combined

with increasing the communications speed, a move to wider use of weighing rain gauges would represent a step change in capability for understanding precipitation in critical catchment areas leading to significantly improved flood forecasting e.g. if the 1000 sites that currently report once a day could be upgraded to report 5 minute data.

5.4.2 Water On and In the Ground

5.4.2.1 Environmental Observation Technologies

For monitoring and predicting floods and droughts, innovative soil moisture sensors, such as COSMOS are being rolled out nationwide by CEH. Collaboration between CEH and the Environment Agency has shown that meteorological event sensing is possible using combined and automated water level and water quality sensors (traditional sensors or state-of-the-art electrochemical microarrays). During floods, mobile equipment would be vital for the effective monitoring of floodwaters e.g. GPS, laser and sonar surveys, and Acoustic Doppler Current Profilers would allow for coupled flow-sediment discharge during flood events. Within the geological and engineering community piezometers are routinely used to measure soil pore pressure, which is the pressure exerted by the moisture in the ground and which has the potential to affect soil stability. Piezometers are used widely on civil engineering projects to monitor the effects that soil moisture has on the stability of slopes. These are now regularly used with automated monitoring systems. Several state-of-the-art sensors are also under development, including distributed fibre-optic sensors for soil moisture and electromagnetic sensors for water chemistry; though not yet at market, these advances represent the direction of innovation, towards discrete, low-cost sensors that can be installed in multiple locations.

There are, of course, barriers to both monitoring and interoperability, from the lack of telemetry for many existing sensor systems, to battery life for certain sensors, to the quality control of an ever-expanding database, to data availability and the front-end visualisation of synthesised data. The large majority of the barriers are technical, however, and resolvable by means of a big data infrastructure and investment therein. CEH and BGS are working at the cutting edge of data infrastructure to provide standardised and tagged data that is virtually co-located and visually accessible.

River and groundwater level monitoring is undertaken in England that allows the Environment Agency to assess at Area level, on a monthly basis, the current flood status and future flood risk. A subset of this network is telemetered, quality assured and uploaded to the internet in near real-time and can be used to inform flood event-related decision-making. Effort is currently focussed on river levels and there are a limited number of examples where groundwater levels are monitored to assess the risk of groundwater flooding. Longer term groundwater flood risk also exists due to groundwater levels recovering from historic over abstraction as groundwater-dependent industries die-out. This recovery can result in the inundation of sub-surface infrastructure, e.g. the underground railway network in central London, and groundwater discharge at surface, e.g. flow of toxic waters from mines. In these cases, location-specific monitoring networks are in place to assess the impact of mitigation measures.

Groundwater monitoring technology has developed rapidly in recent decades, with digital loggers capable of collecting high resolution temporal data now common, but several challenges need to be addressed. Sensors are still relatively expensive, and if boreholes need to be drilled installing new monitoring requires significant capital. Relatively few sites are telemetered. Designing networks that capture the full range of spatial heterogeneity in groundwater behaviour is a challenge. Satellite, airborne and terrestrial geophysical techniques have been used to measure groundwater movements,

but generally only in an academic, rather than operational, context. Techniques such as Fibre Optic Direct Temperatures Sensors can be used to monitor groundwater surface water interactions.

During prolonged flooding events a range of radar and optical techniques (SAR, hyperspectral imaging and terrain scanning LiDAR) are used to map and monitor estimate of flood extent.

All of these observation types support the Environment Agency in its role of managing the hydrometric network to inform warnings in England.

5.4.2.2 Challenges and Opportunities

The current environmental monitoring effort is a mixed picture with regards spatial and temporal resolution. For example, whilst gauging stations are largely telemetered, offering near-real-time data (largely hourly), some still have to be read manually, and water quality measurements are certainly not fully automated and do not approach real-time, with the best available data being hourly for certain catchments. Whilst for many sites the frequency of observation meets the current requirement greater use of the data in delivering forecasts could be made if more of the data were available in near-real time.

Many predictive models are constrained by a lack of high quality, high spatio-temporal resolution data on a variety of parameters, from sediment load in rivers to water temperature. Predictive models are advancing at a fast pace and innovation will only increase the disparity between models and data; there is a need for this data to be consistent and fit for purpose, to enable the accurate modelling necessary for better environmental prediction. The need for better data and the associated enhanced modelling capabilities this brings is driven by the need to improve our understanding, prediction and management of floods and droughts. It is fundamental that we better understand the dynamic physics of different flood and drought events so that our models are able to capture these subtleties and thus can enhance prediction and inform management.

Once the precipitation has been measured the movement of the water in the land system is the next important step in predicting and managing flood risk. A historical understanding of the state of the soil moisture is required. For many years the measurement of soil moisture has required burying probes in the soil. These probes, typically around 1m long, are difficult to install and whilst they have provided useful scientific data there are several issues that limit their wider applicability. Firstly the process of installing the probe can change the local soil properties through compression or disturbance and also they only provide the soil moisture at the single fixed location. More recently the COSMOS has been developed. The cosmic ray soil moisture probe provides spatially integrated soil water content representative of near-surface conditions across a large area (of approximately a 350m radius and to a depth of about 0.5m, although the sampling volume changes with soil moisture). The sensor actually detects fast neutrons, which have been generated from cosmic rays. At the Earth's surface, fast neutrons are absorbed by water (or the hydrogen atoms within water molecules), so fewer neutrons detected imply higher water content. In this way the neutron count can be related to soil moisture and other stores of water, such as that contained within plants. Since these sensors sit above the surface their installation does not disturb the soil being measured and they provide a wider spatial measurement of soil moisture which is superior to a single point measurement.

The biggest challenge for future flood and drought observation is to be able to provide high spatio-temporal resolution data on water levels across the UK (the addition of chemical information would also be beneficial). Associated with this challenge is the need for more out-of-stream water monitoring, in particular soil water fluxes and soil moisture data. The COSMOS soil moisture network established by CEH goes some way to addressing this, but there is a need to expand this in order to understand whole-system water flows under localised conditions.

The NRFA catalogues mean flow data from the UK's gauging stations, along with some peak flow data. The data are vital for water management and flood and drought monitoring. Periods with no data are commonplace, however, particularly during low-flow and high-flow events. The current monitoring network struggles to provide flow data during flood and drought events, preventing accurate assessment of their extent and thus preventing precise, predictive modelling. In-stream sediment monitoring is also a challenge that needs addressing, as evidenced by recent flood events in the southwest. The challenge is to both monitor sediment load and to provide coupled flow-sediment discharge data during flood events.

Groundwater monitoring data is concentrated on aquifers exploited for water resources, and there are very few stations reporting groundwater levels in the shallow superficial groundwater systems with the most direct interaction with, and impact on, surface and fluvial flows.

Satellite-borne systems (instruments and sensors), which remotely image the Earth at a range of scales and imaging resolutions, are now emerging to complement surface based terrestrial systems. The Soil Moisture and Ocean Salinity (SMOS) is an ESA satellite which has the goals to globally monitor soil moisture over land surfaces and the surface salinity of the oceans, and contribute to improving the management of water resources. The satellite has a typical spatial resolution of 35-50km and provides soil moisture data with 4% accuracy (volumetric), with a return period of three to four times a day, depending on the satellite's orbits and latitude on the target site. SMOS data has been acquired since October 2010.

Groundwater flooding is generally recognised to be an area where monitoring and prediction remains a challenge.

Challenges:

- Developing a groundwater monitoring network that incorporates locations that are optimal for groundwater flood risk assessment, as much of the existing network was put in place with resource assessment in mind.
- Obtaining the information on hydrogeological properties to enable the calibration of regional groundwater models to allow groundwater flow in the near-surface horizons to be simulated adequately; again, models are currently calibrated to assess groundwater resource rather than flood risk.
- Lack of capacity at local level – the responsibility for groundwater risk assessment is established within the Floods and Water Management Act 2010 as being with the Lead Local Flood Authority (LLFA) (e.g. County Council). These LLFAs often do not have the resources or the technical capacity to develop or interpret observational relating to groundwater flooding.
- Providing information relating to groundwater flooding in a form that can be understood by those making decisions. This may be LLFAs but will also include a diverse set of users such as emergency responders (e.g. Fire Service) and property owners.
- The observation of urban and pluvial flooding for verification of surface water flood forecasts.

Opportunities:

- Given the local level at which groundwater flood risk is meant to be managed, crowdsourcing and citizen science provide the potential for the development of community-based networks. Citizen-sourced data can be combined with data collected by the LLFAs and the environment regulators, and put in a web-based form that is easily accessible to a wide group of potential users in the community.
- Remote sensing of land surface temperatures has the potential to allow groundwater discharge at-surface and shallow groundwater to be efficiently mapped.

5.5 The coastal environment

5.5.1 Environmental Observation Technologies

A storm surge is a high water level brought on through the combined effects of low atmospheric pressure and strong winds. Coastal flood impacts tend to be greatest when a surge coincides with high astronomical tides and strong onshore winds. The ability to model and forecast storm surges can support preparation and mitigation activities, bringing enormous benefits, including to some of the world's poorest countries. Measurement of wave conditions near the coast are also a crucial factor, especially since wave forecasting models close to the shoreline, where the effects are most felt, are at their most complex.

Earth observation data from satellites has an important role to play in surge monitoring and forecasting, but the full uptake of the data by users such as environmental agencies and tidal prediction centres has not been as high as it might be. This is especially true for newer data types such as coastal altimetry and high-resolution scatterometry. The data from scatterometers are used widely in ocean modelling. Recognising this, the ESA is funding the eSurge project, led by CGI (UK), which will make access to such data easier than it has been, including providing new data types.

Spaceborne radar altimeters have proven to be superb tools for mapping ocean-surface topography, the hills and valleys of the sea surface. These instruments send a microwave pulse to the ocean's surface and time how long it takes to return. A microwave radiometer corrects any delay that may be caused by water vapour in the atmosphere. Other corrections are also required to account for the influence of electrons in the ionosphere and the dry air mass of the atmosphere. Combining the data with the precise location of the spacecraft makes it possible to determine sea-surface height to within a few centimetres. The strength and shape of the returning signal also provides information on wind speed and the height of ocean waves. The data are used in ocean models to calculate the speed and direction of ocean currents and the amount and location of heat stored in the ocean, which, in turn, reveals global climate variations.

The Ocean Surface Topography Mission on the Jason-2 (launched in 2008) satellite is an international Earth observation satellite mission that continues the sea surface height measurements begun in 1992 by the joint NASA/CNES TOPEX/Poseidon mission and followed by the NASA/CNES Jason-1 mission launched in 2001.

Observation of pollutants such as salt, nutrients and living organisms are needed for effective prediction and monitoring of events. Only very limited observation of water pollutants is possible remotely using satellite ocean colour measurement. Satellite data are limited in spatial resolution and measurement of ocean colour is impacted in shallower waters where effects from the sub-ocean land surface colour need to be accounted for.

Apart from satellite we are limited to onerous and time consuming *in situ* sampling and laboratory analysis which is unable to contribute to real-time monitoring or prediction. There is a requirement for autonomous (or guided) marine floats that can carry out sampling and analysis automatically and report the results in real time.

5.5.1.1 Challenges and Opportunities

The coastal marine environment is not well observed – a greater understanding of the ocean currents around the UK coastline out to a few hundreds of kilometres from shore could be gathered through the development of an HF radar network. In addition to providing data for forecasting coastal oceans such networks provide critical information to support pollution tracking, search and rescue, harmful algal bloom monitoring and navigation.

Flooding and coastal inundation can impact coastal erosion which in turn can have significant impact on the effect of the next flooding event. The second storm is likely to be the critical one, once the defences are breached or damaged and the beach has been swept away. In order to understand this interaction rapid updating on the state of changes to the coastline and beach sediment and defences is necessary. The Environment Agency uses airborne terrain scanning LiDAR to monitor changes in coastal defences. The Channel Coastal Observatory¹⁸ is a partnership of maritime local authorities which monitors the beaches and makes all the data freely available under the Open Government Licence.

18. www.channelcoast.org

To provide effective response to a large East Coast storm surge, the FFC and Met Office require the capability to provide initial indications of coastal flooding with an eight day lead time. Therefore, a greater than eight day assessment of forecasts is required in the lead up to a potential coastal flood. Currently, the Met Office Global and Regional Ensemble System drives the Continental Shelf (CS3x) model to provide surge ensembles, but surge output (ideally combined with wave ensembles) should be extended.

5.5.1.2 Key Research Themes and Activities

As with all natural hazards the ability to observe the phenomenon is of essential importance but this needs to be developed in concert with advanced models able to assimilate the data allowing forecasts of impact to be disseminated.

Following the flooding in 2012 and over the winter of 2013 – 14, the FFS, EA and Natural Resources Wales (NRW) have reviewed capability and identified the following ‘gaps’:

- Estuaries – Grid to Grid not able to forecast flooding in river sections influenced by tides despite some of these being high risk areas identified as part of the National Flood Risk Assessment (NaFRA).
- Ground water – benefits could be realised from a national ground water capability and susceptibility model allowing impact to be assessed.
- Longer range precipitation and fluvial ensembles to forecast response in slower responding rivers (e.g. River Thames 2014).
- Longer lead time projections – all sources of flooding, and beyond day five, ideally monthly and seasonal projections as lead indicators.
- Improved understanding of concurrent flood risk (multiple sources and joint probability).

- Contextual information, understanding of severity of floods, detection and attribution. This could be gathered through enhanced use of crowdsourcing sites such as the Met Office Weather Observations Website (WOW).
- Nowcasting science to forecast rapidly developing situations – flash flooding in urbanised areas and rapid response catchments. Key areas: rainfall intensity, pattern of rainfall profile (intense rainfall once catchment has wetted up), antecedent conditions.
- Real time ensemble modelling of inundation.
- Near shore wave modelling and monitoring – local wave transformation models and information sharing (EA and FFC).
- Total water level ensembles to days five to seven: combining surge and wave ensembles.
- Coastal impact assessment – develop and refine East Coast Decision Support Tool and apply to other coasts or approach using HIM framework.
- Very high resolution coupled ocean-atmosphere-land modelling with probabilistic spatial (inundation) output. This would be along the lines of the UK Environmental Prediction System, but accelerated development over high risk areas identified by NaFRA, e.g. Humber Estuary.
- Coupling of ‘current’ coastal and fluvial models, e.g. Grid to Grid and Continental Shelf Model (CS3x / NEMO).

Further gaps identified by coastal authorities include nowcasting of coastal overtopping and impacts of long period swell waves.

5.6 Volcanic ash

The WEather HaZARD for aeronautics (WEZARD)⁹ project co-funded by the European Commission within the Seventh Framework Programme (2011 – 2013) has reported on the requirement for observations to facilitate our understanding of the distribution of volcanic ash and gases in the atmosphere. Permission has been obtained from the WEZARD project to repeat some of their key conclusions herein.

Decision makers in the aviation industry require more information on the geographical and vertical extent of volcanic ash and associated levels of contamination in order to decide where it is safe to fly. Current systems cannot provide the information required and an enhanced observational network of complementary monitoring systems is needed to initialise, validate and verify volcanic ash dispersion model output and forecasts. No single observing technology can provide a complete and fully resilient solution – all observational techniques have strengths and weaknesses. Satellite-derived imagery provides regular ‘big picture’ views of the atmosphere, but cannot provide the necessary detail when it comes to the vertical characterisation of volcanic ash layers.

Furthermore, the application of satellite imagery for volcanic ash detection is rendered largely ineffective when high cloud is present (which is very common in the North Atlantic). The continued development of volcanic ash related satellite-derived applications for model initialisation purposes and for verifying and ‘adding value’ to dispersion model output (in line with end-user expectations and requirements to reduce model uncertainties) would be greatly enhanced and complemented by a concerted research and development program.

Ground-based remote sensing systems can provide vertical profile data and so, when integrated with other measurements, can help to provide estimates of mass concentrations, i.e. the parameter actually required by the end-user. *In situ* measurements from research (often not available) and civil contingency aircraft and sondes can effectively characterise aerosols in the atmosphere, but individual sampling operations can only cover narrow geographical areas over short timescales.

The principle of investing in a range of quality observational measurements of the atmosphere in order to improve the accuracy of weather forecasts is a tried and tested philosophy. It is, therefore, essential that a future volcanic ash monitoring network should also integrate a range of ground based, airborne and space-based techniques, both at and near the eruptive source and in distal plumes, to allow the best possible analysis of volcanic ash in the atmosphere. It is very important to note that for the UK a key international partner is the Icelandic Meteorological Office which is the volcano observatory for Iceland. The Icelandic Meteorological Office not only gather a vast array of data directly but also act as coordinators and local experts in many areas.

Moreover, in addition to the volcanic ash hazard, the potential hazards to aviation, the public and the environment posed by other volcanic emissions, e.g. sulphur dioxide (SO₂) and sulphate aerosols, are yet to be fully understood, therefore an observing network encompassing a range of techniques and enabling detection of different kinds of emission, would undoubtedly provide additional value in the future. Focus should be directed to observing new and evolving volcanic ash and other particulate aerosols (e.g. dust and sand) and geophysical monitoring technologies and systems identified by the WEZARD project e.g. satellite, LiDAR, ceilometers, radar, aerosol sondes, UAVs and aircraft mounted probes and sensors.

5.6.1 Environmental Observation Technologies

All techniques used to measure/monitor variables furnished as inputs to Volcanic Ash Transport and Dispersion Models (VATDM) have application limits. Ideally, a range of techniques should be used simultaneously and combined to cover all the observation spectra and to get as many variables as possible. Key variables to VATDM that characterize the source term are: i) plume height, ii) mass eruption rate (MER), iii) total grain size distribution, iv) erupted mass and the v) onset and vi) end of an eruption.

Particle concentration and SO₂ observations can also be important (e.g., for data assimilation or model validation, provided SO₂ transports similarly as ash). There is the need for a shared high-quality database gathering all critical parameters standardized based on same formats. A leading example of such is being constructed for observation in Iceland under the FP7 FUTURVOLC²⁰ project though this is only part of the required larger database.

Plume height is usually the easiest parameter to constrain in real time (e.g. using radar, satellite, LiDAR, ceilometers, PiReps or ground visual observation, infrasound, thermal camera, seismic amplitude, aircraft measurements, dropsondes, balloon sondes, lightning detection). Each technique is associated with a certain measurement uncertainty and, therefore, a range of plume heights should be provided for each technique rather than a single absolute value. Second, the part of the plume/cloud for which the height is derived needs to be specified (e.g. neutral buoyancy level, overshooting, top of umbrella cloud). Third, the distance from the vent at which the height is detected also needs to be specified (in particular for bent-over plumes).

MER is hard to measure directly and a distinction should be made amongst MER (i.e. at vent), mass transport rate (MTR) in the cloud at the neutral buoyancy level and local MTR (i.e. at a given distance from the vent). A distinction should also be made between MER/MTR of all particle sizes and MER/MTR of small particles (i.e., particle detected by satellite sensors). Ash dispersal forecasting associated with aviation safety and long-range dispersion mainly requires information on MER of fine particles that enter the horizontally-spreading cloud. If MER is calculated from plume height, then the most appropriate parameterization should be used. Examples of techniques that could help constrain MER/MTR (of selective particle sizes) are: i) radar, ii) LiDAR, iii) ground-based IR or UV camera, iv) satellite, v) seismic energy release, vi) infrasound, vii) *in situ* aircraft for local MER.

Unfortunately a comprehensive real-time technique that can provide the erupted mass associated with the whole particle size spectrum does not exist. As an example, satellite retrievals can only determine the effective particle radius of the ash cloud within the field-of-view only if the actual effective radius is <15 µm (with spatial resolution issues), while meteorological Doppler radar (S, C, X and Ka bands) can only detect particles with radius >30 µm. *In situ* sampling (e.g. piston engine aircraft) can detect particles between 250 nm and 32 µm. As a result, total grain size distribution (and the associated mass) can only be derived from the combination of various techniques. In addition, information should also be given on whether the resulting cloud is ash-rich or gas-rich.

20. <http://futurevolc.hi.is>

The concentration of ash in the cloud can be derived from both remote sensing (e.g. radar, LiDAR and satellites) and *in situ* techniques (e.g. dropsondes and research aircraft), although it should be noted that currently only satellite and aircraft provide real time data. In the UK the Met Office Civil Contingency Aircraft (MOCCA) funded by the Civil Aviation Authority is on permanent stand by to measure the distribution and concentration of ash in UK airspace in order to validate ash forecasts from the Volcanic Ash Advisory Centre. MOCCA uses optical particle counters to measure mass concentration and LiDAR to detect the vertical distribution of ash in the atmosphere. The distribution and mass concentration of ash around the UK will also be monitored by the Met Office in the future (2015/16) using a network of LiDARs and sun-photometers being installed across the country using Department for Transport funding.

For better constraints on aggregation processes, more information should be gathered on: i) particle-number concentration for different sizes, ii) ice vs. liquid water content, iii) depolarization ratio of aggregates vs. individual particles (in LiDAR signal), iv) electrical charges through lightning detection, electric field measurement or direct sampling.

Eruption onset, ongoing changes in eruption intensity and eruption end are crucial to ash forecasting and for aviation-safety purposes. Various techniques can be used to detect the onset of an eruption. Satellite and seismic analyses, direct personal observation and via webcam are traditional techniques. Infrasound, radar, LiDAR and lightning analyses are newer techniques. Notification of the end of an eruption (or an event) is essential for regulators and decision-makers.

5.7 Space weather

Space weather is a medium high risk on the UK's National Risk Register. A severe space weather event could result in a range of impacts: damage to the electricity grid resulting in localised power blackouts, damage to satellites and also disruption of signals to/from satellites and radiation storms which may present a risk to human health for airline crew and passengers. Recognising this risk BIS, on behalf of the UK Government, has invested in the development of a space weather forecasting capability, the Met Office Space Weather Operations Centre (MOSWOC).

GNSS, (often known as GPS), would also be impacted, making such systems inoperable for a number of days. This will cause operational impacts to industries such as aviation and shipping but could also impact those which rely on GNSS for critical timing information. Holdover clocks are available to maintain systems reliant on high precision timing for a few days.

However, as a new and developing area, there are significant gaps in the environmental monitoring capability that acts as a barrier to improving our scientific understanding and hence actionable forecasts.

5.7.1 Environmental Observation Technologies

The most important determinant of space weather impacts on the Earth's environment is being able to detect measure and ultimately forecast events originating from the Sun and travelling through the heliosphere. The Solar and Heliospheric Observatory (SOHO) satellite measures the internal structure of the Sun. The Advanced Composition Explorer (ACE) measures low and high energy particles at the Earth-Sun gravitational equilibrium point (known as L1). The Solar Terrestrial Relations Observatory (A and B) (STEREO) one ahead of the Earth in its orbit and one behind the Earth in its orbit provide 3D structure of coronal mass ejections. All these missions provide critical data to support assessment of risk to the Earth from space weather.

21. www.intermagnet.org

22. <http://www.bgs.ac.uk/data/Magnetograms/home.html>

This area has not been addressed in this report but is extremely important for the maintenance and future development of space weather forecasting.

The European Incoherent Scatter Scientific Association (EISCAT-3D), to be located in northern Scandinavia, is the next-generation European radar for space weather science. The £100 million multi-national project is one of twelve research infrastructures selected by the European Strategy Forum on Research Infrastructures for implementation funding, and was included in the last RCUK Capital Roadmap.

The EISCAT-3D project will provide a step change in our ability to study the two-way interaction between space weather and the atmosphere that is necessary to understand and predict the ultimate impact of potentially-damaging space weather events originating from the Sun. For MOSWOC, use of EISCAT-3D observations should lead to a better representation and forecast of the solar wind, ionosphere and upper atmosphere in our models.

This endeavour will be augmented by the Space Weather Observation and Operations Network (SWOON), a geographically-distributed network of smaller space weather instruments in the Scandinavian, British and Atlantic sectors, modelled on observing requirements drawn up by the World Meteorological Organisation. SWOON will provide a UK contribution to a worldwide observing infrastructure for space weather research and services. This is essential to transfer space weather research knowledge into operational atmospheric models and environmental services under development by the Met Office.

A risk of major concern is damage to transformers in the National Grid during a major magnetic storm. The risk results from exposure of the grid, because of its earthing points, to the flow of Geomagnetically Induced Currents driven by electric fields created by rapid geomagnetic field variations. British Geological Survey (BGS) monitors geomagnetic field changes at the three magnetic observatories it operates in the UK at Lerwick (Shetland), Eskdalemuir (Scottish Borders) and Hartland (North Devon), with data transmitted to the BGS offices in Edinburgh in real time.

BGS also operates magnetic observatories overseas on Ascension Island, at Port Stanley (Falkland Islands), King Edward Point (South Georgia) and on Sable Island (Canada) and plays a leading role in the International Real-time Magnetic Observatory Network (INTERMAGNET) programme,²¹ a consortium of worldwide institutes and observatories that make measurements of the Earth's magnetic field to agreed quality standards.

Over the last decade BGS has worked with Scottish Power and National Grid to develop a geomagnetically induced currents model tool (MAGIC – Monitoring and Analysis of Geomagnetically Induced Currents), using data from the UK magnetic observatories as input. This includes a geology-based model of ground conductivity in the UK and a detailed representation of the high-voltage transmission system in Great Britain. This tool is used by National Grid to assess the level of GIC flowing at transformer nodes in the grid.

BGS supports the MOSWOC by streaming UK magnetic observatory data to MOSWOC and by providing local and global magnetic index data products.

23. <http://www.bgs.ac.uk/products/geosure/>

The electric field is not measured routinely anywhere in the UK. To help validate modelling of GIC, BGS is installing surface electric field monitoring systems at the UK observatories and plans to establish long-term records. It is anticipated that the National Grid will make direct measurements of GIC at some of its transformers, providing 'ground truth' data for modelling. A challenge is to increase the frequency of sampling at magnetic observatories to better record the rapid fluctuations during geomagnetic storms. BGS is developing systems to collect and transmit one-second data and there are challenges in sensor technology and electronics design to meet observatory standards for instrumentation. This effort is being promoted worldwide through INTERMAGNET.

BGS has scanned 250,000 historical magnetograms from magnetic observatories operating in the UK over the last 160 years. These provide a rich resource for space weather investigations, though the next step of generating digital data is required. Access to near real-time data from observatories worldwide is provided by INTERMAGNET and BGS operates a World Data Centre for Geomagnetism.²²

There is the potential to improve real time knowledge of the state of the ionosphere by using the various GNSS to determine Total Electron Content (TEC). The vertical profile of TEC is measured using ionosondes which are ground based transceivers that send and receive radio pulses at different frequencies.

5.7.2 Challenges and Opportunities

Space Weather forecasting is critically dependent on a series of satellites (SOHO, ACE, STEREO A+B) that are in extended mission phases and not designed with optimal cadence, resolution or sensitivity for an operational service. There is a significant challenge to provide space weather missions to replace the aging science missions that we are currently reliant upon. The UK has considerable expertise in the development of space weather instrumentation (both space and ground based) and hence there is an opportunity in this field.

An increased density of magnetometers is required to improve our understanding of geomagnetically induced currents in power lines to facilitate better warnings and remedial actions. Better knowledge of the impact of radiation on airline crew, passengers and future commercial space flight activities is required. The development and production of airborne radiation monitors is desirable to be complemented by more ground based neutron monitors. For exposure on aircraft, prediction and measurement of the highest energy protons incident on the Earth's atmosphere needs to be improved, because this strongly influences the dose rates onboard aircraft. Space weather can also impact space based communications systems through its interaction with the ionosphere leading to significant disruption of services. The Rutherford Appleton Laboratory operate ionosondes out of Chilton in the UK – this facility requires renovation and a new site could be created in Scotland, for example at Lerwick a site where radiosondes are operationally launched and ionosondes used to be launched up until 1998.

To allow the additional data to be effectively used by the science community, a UK space weather data archive facility will need to be created to effectively store the new data and other existing data in a coherent and accessible manner.

5.8 Natural ground instability (landslides and subsidence)

5.8.1 Environmental Observation Technologies

Natural ground instability (i.e. not anthropogenically induced ground movement from mining related activity) can develop due to landslide/slope instability, dissolution of dissolvable rocks causing ground subsidence and the shrinking and swelling of clay soils causing ground movement. A mixture of techniques and technologies are used to monitor and observe naturally induced ground instability. These observations use a mixture of terrestrial, airborne and space-borne assets to give a variety of scales and types of measurements which, directly or indirectly (i.e. once the measurement is processed), give observational data on ground instability in terms of monitoring movement and soil/rock parameters that give an indication of instability of the materials (e.g. volumetric moisture content, pore pressure, strain). BGS has also developed National Ground Stability event datasets (National Landslide Database and National Karst Database) that have collected event data across the UK from both reported and historical data. This observational data has enabled BGS to gain a broad understanding into the processes and conditioning factors that cause natural ground instability events. This knowledge has enabled BGS to identify and highlight areas across the UK where ground instability can potentially be a problem through BGS's National Ground Stability datasets.²³

Much of the data gathered from the techniques are being integrated at the interpretation stage on a project by project basis. This is usually for more commercially orientated short-term (1 to 2 months to 2 years) objectives, within civil engineering projects (building new structures and/or remediation of problematic sites). This data is not regularly collected in real-time within one observational platform for longer-term research driven objectives (5 years). The integration of data and the development and use of real-time data is an emerging area of application and research. This is starting to enhance the understanding of the conditioning factors that contribute to triggering natural ground instability events. Research being undertaken by BGS, in collaboration with partners within the Natural Hazards Partnership and within the commercial sector (e.g. SMEs, infrastructure owners/operators), is contributing to the development of methodologies that will, in the future, forecast natural ground instability events.

5.8.2 Challenges and Opportunities

Ground instability is generally recognised to be an area where longer-term monitoring and forecasting remains a challenge. There is a requirement to develop a ground instability real-time monitoring network that incorporates locations that have a variety of conditioning factors that contribute to triggering natural ground instability events. This additional capability should be developed in parallel with securing data that is already captured for civil engineering projects and current observatories (e.g. BGS landslide observatories, CEH COSMOS).

The integration of meteorological, hydrological, hydrogeological and ground property data into models that simulate ground instability events would be the most effective utilisation of existing and new observation types. Such models would provide information relating to the impact of ground instability in a form that can be understood by those making decisions, and enable them to make appropriate decisions in a timely fashion. This may be for: Government, emergency responders (e.g. Fire Service), local authorities, insurance sector, infrastructure owners/operators and property owners.

5.9 Wildfires

Remote sensing of heat using high resolution thermal imaging from satellite is required to monitor the evolution of wildfires. Limited data is available from the USA via the Moderate Resolution Imaging Spectrometer (MODIS) satellite. In addition high resolution visible satellite imagery can be used to monitor smoke. For the prediction of fire risk the soil moisture is important (see section on flooding) but in addition monitoring of dead vegetation volume and moisture content is required. Once the fire exists very high resolution wind measurements are required in forecasting its complex evolution. For large fires, effective wildfire prediction requires the fire to be represented explicitly within a meteorological forecast model allowing the spread of the fire to evolve with the changing wind field and any feedbacks to be represented. Within the UK wildfires are seldom large enough to warrant full coupling but the forecast of their spread does rely on accurate wind forecasts and an understanding of available fuel – the latter is not always available.

5.10 Air quality

Air pollution/quality is often mistaken for a wholly anthropogenic issue, when in fact, natural and biogenic emissions of air pollutants, e.g. from pollen and biogenic volatile organic compounds, windblown dust from eroded sediment, sea salt and forest fires and even volcanoes, contribute to air pollution events as well. Air quality is also driven by gaseous chemistry and the complex interactions of the complete mixture of gases and particulates, both anthropogenic and natural. Poor air quality can present a barrier to human health that could be addressed if monitoring were improved.

5.10.1 Environmental Observation Technologies

Environmental sensors that could help to address these challenges and fulfil these opportunities are increasingly available, increasingly affordable and increasingly well resolved. For example:

- Wideband Integrated Bioaerosol Sensors (WIBS) are now available, providing real-time, continuous bioaerosol detection and classification using UV-excitation particle fluorescence and particle shape analysis; these sensors can classify and count bacteria, fungal spores, and pollen. Current WIBS sensors are however limited in their ability to distinguish between different pollen species and hence currently the UK pollen monitoring network is reliant on the use of microscope slides being examined by trained staff.
- Electrical Ultra-fine Particle sensing is now possible, using electrical diffusion charging of aerosols to count them and measure their particle size; these sensors can operate at real-time resolution, though battery life is still typically an issue with portable sensors. A recently released OPC-N1 laser particle counter by Alphasense for instance allows the direct measurement of up to 16 size bins, enabling the identification of size distribution footprints for individual sources and thus provide coarse source-attribution potential.
- Low-cost, wireless sensors for ozone are now available, enabling high spatial-resolution studies of ozone dynamics within urban and peri-urban environments; for example, Alphasense's B4 series ozone monitor.

24. For example <http://uk-air.defra.gov.uk/> or <http://www.airqualityengland.co.uk/>

There is a scarcity of data with which to test and calibrate models, particularly scaling across from urban to rural environments. The implementation of state-of-the-art environmental sensing, such as those exemplified above, could allow air quality to be resolved at such a scale that it could be useful for personal decision-making. With smaller, cheaper and more affordable air quality sensors becoming more widely available, they pave the way for a more direct interaction of the general public and local authorities on local air quality issues. But while air quality information based on crowdsourcing and citizen science activities requires the development of new approaches for quality control and data governance, the potential for the generation of Big Data on air pollution may offer substantial benefits to complement the scarce and expensive regulatory monitoring site network. Recent pilot projects in Scotland funded by SEPA have identified both challenges and opportunities of developing citizen science approaches for air quality. In a similar way to many other fields of environmental observation, opportunistic data on consumer health impacts from poor air quality could be recorded through apps and websites like WOW.

Monitoring of air quality could be improved using compact instrumentation installed in city centres to provide greater input into the evaluation and forecasting of air quality and the effects on health. Some of these installations could be included in school weather stations (see Section 4.1).

5.10.2 Challenges and Opportunities

The UK's air monitoring is based on the statutory reporting from its 133-site Automatic Urban and Rural Network (AURN) allowing for a detailed analysis of daily air quality at the national scale, though not sufficient for the forecasting of, in particular, secondary pollutants and events, e.g. ozone or PM_{2.5}. Local authorities also monitor air quality more widely but the sites are often poor from a modelling point of view (many are curb side and hence too close to highly variable sources) and access to the data is difficult and not timely. If the local authority data could be gathered effectively in a centrally accessible database

this would represent a significant step forward in monitoring and modelling air quality. Furthermore, specific gaps do exist in both the instrumentation of (and its coverage and integration) and our knowledge of air quality. Additionally, the current network reflects and delivers into a regulatory framework and is not designed to underpin scientific research, detailed regional/local variation or forecasting. Finally, current economic constraints may lead to a reduction in the monitoring capability over the next decade, as site closures are already in progress.

Regarding instrumentation, the two UK 'supersites', at Auchencorth Moss and Harwell, provide the most comprehensive, automated and temporally resolved air quality data available, integrated with hourly meteorological data and both soil and vegetation measurements. Yet, these sites are only representative, crudely, of the North and South, of rural background environments away from major emission sources, and cover only two different geologies. Clearly, a specific gap in instrumentation is the lack of an automated monitoring network that records hourly data on diverse air quality measures, extends across the UK and across differing geologies and land uses, integrates with meteorological and ecological data, and integrates far better with existing European activities, so that both long-range transport and local air quality can be more effectively monitored. Regarding knowledge gaps, there is a need to better understand:

- Emissions of gases and particulates
- The long-range transport of aerosols and particulates
- The specific composition of particulate/aerosol deposition
- Fluxes across rural-urban fringes
- Variability across different biome types

While it is clear that substantial investments to increase the spatio-temporal resolution of statutory monitoring using existing highly precise, but expensive and labour-intensive measurement technologies are unlikely, the emerging medium to low-cost monitoring approaches, e.g. the AQ Mesh or eMote fixed monitoring packages may provide a way forward. In addition moves to share and make more effective use of existing local authority and other agencies data more effectively should be encouraged.

Additionally, the link between existing environmental data and population health information is poor. There is a front-end for some general air quality data,²⁴ but statutory reporting must improve. The lack of available, high-resolution data and detailed composition information prevents a step-change towards highly accurate and specific population health information, for instance air quality forecasting, at the local scale, which could be provided by apps direct to the customer.

Rates of allergy are increasing, affecting some 30-35% of people at some point in their lives. In order to address this, we need to better understand the fluxes of allergens across the UK, from ozone and pollen to organic aerosols and ultra-fine particles. For example, it is crucial that we can better identify the key sources of natural volatile organic compound emissions, what factors cause these emissions, how long they remain within the atmosphere and how far they travel. Equally, the dynamics of ozone within an urban environment are complex and require a better spatial understanding.

Finally, bioaerosols, including pollen, show fluxes of high spatio-temporal variability and in order to be able to provide useful consumer health information, we must understand their composition and spatio-temporal fluxes across the UK.

5.11 Earthquakes, volcanoes and tectonics

The NERC-funded Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) is a world-leading centre for understanding tectonic and volcanic processes and hazards using Earth observation techniques, ground-based measurements, and geophysical models. It brings together scientists from across eight UK universities to provide national capability in EO and geohazards. Since April 2014, COMET has also been working in partnership with the BGS to deliver cutting-edge research on earthquakes and volcanoes as well as high-impact hazard monitoring services.

5.11.1 Environmental Observation Technologies

EO has changed dramatically over the last 10-15 years. Ground deformation caused by both tectonic and volcanic processes can now be monitored remotely using satellite radar interferometry (InSAR). High-resolution images and topographic datasets also now allow these processes to be identified and characterised, meaning that hazards can be assessed remotely, in conjunction with detailed field investigations where required.

Importantly, the ESA's new satellite, Sentinel-1A, launched in April 2014, will radically improve our ability to measure deformation. COMET is establishing an InSAR processing facility that will make information from Sentinel-1A available to the entire EO community in near real-time, covering all of the tectonic belts, including the entire Alpine-Himalayan Belt and East African Rift, all active volcanoes in the world, and all of the UK and its overseas territories. Data from Sentinel-1 are freely available from the EU Copernicus program.

It is worth noting that the development of new and emerging technologies is still led by ESA and NASA. For optical EO there is a focus on improving spatial and particularly spectral resolution. ESA, through the Infrared Atmospheric Sounding Interferometer (IASI) suite, can legitimately claim to lead in this area for applications in volcanic gas and ash tracking/detection. ESA has also clearly been at the forefront of the development of satellite radar, with the Sentinel-1 program the culmination of over 20 years of investment and development in radar technology.

The last decade has also seen huge growth in high-resolution imagery, which scientists have exploited to make advances in tectonic geomorphology, topographic modelling, and measuring fault slip through image matching. These have been mirrored by advances in airborne and ground-based techniques, notably LiDAR and photogrammetry from non-standard platforms. The latest optical satellites (e.g. the French Pleiades satellite) enable the production of elevation models at approximately 1m spatial resolution. The Tandem-X global DEM, with 12m resolution, about to be released, represents a step-change in our ability to quantify the Earth's morphology at the scale of entire continents. None of these topographic datasets are available free of charge to users.

The IASI-II data stream (opened in late 2013) from the MetOp-B weather satellite will double the SO₂ measurement frequency provided by IASI-I. IASI-III (onboard MetOp-C) is scheduled for launch at the end of 2017, while Eumetsat's Infrared Sounder is due for launch in 2018 and will deliver infrared spectra every 60 minutes, with a ~2km spatial resolution. This powerful combination of hyperspectral sounders is allowing the development of gas and ash retrieval algorithms to build a global long-term dataset and allow monitoring of hazard events.

In terms of ground-based sensors for ash and gas, current technologies are based around spectral imaging and networks of instruments (and their integration into broader geophysical observations).

The BGS operates the UK seismic network, which includes 40 broadband stations operating to modern international standards for dynamic range and frequency response. Continuous data from all broadband stations are transmitted in real-time to the BGS office in Edinburgh, where the data are analysed and archived. In addition, there are 40 older short-period stations across the UK augmenting the broadband network. These improve the detection capability of the network as a whole. Data from the majority of the short period stations are also transmitted in real time to Edinburgh.

BGS responds to significant seismic events within an hour, 24/7, providing information to the UK Government and to a variety of public and private sector bodies. Reports are published on a similar time scale on the BGS website where members of the public are able to input their observations of earthquakes into a web tool which builds an online map of the felt intensities of events.

A highly significant aspect of seismic monitoring, with important policy implications, is subsurface events induced by anthropogenic interventions. This includes activities associated with energy (e.g. geothermal, shale gas), waste disposal (e.g. radioactive waste) and underground storage (e.g. gas, compressed air). For example, the 'traffic-light' system outlined by DECC will require hydraulic fracture stimulation ('fracking' for shale gas) to cease if earthquakes with magnitude of 0.5 or greater occur. However, the existing network of permanent seismic sensors in the UK cannot reliably detect events of magnitude lower than 2.0 and there are several thousands of earthquakes of magnitude 0.0 or above that are undetected each year in the UK. This highlights an important challenge to improve our capability to detect small earthquakes in order to establish baseline natural seismicity and support and regulate industrial activities. To help address this, BGS together with the Universities of Bristol, Edinburgh, Leicester and Liverpool will operate UK Array deploying a dense temporary localised array of 40 sensors that moves progressively across the UK, over a period of several years.

The UK seismic network is part of the observing system composed of networks in countries around the world and many of these provide data in real time. BGS can access data from more than 200 seismic stations worldwide using a system originally developed to provide UK capability for the seismic component of a tsunami warning system.

Looking to the future it would be advantageous to have a network of borehole seismometers (to reduce noise experienced by surface seismometers). Additionally there are recent developments in optical fibre technology producing seismometers for down-hole application in the hydrocarbons industry that may be applicable to a future borehole seismometer network and help to achieve the objective of lowering the detection threshold for natural seismicity (which will remain dependent on the density of measurement sites).

5.11.2 Challenges and Opportunities

Research is being conducted to develop new means of measuring and modelling deformation. This includes the development of a prototype combined GNSS seismometer which combines the sensitivity of broadband seismology to rapid motions (up to a few minutes) with the ability of GNSS to track permanent displacements.

The future will see the development of an open architecture to incorporate multiple motion sensors. This could have particular benefits for volcanoes, where deformation over long timescales can help to assess risk, and for Earthquake Early Warning. Effort will also pursue new missions, including the dual beam and geosynchronous SAR systems previously proposed for ESA's Earth Explorer 8 competition.

Structure from Motion – a technique that estimates three-dimensional structures from two-dimensional photographs – is an emerging technology proving useful for small to large scale mapping and modelling. It can be applied to photographs acquired from the ground, or from balloons/drones/aircraft.

Both earthquake and volcanic studies benefit from advances in our abilities to provide accurate dates for samples. A number of different tools are used to cover different materials and time spans, but all have improved significantly in the last decade, in particular cosmogenic dating techniques.

COMET is creating alert systems for volcanoes, including a near real-time eruption alert based on the detection of SO₂ emissions, and a longer-term system based on identifying and characterising unusual deformation. Their algorithms differ from existing systems in that they quantify not only the amount of emissions but also estimate altitude; and they have a sensitivity of 12 Mg SO₂/day so can be used to detect the first signs of unrest as well as major eruptions. The alert systems will be based at the Facility for Climate and Environmental Monitoring from Space at Harwell, collaboration with the Satellite Applications Catapult aims to ensure that they are accessible and user-friendly.

Regarding volcanic hazards specifically, our understanding of aerosols is a limiting factor. A better understanding of ash cloud heights would assist with this (with the new Met Office LiDAR system providing new data when online) and particle size distributions, the latter requiring UAVs for direct sampling. In general, UAVs could revolutionise observations of volcanoes in the next few years. Continued improvement to broadband spectral imagers (in both UV and Infrared) and the development of imaging Fourier Transform Infrared spectroscopy should also be given priority, especially given the interest in plume tomography.

A practical barrier can be the cost of access to high resolution EO data. High-resolution topographic models are vital if we are to identify earthquake faults from their signatures in the landscape, track the evolution of eruptions, or predict which valley a pyroclastic flow might use.

There are also cost and time barriers when it comes to obtaining accurate dates for samples. While the UK has excellent facilities, access to these can be limited. In terms of the science, COMET has meanwhile identified a number of key research challenges in EO which it will work to address between now and 2019. These are:

- Assessing the distribution of tectonic strain and seismic hazard in the continents.
- Assessing how seismic hazard varies in space and time following major earthquakes.
- Understanding the mechanical structure of continental lithosphere.
- Understanding patterns in volcanic deformation and degassing on global and regional scales and how they relate to the distribution of global volcanic hazard.
- Generalising models of subsurface processes to understand variations in volcanic behaviour.

5.12 Invasive species and disease

Invasive alien species (IAS) are considered to be one of the greatest threats to biodiversity, particularly through their interactions with other drivers of change (Millennium Ecosystem Assessment, 2005). Understanding both their pathways of arrival and their impacts on biodiversity are acknowledged as critical elements within biodiversity strategy. Early warning, prevention and control measures for IAS rely on information such as identity, associated biology and distribution. The two most expensive biological impacts in recent times for the UK have been foot and mouth (virus) and blue tongue (vector transmitted virus).

5.12.1 Environmental Observation Technologies

CEH have developed on-line systems and apps to enhance surveillance of non-native species coupled with rapid feedback, for example, the iRecord series for ladybirds and butterflies and the PlantTracker app for invasive plant species. Whilst image recognition technology does exist, the high demand for quality control coupled with the relatively high (but falling) costs prevent this technology from being widely deployed, unlike citizen science using low-cost apps. Building the citizen science capability for early-warning surveillance is likely to be increasingly important, and linking these capture systems to models for feedback to participants is an engagement opportunity that should not be overlooked. This would require some capacity building in order to support the verification processes within these systems. Such techniques could be used for monitoring invasive species and viral diseases.

Another state-of-the-art environmental observation technology for IAS is environmental DNA (eDNA). The eDNA approach is to use traces of DNA in the water to monitor the freshwater species that live there, simply by collecting a water sample from the pond or stream. The approach has been successfully used in monitoring native and endangered Great Crested Newt populations in the UK and is now being used to monitor invasive American Bullfrog populations. Whilst the approach is currently not automated, advancements in automated sample collection and online qPCR mean that automation could be considered, particularly as the cost of qPCR technology reduces.

5.12.2 Challenges and Opportunities

Maintaining a list of IAS within Great Britain is essential for underpinning decision-making concerning control, mitigation and eradication of IAS. Information on IAS is often scattered among a multitude of sources, such as regional and national databases, peer-reviewed and grey literature, unpublished research projects, institutional datasets and with taxonomic experts. As such, creating and maintaining an international database of invasive species that is comprehensive and up-to-date is a pivotal challenge. CEH have been compiling species information and associated distribution observations on IAS both in Great Britain and across Europe, creating the foundations for such a database. The opportunity exists for this database to expand to become an early-warning system, through integration of monitoring data.

There is an urgent need to anticipate which IAS are likely to cause future problems so that preventative action can be taken promptly. CEH have developed a method for horizon scanning that combines the structured approaches of literature review and risk assessment with dynamic consensus methods. Such information is used for underpinning and prioritising management for both the species and, perhaps more importantly, their pathways of arrival. In order to identify pathways of arrival, deliver real-time analysis on species arrivals and distributions, and make decisions as to the control, mitigation and eradication of AIS, observation is necessary.

Further challenges include the need to engage more people in recording IAS, and the need to better understand the mechanisms of both spread into and impact upon specific ecosystems. The latter could be addressed by embracing the opportunity to combine IAS data with other landscape data, from simple land cover data to more complex chemical, hydrological and biological data.

5.13 Data

Across the UK there are a multitude of environmental observations being made. Many Government agencies and private companies make environmental observations and the effective sharing of the data would significantly benefit the ability to forecast, monitor and deal with the impacts of natural hazards.

Examples of data include road side meteorology from highways sensors, road temperature data from gritting lorries, meteorological data from power companies and offshore wind farms, and CCTV networks widely operated by agencies such as district councils, highways departments and railway operators. Imagery from these networks can be useful in understanding current weather (e.g. seeing where it is snowing or foggy).

In addition they can also prove very valuable in dealing with impacts from localised natural hazards – for example during the Buncefield fire incident the motorway cameras were useful for the forecasters to monitor the evolution of the smoke at the scene. The ability for forecasters and responders to have access to the data would transform the UK's ability to deal with natural hazards.

The insurance sector and private asset owners and operators have significant data on damage to building and infrastructure. This has the potential to give huge amounts of data that can indicate the impact of natural hazards. At the moment this is commercially sensitive and hence very difficult to gain access to. In many cases the improvements in forecast services that could result from access to the data would be of direct benefit to the owners of the data who may not be aware of its benefit.

In addition to these obvious observation sources there are additional sources of environmental data that could be utilised. One example is the data gathered by cars. Most modern cars have air temperature sensors, some have road temperature sensors but in reality their ability to contribute to the understanding of natural hazards like snow and ice goes far beyond that. The computers on cars are continually monitoring a wide range of performance data like anti-lock braking performance, wheel traction, wiper blade activity and headlights. The combination of all the data, if accessible in real time, could provide a valuable resource to forecasting and monitoring severe weather. If communications were set up to allow the computers on cars to share this information via mobile phone or road side transponders then in turn up to date weather information and road condition data could be fed back to the cars through the same route directly into satnav systems allowing motorists to take avoiding action or at least moderate their driving accordingly.

There are other sources of environmental data that should also be harnessed to assist in weather forecasting which include:

- temperature and wind data from civil aircraft by intercepting Mode-S (navigational data) transmissions;
- path average rainfall rate from attenuation on mobile phone network back-haul links;
- near-surface fields of refractivity from digital audio broadcast receivers;
- data from ships and buoys received via marine navigational broadcasts (AIS);
- temperature and pressure data from the simple sensors built into phones; and
- short-wave radiation estimates from PV solar installations received via 'smart' meters.

All of the data has the potential to enhance weather forecasting at small spatial scales which has a direct impact on the prediction of weather related natural hazards.

Crowdsourcing of data can also be used for wider environmental observations like flood impacts, public monitoring of invasive species and pests and diseases (e.g. ash die back), public monitoring of air quality, and twitter feeds. The technological challenge lies in the gathering and interrogation of the data.

The Met Office has developed the WOW. It is designed as a portal to allow third party crowdsourced data and data from formal collaborators to be brought in to the Met Office. Research and development activity is required to make it more resilient and add additional functionality that will allow it to routinely feed data direct to the Met Office models and provide improved visualisation to users and collaborators. The system will be enhanced to allow input from moving platforms on the ground, sea or in the air. Development of such systems is critical in facilitating access to the very diverse range of data sources already available and represents a cost effective way of gathering environmental observations at high spatial and temporal resolutions.

The BGS in collaboration with the Smithsonian Institution in Washington has developed the MyVolcano App which allows users to contribute observations including photos and video during volcanic eruptions. There is also advice on ash sample collection with national contacts provided. The first version of the app has been developed for the UK but further development for use close to erupting volcanoes will further support eruption response and engage impacted populations.

High resolution numerical weather prediction of severe weather would benefit from a denser network of measurements. Basic data with traceable national standards quality could be achieved through installation of a high quality weather station, and other possible sensors, at every secondary school in the country. The data could be fed in to WOW and in addition to feeding the Met Office with a valuable source of data could be used within the education sector in the teaching and understanding of maths, physics and geography.

In some cases data and observations are required from overseas and in these cases collaboration is key in order to facilitate timely data-sharing. In some cases the UK may need to make resources available in order to ensure that critical data for UK interests are collected.

5.14 Collaboration

Effective collaboration is the key to unlocking the potential that exists within the UK for dealing with natural hazards. It can facilitate exchange of data, knowledge sharing and improved response to civil contingencies. Effective collaboration is needed at the national level but also at regional and international levels.

This has been demonstrated by the FFC and the SFFS, the successful partnership between the Met Office and Environment Agency and SEPA and Met Office (respectively) which has a remit to forecast all sources of flooding. These combined flood forecast centres brings together the sciences of hydrology and meteorology in a jointly staffed specialist operational centre.

The NHP Operating Plan 2014 – 17 has identified that collaboration is required to enhance the verification of hazard impact model output against hazard impact reports. This is fundamentally important if we are to gain an improved scientific understanding of the complex relationships across the hazard, vulnerability and exposure functions. Such information is required in near real time to enable expert users to be able to add value to the raw model output. The gathering, quality control and archiving of such reports and databases is therefore an area that deserves a particular focus if we are to advance and improve hazard impact science and services in line with end user experience.

To facilitate this the NHP recognised it needed improved access to spatially and temporally explicit information about the occurrence and magnitude of natural hazards from media reports and various administrative records maintained by the emergency services and critical infrastructure providers. The NHP recommended the development of business rules and capabilities for utilising social media sourced hazard impact reports based on existing and emerging initiatives.

Priorities in terms of gathering data are however not always aligned. For example for volcanic hazards and risks, effective collaboration of UK institutions with mandated volcano observatories is essential to achieve effective response to volcanic unrest and eruptions. Volcano observatories provide 24 hour monitoring and observation of volcanoes. They work closely with emergency managers to establish thresholds for potential evacuation on the ground and with Volcanic Ash Advisory Centres on volcanic ash forecasting to facilitate diversion of aircraft. The needs and priorities of the UK may be different to the needs and priorities of a volcano observatory and so resourcing to ensure suitable data collection, monitoring and availability of data streams may be needed. Collaborative research projects with funding made available to both partners (countries) could help in the preparation for, understanding and response to cross-border hazards.

5.15 Challenges and Barriers

The UK invests considerable resources via ESA and the UK Space Agency in developing and launching EO satellites. The resulting datasets have the potential to make a major impact in geohazard mitigation and research, but missions are conceived, designed and operated on time scales that are far longer than normal research grants.

Without a stable, long-term platform through which the UK can influence the design and operational program of EO missions, and maximise the benefits of the up-front investment in EO infrastructure, it will be difficult to maintain our international standing in this area.

In terms of technical barriers, although Sentinel-1A represents a step change in EO, there are still temporal limits as well as a lack of sensitivity in north-south direction. Potential new technologies like squinted SAR or geostationary SAR could address these issues, and would also be hugely useful for monitoring volcanic deformation as well as landslide and earthquake hazard.

Given the scale of the challenge, continued investment in national capability for EO is clearly needed, allowing further development of research infrastructure as well as the skills and expertise needed to maximise opportunities for the use of EO in hazard monitoring and assessment.

In the past, knowledge has mainly been disseminated through scientific publications. Outreach and knowledge exchange are however increasingly important for both developing the next generation of EO specialists and ensuring that research engages stakeholders and delivers impact.

A wide range of environmental data is gathered and its ownership, licensing and subsequent utilisation are a growing concern. Consideration should be given to promoting the release of environmental data for the common good, particularly for data collected by public bodies. The Open Government Licence is a highly suitable means of making such data widely available. Compulsory sharing of environmental data could be considered as part of the Government approval for significant new developments like mobile phone reception development and wind farms. Such sharing should be done using common standards in measurement, formats and metadata.

5.16 Summary

This chapter has identified a diverse range of observational techniques that can be brought together and utilised to further our understanding and enable us to deal with the impacts of natural hazards.

There is significant scope for the UK to take a leading role internationally in demonstrating the ability to respond in a coordinated way to natural hazards with significant benefits in terms of saving lives and infrastructure. However Government needs to support investment in the development of future research leaders in EO so that the UK remains at the forefront of development and exploitation of EO data for high-impact natural hazard research enabling UK researchers to compete internationally, and have genuine, long-term impact. Any future strategy for enhancing the observational capability of the UK must have in tandem a strategy for promoting science in the education system and encouraging the best scientists to study the environmental sciences which should also address the growing differences in financial reward between different sectors (e.g. finance and science).



Chapter six

International

Edited by

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Left

Panoramic view of an
urban landscape, Asia.

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International

6.1 International context

There are three main reasons why an international perspective by the UK on Earth observations is necessary, even when considering a focus on national motivations and benefits.

Firstly, the availability of data, notably from Earth-observing satellites, is coordinated on an international basis and, with increasingly open access to data, represents an invaluable resource for UK interests.

Secondly, many of the potential policy and economic benefits to the Government and its citizens are found in the relations between national interests and the international political context. Many international bodies of significant economic weight, such as the World Bank, are major users of EO data in implementing projects and in developing their investment policies. There is an increasingly important nexus between economic and environmental information that reinforces the value of spatially referenced information about the environment, both nationally and internationally. International policy agreements require supporting evidence which is agreed, accepted and accessible.

Thirdly, there are policy and legal aspects of some sources of EO data that can only be addressed on an international basis. Examples are the privacy and/or public safety aspects of airborne sensor data, and issues related to both national security and economic return when broad, open data policies and practices are adopted. The number of satellites observing the Earth is increasing rapidly. Euroconsult reports an increase in planned launches of satellite systems (excluding weather satellites) from 133 (2004 – 2013) to 283 (2014 – 2023). Many of these systems offer their data freely to all users.

Many international agreements and undertakings, in addition to military use, depend on high quality geospatial data collected by satellites, airplanes, and UAVs. Land ownership and management in Africa, monitoring of international payments among countries to reduce deforestation, oversight of development aid to sub-Saharan Africa, food security, refugee and crisis management, disaster risk reduction and relief, climate prediction, mitigation and adaptation are all examples of the intersection of policy objectives and major implementation regimes based on access to geospatial data and services. The economic scale of such agreements is of the order of billions of dollars per year with the UK as a significant contributor. Furthermore, the management of fishery and agricultural policies, marine security, water-resource management and illegal immigration are addressed at a European level through programmes which can be implemented only with timely access to reliable geospatial information – from space, airborne and *in situ* or ground measurements.

In addition to data collected remotely, reliable ground-based information is fundamental to successful policy implementation, as is well illustrated in Rwanda where the UK Government contributed substantially to land parcel registration. The combination and/or integration of space-based observations (for broad-area coverage) with *in situ* or ground-based observations (for site-specific details) helps strengthen the analysis and understanding of not only environmental processes, but also the impact of policy implementation at landscape scales. The UK has a strong record in integrating space-based and *in situ* data.

Successful uptake of the appropriate data is increasingly reliant on retrieval algorithms that can access a wide variety of international environmental databases. With ever-increasing data availability from many sources and open data policies, retrieval algorithms are crucial for identification and extraction of appropriate and relevant data from an abundance of environmental observations. Retrieving these data opens a wealth of information that can feed the information picture used to drive policy decisions across Government.

All of the above demonstrates that in addition to the beneficial use of EO of UK sovereign territory, substantial benefits can be realised through the effective use of such data and services when applied to geographical areas beyond national boundaries, and up to the global scale.

6.2 The UK role in the international environmental observation community

The UK is world leading in environmental science with a high international profile. We are well placed to advance data interpretation and work towards more holistic approaches. Particular strengths are in land management, polar science, numerical weather prediction, climate studies, atmospheric chemistry and physical oceanography and contributing to how the future Sustainable Development Goals of the United Nations will be measured and monitored. There are global environmental concerns where observation technologies and UK-led science can play a key role but where the UK could have more visibility – notably tropical deforestation, an area of policy concern for the DECC.²⁵

In addition to environmental science, the UK has been particularly good in acting as a test-bed for new observation technologies, which has potential to be delivered both nationally and through the ESA (if competitive against other proposals). This effort has been led by the Centre for Earth Observation Instrumentation, collaboration of UK industry and academia, and by the wider Earth science community in the development of innovative science missions.

The UK is a full member of the ESA and the majority of our national investment in space is through ESA programmes. The UK contributes to ESA's Earth Observation Envelope Programme through the UKSA under a dual-key arrangement with NERC; considerable benefits accrue to EO academic, operational and industrial communities. A particular highlight is the UK-led Earth Explorer BIOMASS mission, a P-band Synthetic Aperture Radar (SAR) designed for assessing above-ground forest biomass and exemplifying the UK's ability to combine science leadership (NERC NCEO and University scientists) with UK industrial build capability.

The UK has participated in funding the European joint EC/ESA Copernicus programme, with specific national interest in exploiting the ESA-operated Sentinel satellite series, now that the Copernicus programme is moving into an operational phase. The UK involvement in Copernicus, an internationally significant EO programme is through the DEFRA, whilst the UK Space Agency provides UK investment in the Sentinel satellites through the ESA. The majority of funding for the satellite series is provided through the EC Medium Term Financial Framework 2014 – 2020. The resulting programme will deliver data for a wide range of services and present great opportunities for UK businesses to build products and information services for both the public and private sectors, helping create many new high skilled jobs over the coming years.

25. A proposal to involve UK teams in a major REDD+ monitoring programme is currently being considered by UKSA.

UK participation in ESA and Copernicus programs benefits from considerable support from NERC through its Centres including the NCEO. The NCEO and other NERC Centres have a substantial role in the international scientific community and work closely with international space organisations, to ensure that our scientific understanding is delivered to the wider community. The NCEO supports a considerable amount of research concerned with enhancing climate data, in cooperation with ESA's Climate Change Initiative, and supporting its exploitation. Further to European support, NCEO scientists are increasingly collaborating on and contributing to NASA missions.

In addition to being a strong partner in the European Copernicus Programme, the UK is a member of the Group on Earth Observations (GEO) – an international collaboration of 95 Member Countries and the European Commission, and 90 other Participating Organisations, including UN Agencies, international scientific organisations and regional organisations, like EEA, ESA and EUMETSAT. Through DEFRA and NERC involvement in GEO, UK programmes, science, and information contribute to a Global Earth Observation System of Systems (GEOSS). In this regard, common approaches for environmental observation systems and advocacy for broad, open data policies and practices aim to improve decision making in nine Societal Benefit Areas (SBAs) including agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather.

The UK is also a member of the CEOS. As the space-component of GEO, CEOS coordinates the activities of the world's major space agencies. UKSA represents the UK in CEOS Plenary and other UK experts have prominent roles in the various committees especially around data quality. Advantages to UK participation in each of these coordination mechanisms not only leverages investments made by other governments to address UK issues, but reinforces UK leadership in selected areas by exposing UK best practices to the international community. However it may be noted that most active partners in CEOS are there to represent their national EO space assets. To date UK does not have an active national EO satellite initiative.

In addition to UKSA, the UK space sector has been a world leader in the development of low-cost microsattellites (through the establishment of Surrey Satellite Technologies Ltd and Clyde Space), primarily for the export market. This has led to innovative business models whereby national owners of the same (or similar) satellites choose to integrate their data acquisition capacities in a coordinated constellation approach. This has created opportunities to improve the temporal revisit rates over a given location with the same observation technology.

The UK has also been a leader in the formation of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) that was established in July 2011 by the United Nations Economic and Social Council. It is the most senior policy and operational forum in the UN involving geospatial information management, and as a global inter-governmental body it has been tasked with making joint decisions and setting directions on the production and use of geospatial information within national and global policy frameworks. The priorities and work programmes are driven by UN Member States.

UN-GGIM is led by the Committee of Experts, made up of senior representatives, usually Ministers from Member States that have an interest in geospatial information and land management. The Committee is mandated, among other tasks, to 'provide a platform for the development of effective strategies on how to build and strengthen national capacity on geospatial information, as well as disseminating best practices and experiences of national, regional and international bodies on geospatial information related to legal instruments, management models and technical standards'. A number of Regional Committees are also currently either established or in development. These cover the Americas, Europe, Arab States, Africa and Asia-Pacific. The regional committees play an important role in promoting UN-GGIM to Member States on a regular basis, and in strengthening and supporting the work being undertaken by the Committee of Experts.

The UK is also a member of the Belmont Forum, established in 2009 by NERC and the National Science Foundation in the US, and comprised of the world's major funding agencies of global environmental change, plus research and international science councils. It serves as a roundtable for these agencies to collectively address the challenges and opportunities associated with global environmental change. Priority focus areas include the Arctic, coastal vulnerability, freshwater security, ecosystem services, carbon budgets, and most vulnerable societies.

6.2.1 UK Role in International Community for Land Observing

With respect to land-related environmental monitoring, the UK's Countryside Survey (joint CEH/DEFRA) has been modelled by other European countries, where the combination of national land cover/land use mapping together with a site-based network of more detailed observations and mapping has supported many scientific investigations. This concept of sampling different landscape zones (or 'strata') as statistically valid exemplars is now applied for national forest monitoring in Finland. UK national land cover mapping also contributes to the European CORINE Land Cover programme.

The Department for International Development (DfID) has also made good use of satellite and airborne-collected EO data and information to enhance its own land management and land cadastre programmes nationally and around the world. The positive steps forward in DfID's usage of EO are to be encouraged. The EO community in the UK are very keen to provide skills and services in collaboration with DfID since harnessing the international power of EO satellites and data has proven to be powerful in enhancing the societal and economic outlook of a range of emerging nations. Capacity building is essential in an international context and an area where the UK has a major role to play.

In addition to the programmes introduced above, there are many complexities and international dimensions to land observations; further discussion of the international context is provided in the land chapter of this report.

6.2.2 UK Role in International Community for Ocean and Ice Observing

Sustained observing of the coupled ocean-atmosphere system is achieved with a mixture of *in situ* and space-based measurements. Over the past two decades the UK has been involved in many EO missions launched by both ESA and NASA that provide ocean and ice environmental observations. For example, it has made extensive use of radar altimeter measurements dating back to the 1980s (Geosat, Topex, ERS-1 and 2, Envisat RA-2, Jason-1 and 2, and AltiKa) for ocean (geostrophic currents, tides, winds and waves) and ice (sea ice thickness and extent), and is at the forefront of the use of SAR Altimetry, such as that which will be flown on the Sentinel-3 mission.

The UK has taken a leading role in the development and exploitation of the data behind the ESA Cryosat-2 mission for monitoring land and sea ice changes. The UK was also involved in proposing the ESA Soil Moisture and Ocean Salinity (SMOS) 1998, which flew in 2009, and was the first satellite mission to measure ocean salinity (a key oceanographic parameter) from space. It is currently involved in exploitation of these data for science.

The UK has also been involved in international ocean colour missions (SeaWiFS, MODIS and Envisat MERIS) for the study of ocean biology (chlorophyll), and in producing a climate quality time series of sea surface temperatures (SST) from UK instruments flown on several ESA missions (ATSR, ATSR-2, and AATSR, originally developed at RAL/Oxford University and led from Leicester University).

The UK is heavily involved in the development of the Global Navigation Satellite System-Reflectometry (GNSS-R) that uses a GPS signal of opportunity reflected from the sea surface, and working with both ESA and NASA, measures winds and waves. Scientists in the UK have an outstanding record in developing instruments, working with international partners to develop and fly missions, and in the exploitation of the resulting ocean and ice environmental observations for science.

The main *in situ* techniques in use now, which will form the core capability for at least the next decade, are ship-borne measurements, fixed-point moored measurements and freely-drifting floats in the Argo program. The ocean has absorbed 25% of the excess carbon dioxide released by human activities. Ironically, without this dynamic, global warming would be occurring even faster. Water samples collected from ships are one of the best ways to track, understand and predict the rate at which the ocean is moderating climate change through the uptake of carbon. The UK provides a delegate to the Executive Steering Group of GO-SHIP, the international coordinating body for ship-based climate observations. Fixed-point moored measurements, such as the trans-basin RAPID measurements at latitude 26°N in the Atlantic Ocean, have profoundly changed our understanding of Atlantic Ocean circulation. In the coupled ocean/atmosphere system, Atlantic Ocean circulation supplies heat from the ocean to the atmosphere resulting in northern Europe having a temperate climate as compared with the equivalent region in northwest Canada. Moored measurements by RAPID have revealed the temporal variability in the supply of that heat, and will underpin future seasonal forecasting. Trans-basin programs can only be achieved by international cooperation, and by initiating the RAPID program the UK has led the world in implementation and scientific exploitation of the results.

The Argo fleet of drifting floats is one of the most successful demonstrations of what can be achieved by international engagement. Over 30 countries have contributed to the systematic global monitoring of ocean temperature over the last 15 years. The UK has been part of the scientific leadership of Argo since its inception in 2000, and has contributed nearly 500 floats to the global array. Argo has become the principal source of *in situ* data on ocean temperature and salinity for weather forecasting, and for climate assessments. The UK has been a major force in the drive to ensure that data of uniformly high quality are made freely available to any researcher or agency that requires them. The British Oceanographic Data Centre has also facilitated participation by a number of smaller countries without the skills or capability to mount a fully independent contribution to Argo. In Europe, Argo has recently established an European Research Infrastructure Consortium, a legal entity to which the UK Government is a signatory. The Euro-Argo European Research Infrastructure Consortium will secure European funding to operate floats for the international constellation.

6.2.3 UK Role in International Community for Disasters

The UK is a member of the International Charter for 'Space and Major Disasters', a group of 14 countries providing satellite imagery for disaster response. To date, the Charter has responded to nearly 450 disasters in almost 100 countries. The Charter provides priority access to its members' satellites for imagery during the response phase of a disaster. The imagery is provided at no cost to relevant national and international groups responding to the disaster. The UK Space Agency contributes to the work of the Charter by supplying imagery support from the Disaster Monitoring Constellation (DMC) and provided early funding support for one of the first DMC missions. The DMC is a constellation of EO satellites constructed by Surrey Satellite Technology Ltd and operated on behalf of the Algerian, Nigerian, Turkish, Chinese and UK Governments by DMC International Imaging (DMCii). Since joining the Charter in 2005, the UK has responded to 250 disasters and provided more than 500 images.

The UN Cartographic Section, which is part of the management team of the previously described UN-GGIM, has benefitted considerably from the leadership shown by the UK military in releasing appropriate geospatial data free-of-charge for use by the global humanitarian community in times of crisis. The UN Cartographic Section attends every session of the UN Security Council and due to data feeds which are now enabled from both the UK and the US in humanitarian crisis, the geospatial information on which the mapping presented to the Security Council is based has improved considerably, as has the geospatial situational data presented to the operational units of the UN on the ground.

6.2.4 UK Role in International Community for Weather, Climate and Atmospheric Chemistry

Meteorology as a science has always relied on international cooperation and collaboration in order to meet the requirements for observations that are critical for the production of weather forecasts.

Prior to the modern age of supercomputing and NWP the deployment of extensive telegraph networks allowed the timely transmission and collection of observations across the world that allowed meteorologists to form an accurate picture of the weather as it occurs, and to use their technical expertise to forecast what it is likely to be in the future.

The International Meteorological Organisation was formed in the mid-19th century with the objective of standardising formats for observations and encouraging their free exchange across borders. The mission of the International Meteorological Organisation was carried on by the WMO, a United Nations specialised agency that was formed in 1953, and continues to this day to form the backbone of international cooperation in the meteorological community.

The underpinning technical infrastructure, the Global Telecommunications System, has played a crucial role in the exchange of observations for many years and is now transitioning to the WMO Information System which seeks to harness up-to-date telecommunications capabilities to dramatically increase the amount of data exchanged globally. Interoperability agreements between the WMO Information System and GEO's Common Infrastructure ensure data, regardless of the source, are leveraged across communities to the greatest extent possible.

Alongside the global meteorological infrastructure that is coordinated by the WMO, the UK Met Office is a member of the Network of European Meteorological Services (EUMETNET). The mission of EUMETNET is to seek to coordinate a consolidated observations network across Europe to ensure that the collective reach of the observations network is greater than the sum of its parts. The UK is also a member of EUMETSAT, which operates both geostationary and low Earth orbiting satellites carrying a variety of sensors essential for observing weather and climate.

The Met Office represents the UK within EUMETSAT. The payloads for these missions are usually designed and developed through the ESA to which the UK Space Agency optionally supports via funding. EUMETSAT exists in order to leverage the collective resources of all the member states, none of whom would be able to operate such a satellite programme in isolation. The data provided by satellites is essential for effective NWP and is the single highest contributing data type to the accuracy of the forecast.

The UK is also very strong in atmospheric composition and chemistry observing systems ranging from WMO GAW programmes to strong contributions to relevant satellite missions such as ESA Envisat and NASA Aura missions. The UK has provided very cost-efficient contributions, in the past, to instruments for relevant missions and continues to provide world-leading algorithms, data and science. The increased significance attached by EUMETSAT and Copernicus to atmospheric chemistry missions is very valuable to the UK. There are also new UK contributions to the EO observing system for climate-chemistry and air pollution that would be very timely and welcomed internationally.

Continued and strengthened involvement is therefore essential for ensuring full UK benefit from these programs and others, such as the international collaboration of NOAA, the Japan Agency for Marine-Earth Science and Technology and increasingly the Chinese in delivering the operational meteorological observing system which is critically important for so many things (e.g. reanalysis) and not just weather forecasting. Further information about the international policy dimensions of weather and climate can be found in the air and climate chapters of this report.

6.3 Potential for future international participation

In order to sustain UK observing capabilities and ensure full access to international capabilities, it is critical that the UK remain an active participant and leader in the international communities for environmental observations and furthermore, actively contribute missions, systems, capabilities and services into the wider community. Continued use of the NWP, for example, is reliant on the number of observations acquired through multinational arrangements and in turn provides internationally respected capabilities and recognition to the UK through the Met Office.

International agreements country-to-country can provide an important foundation. In particular, it would be very advantageous for the UK to foster further key strategic relationships with the strong EO providers in the US (NASA, NOAA) and the emerging EO-capable nations (e.g. China, India). This could be on the basis of data-sharing, shared missions or cost-effective contributions of instruments from the UK.

Cross-cutting policy issues related to EO require considerably more attention than they have had to date, and as described above, have a strong international component. The debate around individual privacy, balanced with the clear benefits of the more agile data collection from UAVs, cannot be realistically solved at a purely national level. Similarly, issues around security concerns of broadly accessible data need to be balanced with the potential of wider data-sharing for economic innovation.

A further crosscutting issue which requires our attention is the data management challenge of exponentially increasing data volumes and complexity. New technologies and techniques are required to exploit the maximum value from the large investments in EO platforms.

The UK has an opportunity to take a leading position in the commercial provision of services for informing policy and commercial activities internationally. There is significant export and economic growth potential for the UK in providing end-to-end services for customers in all sectors. For example, two UK companies are world leaders in the provision of satellite observation based information on natural oil seepages in ocean basins; this is used by global energy companies as a key indicator for offshore oil exploration.

The UK private sector also has an opportunity to take a leading role in delivering critical environmental monitoring systems in the way that PlanetIQ is doing for weather-related observations in the US. The UK Government is taking a welcomed forward thinking approach to these opportunities through UKTI activities, the establishment of the Satellite Applications Catapult, and UKSA's International Partnership Space Programme.

With regard to satellite observations, UK's major involvement to date has been on the technical side. For example, the Met Office is internationally recognised, through assessment using WMO metrics on forecast skill, as the most accurate national meteorological service. It is essential to maintain international leadership in this area to ensure UK observation needs are met, as well as capitalising on our longstanding heritage.

An area for further involvement, however, is on the policy side. These are topics applying to all thematic areas, and ones in which the UK is well placed to take a strong, if not leadership, role. Indeed we should also do this from a self-interested point of view to ensure that international policy developments are in keeping with our environmental perspectives and enable rather than create barriers to our own aspirations.

Each of the international coordination mechanisms described above are important, and require strong UK participation. While some focus on developing international frameworks in selected domains, others focus on increased harmonization and standardization of selected observations. Regardless, it is the sum total of these mechanisms that will ultimately deliver the integration of Earth observations and *in situ* measurements that will benefit the UK and the world at large for policy, science, innovation, and commerce. The UK has had a major role in many of these and is, therefore, well positioned to continue to do so, thereby playing a significant role in how global environmental policy issues are resolved internationally.



Appendices

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Aerial view from 30,000 feet
above Arizona. © wwing.

Appendices

Appendix 1: Technical primer

A1.1 Introduction

This technical primer supplements and supports the information in the chapters.

Environmental observations typically require networks of sensors. A network can be defined as a distributed set of sensors that are deployed for a common or related purpose. A clear distinction should be drawn between networks that are designed to continuously monitor the environment – providing data to support operational decision making; and research and development networks designed to study the environment – providing the data to further our understanding of the environment.

The purpose of a network has a profound impact on how it is designed, the technology that is deployed, and its overall performance.

Networks of sensors and instruments can be deployed at or near the surface (ground-based) or be located on satellites, aircraft, balloons, ships and buoys. These different platforms are discussed in Section A1.2.

There are three distinct groups of instruments or technologies:

- *In situ* sensors are those that measure the immediate environment of the instrument. For example, a mercury-in-glass thermometer measuring the temperature of the air.
- Remote sensing instruments are remote from the target area or volume that is being sensed. Remote sensing is made possible by exploiting radiative properties of the target. The radiative properties that can be measured will in general not be the parameters of most interest, but will be related to it indirectly.

Of note, the instruments can be passive sensors, active sensors, or both. Passive sensors measure how naturally occurring electromagnetic or sound waves are emitted by an object of interest, transmitted through matter (e.g. clouds), or scattered by objects. Active sensors emit a signal of some sort and process the ‘return’ of this emitted signal. In order to interpret remotely-sensed data correctly, several unwanted sensitivities and sources of uncertainty have to be understood and quantified.

Exploitation of remote-sensed data is critically dependent on whether mathematical, statistical and/or physically based techniques are available to combine the data with a model (and its physical equations) to produce information on the current state of the environment. This methodology is known as data assimilation and is used extensively in the science of weather forecasting, for example.

- Opportunistic observations exploit some sensitivity in a system that was not designed for environmental observation. That is, no purpose built sensors or instruments are involved. An example might be the use of solar power installations to estimate incident sunlight.

Further examples of all three types of technology are given in Section A1.3.

Each observing technology has its own advantages and weaknesses. For example, systems with very good coverage may not possess the highest accuracy. Generally a combination of techniques is used to provide a more complete picture of the environment. For example, a relatively small number of *in situ* measurements are often used to calibrate or interpret the data from remotely-sensed measurements of related parameters.

Important aspects of observing system performance include:

- spatial resolution (as determined by sample volume or network density);
- temporal resolution (sampling frequency);
- sensitivity (e.g. signal to noise ratio); and
- accuracy (precision, reproducibility, and uncertainty).

Performance needs to be assessed relative to the detailed requirements. A reasonable ambition might be for research observations to be able to resolve all scales of scientific interest, albeit over a restricted area or time period. On the other hand, operational networks will be required to resolve those scales that are pertinent to the particular application, and to cover a domain that is the operational service area. Cost is likely to be a much more important consideration for operational networks, not just the capital cost of the instrumentation, but the costs of maintenance, data communication and storage.

A1.2 Platforms

A1.2.1 Space-based platforms

Space-based platforms are artificial satellites carrying remote sensing instruments – either in a geostationary or low-Earth orbit (LEO). A geostationary orbit is where the satellite remains at a fixed point above the Earth's equator at an altitude of approximately 36,000 km. Weather satellites and communication satellites are commonly placed in geostationary orbit. LEO is a circular orbit at an altitude between 150km and 2000km. Examples of LEO satellites are navigation satellites, Earth observation satellites and the International Space Station.

Typically, traditional satellites have a wet (fully fuelled) mass above 500kg, which requires large and expensive launch vehicles. In recent years, progress has been made in reducing costs associated with satellite platforms, through miniaturisation. The most well-known smaller sized satellites are microsattellites and nano-satellites. Microsatellites are satellites which have a wet mass between 10kg and 100kg while nano-satellites have a wet mass between 1kg and 10kg. In addition to their smaller mass and volume, other advantages of these satellites include their lower power requirements and the fact that it is possible to launch multiple smaller sized satellites simultaneously.

A1.2.2 Airborne platforms

Airborne platforms are used to support a wide range of atmospheric and environmental measurements, both remote sensing and *in situ*. All other things being equal, coverage is inferior to space-based platforms, but the lower altitude provides for high resolution. Civil aircraft fleets can be equipped with simple sensors to provide operational measurements, whereas special research aircraft can be used to carry the most complex and extensive sensor suites for research and development purposes. Research and development aircraft also have a particular role in environmental crisis situations, where the combination of rapid deployment and detailed observations is invaluable.

UAVs are becoming more widely used for environmental monitoring, as the technology improves and costs fall. Low altitude aircraft and multicopters are particularly suited to research and development observations of the surface and lower atmosphere.

Balloons can be either tethered or free flying. Tethered balloons can be used to lift large instrument packages weighing many kilograms up to heights of the few kilometres. They have traditionally been used in research and development campaigns and only rarely to provide operational data. On the other hand, weather balloons, filled with hydrogen or helium are capable of lifting instrument packages of up to a few kilograms to altitudes of approximately 30km. Such ‘ascents’ by standard sensor packages measuring wind, temperature pressure and humidity have formed the backbone of the global meteorological observing network for many decades.

Very high-altitude platforms – either high-flying solar powered aircraft or balloons in the stratosphere, with endurances of months or years – may offer significant opportunities in the future.

A1.2.3. Ground-based sensing

Although space-based remote sensing has a large advantage over other platforms in terms of coverage, there are many parameters that are difficult or impossible to sense from space, because of the intervening atmosphere (e.g. clouds).

Ground-based *in situ* or remote sensing continues to provide important data over the land areas of the world. Increasingly, even ground-based measurements use remote sensing techniques to obtain information from above the surface, or over a wide area.

Data can also be collected wherever people are through crowdsourcing, which is the outsourcing of internal tasks or projects to a group of volunteers, usually via smart phones or the internet. This is usually done through smart phones with participants either actively uploading data (e.g. documenting disaster damage by submitting photos with location data) or data generated passively through the phone being used (e.g. measuring rainfall from the interference of the microwave signals between mobile phones and cell towers). An example of a large scale initiative is the Met Office WOW program that allows submission of weather observation data by the public.²⁶

A1.2.4. Marine-based platforms

These comprise specialist research vessels, moored buoys, drifting buoys, ocean gliders and commercial shipping. Buoys are particularly important for monitoring the vast areas of the world’s oceans that are not regularly traversed by shipping or aircraft. Even unmanned buoys can be very sophisticated in their capability, for example to perform profiles through the upper levels of the ocean. A newly developed platform is the wave-rider buoy that has the capability to extract and utilise energy from the waves to manoeuvre.

A1.3 Sensors

Tables 1, 2 and 3 list some examples of the types of environmental information that is currently obtained in three general areas and the sensors or technologies that are used to supply data. The list is not exhaustive, but serves to illustrate the extent and diversity of both the requirements and the available technologies.

The subsequent sections provide more technical information about the corresponding sensors and technologies.

26. <http://wow.metoffice.gov.uk/>

TABLE 1

Topographic and geological sensing

Type of information	Sensors
High-resolution images of Earth's surface	SAR (satellite) LiDAR (ground based or airborne) (3D mapping)
Mapping vegetation	Near infrared detectors (satellite) Mid infrared detector (satellite) High-resolution optical imagers (satellite) Hyperspectral optical imagers (satellite)
Mapping soil	High-resolution optical imagers (satellite) Hyperspectral optical imagers (satellite)
Forest canopy structure	LiDAR (ground based or airborne). (3D mapping)
Soil moisture	Microwave radiometer (satellite) Mid infrared detector (satellite) COSMOS (ground-based) <i>In situ</i> sensors (ground-based)
Pressure exerted by soil moisture	Piezometers (ground-based)
Mining and hydrocarbon exploration	Hyperspectral optical imagers (satellite)
Flood Inundation	LiDAR (ground based or airborne)
Wildfires	High-resolution optical imagers (satellite) Thermal infrared (satellite)
Earthquakes and volcanic eruptions	Seismometer (ground based) Radar altimeter (satellite)
Ground deformation caused by tectonic and volcanic processes	SAR (satellite) Laser surveying systems (ground based)
Earth's magnetic field	Magnetometer (ground based or satellite)

TABLE 2

Atmospheric sensing

Type of information	Sensors
Rainfall	Rain gauges (ground based) Weather radar (ground based) Mobile phone networks (opportunistic)
Cloud properties	Thermal infrared (satellite). LiDAR (ground based or airborne) Cloud radar (ground based or airborne) Disdrometers (ground based, aircraft or radiosonde) Passive microwave sounding (ground based or satellite)
Fog	Thermal infrared (satellite) Cloud radar (ground based) Disdrometer (ground based) Acoustic sounding (ground based)
Visibility	Visiometer (ground based)
Air humidity	Thermal infrared (satellite) Radiosonde (balloon) Commercial aircraft (airborne) Microwave radiometer (satellite and ground-based) Refractivity from weather radar (ground-based) GNSS (space based or ground based) Thermometers (ground-based) Humidity sensors (ground-based)
Air temperature	Thermal infrared (satellite) Microwave radiometer (satellite or ground based) Radiosonde (balloon) Commercial aircraft Thermometers (ground-based)
Wind direction and speed	Wind profiler (ground-based) Microwave wind scatterometer (satellite) Radiosonde (airborne) Aircraft (by design and opportunistic) Weather radar (ground-based) Atmospheric Motion Vectors from Geostationary and low earth orbit satellites

TABLE 2 (CONTINUED)

Type of information	Sensors
Aerosol concentration	LiDAR (ground-based) Ground-based sampling Sun photometers (ground based) Thermal infrared (satellite) Visible remote sensing (satellite)
Bioaerosols (eg pollen, mould)	WIBS (airborne and ground-based) Slide and microscope
Atmospheric composition	Ground-based sensors GHG measuring satellites Radiosonde sensors – e.g. ozone (balloon)
Air pollutants	Chemical sensors networks (ground-based)
Volcanic ash clouds	Microwave weather radars (ground-based) Optical particle counters (research aircraft) Thermal infrared (satellite)
Volcanic eruption plume height	LiDAR (ground based or airborne) Ceilometers (ground-based) Thermal infrared (satellite) Balloon sondes (airborne) Aircraft
Ionisation of the ionosphere	Ionosondes (ground-based) Magnetometers (ground-based; satellites)
Tornadoes	Weather radar (ground-based)

TABLE 3

Information about oceanography and glaciology, and related sensors

Type of information	Sensors
Ocean surface wind speed	Ocean buoys and wave riders (marine-based) HF radar (ground-based), coastal areas Microwave wind scatterometer (satellite) Microwave radiometer (satellite), coarse resolution Reflectometry (satellite)
Waves and ocean surface currents (including tsunamis)	Ocean buoys and wave riders (marine-based) HF radar (ground-based) Radar altimeter (satellite) SAR (satellite)
Ocean sub-surface currents	Argo floats (marine-based) ADCPs (marine-based), current direction, water velocity
Ocean bottom pressure	Radar altimeter (satellite)
Ocean and air temperature	Ocean buoys and wave riders (marine-based) Microwave radiometer (satellite) Argo floats (marine-based), surface and sub-surface Thermal infrared (satellite) Mid infrared detector (satellite) Shipboard surveys
Ocean salinity	Argo floats (marine-based) Microwave radiometer (satellite) Shipboard surveys
Sea level / wave height	Radar altimeter (satellite) Reflectometry (satellite) Tide gauges (coastal areas)

TABLE 3 (CONTINUED)

Type of information	Sensors
Ocean colour and chlorophyll concentration	High-resolution optical imagers (satellite) Hyperspectral optical imagers (satellite) Shipboard surveys
Detection of harmful algal blooms	Imaging from aircraft
Mapping coastal water	Imaging from aircraft and UAVs High-resolution optical imagers (satellite) Hyperspectral optical imagers (satellite) Shipboard surveys
Coastal water quality	Shipboard surveys
Fish stocks	Shipboard surveys
Sea ice thickness and extent	SAR (satellite)
Sea ice extent	Microwave radiometer (satellite)
Land ice	Airborne radars and lasers
Oil spill detection	Aircraft and UAVs SAR (satellite) Mid infrared detector (satellite) UMV, oil plumes sub-surface monitoring

A1.3.1 Sensors carried by satellites

Magnetometer

The magnetometer is one of the most commonly used satellite instruments. This instrument measures the direction and strength of Earth's magnetic fields. Furthermore, the magnetometer can also be used to support the satellite's altitude control. There are two main categories of magnetometers: the search-coil magnetometer and the fluxgate magnetometer. The most widely used magnetometer, the fluxgate magnetometer, consists of a ringcore sensor (made out of magnetic material) and a coil surrounding the ringcore sensor, which enables this instrument to measure the magnetic field surrounding the satellite. Similarly, the search-coil magnetometer consists of a magnetic core and a copper coil, where the coil has been looped around the magnetic core.

Microwave instruments

Microwave wavelengths range from 0.1cm to 100m, which makes them ideal for space-based Earth observation. Notably, the microwave wavelengths are less affected by clouds compared to other wavelength ranges such as infrared.

One of the most commonly used microwave instruments is the radar altimeter, which primarily indicates the height of a satellite above the sea surface. Furthermore, it provides information regarding gravity, geostrophic currents, sea level, significant wave height and wind speed. The microwave altimeter determines the height as follows: a pulsed and sharp signal is emitted towards the ocean surface at a specific speed from a satellite. Once the signal reaches the sea surface the signal gets scattered and returns to the satellite. The time the signal takes to return indicates the approximate height of the spacecraft above the sea surface.

The microwave wind scatterometer is another microwave instrument commonly used on a satellite. It measures wind speed and direction using three wind scatterometer antennas. One of these three antennas is pointed nadir (downwards) while the other two antennas are pointed +45° (forward) and -45° (backward). This provides the satellite with information about the ground wind speed with an accuracy of $\pm 2\text{m/s}$.

The SAR is a satellite microwave instrument, which creates high spatial resolution images of the Earth using radar. This day and night operating instrument has multiple applications such as the ability to detect an oil spill, surface wave spectra and ocean currents. SAR (altimetry) instruments can measure the distance from the satellite to the ground as well as displacement and take high resolution sea level measurements as well as wind and wave measurements. This technology has not been deployed yet (Sentinel-3 will be launched in late 2015).

A third SAR instrument called SAR wavenill is a SAR interferometric instrument (InSAR) capable of detecting ocean currents as well as ice. InSAR is also used to monitor ground deformation caused by tectonic and volcanic processes.

The instruments described above are called active instruments. Passive instruments are instruments that use natural sources of radiation such as solar light to complete their measurements. A microwave radiometer is a passive instrument which can be used to determine sea surface temperature, sea ice extent, soil moisture, atmospheric water vapour, coarse resolution wind speed and direction. A specific microwave-wavelength band (15–30cm) called the L-band can further support passive radiometers by providing measurements concerning sea surface salinity and wind speed and direction.

Some technologies such as reflectometry use both active and passive microwave remote sensing. Reflectometry uses a Global Navigation Satellite System (GNSS), which analyses wind speed, sea state and sea surface height.

Other electromagnetic instruments

There are three main types of infrared detectors. Firstly, the near infrared detector detects wavelengths between 0.5 μm and 3 μm which allows the mapping of vegetation and biomass content. Secondly, the mid infrared detector detects wavelength between 3 μm and 6 μm and supports the mapping of vegetation, soil moisture content, oil on water and sea surface temperature. Finally, the thermal infrared (long IR) wavelength detector identifies electromagnetic wavelengths in the region of 6 μm and 15 μm . The thermal infrared detector can measure the temperature and water vapour structure of the atmosphere, from cloud tops and from the sea and land surface. Across all these wavelengths, there are features of many trace gases; indeed current satellite sensors can measure the concentrations of more than forty gases.

Advanced hyperspectral sounders like the Infrared Atmospheric Sounding Interferometer (IASI) on the European Metop satellite measures the radiance leaving the planet at 8641 spectral intervals between 3 and 15 microns. Data from this single instrument are used in the measurement of temperature and water vapour profiles, land and ocean surface temperature, land surface emissivity, aerosols and numerous trace species (CO_2 , O_3 , CH_4 etc.).

Recently satellite-born infrared sensors were further developed to measure GHGs – they do so by observing a wide range of wavelengths within the infrared band to enhance observation accuracy. This technology allows the measurement of carbon dioxide and methane concentrations with very small variation.

Other commonly used space-based electromagnetic detectors are very high resolution optical imagers. These take high resolution images of the ground with a high degree of accuracy. Multispectral imagers usually have multiple colour filters, which cover the wavelength ranges between 400nm and 1040nm. A multispectral imager can provide spatial images which can detect agriculture, forestry, coastal change, flood, desertification, ocean colour, chlorophyll concentration, suspended sediment, phytoplankton population and dissolved organic material.

The three most commonly used colour filters are the blue (450nm–510nm), green (510nm–580nm) and red (700–740nm) filters. The blue detectors (detector with a blue filter) can map coastal water, soil, vegetation discrimination, forests and other cultural identification features. The green detector can show vegetation discrimination and cultural identification features as well as vigour assessment. The red detector can also recognise cultural identification features and differentiate between plant species. Furthermore imagers can produce images without applying the colour filters which results in panchromatic black and white images (400nm–800nm). The advantage of a panchromatic detector is that it is used to sharpen the optical image to obtain higher resolution data. The hyperspectral imager is similar to the multispectral imager. Hyperspectral imaging is a more detailed process covering the entire spectrum to develop a more detailed image: it covers all the functions of the multispectral imager and also allows detection of hydrocarbon exploration as well as mining.

Atmospheric spectrometers operating in the visible and very near ultraviolet extend the hyperspectral sensors to very high spectral resolution, allowing measurements of many gases (including ozone), aerosols and clouds. They are also sensitive to surface factors such as vegetation and albedo.

The Light Detection and Ranging instrument (LiDAR) is an instrument which applies a laser beam to determine distances. LiDAR instruments develop 3D mapping, terrain mapping, flood modelling and can analyse urban planning and forest canopy structure.

Geostationary satellites are used to track cloud systems and this provides valuable atmospheric motion vectors that are assimilated in weather forecast models.

Space borne Lidar and Radar can be used to detect clouds and aerosols in the atmosphere.

A1.3.2 Sensors carried by airborne platforms

Commercial aircraft sensors (AMDAR, E-AMDAR and Mode-S)

Commercial aircraft are used to supplement radiosonde measurements of temperature, humidity, pressure altitude, wind directions and speed. One of the most well-known commercial aircraft programmes is the Aircraft Meteorological Data Relay (AMDAR) which was originated by the World Meteorological Organization. The E-AMDAR (EUMETNET–AMDAR) system, which is part of the AMDAR programme, gathers data registered and transmitted by all individual commercial aircraft and makes them available to meteorological offices for further processing.

One of the instruments used in the AMDAR programme for civil commercial aircraft is the WVSS-II, which measures water vapour in the upper atmosphere for weather forecasting purposes. This instrument uses a laser at a selected wavelength which matches the water vapour's absorption band. The air surrounding the aeroplanes is continuously flowing through the WVSS-II's sample cell and the air is analysed by the rest of the instrument.

Commercial aircraft broadcast position and velocity data at regular intervals (ADS-B / Mode-S DF17) for use by air traffic management (ATM) and other aircraft. Further information (true airspeed, roll angle, etc...) can be requested by ATM secondary surveillance radar (Mode S DF20/21). These transmissions can be freely intercepted using equipment designed for and by aircraft enthusiasts. Analysis of the aircraft transmissions can allow derivation of wind speed and direction data from the aircraft position and velocity data and temperature can be derived from the aircraft speed and Mach number data.

Research aircraft carry a wealth of sophisticated instrumentation capable of measuring a wide range of parameters in the atmosphere. They are used for process studies with the aim of improving our understanding of the environment.

Research aircraft can also carry sensors for monitoring of the ocean and land surface to determine surface type, vegetation cover, flood monitoring, pollution monitoring, terrain elevation mapping etc.

Ozonesondes

Ozonesondes are lightweight, balloon-borne instruments which use electrochemical concentration cells to sense the concentration of ozone through a current produced by a chemical reaction. The ozonesonde typically ascends to up to 35 km before the balloon bursts, measuring the vertical profile of ozone as it ascends.

Radiosondes

Radiosondes are instruments usually carried by weather balloons which makes atmospheric measurements and communicates them to ground-based stations by telemetry. Typical measurements include temperature, humidity, pressure, altitude, wind direction and speed.

A1.3.3 Sensors carried by ground-based platforms

Automatic and Urban Rural Network (AURN)

Air quality systems in the AURN network use ultraviolet absorption (O₃), ultraviolet fluorescence (SO₂), chemiluminescence (NO/NO₂), infrared absorption (CO), and microbalance/gravimetric techniques for aerosol particles (PM_{2.5} and PM₁₀). These techniques have been developed as standard reference techniques and the outputs are collected hourly for both monitoring and public information.

Automatic Weather Stations (AWS)

AWS provide compact and robust meteorological observations, usually with quality controls. Typical instruments are thermometers, anemometers, hygrometers and barometers.

Ceilometer

A ceilometer is a device that uses a laser or other light source to determine the height of a cloud base. Ceilometers can also be used to measure the aerosol concentration within the atmosphere.

Weather radar

Radar is widely used to measure precipitation. Modern Doppler Radars also measure wind speed.

Cosmic Ray Soil Moisture Observing System (COSMOS)

COSMOS is a ground-based instrument which measures the moisture content in soil. The results achieved by COSMOS instruments ensure accurate weather forecasting, land density measurements, water cycle and ecosystem measurements. These findings also significantly contribute to climate change science and atmospheric science. The COSMOS instrument uses cosmic rays. Cosmic rays are high energy radiation which is constantly bombarding the Earth from space. The Earth's magnetic field captures these high-energy cosmic ray protons, which then enter Earth's upper atmosphere. Once these cosmic rays enter the atmosphere, many secondary cosmic rays are created. These then pass through the atmosphere until they reach the soil, where they generate a spectrum of neutrons. These (fast) neutrons are scattered into the soil and, in the majority of cases, are absorbed by the soil after losing energy. The COSMOS instrument allows detection of the intensity of these fast neutrons. As a result, the moisture content of the soil can be determined, as the density of neutrons above the soil surface is strongly related to the composition of the ground.

HF radar for coastal monitoring

HF radars are commonly used for coastal monitoring. HF radars monitor environmental changes of liquids in motion (hydrodynamic), which include wind and wave parameters as well as ocean surface currents. The radar transmits electromagnetic waves (towards the sea), which get backscattered by the sea-surface to the radar. This process provides information concerning the wind and wave parameters.

LiDAR

LiDAR can also be carried by satellites – see Section 3.1.

Magnetometers

Magnetometers can be ground based or carried by satellites – see Section 3.1.

Piezometer

A piezometer is a ground-based device that measures water pressure. Piezometers are essentially tubes that are open only at their end, and the height of water in the tube is dependent on the water pressure at the point in the soil that the tube has been inserted into. They can be used to measure the pressure exerted by the moisture in the ground, which has the potential to affect soil stability.

Present weather sensor

The present weather sensor is an instrument which measures present weather and visibility. The detector determines the water content of precipitation in a sample volume and combines this information with temperature and forward scatter (near infrared beam) measurements.

Radioactive Incident Monitoring Network

Following the Chernobyl nuclear reactor accident (1986), the UK created 96 monitoring stations across the country. Together these are known as the Radioactive Incident Monitoring Network. These monitoring stations collect hourly readings to analyse and record the levels of radioactivity across the UK. If multiple monitoring stations record unusually high levels of radiation caused by specific isotopes simultaneously, an emergency alert will be raised across the UK. Furthermore, apart from having its main purpose as a radiation alert system, the monitoring stations also record the data for historical comparison.

Rain gauges

A rain gauge is a ground-based instrument which measures the amount of rainfall over a set period of time. A range of techniques are used. Traditional measuring cylinders are used to catch the rain and measure the precipitation in millimetres. Tipping bucket raingauges record rainfall intensity as well as total rainfall amount. Modern techniques include weighing precipitation gauges which measure the mass of a rain-water storage bin providing improved accuracy and sensitivity.

Seismometers

A seismometer is an instrument which can determine up and down motions of the Earth that can occur during a volcanic eruption or an earthquake. This instrument consists of five main components: a rotating drum, a spring, some weights, a pen and a frame (holder). The weight hangs from the spring, which is attached to the frame. When the Earth moves up or down, the spring and the weight begin to move relative to the Earth's motion. In order to record these movements, a pen is attached to the weight and draws a line on the rotating drum, which reflects the up and down movement.

Visiometer

The visiometer is a visibility sensor, which measures the number of specific particles in the atmosphere. The visiometer consists of two main components, which are the light projector and the receiver. The light projector transmits light towards the receiver, which gets scattered by particles in the atmosphere. The receiver's purpose is to record the scattered light. As the light projector is not pointed directly at the receiver, only scattered light can be registered by the receiver. This process indicates the amount of particles in the atmosphere and therefore the visibility.

Wideband Integrated Bioaerosol Sensors (WIBS)

WIBS can also be airborne – see Section 3.2.

Wind profilers

A wind profiler is a ground-based instrument which measures wind direction and speed at altitudes between 500m and 16km above sea level. Therefore this instrument is also suitable for weather forecasting. A wind profiler uses radar to be able to detect wind speeds.

Ionosondes

Ionosondes measure the total electron content of the ionosphere using ground based transceivers that send and receive radio pulses at different frequencies.

A1.3.4. Sensors carried by marine-based platforms**Acoustic Doppler Current Profilers**

The Acoustic Doppler Current Profiler is an instrument which measures water current velocities. Typically, this type of instrument is used on vessel hulls where its purpose is to track the bottom of the ocean. It is also used in monitoring floods. This instrument functions like a sonar. The instrument sends out an acoustic pulse and waits for that pulse to get backscattered from suspended particles. The time the pulse needs to return to the vessel indicates the ocean's depth. Furthermore, as the particles also travel with the water current, a change in the frequency of the returning pulse occurs. This change of frequency (Doppler shift) and the time the pulse takes to return enables the ADCP to determine the current direction, water column depth, the water velocity and the overall water column depth (ocean floor).

Argo floats

More than 3560 Argo floats are distributed across the world's oceans to measure the local ocean's pressure, density, temperature, currents and salinity. For 9 days the Argo float measures the ocean's current and temperature at approximately 1000m beneath the ocean's surface. On the tenth day the Argo float sinks further down to 2000m. Once it reaches 2000m beneath the surface, the Argo float begins to rise slowly to the surface, where it measures the ocean's salinity, pressure and temperature, depending on the ocean's depth. Once the Argo float reaches the ocean's surface, it uses its antenna to communicate with satellites in order to transfer its data.

Commercial ship Automatic Identification System (AIS) tracking

AIS is a marine-based environmental observation system used to track and improve maritime traffic. This system was developed by the International Maritime Organization and provides information, directions, exact positions and speed of ships through the ships' transponders. The aim of AIS tracking is to avoid collisions between ships and to locate the whereabouts of nearby ships or ports by applying radio communication systems. AIS tracking is also possible via satellite whereby the positions of ships are shown on a global scale.

Ocean buoys and wave riders sensors

Ocean buoys measure wind speeds and directions, as well as wave energy, height, direction and period. Furthermore, ocean buoys help to measure ocean and air temperature. Wave riders also measure wave characteristics. An example of a buoy array is the Global Tropical Moored Buoy Array.

Sonar

Originally an acronym for SOund Navigation And Ranging, sonar is a technique that uses sound propagation (usually underwater, as in submarine navigation) and backscattering to navigate, communicate with or detect objects on or under the surface of the water, such as other vessels. Single beam sonar is a portable and inexpensive depth measurement system, which can be used, for example, in flood monitoring.

Tide gauges

A tide gauge is a device for measuring the change in sea level relative to a specific location. Sensors continuously record the height of the water level with respect to a height reference surface close to the geoid. Water enters the device by a bottom pipe and electronic sensors measure its height and send the data to a tiny computer.

Appendix 2: Agencies responsible for natural hazards

Hazard	Monitoring and Detection	Forecasts and Advice	Mandated or Legislated Warnings
Severe Weather: Rain, Wind, Snow, Ice, Fog	Met Office, SEPA/EA/ NRW Public (WOW)	Met Office	Met Office National Severe Weather Warning Service
Flooding (River)	EA/SEPA/NRW/NIRA LLFA NIRA Local Authority	FFC/SFFS EA/SEPA/NRW/NIRA LLFA NHP Hydrological Outlooks CEH/BGS/NFRA	EA/NRW Floodline Warnings Direct Service SEPA Floodline
Flooding (Coast)	EA/SEPA/NRW/NIRA National Oceanography Centre LLFA Local Authority Channel Coastal Observatory - Regional Coastal Monitoring Programmes	FFC/SFFS EA/SEPA/NRW/NIRA LLFA	EA/NRW Floodline Warnings Direct Service SEPA Floodline
Flooding (Surface Water)	LLFA SEPA/NRW/NIRA	LLFA FFC/SFFS SEPA/NRW/NIRA	SEPA
Flooding (Groundwater)	LLFA SEPA/NRW/NIRA BGS/EA	LLFA FFC/SFFS EA/SEPA/NRW/NIRA NHP Hydrological Outlooks CEH/BGS/NFRA	EA/NRW
Storm Waves	Local Authority Channel Coastal Observatory - Regional Coastal Monitoring Programme Centre for Environment, Fisheries and Aquaculture Science (WaveNet)		

Hazard	Monitoring and Detection	Forecasts and Advice	Mandated or Legislated Warnings
Volcanic Ash	<p>Monitoring of unrest and eruptions: BGS/International Meteorological Organisation / Smithsonian Institution (US) BGS (overseas territories)</p> <p>Atmospheric volcanic ash: Met Office, Civil and Military observations, MOCCA, Universities and Research Institutes</p> <p>Ash deposition: BGS, CEH, DEFRA, SEPA</p>	Met Office (VAAC) NCAS (Advice) BGS, CEH, DEFRA, SEPA (Advice)	Met Office VAAC is mandated to generate volcanic ash charts
Space Weather	MOSWOC BGS UK Universities and Research Organisations	MOSWOC BGS BAS	Nil
Natural Ground Instability (landslides and subsidence)	Site owners/operators Infrastructure owners and operators Local Authority BGS Public (Social media)	BGS	Nil
Wildfires	Fire Authorities Met Office Natural England National Parks Forestry Commission	Met Office Natural England NRW	Nil
Temperatures (hot or cold)	Met Office PHE	Met Office PHE Department of Health	Nil

Hazard	Monitoring and Detection	Forecasts and Advice	Mandated or Legislated Warnings
Air Quality	DEFRA EA (incident response only) SEPA MRW NI DoE CEH	Met Office under contract to DEFRA	DEFRA issue air quality alerts
Aero Allergens	Met Office CEH	Met Office	Nil
Earthquakes	BGS	BGS	Nil
Drought / Water Resources	SEPA Met Office EA, CEH, BGS, Water Companies, NRW, Department for Regional Development	SEPA Met Office EA, CEH, Water Companies, NRW, Department for Regional Development Water Sit Report	Drought permits, Ordinary drought orders and Emergency drought orders: EA/SEPA/NRW/NI?
Space Objects and Near Earth Objects	British Atmospheric Data Centre UKSA NASA	UKSA	UKSA
Effusive volcanic eruptions/SO ₂	See Air Quality	Unofficial service provided by VAAC PHE/Department of Health	Nil
Avalanche	Sport Scotland Public (social media)	Sport Scotland Met Office Mountain Weather Information Service	Nil
Tsunami	Lisbon BGS Norway Intergovernmental Oceanographic Commission	Lisbon BGS	Nil

Appendix 3: Working group membership

Working Group members

The members of the Working Group involved in producing this report are listed below.

The Working Group members acted in an individual and not organisational capacity and declared any conflicts of interest. Members contributed on the basis of their own expertise and good judgement.

Chair	
Professor Sir Martin Sweeting	OBE FRS FREng FIET, Director, Surrey Space Centre
Members	
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Professor Stephen Briggs	Senior Adviser in Earth Observation, European Space Agency and Chair, Global Climate Observing System. ESA/ECSAT, Oxford-Harwell Campus.
Professor Harry Bryden FRS	Emeritus Professor in Ocean and Earth Science, University of Southampton
Alistair Lamb	Head of Research and Development – Thematic, AIRBUS Geo-Intelligence
Dr Vanessa Lawrence CB	Secretary General of Ordnance Survey International
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Appendix 5: List of acronyms

Acronym	Definition
ACE	Advanced Composition Explorer
AGB	Above Ground Biomass
AIS	Automated Identification System
AMDAR	Aircraft Meteorological Data Relay
AURN	Automatic Urban and Rural Network
AUV	Autonomous Underwater Vehicle
AVOID	AVOID is a research programme that provides advice to the UK Government on avoiding dangerous climate change brought on by GHG emissions
AWS	Automatic Weather Station
BGS	British Geological Survey (NERC Centre)
CEH	Centre for Ecology and Hydrology (NERC Centre)
CEOS	Committee on Earth Observation Satellites
CNES	Centre National d'Études Spatiales – the French Space Agency
COMET	Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (NERC Centre)
CORINE	Coordination of Information on the Environment. A 44-class European land cover mapping programme initiated in 1985, managed by the EEA and built from harmonised contributions from Member States, with the goal of a 6-yearly update cycle
COSMOS	Cosmic Ray Soil Moisture Observing System
CS3x	Continental Shelf model
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DEM	Digital Elevation Model (where the Digital Surface Model and Digital Terrain Model form derivatives)
DfID	Department for International Development
DMC	Disaster Monitoring Constellation – a UK-led portfolio of similarly specified EO satellites under various national ownerships, but all built and coordinated by Surrey Space Technology Limited
DMCii	DMC International Imaging
DNA	Deoxyribonucleic Acid
EA	Environment Agency
E-AMDAR	EUMETNET-Aircraft Meteorological Data Relay
EBV	Essential Biodiversity Variable
ECN	Environmental Change Network – a long-term national network of instrumented terrestrial and freshwater sites led by the CEH
ECV	Essential Climate Variable
EEA	European Environment Agency
EISCAT	European Incoherent Scatter Scientific Association

Acronym	Definition
EM spectrum	Electromagnetic spectrum
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETNET	Network of European Meteorological Services
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FFC	Flood Forecasting Centre
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System –a collaborative programme to build and coordinate a global observation network, sponsored by the World Meteorological Organisation, the UN and the International Council for Science
GEO	Group on Earth Observations. An international voluntary partnership of governments and international organisations with its own secretariat, established in 2005 to coordinate international efforts to build a GEOSS
GEOSS	Global Earth Observation System of Systems (see GEO)
GERB	Geostationary Earth Radiation Budget
GHG	Greenhouse Gas
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GNSS-R	Global Navigation Satellite System-Reflectometry
GOSAT	GHGs Observing Satellite
GPS	Global Positioning System
HAP	High Altitude Platform
HF	High Frequency
IAS	Invasive Alien Species
IASI	Infrared Atmospheric Sounding Interferometer
InSAR	Interferometric Synthetic Aperture Radar
INTERMAGNET	International Real-time Magnetic Observatory Network
IPCC	Intergovernmental Panel on Climate Change
LCM	Land Cover Map – a component of the Countryside Survey
LEO	Low Earth Orbit
LiDAR	Light Detection And Ranging
LLFA	Lead Local Flood Authorities
MER	Mass Emission Rate
MOC	Meridional Overturning Circulation
MOCCA	Met Office Civil Contingency Aircraft
MODIS	Moderate Resolution Imaging Spectrometer
MOSWOC	Met Office Space Weather Operations Centre
MTR	Mass Transport Rate

Acronym	Definition
NaFRA	National Flood Risk Assessment
NASA	National Aeronautics and Space Administration (USA)
NCAS	National Centre for Atmospheric Science (NERC Centre)
NCEO	National Centre for Earth Observation
NEMO	Nucleus for European Modelling of the Ocean
NERC	Natural Environment Research Council
NGO	Non-governmental organisation
NHP	Natural Hazards Partnership
NIRA	Northern Ireland Rivers Agency
NOAA	National Oceanic and Atmospheric Administration
NRFA	National River Flow Archive
NRW	Natural Resources Wales
NWP	Numerical Weather Prediction
OPC	Optical Particle Counter
RAPID array	Mooring in the Atlantic monitoring the meridional overturning circulation
SAR	Synthetic Aperture Radar
Sentinel-1	An ESA-operated satellite system, forming part of the Copernicus programme, hosting a C-band synthetic aperture radar (SAR) instrument. Sentinel-1a was launched in April 2014
Sentinel-2	An ESA-operated satellite system, forming part of the Copernicus programme, hosting a wide-swath superspectral, high-resolution optical instrument. Sentinel-2a is due to be launched during 2015
Sentinel-3	An ESA-operated satellite system, forming part of the Copernicus programme, hosting a multi-instrument payload for both global land and global marine monitoring
SEPA	Scottish Environment Protection Agency
SFFS	Scottish Flood Forecasting Service
SMOS	Soil Moisture and Ocean Salinity
SOHO	Solar and Heliospheric Observatory
SRTM	Shuttle Radar Topography Mission – an international research effort that obtained digital elevation models on a near-global scale from 56°S to 60°N, to generate the most complete high-resolution digital topographic database of Earth prior to the release of the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model in 2009
SSS	Sea surface salinity
SST	Sea surface temperature
STEREO	Solar Terrestrial Relations Observatory
SWOON	Space Weather Observation and Operations Network
TRUTHS	Traceable Radiometry Underpinning Terrestrial and Helio Studies
UAV	Unmanned Aerial Vehicle, also known as drones
UGV	Unmanned Ground Vehicle

Acronym	Definition
UK IMON	UK Integrated Marine Observing Network
UKSA	UK Space Agency
UKTI	UK Trade and Investment
UN	United Nations
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
VAAC	Volcanic Ash Advisory Centre
VATDM	Volcanic Ash Transport and Dispersal Models
VHR	Very High Resolution – applied to satellite imagery (typically) in the sub-5 metre (down to 40cm) class
WEZARD	Weather Hazard for Aeronautics
WIBS	Wideband Integrated Bioaerosol Sensors
WMO	World Meteorological Organization
WOW	Weather Observation Website
WVSS-II	Water Vapour Sensing System



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