EVALUATION OF NERC CENTRES 2013

IMPACT CASE STUDIES: NATIONAL CENTRE FOR ATMOSPHERIC SCIENCE

Note: confidential aspects of the case studies have been deleted where necessary.

NCAS1	Airborne and ground-based response to the atmospheric impact of volcanic eruptions.
NCAS2	Monitoring the gas leak at Total's Elgin North Sea gas platform, 2012
NCAS3	Impact on the Met Office
NCAS4	Impact on the Intergovernmental Panel on Climate Change
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NCAS8	Impacts on the Insurance Industry
NCAS9	Air Quality in Extreme Events (Public Health)

Case study code and title

NCAS_1 Airborne and ground-based response to the atmospheric impact of volcanic eruptions.

1. Summary of the impact (maximum 100 words)

In March 2010 the Icelandic volcano Eyafyallajökull erupted and the resulting ash plume caused the closure of much of European airspace. Through airborne and ground-based observations, plus modelling, NCAS supported the Civil Aviation Authority (CAA) in its development of new procedures allowing safe operation in limited ash concentrations. Successful implementation of these new procedures limited losses to the aviation industry. Further development of ground-based observing systems in Iceland subsequently considerably reduced the period of closure at Keflavík airport during the 2011 eruption of Grimsvötn.

2. Nature of the impact

On 20 March 2010, Eyafyallajökull, an Icelandic volcano, began a small eruption. On Wednesday 14 April the eruption suddenly intensified and large quantities of ash began to be ejected into the atmosphere up to altitudes of 30,000 ft. The ash reached UK airspace on the morning of 15 April. At the time, the International Civil Aviation Organization (ICAO) guidance, based on a zero threshold for ash in air, was that it would no longer support service to commercial air traffic into the affected region. The shutdown of airspace was estimated to cost the airline industry worldwide $400M per day (on 19 April at the height of the closures) and a total loss of revenue to the industry of $1.7 billion [1].

This case is concerned with how impact on aviation was limited. NCAS joined with other organisations nationally and internationally to assist the UK CAA in establishing new procedures for flying close to or in volcanic ash. The resulting agreement allowed substantial re-opening of UK airspace after 6 days of the eruption. In particular, NCAS provided the instrumentation and scientists to make airborne observations of the ash plume, provided ground-based LIDAR measurements of the ash and independently verified the dispersion forecasts of the Volcanic Ash Advisory Centre. The contribution which this made to the new operating agreement is verified by the CAA [2]. NCAS further assisted in the response to the emergency by contributing to the Chief Scientist's Scientific Advisory Group in Emergencies (SAGE).

Following the Eyafyallajökull incident NCAS has worked to establish improved infrastructure to limit the impact of future eruptions. This was tested in May 2011 when the Icelandic volcano Grimsvötn erupted. A LIDAR system installed and managed by NCAS was used to cut by half the time during which the international airport at Keflavík was closed on certain days [4].

The CAA has published the full timeline of events [15].

3. How the Centre contributed to the impact

The eruption of Eyafyallajökull intensified on 14 April 2010, with the plume reaching up to 30,000 ft. The resulting ash plume reached UK airspace in the morning of 15 April. Airspace closures began immediately as a consequence of the guidance of the International Civil Aviation Organization (ICAO) which set a tolerance for flying in ash at zero. On 17 April the UK CAA started to coordinate a regulatory response and began a series of daily international teleconferences to gather together the world’s leading aircraft and engine manufacturers to focus on the issue. Supporting these discussions were leading scientific experts in meteorology, geology and volcanology, Air Traffic Services experts, airspace managers and leading airlines. Professor Stephen Mobbs and Dr Guy Gratton from NCAS took part in these meetings [2] representing atmospheric science and aero-engineering expertise respectively. Responsibility for predicting the atmospheric dispersion of volcanic ash rests with Volcanic Ash Advisory Centres (VAACs). For the North Atlantic and NW Europe the VAAC is hosted by the UK Met Office. Practical implementation of the closure of airspace over Europe consisted principally of the CAA closing all regions where the VAAC predicted any volcanic ash (irrespective of concentration). In addition, aircraft were excluded from any region of “visible ash” (although it has long been a concern that this is a vague concept). The

teleconferences highlighted several issues:

1. the urgent need to establish more realistic and verifiable concentration limits for flying in ash (a question for engine manufacturers and for those observing and modelling the dispersion);
2. under severe pressure to resume flying, the airlines expressed a serious concern and lack of confidence in the VAAC predictions;
3. the need for more accurate and more timely measurements of airborne volcanic ash concentration and properties.

NCAS responded immediately to all three issues. NCAS is a world leader in airborne and ground-based aerosol measurements. The scientists are based mainly at Manchester working with Professor Hugh Coe, with the main observing platform being the Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 research aircraft. In April 2010 the FAAM aircraft was undergoing a refit and was unavailable. The operators, Directflight Ltd and their engineering contractors Avalon Aero began work immediately to bring the aircraft into service and this was achieved by 20 April. In the meantime, NCAS scientists transferred a number of aerosol instruments to the NERC Dornier 228 aircraft. The Do-228 aircraft first flew on 16 April, less than 48 hours after the start of the eruption. Data and their interpretation were supplied to the VAAC for comparison with their NAME dispersion model and to the CAA. A further 4 flights into the closed airspace were made by the Do-228 in the period up until 23 April. In parallel with the aircraft observations, NCAS began ground-based LIDAR measurements from a number of UK sites and was the first to detect the arrival of the ash above the UK (this was communicated immediately to the VAAC). At the same time, NCAS undertook to make independent dispersion forecasts, using the NOAA HYSPLIT model [3]. These predictions were made available to the CAA, not for operational use (that is the responsibility of the VAAC) but to provide independent confirmation of the accuracy of the VAAC forecasts, addressing issue (2) above. In making these predictions, NCAS drew on advice regarding the volcanology from the British Geological Survey.

As a result of a huge amount of intensive work, coordinated by the CAA through their daily international teleconferences, engine manufacturers and regulators were able to agree new procedures on 20 April. These allowed flights into areas of ash with concentrations predicted (by the VAAC) to be below 2000 μgm-3, with extended maintenance procedures to be applied for concentrations above 200 μgm-3. The details of the new agreement, along with the technical rationale, are described in full by the CAA report on the teleconferences [2]. This publication provides the independent confirmation of the role of NCAS in allowing the new operating procedures to be introduced. The new procedures had the immediate effect of re-opening airspace and it remained substantially open up to the end of the eruption around 21 May except for a brief and predicted period of closure between 3 and 5 May.

In their report [2] explaining the introduction of new procedures, the CAA list 11 technical reasons supporting the changes. Two of these are:

- *"An independent assessment of the London VAAC forecasts by the UK National Centre for Atmospheric Science confirming confidence in the Met Office products.*
- *Instrumented flight test measurements from the UK Facility for Airborne Atmospheric Measurements (FAAM) and NERC, the UK Natural Environment Research Council, LIDAR laser measurements and meteorological balloon data all confirming that the forecast levels accorded well with the peak values being measured in the atmosphere."*

The new limits on flying in volcanic ash placed an immediate additional responsibility on the VAAC, since the dispersion forecasts now had to predict the boundary of the region of 2000 μgm-3 concentration rather than simply predicting the presence of ash. This required accurate quantitative measurements of ash concentration for validation and development purposes. For this reason the FAAM BAe-146 aircraft flew 5 missions between 20 April and 18 May measuring ash properties

(principally using NCAS aerosol instrumentation) and collecting samples for lab analysis [5,6]. These airborne measurements also provided the characterisation of the ash necessary for LIDAR data to be used quantitatively thereafter. With this additional information concerning the ash properties, it rapidly became clear that a network of ground-based LIDARs could in the future provide the much needed monitoring network for future incidents. In the UK, plans for such a network are being progressed by the DfT and Met Office.

The change from zero ash tolerance to a specified concentration of 2000 µgm-3 immediately required that VAAC to produce forecasts which could give accurate ash concentrations. This is not possible without good characterisation of the ash at or near the source (both quantity and particle properties) [7]. For this reason NCAS added an additional focus to its research in the months following the eruption of Eyjafjallajökull. A further Doppler LIDAR was procured and deployed to Iceland, working in collaboration with the Icelandic Meteorological Office (IMO). As there were no personnel in Iceland with previous experience of LIDAR operation or interpretation, the system was set up to be controlled and monitored by NCAS in the UK, using software developed by NCAS. The system was fully functional by the time the Icelandic volcano Grimsvötn erupted in May 2011. On NCAS instructions, the LIDAR was relocated to the international airport at Keflavík, allowing the Grimsvötn ash plume to be monitored in real time and expert interpretation added [8]. During the period 12 UTC on 24 May to 12 UTC on 12 May, using the LIDAR interpretations supplied by NCAS, the airport operator Isavia was able to keep the airport open for 12 of the 24 hours when it would have been closed on the basis of the VAAC forecasts. This has been reported by the IMO to ICAO [4]. IMO have stated that "Due to their [NCAS] support, in addition to satellite information, IMO was able to assist Isavia in decisions of opening of the Keflavík airport, which would have otherwise been closed based on forecasts from dispersion models only. As an example of the use of the Lidar and in-situ measurements taken, it was possible to have the Keflavík airport open 12 hours out of 24 that would otherwise have been closed in the period 12 UTC the 24th to 12 UTC the 25th. Substantial savings were made due to these extra measurement efforts." This dramatic illustration of the importance of real-time LIDAR monitoring in keeping airspace open has led directly to Isavia issuing an invitation to tender for supply of a LIDAR network and associated services [9]. (For note, because of the short-lived nature of the Grimsvötn eruption and the wind direction at the time, this eruption only closed UK airspace briefly.)

Much of the impact of this work was only achievable by close cooperation of research scientists and operational services in the UK and Iceland. For this reason NCAS joined with the IMO, British Geological Survey and the UK Met Office to sign a Memorandum of Understanding within two weeks of the Eyjafjallajökull eruption beginning [10]. Much of the impact achieved during the two eruptions and the ongoing development work in preparation for further eruptions has been done under that agreement.

NCAS expertise was used by the Government Office for Science (GO-Science) Scientific Advisory Group in Emergencies (SAGE), which reported through the Chief Scientist to COBRA and the Cabinet Office throughout and following the Eyjafjallajökull event [11, 12, 13, 14]. Professors Coe and Mobbs were members of SAGE during the period of 4 meetings in May and June 2010 when an expert panel was put together to advise GO-Science of the issues and risks surrounding the ongoing volcanic ash event, the necessary predictive capability at the time and in the future and to develop improved understanding and establish risk of future, potentially more damaging, events.

4. Evidence and sources to corroborate the impact

1. IATA Economics Risk Analysis of the impact on industry operations and revenues from the eruption of Iceland's Eyjafjallajökull volcano in April 2010. http://www.iata.org/publications/economics/market-issues/Pages/risk.aspx
2. CAA report on the 2010 international valcanic ash teleconferences.

http://www.caa.co.uk/docs/2011/Teleconferences%20log.pdf

3. Draxler, R. and Hess, G. 1997: Description of the HYSPLIT 4 modelling system. NOAA Tech. Memo. ERL ARL-224. Technical report, NOAA Air Resources Laboratory, Silver Spring, MD.
4. Snorrason, A. Grímsvötn eruption 2011 – Lidar and in-situ measurements; info paper from IMO and Isavia. International Volcanic Ash Task Force (IVATF), second meeting, Montréal, July 2011.
5. Marenco, F., B. et al. 2011. Airborne lidar observations of the 2010 Eyjafjallajökull volcanic ash plume, J. Geophys. Res., 116, D00U05, doi:10.1029/2011JD016396.
6. Johnson, B., et al. 2012. In situ observations of volcanic ash clouds from the FAAM aircraft during the eruption of Eyjafjallajökull in 2010, J. Geophys. Res., 117, D00U24, doi:10.1029/2011JD016760.
7. Webster, H. N., et al. 2012. Operational prediction of ash concentrations in the distal volcanic cloud from the 2010 Eyjafjallajökull eruption, J. Geophys. Res., 117, D00U08, doi:10.1029/2011JD016790.
8. Petersen, G. et al. 2012. Utilising a Lidar to detect volcanic ash in the near-field. Weather, 67, 149-153.
9. http://www.rikiskaup.is/utbod/utb/15311. Full tender document may be downloaded from the website above.
10. Signed Memorandum of Understanding between IMO, UK Met Office, NCAS and BGS dated 27 May 2010. Full document may be downloaded from the website above.
11. SAGE minutes 21 April: http://www.bis.gov.uk/assets/goscience/docs/s/10-1371-sage-volcanic-ash-minutes-21-april-2010
12. SAGE minutes 5 May: http://www.bis.gov.uk/assets/goscience/docs/s/10-1372-sage-volcanic-ash-minutes-5-may-2010
13. SAGE minutes 19 May: http://www.bis.gov.uk/assets/goscience/docs/s/10-1373-sage-volcanic-ash-minutes-19-may-2010
14. SAGE minutes 24 June: http://www.bis.gov.uk/assets/goscience/docs/s/10-1374-sage-volcanic-ash-minutes-24-june-2010
15. Timeline of events: http://www.caa.co.uk/default.aspx?catid=2011&pagetype=90&pageid=12637

5. Contacts for further information

Prof. Stephen Mobbs

Prof. Hugh Coe

Case study code and title

NCAS_2 Monitoring the gas leak at Total's Elgin North Sea gas platform, 2012

1. Summary of the impact (maximum 100 words)

In March 2012 a leak developed at Total's Elgin North Sea gas platform. As part of their relief work, Total needed to know the leaking gas flowrate and composition. Total engaged the services of NCAS and six missions were flown using the FAAM aircraft. The data and its interpretation by NCAS provided Total with information which enabled their engineers to reoccupy the platform. Total confirm that the NCAS services were “the most robust and valuable of all”. This contributed to limiting the duration of the incident, which cost Total $1.5m/day and the UK economy £2.8bn in lost corporation tax receipts.

2. Nature of the impact

In March 2012 a gas leak was reported at Total's Elgin production platform in the North Sea. NCAS, though use of the NERC/FAAM BAe-146 atmospheric research aircraft, flew six missions to monitor the leak flowrate and composition [1]. The data and services provided to Total by NCAS were reported by Total to be consistently the most robust and valuable of all the sources of information on which they drew to support their relief operations [2,3]. This kept the time taken by Total to stop the leak to a minimum. The platform was reoccupied by engineers on 5 April after NCAS had reported the methane leak flowrate to Total. Engineers were able to stop the leak on 16 May. Whilst relief operations were in progress NCAS flew four more missions and were able to report both total leak flowrate and gas composition to Total. Following a final mission on 15 August NCAS was able to provide independent confirmation that the leak had stopped.

The assistance provided by NCAS was the leading external factor limiting the duration of the leak and hence limiting lessening the economic losses to both the company and the UK Treasury. Regarding the economic impact on Total, the company reports losses of $1.5M per day between the start of the leak and the end of Q2 and anticipated losses of $130M during Q3/4 [5]. The Office of Budget Responsibility (OBR) reports a 12% fall in UK oil and gas revenues in 2012/13 compared with 2011/12 (despite almost identical oil prices). It reports a consequent fall of £2.8 billion in offshore corporation tax receipts [6]. The consequence was a surprise deficit in UK public finances in July 2013, when a surplus was expected [e.g. 7]. The same factors are cited by the Bank of England in its August 2012 Inflation Report as having contributed to the UK falling back into recession [8].

Since the incident, NCAS and Total have been discussing longer term arrangements under which the company can call on NCAS services in the future, should similar incidents occur. The types of airborne measurement made by NCAS have similarities with those made by NOAA in the USA after the Deepwater Horizon incident in the Gulf of Mexico in 2010. NCAS and NOAA are developing an agreement to share best practice (an MoU between NCAS and NOAA is about to be signed [9]). There is little doubt that the lessons learned during the support for the Elgin relief effort, and the discussions with NOAA regarding further refinement of procedures, will enable any future responses to be even more timely and effective.

3. How the Centre contributed to the impact

This activity was enabled by:

- The availability of the FAAM BAe-146 aircraft, associated core instruments and scientists, plus willingness of staff to work beyond the call of duty in an emergency.
- NCAS specialist expertise in hydrocarbon trace gas analysis and in dispersion modelling.
- Management and planning by NCAS of FAAM (including flight planning) and of the relationship with Total, translating evolving Total requirements into contract delivery on timescales of a few hours to days.
- Ability of NERC legal team to translate the needs of scientists and engineers at NCAS and

Total into a legal agreement in 4 days.

On 25 March 25 2012 a gas leak occurred at Total's Elgin wellhead platform in North Sea, approximately 240 km east of Aberdeen. This resulted in immediate evacuation of the platform and the beginning of a comprehensive relief operation, managed by Total. A three mile air exclusion zone around the platform was established. NCAS contacted Total to offer assistance by means of measurements of the atmospheric plume using the FAAM (Facility for Airborne Atmospheric Measurements) BAe-146 research aircraft. Between 3 April and 4 May NCAS undertook five flights through the plume, providing data to Total in rapid time (usually within 24 hours of the flight). The principal measurements were of methane concentration (allowing a calculation of the total methane leak flowrate) and of the non-methane hydrocarbon composition of the plume. The data provided by NCAS was one of the factors in the safety assessment which allowed Total engineers to reboard the platform on 5 April. Between 5 April and 16 May the four flights using the FAAM aircraft provided Total's relief team with data concerning the changes to the leak (both total flowrate and composition) to support their work. The well intervention operation carried out by the engineers, which involved pumping heavy mud into the leaking well, began on May 15th and the leak was stopped 12 hours later. Following five days of monitoring Total was able to confirm that the leak had stopped on 21 May. At Total's request, NCAS undertook one further flight on 15 August and was able to confirm independently that there were no residual emissions from the Elgin platform.

Each mission began with agreement of a safety case with FAAM's operator, Directflight Ltd and agreement of a flight plan with Directflight and Total. The key instruments were FAAM's Fast Greenhouse Gas Analyzer (FGGA) for methane concentration measurement and a Whole Air Sample (WAS) capability which allowed plume samples to be collected and analysed post-flight in the laboratory for non-methane hydrocarbons using gas chromatography techniques. The basic flight plan was to establish background trace gas concentrations upwind of the leak and then to transit around the air exclusion zone and cross the plume multiple times downwind at several heights. This allowed the structure and concentration of the plume to be established and subsequently used to estimate the total leak flowrate. The principal challenge in flight planning was to take account of all available meteorological data (forecasts, satellite images) and develop a plan which adequately sampled the plume whilst avoiding low-level flight in cloud. In spite of challenging conditions on several flights, in all cases plume data was successfully supplied to Total. Full technical details are contained in the final report to Total [10].

The flights and associated data analysis and interpretation activities were paid for under individual legal agreements for each flight between NERC and Total. These covered the costs of provision of the aircraft and its operation by BAe Systems and Directflight at their commercial rates.

The primary route to impact during the emergency was daily discussions and reports from NCAS to Total. The information supplied was used directly by Total in order to manage their relief operations at the Elgin platform. Total engaged with a number of organisations in order to obtain the necessary information and have noted in communications to the Science Minister and privately to NCAS that the NCAS services “proved to be the most robust and valuable of all”. Throughout the incident Total were in constant dialogue with DECC and this, including the NCAS contribution to the relief effort, are noted in DECC's report at the time from its Government Interest Group [4]. NCAS has subsequently provided evidence independently of Total to DECC as part of DECC's enquiry into the incident (this is yet to report).

The primary effects of the NCAS work have been:

- Provision of data and interpretation which shortened the duration of the incident (particularly the planning of the reoccupation of the platform by the engineers).
- Subsequent assessment of the overall environmental impact of the incident in terms of gases released into the environment.

4. Evidence and sources to corroborate the impact

1. Total's website for the incident (http://www.elgin.total.com) and specifically http://www.elgin.total.com/elgin/page.aspx?contentid=747
2. Letter from Total E&P UK Managing Director Philippe Guys to the Rt Hon David Willetts MP, Minister of State for Universities and Science, dated 18 December 2012.
3. Covering letter from Total to DECC supplying information concerning the NCAS contribution to the relief efforts and similar information supplied by Total to a Health and Safety Executive conference on this incident.
4. Web page of DECC's Elgin Gas Release Government interest Group and updated report linked therein:
   http://og.decc.gov.uk/en/olgs/cms/environment/about_the_offs/elgin_gig/elgin_gig.aspx
   http://og.decc.gov.uk/assets/og/environment/5283-elgin-gas-release-gig-update1.doc
5. Total's published Financial Report 1st Half 2012. Copy available on request and freely available here:
   http://www.total.com/en/investors/publications/annual-publications-601436.html
   http://www.total.com/MEDIAS/MEDIAS_INFOS/5917/EN/Financial-Report-1st-half-2012.pdf
6. Office of Budget Responsibility publication “Economic and fiscal outlook December 2012” Copy available on request and freely available here:
   http://cdn.budgetresponsibility.independent.gov.uk/December-2012-Economic-and-fiscal-outlook23423423.pdf
7. Numerous press articles dated 21 August 2012. For example:
   http://www.standard.co.uk/business/business-news/elgin-shutdown-scuppers-july-surplus-for-treasury-8069520.html
8. Bank of England Inflation Report August 2012. Copy available on request and freely available
   here: http://www.bankofengland.co.uk/publications/Pages/inflationreport/ir1203.aspx
9. Memorandum of Agreement between the National Oceanic and Atmospheric Administration Earth System Research Laboratory and the National Centre for Atmospheric Science.
10. Final report from NCAS to Total concerning the response to the Elgin gas leak.

5. Contacts for further information

Prof. Stephen Mobbs

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Case study code and title

NCAS_3 Impact on the Met Office

1. Summary of the impact (maximum 100 words)

NCAS works closely with the Met Office to make significant contributions to the development of their operational systems for weather and climate forecasts and thereby impacts the economy, health, environment and quality of life in the UK and worldwide. This is achieved both through pioneering new approaches and through direct collaborative evaluation and development of forecasting models and observational capability. The Met Office has said that *"there is no doubt that NCA… has made significant contributions to scientific developments that have helped the Met Office maintain its position at the forefront of weather forecasting and climate prediction…"* [1].

2. Nature of the impact

NCAS activities have had a direct impact on public weather services provided by the Met Office and, through them, on the economy, health, environment and quality of life in the UK and world-wide.

The Met Office's primary role is to provide public weather forecasting services on timescales that range from hourly to seasonal and to provide advice on future climate change on decadal and centennial timescales. The prime beneficiaries of these services are the UK public, UK and international governments, public sectors and private organizations. The impact of these forecasts is widespread, for example through provision of weather forecasts, high risk weather alerts (flooding, heat waves, pollution hazards), support to national defence agencies, transport (aviation, marine, road, rail), industry (construction, retail, finance, utilities, insurance) and through input to international climate change assessments and adaptation policy formulation.

Over many years NCAS scientists have taken the lead in ground-breaking initiatives that have had a major impact on Met Office science strategy and operational capabilities: *"NCAS has played a very important role in pushing the boundaries… by taking on projects that are truly at the cutting edge, and yet are too high-risk and beyond the range of what the Met Office can undertake in response to its customer requirements"* [1]. For example, NCAS pioneered the approach of assessing climate in terms of the statistics of weather, which "has shaped the paradigm of seamless science, modelling and prediction, which is now at the heart of the latest Met Office Science Strategy and is helping to sustain the UK's position as a world leader in weather and climate prediction"[1]. The prime manifestation of this strategy is that the Met Office now follows a unified development strategy for physical parameterisations in the "Unified Model" (UM) across all timescales for weather and climate prediction, so that improvements can easily feed through to both weather and climate forecasts.

To remain competitive requires on-going development of the operational prediction systems, including both forecast models and observational systems. NCAS has made significant contributions to these through a wide range of collaborative activities, primarily involving evaluation and improvements to the current operational systems and development of new modelling and observational capability. A recent joint NCAS-Met Office Register of Collaborative Projects and Their Impacts[2] identified over 30 major areas in which NCAS has had *"a demonstrable impact on Met Office operational capabilities"*[1].

For example, NCAS pioneered with the Met Office the importance of high horizontal resolution in coupled atmosphere-ocean climate modelling: *"The legacy of this work can be seen in the implementation… in operational seasonal forecasting… in autumn 2012. This will place the UK way ahead of other operational systems, with the capability to look… to weather regimes and high-impact weather, both of significant relevance to customers"* [1]. NCAS has also identified the need for high vertical resolution of the upper ocean mixed layer to capture essential interaction between ocean and atmosphere: *"This… has now been implemented in the latest versions of the Met Office coupled models ....again a world first… already demonstrated significant benefits in forecast skill"* [1].

In addition, joint NCAS-Met Office aircraft campaigns have made measurements of atmospheric dust that have been used to represent the impact of dust on atmospheric and surface heating in the Unified Model: *"This model is being used in the military theatres of the Middle East (Iraq, Afghanistan) and Africa (Libya, Mali) to support / aid military operations. The MOD, Army, Navy and RAF have benefitted"*[2]. In addition, as part of the NERC – Met Office Joint Weather and Climate Programme (JWCRP) UK Chemistry and Aerosols (UKCA) project NCAS scientists have developed detailed chemistry and aerosol schemes for the Unified Model that were used *"to provide the first fully interactive air quality forecasts which formed part of our Olympics showcase"* [1].

3. How the Centre contributed to the impact

The following summarises some of the major activities recently identified in the joint NCAS-Met Office Register of Collaborative Projects and their Impacts[2] as making a substantial contribution to Met Office operational capabilities. Further details and references to collaborative papers and reports are provided in the Register. These impacts were achieved primarily through collaborative projects with the Met Office funded directly by NCAS, through the JWCRP or through NERC grants in which NCAS scientists were the Principal Investigators.

- High Resolution Global Modelling: Through a long standing collaboration (2006-) between NERC and the Met Office led by NCAS (Vidale, Shaffrey, Demory) high resolution versions of the Coupled Ocean Atmosphere UM have been developed. This involved scientific and technical development to extend the atmospheric resolution from N96 (~140km) up to N216 (~60km) and from 1° to ¼° in the ocean, and evaluation of the impact of improved resolution on the simulation of key climate processes. Informed by this programme, the Met Office has upgraded its seasonal forecasting model to this resolution. Additional NCAS development and evaluation of atmosphere-only climate simulations at higher resolutions N512 (24km) and N1024 (12km) is continuing through the joint UPSCALE3 project, thus ensuring that the Met Office maintains its international lead in climate modelling.
- Joint Aircraft Campaigns: Joint NCAS – Met Office aircraft campaigns have measured dust and biomass burning aerosols over West Africa as well as aerosol composition around the UK (Coe Allan, Williams). The measurements have been used to improve the representation of dust and aerosols in the UM, The model is being used for forecasting in military theatres in the Middle East and Africa and to correct a major deficiency in the Met Office visibility model over the UK.
- Chemistry and Aerosols: NCAS Scientists (Pyle, Braesicke) have developed new chemistry and composition modules for the UM as part of the JWCRP UKCA project, including gas phase composition schemes for troposphere and stratosphere, a modal aerosol scheme and improved photolysis scheme. This was used by the Met Office to contribute to the WMO/UNEP Ozone Assessment (2011), international chemistry-climate model assessments (CCMVAL, 2010), a Met Office study on the effects of the Mt Pinatubo Volcanic eruption and as input to the Met Office Air Quality model employed during the Olympics[1].
- Increased Vertical Domain: NCAS scientists (Gray, Osprey, Warner) contributed to raising the upper boundary of the UM from 38km to 80km to fully resolve the stratosphere, by developing the gravity wave scheme, ozone climatology, solar variability code and extensive validation. This has been used operationally since 2006, for seasonal predictions since 2011 and in climate runs submitted as part of the Met Office's contribution to the IPCC Assessment in 2012.
- Upper ocean-atmosphere coupling: NCAS scientists (Woolnough, Klingaman) assessed the impact of daily versus monthly-mean sea-surface temperatures (SSTs) in atmosphere-only climate simulations and increased the near-surface vertical resolution in the ocean from 10m to 1m. The improved SST interaction and diurnal cycle improved the strength, organisation and propagation of tropical convection, including the Madden Julian Oscillation and active and break cycles of the Indian monsoon. The enhanced vertical resolution is now implemented in the short-term and seasonal forecast systems, a world-first. The high-frequency coupling has

demonstrated significant benefits in forecast skills[1].

- Operational radar network: NCAS scientists (Nicol) provided a demonstration of improved ground clutter detection in the operational rain radar network, which has now been implemented operationally to provide composite rainfall maps across the UK. NCAS scientists (Nicol) worked with the Met Office to implement radar refractivity capability to provided low-level humidity observations, advised on developments of acquisition software and provided processing software. The Met Office is evaluating the use of this new data in the operational and developmental forecast systems for short range prediction of convective storms over the UK.
- Decadal Forecast System (DePreSys): NCAS scientists (Sutton, Robson) helped assess the DePreSys decadal forecasting system (2009 -), particularly for the North Atlantic and pioneered a process-based approach and statistical forecasts as benchmarks for evaluation. Large biases were identified that directly impacted forecast skill. These insights guided the next versions of DePreSys and statistical forecast benchmarks are now routinely employed. This work evolved from an NCAS-led PhD thesis to a NERC consortium grant (VALOR) and EU projects (THOR; SPECS). SPECS (Nov 2012 -) is now leading EU development of climate services.
- Convective storms: NCAS scientists (Blyth) led the Convective Storm Initiation Project (CSIP), a field campaign to study processes leading to convective initiation over the South of England. CSIP results were used to validate and optimize the high-resolution (1 km) version of the UM prior to its adoption in the operational forecasting system.
- Convective Processes: NCAS scientists (Woolnough, Klingaman) developed and tested increased entrainment and adaptive detrainment rate for deep and mid-level convection in the UM. This improved the Madden-Julian Oscillation, tropical-cyclone frequency, monsoon intra-seasonal variability and reduced mean-state biases in tropical rainfall. The Met Office plans to adopt the improvements in the next short-term and seasonal forecasting systems.
- Seasonal Forecast System (GloSEA): NCAS scientists (Sutton) worked with the Met Office (2011 -) to identify and understand the impact of North Atlantic sea surface temperature biases on European climate, arising from a poor simulation of the Gulf Stream. This study contributed directly to the case to increase the ocean resolution of the GloSea operational seasonal forecast system, which now has a much improved simulation of the Gulf Stream, and recent skill correlations for seasonal forecasts over Europe have risen from near zero to 0.6.
- Land Surface Processes: NCAS scientists (Vidale) implemented and tested new soil physics parameters and parameterisations in the UM land surface schemes and analysed evaporative flux from terrestrial ecosystems. The new parameters were adopted by the Met Office in 2009 and resulted in improved short-range forecast skill scores.
- Monsoons: NCAS scientists (Turner, Klingaman) performed the first ever assessment of Australian rainfall mean and variability in the UM and highlighted biases in monsoon rainfall over land and weak variability associated with ENSO and the Southern Ocean storm-track. An analysis of seasonal prediction for the Indian summer monsoon identified loss of skill associated with the simulation of the monsoon – ENSO teleconnection. A set of assessment metrics for Indian monsoon sub-seasonal variability and monsoon - ENSO teleconnections were developed and adopted by the Met Office. This work contributed to Met Office collaborative agreements with the Australian Bureau of Meteorology.
- Sea Ice: NCAS scientists (Gregory) implemented a T-fold tri-polar grid in the Los Alamos sea ice model CICE and corrected a bug in the NEMO-CICE coupling. This work allows the Met Office to run the NEMO-CICE (ocean and sea-ice model) model at resolutions of 2° and ¼°, in which the T-fold grid is required, and corrects a long-standing error at other resolutions.
- Land Ice: NCAS scientists (Gregory, Smith) improved the snow scheme for ice sheets by implementing sub-grid hypsometry. This contributes to the Earth System version of the UM and

increases the Met Office portfolio of models to include fully coupled Earth system interactions.

- JWCRP: NCAS has played a leading role in development of the NERC-Met Office strategic partnership: the Joint Weather and Climate Research Programme (JWCRP). An NCAS scientist (Mobbs) chairs the Joint Facilities Group and is a member of the Science Programme Board. 3 NCAS scientists are members of the Science Strategy Group. Through JWCRP NCAS played a leading role in the development of the first national (NERC-Met Office) strategy for climate and earth system modelling, to provide the next Generation UK Earth System Model and increase the Met Office's portfolio of forecasting tools.
- MOSAC: 3 NCAS scientists (Mobbs, Vaughan, Pyle) are members of the Met Office Science Advisory Committee (MOSAC), and an NCAS scientist (Pyle) chairs the DEFRA Met Office Hadley Centre Science Review Group (SRG). Both committees provide advice to the Met Office on the quality and relevance of its scientific programmes and research. An NCAS scientist (Sutton) is also a member of the Steering Group for the DFID - Met Office Climate Science Research Partnership.

4. Evidence and sources to corroborate the impact

- Supporting letter from the Chief Scientist at the Met Office.
- NCAS-Met Office Register of Collaborative Projects and Their Impacts.
- http://www.metoffice.gov.uk/research/news/upscale

5. Contacts for further information

Prof. Lesley Gray

Prof. Geraint Vaughan

Case study code and title
NCAS_4 Impact on the Intergovernmental Panel on Climate Change

1. Summary of the impact (maximum 100 words)
NCAS has had an impact on the IPCC through major contributions to the preparation of the Fifth Assessment Report. The impact arises from analysis of observed and simulated climate variability and change, development of climate models and metadata standards, leading roles in managing the international CMIP5 database, participation in IPCC meetings, and serving as authors and review editors of the Report. The Report itself is expected to make a large contribution for several years to the communication of the latest state of climate science to the world's governments as they address the urgent challenge of global climate change.

2. Nature of the impact
The NERC strategy requires it to deliver world-leading environmental research at the frontiers of knowledge in three areas, one of which is to enable society to respond urgently to global climate change. The UK government view is that climate change is arguably the greatest challenge facing the world today, and is a global issue that demands a global response (www.bis.gov.uk/go-science/science-in-government/global-issues/climate-change). On account of the international nature of the challenge and its magnitude, governments established the Intergovernmental Panel on Climate Change (IPCC) a quarter of a century ago to provide the world with a rigorous and balanced scientific view of the current state of knowledge in climate change [1]. The IPCC now has 195 member countries and has become the leading international scientific body for the assessment of climate change. It informs policy-makers through the reports that it produces, especially the comprehensive Assessment Reports, whose authority is acknowledged by governments by their being accepted at IPCC plenary approval meetings. The IPCC does not propose or evaluate policy, but offers a means for scientists working on climate change research to have a direct impact on the thinking of international policy-makers. It is a unique and remarkable opportunity for scientists to help global society address the challenge of climate change.
NCAS-Climate scientists have contributed to the IPCC during 2007-2012 through carrying out and publishing their research, through provision of climate model simulations, through design of metadata describing climate model simulations and climate models, and by taking specific roles in the IPCC, as part of the preparation of the IPCC Fifth Assessment Report, which will be completed in 2013-2014. These contributions are nearly all to working group I of the IPCC, which deals with the physical science basis – although NCAS BADC also provides direct support to the IPCC Task Group on Scenarios for Climate and Impact Assessment (TGICA) which itself has a specific mandate to support all the working groups (including working group II on Impacts, Adaptation and Vulnerability and working group III on Mitigation of Climate Change). BADC engagement in support of IPCC is discussed in more detail in the "Big and Open Data" NCAS impact statement. The beneficiaries of these activities are the IPCC itself (which prepares the report), the governments of the member countries (which receive it), the scientific community (for whom the IPCC reports are an extremely useful resource), and indirectly all climate-sensitive aspects of human society and natural ecosystems which government policy worldwide might influence.
The Fifth Assessment Report, like the fourth before it, will be heavily influenced by the massive international model intercomparison projects organised by the World Climate Research Programme (WCRP). NCAS has put significant effort into supporting CMIP5 [2], both by contributing to the development and the running of important simulations, and by providing underpinning data services for UK and global scientists. Even when (if) the Fifth Assessment report is superseded by future reports, the impact of this work will remain high – CMIP5 and other data will remain germane for decades to come, and the ramifications of consequential policy decisions ought to impact on humanity for centuries. If the IPCC does decide to produce more assessment reports, the next one is likely to be published around the end of this decade. Insofar as scientific research contributes to a growing and enduring scientific understanding, that included in the Fifth Assessment Report will continue to have an impact beyond 2020. The impact of the Fifth Assessment Report and the size of the NCAS-Climate contribution to it cannot be measured until after the Report is published. We can, however, expect that the impact of the Report as a whole will be similar to that of the Fourth Assessment Report (2007), whose chapters have been cited thousands of times in the scientific literature, and which has been since its publication the main source of scientific information for the Conference of the Parties to the UN Framework Convention on Climate Change. The UNFCCC website notes the publication of the Fourth Assessment Report in its timeline of the international response to climate change, remarking that "climate science entered into popular consciousness".
NCAS-Climate staff had an impact on the Fourth Assessment Report too in various ways, especially

as authors of that Report and of papers cited by it. NCAS-Climate staff frequently make presentations to public audiences and particular interest groups on climate science, and in doing so they contribute to dissemination of IPCC assessments. For instance, an NCAS-Climate core staff member (Gregory) presented the assessment of projections of climate and sea level change at a high-profile "showcase" event of the Fourth Assessment Report arranged by the Royal Society in early 2007. The impact of the Fourth Assessment Report on climate science and international affairs has materialised since it was published in 2007, but the impact of NCAS-Climate on that Report occurred during its preparation, which took place before the evaluation period, and is therefore not included in this case study.

3. How the Centre contributed to the impact

- Three NCAS-Climate staff members (Sutton, Guilyardi and Gregory) and three NCAS-Climate PIs (Hegerl, Allen and Stephenson) are serving as Lead Authors of chapters of the Fifth Assessment Report. The Lead Authors were selected by the IPCC in 2010 on the basis of expertise and international standing. Their responsibility is to write the chapters.
- Two NCAS-Climate PIs (Palmer and Tett) are serving as Review Editors for chapters of the Assessment Report. Each chapter has three Review Editors, whose responsibility is to ensure that comments on drafts from experts and governments are properly addressed. The Review Editors were selected by the IPCC in 2010.
- One NCAS-Climate staff member (Gregory) is serving is a Lead Author of the Technical Summary and is on the writing team for the Summary for Policymakers (SPM). The SPM is a short document that sets out the most important and policy-relevant findings of the report. This document is the one which the governments will discuss and modify when they meet, with the Lead Authors in attendance, at an IPCC Working Group I Plenary in September 2013 to approve the Report.
- One NCAS-Climate PI (Hegerl) is serving on writing team of the Synthesis Report, which is a document that combines and relates the main findings of all three IPCC Working Groups (including WG II on impacts, adaptation and vulnerability, and WG III on mitigation). The Synthesis Report is the final part of the Assessment to be approved by governments.
- One NCAS-Climate core staff member (variously Lawrence and Juckes) has served on the IPCC Task Group on Scenarios for Climate and Impact Assessment since 2006.
- About 10 NCAS-Climate staff have been named as Contributing Authors to various chapters. Contributing Authors are people who have been asked by Lead Authors to contribute text, diagrams or other help in writing the chapter. We cannot be certain exactly how many staff will be named as Contributing Authors until the report is finished.
- About 80 papers with NCAS-Climate staff as authors are cited in the Report. We cannot be certain exactly how many papers are cited until the Report is finished. These papers have been submitted or published during the period 2007-2012. Earlier papers by NCAS-Climate authors are also cited. Many of the papers are based on analysis of data from the international Coupled Model Intercomparison Project Phase 5 (CMIP5) and its predecessor CMIP3.
- Through the SRSIMS collaboration with the Met Office, NCAS-climate staff (Gray, Osprey) contributed to the development of a version of the Met Office climate model HadGEM2-AO with greater resolution of the upper atmosphere. Historical and future simulations using this vertically extended model have been contributed to CMIP5.
- NCAS-Climate staff (Gray, Osprey) provided specifications for the inclusion of the solar cycle in ozone datasets recommended by CMIP5 for use in climate simulations by all models.
- Through the UKCA collaboration with the Met Office, NCAS-climate contributed to the development of atmospheric chemistry in the Earth system model HadGEM2-ES, whose results for historical, future and other simulations were contributed to CMIP5 by the Met Office.
- NCAS-Climate develops and maintains the FAMOUS low-resolution AOGCM as an element of NERC national capability in Earth system modelling. Results from standard experiments using this model have been contributed to an intercomparison of Earth system models of intermediate complexity, carried out in connection with the Assessment Report (Eby et al., 2012; www.clim-past-discuss.net/8/4121/2012). Such models can provide projections on longer timescales than the higher-resolution AOGCMs of CMIP5.
- An NCAS-Climate staff member (Gregory) is one of the original and main authors of the CF [3] metadata convention and a member of its governing committees. This convention is the standard for exchange, archiving and intercomparison of climate model data (and increasingly for forecast and observational data) and is used in CMIP3 and CMIP5. It has greatly facilitated the processing and analysis of the data, and thus the hundreds of papers from CMIP3 and

CMIP5 that are cited in the Report.

- The EU FP7 METAFOR project [4], led by an NCAS-Climate staff member (Guilyardi) and involving four other NCAS staff members, has provided a means to describe climate models and the data they produce in a standard way. The project was given the task of doing this for CMIP5 and the information collected about CMIP5 models and data [5] are an important resource for scientists carrying out analyses.
- One NCAS-Climate staff member (Gregory) and one NCAS-Climate PI (Hoskins) participated in the Joint IPCC-WCRP-IGBP workshop in 2009 on new science directions and activities relevant to the IPCC Fifth Assessment Report. This workshop sought to identify and stimulate relevant research activities.
- One NCAS-Climate PI (Hegerl) attended the scoping meeting in 2009 for the Report. This meeting decided the set of chapters and the contents to be covered by each.
- Two NCAS-Climate staff members (Guilyardi and Gregory) and one NCAS-Climate PI (Hegerl) were invited participants at the IPCC expert meeting in 2010 on Assessing and Combining Multi Model Climate Projections. This workshop informed the analyses of CMIP5 results.
- An NCAS-Climate staff member (Gregory) was a member of the scientific steering committee and an invited participant in the IPCC workshop in 2010 on sea level rise and ice sheet instabilities. This workshop stimulated research relevant to projections of sea level rise to be assessed in the Report.
- NCAS made five grants in 2010 to fund analysis projects of CMIP5 results. In 2012 NCAS jointly convened a workshop with the Met Office to bring together scientists working on these and other analysis projects of relevance to the Assessment.

The work of NCAS-Climate staff as IPCC lead authors is funded by the NCAS-Climate contract with travel expenses from DECC. This is part of the UK's contribution to the IPCC, which expects developed nations to support their scientific experts in participating in the IPCC process. The research and dissemination activities of NCAS-Climate staff are funded partly by the NCAS-Climate contract and partly by various research grants held by NCAS-Climate senior staff and PIs.

4. Evidence and sources to corroborate the impact

1. IPCC publications, reports of meetings, author and participant lists are available from www.ipcc.ch. However, the Fifth Assessment Report is in preparation and not currently publicly available. It must not be cited, quoted or distributed until it has been accepted by governments in 2013-2014.
2. CMIP5 is described at http://cmip-pcmdi.llnl.gov/cmip5.
3. The CF metadata convention is described at http://cf-pcmdi.llnl.gov.
4. Metadata collected by METAFOR can be viewed at http://q.cmip5.ceda.ac.uk.
5. CMIP5 data can be downloaded from http://esgf-index1.ceda.ac.uk/esgf-web-fe/ (as part of a global federation of data centres).

5. Contacts for further information

Prof. Rowan Sutton.
Prof. Bryan Lawrence.

Case study code and title

NCAS_5 WMO Scientific Assessment of Ozone Depletion

1. Summary of the impact (maximum 100 words)

The research team led by Professor Pyle has played a leading role in demonstrating that the ozone layer has been depleted following anthropogenic emissions. This research has been a key input into the ongoing assessment of the Montreal Protocol on Substances that Deplete the Ozone Layer through World Meteorological Organisation reports which have made the case to policy makers for strengthening the Protocol. The research has made a vital contribution to amendments to the protocol that have ensured a more rapid phase-out of a wider range of ozone depleting compounds and led to significant global health and climate benefits.

2. Nature of the impact

The Montreal Protocol on Substances that Deplete the Ozone Layer came into force in 1987, in response to the scientific evidence that human-induced depletion of the ozone layer was indeed occurring. The Protocol mandates that the control measures that it introduced must be regularly assessed "…on the basis of available scientific, environmental, technical, and economic information". In particular, it specifies a scientific assessment process by which panels of experts are required to prepare reports to guide policy makers in their decisions regarding the protocol. The World Meteorological Organisation has published seven Scientific Assessment of Ozone Depletion reports since 1987, the most recent of which is the 2010 report (published in spring 2011)[1, 2].

The main contribution from NCAS has been to use numerical models to understand the observed temporal and spatial behaviour of atmospheric ozone: to explain the different processes of polar and middle latitude ozone decline and to use this improved understanding to make projections of how the ozone layer will change in the future, in response to the Montreal Protocol and to changing greenhouse gas concentrations. The various assessments, informed by the NCAS research and that of the international community, have led to a strengthening of the regulations covering production and emission of ozone depleting substances.

The Montreal Protocol has had a major impact in avoiding ozone depletion, in avoiding climate change thanks to the phase out of those ozone-depleting substances which are also greenhouse gases, and in preventing UV-related health issues. A recent paper, using model calculations by the NCAS group, indicates that, by 2030, the Protocol will have prevented two million cases of skin cancer annually [3] Ensuring that the Protocols are adjusted and amended according to the latest scientific developments is essential to their continuing impact.

The reports, and in particular their summaries, have also been used internationally to monitor the success of the Montreal Protocol in protecting the ozone layer and climate, and to inform the wider public about the process.

3. How the Centre contributed to the impact

On the evidence of their ongoing research contributions the group led by Pyle was asked to contribute scientific evidence to all the WMO assessments. Professor Pyle has also acted as lead author on a number of the Assessments. In addition Dr Braesicke was a chapter co-author on the 2010 report.

On the basis of their expert knowledge and research contribution, the NCAS team has also been selected to contribute to the shaping of report summaries for policy makers that accompany the reports. Additionally, and on the basis of his significant research contribution in 2007, Professor Pyle became one of four international Co-Chairs of the Science Assessment Panel, who provide direct

advice to the Meetings of the Parties to the Montreal Protocol. By undertaking these roles, it has been possible to ensure that the group's research findings are effectively communicated to the policy makers. Dr Amanatidis (European Parliament) confirms the impact on public awareness, and the impact on policy and legislation in respect of environmental protection[4].

4. Evidence and sources to corroborate the impact

1. WMO (World Meteorological Organization), Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project–Report No. 52, 516 pp., Geneva, Switzerland, 2011. http://ozone.unep.org/Assessment_Panels/SAP/Scientific_Assessment_2010/index.shtml

2. Web pages:

   Newsweek Magazine: A Climate Cure's Dark Side by Sharon Begley
   http://www.thedailybeast.com/newsweek/2011/01/30/a-climate-cure-s-dark-side.html

   Special Issue of "The Conversation" (Australian online science magazine, further media links)

   http://theconversation.edu.au/saving-the-ozone-layer-saved-human-lives-9494

   SBS Australia: http://www.sbs.com.au/news/article/1693247/Ozone-layer-agreement-saved-human-lives

   Naked Scientist:
   http://www.thenakedscientists.com/HTML/content/interviews/interview/1569/

3. Dijk *et. al.* 2012, http://onlinelibrary.wiley.com/doi/10.1111/j.1751-1097.2012.01223.x/pdf

4. Amanatidis, letter of support (European Parliament)

5. Contacts for further information

Prof. John Pyle

Prof. Mat Evans

Case study code and title
NCAS_6 Climate data services: Big and Open Data

1. Summary of the impact (maximum 100 words)
NCAS has developed technology, leadership and data provision leading to major policy decisions at the local, regional and international scale, both through the IPCC process and direct usage of data by for example engineering consultancies. Contributions include: underpinning technology for operational forecasting in the Met Office, technology which exposed the UK climate impact projections to users throughout the country; technologies, operational deployment, and user support for global access to a globally distributed database of climate simulations; leadership for the IPCC Data Distribution Centre; and promoting the establishment of data journals – a new branch of the publishing industry.

2. Nature of the impact
Data needs to be organised, structured and documented to be usable but in itself does not create any impact. Data needs to be turned into information to create knowledge that informs decisions – be it commercial planning or national policy. NCAS BADC (British Atmospheric Data Centre) contributes science and technology which aims to improve all of the steps in this information pipeline, and this activity has led to demonstrable impact. The examples chosen here show how BADC activities have at each of these stages contributed to this impact:

1: Data organisation, structure and documentation delivering better science and prediction. We have worked in partnership with the Met Office to give the improved data structures needed for international regulation and for managing research datasets effectively (including the climate data at UEA which prior to this was the subject of much controversy) [1,2]. By enhancing the methodologies used to support the information flow, significant impacts have been seen in the delivery of Met Office operational information, which has major economic impact, and in the second case enhancing public confidence in important climate science activities.

2: Enabling global access to very big data sets with global policy implications: Support for CMIP5. Without NCAS BADC involvement in delivering petascale archive capability and technology, the global distributed database needed for the international IPCC Fifth Coupled Model Intercomparison Project (CMIP5), would not have been delivered [3]; the size of the datasets meant that the traditional single archive could not have sufficed [11]. Hence, much of the delivery of CMIP5, and the consequential global science which will appear in the IPCC Fifth Assessment Report, could not have occurred or would have been late without this support and innovation.

3: Providing the tools to manipulate and visualise big data: Delivering the User Interface for the UK Climate Projections (UKCP09) [5][6][7] The probabilistic climate projections made by the Met Office under contract to Defra [4] were at the time an innovative way of providing climate projections. No tools existed however to interrogate these datasets that were accessible to the desired end users (individuals, companies, local and national government). NCAS BADC developed [5], and now runs, a specialised toolkit (and front-end website) to enable users to interrogate the data for quantities of interest to their own geographical areas or business interests [13]. Over 7,500 registered users representing a wide range of economic sectors have used this (see Table 1) and use of the website has been an integral part of the UK Climate Change Risk Assessment process.

4: Making key scientific data underpinning policy advice available to the public. [8] [9] BADC has provided leadership on data delivery for the IPCC by running the lead IPCC Data Distribution Centre (DDC) under contract to DECC. The IPCC data centre is central to activities of the IPCC reporting on the impacts of climate change. There are three data centres worldwide that support this work, based at the BADC, the German Climate Research Centre (DKRZ) and at Columbia University. The BADC, via Dr Martin Juckes, leads the delivery of this coordinated activity, and the location of the lead data centre in the UK helps enhance the global influence of the UK in climate impacts and prediction. Data from the IPCC DDC has underpinned the workings of both Working Groups II and III of the IPCC – the impact of the IPCC itself is discussed elsewhere in the NCAS impacts documents.

5: The advent of data publication, a new publication industry. Data is a valuable resource, yet is often inaccessible to anyone other than the originator. Allowing new users in research, government and business to use and exploit datasets needs clarity and stability in data sources and clear visibility [15]. NCAS BADC has been working towards formal data publication – and recently provided leadership for NERC activities in this direction. Using a variety of funding sources, a range of projects culminated in 2012 with a new Wiley Journal: the Geoscience Data Journal [10]. By creating a route to formal publication for datasets, the impact of this work is not only on the science and scientists and other

users, but on the publication industry itself. Data journals are likely to proliferate, and the interest and active engagement of Wiley is evidence of its importance.

3. How the Centre contributed to the impact

1: Data organisation, structure and documentation delivering better science and prediction. The UK Met Office exchanges meteorological data with other international Met agencies on an operational basis to provide the most accurate and up-to-date weather forecasts for the UK – the economic and social impact of these forecasts is obvious. What is less well known is that some of the basic technology used in the forecast chain is based on use of application schema of the Geography Markup Language (GML). NCAS BADC has been collaborating with the Met Office on information systems since the advent of the NERC DataGrid project – and was instrumental in introducing the relevant technology to the Met Office [1,2]. The BADC role in this was to develop some of the fundamental principles of using GML in the met domain, which the Met Office have now taken further, and applied in many different activities. This work is currently impacting directly on the EU INSPIRE legislation and, via the WMO, changes to ICAO international regulations on the Meteorological Service for International Air Navigation (Amendment 76 to ICAO Annex 3) to be published in November 2013. Another recent Met Office - BADC collaboration extended to a joint project, funded by the Joint Information Systems Committee, to provide information systems and introduce working methodologies, for the Climate Research Unit (CRU) at the University of East Anglia. There the aim is to ensure that all the input data and program codes leading to the CRU datasets and publications is versioned and available: had this work been done before “ClimateGate”, many of the issues which played out in public related to unavailable datasets and codes could have been avoided. How the Copenhagen summit might then have transpired will never be known.

2: Enabling global access to very big data sets with global policy implications: NCAS BADC Support for CMIP5 [3]. CMIP5 is the international, coordinated modelling effort specifically aimed at providing evidence for the IPCC's 5th assessment (AR5). CMIP5 provides a framework for coordinated climate change experiments for AR5 and beyond and so has a direct bearing on the policy decisions which will flow from the AR5. BADC was a founding member of the Global Organisation for Earth Science Portals (GO-ESSP) – the international organisation that came together to provide the software and operational implementation of the Earth System Grid Federation. BADC staff have managed the vocabulary services which were integral to describing the data (via the Climate and Forecast Conventions for NetCDF) and had an integral role in establishing the fundamental technologies that allowed the construction of the federation [12] and are co-leaders of the data service package of the European Network for Earth System Simulation – which delivered the European coordination, and co-ordinated global user support for CMIP5. BADC provided the UK data node under contract from the Met Office. BADC is currently holding 90 TB of Met Office data and 620 TB of data replicated from other modelling groups (1/3 of the entire archive).

3: Providing the tools to manipulate and visualise big data: Delivering the User Interface for the UK Climate Projections (UKCP09). The UK Climate Projections (UKCP09) sets out to provide the best available climate advice for UK users. It is designed to help those needing to plan how they will adapt to a changing climate. This includes, for example, policy-makers and commerce. The data were generated in the years up to 2009 by Met Office application of the best prediction methods then available. It is focussed on the UK. BADC developed a complete customised public web interface [13, 14] for interrogating the UKCP09 probabilistic climate projections provided by the Met Office, including the development of specialised plotting code that was used both in the web site and all the published reports on UKCP09. This work was done under two contracts to Defra (one for development, and one for deployment). The dataset and the interface are a key means by which UK businesses can gain information on climate of relevance to their industry and geographic location. It has enabled NERC and the Met Office to translate basic climate research through in to economically valuable information that allows businesses to maintain competitive advantage. The users of this interface are many and widespread, but are illustrated by business sector below.

Table 1: Users of UKCP09, by sector (figures produced by the interface itself)

Sector	Users	Sector	Users
Agriculture and horticulture	320	Leisure, Tourism and Lifestyle	67
Biodiversity and nature conservation	614	Manufacturing and Industry	50
Buildings	501	Multi-sector	660
Defence and security	123	Non-sector specific	1535
Emergency planning and services	103	Planning incl. spatial and sustainable development	686
Energy	465	Retail	18
Financial services/insurers and investors	66	Services	173
Fisheries	45	Telecommunications	24
Flood management and coastal issues	1003	Transport	198
Forestry	96	Waste management	82
Health and healthcare	122	Water resources	789
Heritage	64		

4: Making key scientific data underpinning policy advice available to the public. The Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre (DDC) provides long-term access to climate data sets in support of the IPCC user community and the public more generally. The DDC also enables research and sharing of information across the three IPCC working groups. BADC has provided the technical leadership for coordinating the global IPCC data centres and gives user support.

5: The advent of data publication, a new publication industry. The bulk of the work leading to the successful development of a business model for what became the Geoscience Data Journal was carried out in two JISC funded projects, the first of which examined various methodologies for data publication, and the second of which – in partnership with the Royal Meteorological Society – evaluated business models for overlay journals. The work was continued as a NERC activity in partnership with the other research centres. The basic concept of data description papers which link to datasets in approved archives (such as the BADC) which resulted in the Wiley Geoscience Data Journal, was one thoroughly explored through this sequence of activities.

4. Evidence and sources to corroborate the impact

1. Tandy *et.al.* 2006. OGC Web Services and GML Modelling for Operational Meteorology.
2. Letter of support from Met Office.
3. Letter of support from Met Office.
4. Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. (2009), UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.
5. I*nfrastructure, Engineering and Climate Change Adaptation ensuring services in an uncertain future*, Royal Academy of Engineering, Feb 2011.
6. *A weather forecast we daren't ignore*, Editorial, The Observer.
7. *Preparing for climate change "will boost economy"*; BBC website, 8 February 2011.
8. Survey of IPCC DDC users:, 2009: http://goo.gl/RFf80.
9. Governance of the IPCC Data Distribution Centre (DDC).
10. Letter from Wiley.
11. Letter of Support from Principal Investigator of CMIP5.
12. P Kershaw, R Ananthakrishnan, L Cinquini, D Heimbigner, B Lawrence, 2011. A Modular Access Control Architecture for the Earth System Grid Federation. In: Arabnia, H., Gravvanis, G., Solo, A. (eds.) Proceedings of the International Conference on Grid Computing and Applications GCA'11. CSREA Press, pp. 3-9. ISBN 1601321813.
13. http://ukclimateprojections-ui.defra.gov.uk/
14. Letter of support from Met Office.
15. Science as an open enterprise: report of the Royal Society, June 2012: http://royalsociety.org/policy/projects/science-public-enterprise/report/

5. Contacts for further information

Prof. Bryan Lawrence.
Dr Martin Juckes.

Case study code and title

NCAS_7 A forecasting system for severe turbulence hazards at airports

1. Summary of the impact (maximum 100 words)

A forecasting system predicting severe air turbulence in the lee of mountains has been developed by NCAS working initially with the Ministry of Defence and then with the Met Office. This has resulted in the Met Office implementing an operational system which is used daily in the UK and Falkland Islands to provide wind hazard warnings for military and civil airports and for transport infrastructure more generally. One specific application in the Falkland Islands has enabled typically five unnecessary diversionary flights per year to be avoided, at an estimated annual saving in excess of £1.25m.

2. Nature of the impact

A particular type of atmospheric turbulence, often called “rotor streaming” by forecasters and associated with atmospheric lee waves is particularly problematic at certain airports and for other transport infrastructure such as high-sided vehicles on motorways. It is prevalent in the lee of hills of modest altitude, especially where the prevailing wind is frequently stably stratified. There are notable examples in the UK and in addition, a particularly severe occurrence in the Falkland Islands. The modern military garrison at Mount Pleasant Airport (MPA) was established after the Falklands conflict in 1982. MPA is often afflicted by severe rotor streaming, which prevents incoming aircraft from landing. Aircraft from the UK perform transit flights to MPA via Ascension Island, over 7 hours flying time away. The consequences of being unable to land at MPA are a diversion to another airport at least 3 hours away, followed by a crew rest period of over 12 hours, during which passengers must be accommodated. The cost of a diversion is therefore large. If diversion is likely to be required, it is preferable for aircraft to remain at Ascension until conditions improve. Anticipation of a diversion requirement therefore requires an accurate forecast of turbulence at least 12 hours in advance. The Ministry of Defence (MoD) had a strong incentive to commission the development of such a forecasting system.

Starting in 1999, the Ministry of Defence contracted with the NCAS-Weather group at the University of Leeds, headed by Professor Stephen Mobbs, to carry out the fundamental research and develop a forecasting system for turbulence at airports. This involved a series of field experiments in the Falkland Islands, UK and Switzerland and in parallel, the development of a new numerical model 3DVOM (3D Velocities Over Mountains). Close integration of the field measurements and the model development provided a model which was comprehensively validated against observations. By 2003 the forecasting system was ready for operational trials and the MoD jointly contracted with NCAS and the Met Office to ensure that the research could be translated into the service which they required. 3DVOM was implemented in the Met Office operational forecast suite in 2006. In 2007 the 3DVOM suite was extended to include two further domains: Northern Ireland and eastern Ireland.

The 3DVOM model now operationally provides forecasters with predictions of vertical wind speed; these are used to produce routine warnings of hazardous conditions for both Defence and Civil Aviation across the UK. Although the initial operational implementation consisted of a Falkland Islands domain, the success of the approach has led to its implementation for four further model domains within the UK: south-west England (Dartmoor and Bodmin moor), north Wales (Snowdonia), northern England (the Pennines and the Lake District) and eastern Scotland (the Grampians) [1]. In 2007 the suite was further extended to two domains in Ireland: Northern Ireland and eastern Ireland [2]. From 2006 forecasts for all these regions were produced once per day and in 2010 3DVOM operational suite was upgraded further so that the forecasts were run 4 times per day, thus giving forecasters with refreshed model predictions every 6 hours. The model low-level winds, in combination with other forecast products, are also used to assess the risk of overturning

for high sided vehicles on exposed routes (e.g. the A1 trunk road to the east of the Pennines).

In the Falkland Islands, the 3DVOM forecasting system has contributed to many avoided diversions –typically five per year (at a cost avoided exceeding £1.25 Million per year). Although the Met Office assesses the impact of its warning systems as a whole, it does not (and probably could not) break down the economic impact at the level of individual forecasting models. However, the fact that 3DVOM is run four times per day for multiple domains, each for multiple applications (see letter from the Met Office, dated 1 February 2013 [3]), demonstrates the range and breadth of its application.

In principle, the turbulence predicted by 3DVOM could be predicted directly within a full operational weather forecasting model such as that used by the Met Office. However, extensive research has shown that this is only possible at model resolutions considerably better than even the today's highest resolution regional forecasting models (computing power and the state of model development does not permit horizontal resolutions better than about 1 km). 3DVOM has therefore enabled a step change in forecasting capability over a period of at least 15 years before direct computation is possible. Eventually 3DVOM will be replaced by direct methods but this is a minimum of 5-7 years away (this is known because the research models to replace 3DVOM do not yet exist). In the meantime the range of applications of 3DVOM is still being expanded by the Met Office (for example to provide a service to balloonists [3]).

3. How the Centre contributed to the impact

In 1999 the Ministry of Defence contacted the NCAS group led by Professor Stephen Mobbs requesting help with development of an improved forecasting system for turbulence at airports. The most immediate concern was the rotor streaming problems at Mount Pleasant Airport (MPA) described above. Up to that time the MoD had relied upon Met Office forecasts, usually locally generated by the duty forecaster, which were produced on the basis of simple empirical rules. These had proved insufficiently reliable. The MoD approached NCAS because of a track record in lee wave modelling based in experiments in the UK [4,5]. This previous work was mostly NERC-funded. Development of a validated modelling system for the Falkland Islands required extensive monitoring over most of the island of East Falkland for over a year. Development and testing of the autonomous systems was begun and tested in Scotland [6] and deployed in the Falkland Islands in 2000-01 [7]. There then followed several years of development of the computer prediction model (3DVOM) [e.g. 8,9], during which the MoD funded three more phases of the project. Increasingly during this time the Met Office were drawn into the project, so that by 2003 a key member of the team, Simon Vosper, was able to transfer to the Met Office to continue the operational implementation there. By this stage it was becoming clear that the modelling system had considerable potential for application at military airfields in the UK, civil airports and infrastructure more generally. As part of this wider development a further 18 month experiment was carried out over the Pennines of northern England (addressing in particular issues at the chain of MoD airfields in North Yorkshire and the wind hazards on the A1 trunk road) [10]. Further work to check the capabilities of the modelling system applied to steeper mountains involved an experiment in Switzerland in 2003 [11]. This ongoing work has led in 2006 to extension of the operational 3DVOM implementation to four UK domains [1] (south-west England (Dartmoor and Bodmin moor), north Wales (Snowdonia), northern England (the Pennines and the Lake District) and eastern Scotland (the Grampians)) and in 2007 to the further extension to two domains in Ireland: Northern Ireland and eastern Ireland [2]. Development and evaluation of the 3DVOM system is still continuing [12].

The successful development and implementation of the 3DVOM model required a sustained research and development effort, initially with NCAS working closely with the MoD and latterly directly with the Met Office operational implementation. The work combined detailed ground-based and aircraft observations of the airflow, tightly coupled with a programme of numerical prediction model development. Eight major field experiments were carried out in England, Scotland,

Switzerland and the Falkland Islands. Key aspects of the research and development were:

- Refinement of sensitive barographs able to measure the effect of the lee waves on the drag force on hills. These instruments were deployed in the Falklands and UK and used to diagnose the physical processes that were the cause of the severe turbulence at MPA.
- Development of the theory of flow over hills based on the Falklands and UK experiments.
- Translation of the improved theory into a new numerical prediction model.
- Increasing coordination of the research with the Met Office as the project developed, so that the Met Office were able to take over as the providers of a new service using the new technology.

4. Evidence and sources to corroborate the impact

1. Paper to the Met Office Working Group for the Operational Suite (WGOS): Proposed implementation of the 3dVOM lee-wave forecasting system, 2006.
2. Paper to the Met Office Working Group for the Operational Suite (WGOS): Implementation of two additional 3dVOM domains, 2007.
3. Letter dated 1 February 2013 detailing the Met Office usage of 3DVOM.
4. Vosper, S.B. and Mobbs, S.D., 1996. Lee waves over the English Lake District. Q. J. R. Meteorol. Soc., 122, 1283-1305.
5. Vosper, S.B. And Mobbs, S.D., 1997. Measurement of the pressure field on a mountain. Q. J. R. Meteorol. Soc., 123, 129-144.
6. Vosper, S.B., Mobbs, S.D. and Gardiner B.A., 2002. Measurements of the near surface flow over a hill. Q. J. R. Meteorol. Soc., 128, 2257-2280.
7. Mobbs, S.D., Vosper, S.B., Sheridan, P.F., Cardoso, R., Burton, R.R., Arnold, S.J., Hill, M.K., Horlacher, V. and Gadian, A., 2005. Observations of downslope winds and rotors in the Falkland Islands. Q. J. R. Meteorol. Soc., 131, 329-351.
8. Vosper, S.B. 2003. Development and testing of a high resolution mountain-wave forecasting system. Meteorol. Appl. 10, 75-86.
9. Vosper S.B., Worthington R.M., 2002. VHF radar measurements and model simulations of mountain waves over Wales. Q. J. R. Meteorol. Soc. 128, 185–204.
10. Sheridan, P.F., Horlacher, V., Rooney, G.G., Hignett, P., Mobbs, S.D. and Vosper, S.B., 2007. Influence of lee waves on the near surface flow downwind of the Pennines. Q. J. R. Meteorol. Soc., 133, 1353-1369.
11. Lewis, H.W., Mobbs, S.D. and Lehning, M., 2008. Observations of cross-ridge flows across steep terrain. Q. J. R. Meteorol. Soc., 134, 801-816.
12. Vosper, S.B., Wells, H., Sinclair, J.A. and Sheridan, P.F. 2012: A climatology of lee waves over the UK derived from model forecasts. Meteorol. Appl., DOI: 10.1002/met.1311.

5. Contacts for further information

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Dr. Ralph Burton

Case study code and title

NCAS_8 Impacts on the Insurance Industry

1. Summary of the impact (maximum 100 words)

NCAS has led research that has worked to disseminate and translate climate model output into products and indicators that allow the insurance industry to robustly quantify the risks related to weather, climate variability and climate change. The work involves provision of expert advice on the hazards that affect different sectors and regions, and has focussed especially on the development of new methodologies for transforming climate model output into a form suitable for use with "catastrophe models", which are central decision making tools for the industry.

2. Nature of the impact

The prime beneficiaries are Willis (particularly its reinsurance division, Willis Re). Willis is a leading insurance and re-insurance broker, with its HQ in London. The NCAS relationship developed through the Willis Research Network (WRN), a global initiative set up by Willis in 2006 to integrate science and insurance.

Risk is globally interconnected; partly due to teleconnections in the climate system and partly due to the globalised nature of the marketplace. Business supply chains are increasingly vulnerable to events all over the world. The insurance industry relies heavily on recent past experience to assess weather and climate related risks. This approach is outdated as it ignores decadal climate variability and anthropogenic climate change, and it is increasingly recognised that this needs to be addressed. Climate science has progressed and the dissemination of this knowledge to the insurance industry was the main goal of the WRN.

The development of new approaches to quantifying weather and climate related risks involves using advances in climate science and numerical climate modelling. Working with the Met Office, NCAS has developed new high-resolution Global Climate Models (GCM). Simulations from these models, as well as observation-based re-analyses provided new information to improve the assessment of weather and climate related risks. This information is then used by the re-insurance industry.

The initial focus has been on tropical cyclones. The model simulations and re-analyses are analysed to provide "synthetic" observations that complement and extend the historical record, enabling understanding of the impact of climate variability and change on tropical cyclone risk, and thereby enabling Willis to improve their approaches to risk assessment: "*You and your team have given Willis access to data and expertise that is helping us transform our offering in terms of tropical cyclone modelling*" [2], Head of Proprietary Modelling, Willis Global Analytics.

The NCAS relationship with Willis is a strategic partnership, including a Knowledge Transfer Partnership (KTP) [1]. The initial impacts on Willis occurred largely through the provision of knowledge and expertise. NCAS supports Willis with the development of the "Tropical Cyclone Laboratory" (TC Lab), a decision-making tool for brokers that combines observational and model data to identify robust evidence of evolving weather and climate risk.

The TC Lab allows WRN scientists combine global climate modelling with catastrophe modelling (including the origin and propagation of uncertainties), by providing an idealised catastrophe model workflow. "*Your input in the Willis Tropical Cyclone Laboratory has been invaluable, and helped prove the concept that such platform can help Willis develop model adjustments for vendor models; build models where none exist, and get a better understanding of TC risk on a global, consistent basis.*" [2]. A further benefit of the KTP fellow's presence in Willis offices has been the ability to provide a scientific contribution to client reports in a fast-response reactive environment.

NCAS has also helped shape the development of the Willis Research Network. The NCAS-Willis KTP project has "*been a template for the increased governance of all Willis Research Network projects*." [2]. More broadly, Prof. Vidale has established the "Weather and Climate Hazards Laboratory" (WCHL) at the University of Reading as a key pillar in the Willis Climate Risk Hub. In a recent speech, the Science Minister David Willetts endorsed these collaborative partnerships, commenting that there was "*huge potential in combining high performance computing and analytics to improve existing models: the better the model, the better the business decision*" [4].

Objective evidence and quantification of the impacts was included in a report that NERC commissioned from DTZ [3]. A number of interviews were carried out with Willis executives in 2009 and they described

the importance of our collaborative work as:

Impact	Value
Willingness to pay (as demonstrated by Willis Re)	£800,000 per annum
Improved assessment and pricing of risk for catastrophe insurance	£62-130 million per annum
Helping to safeguard the UK's competitive position as a centre for reinsurance	A proportion of £7.2 billion per annum

3. How the Centre contributed to the impact

The key NCAS activities that have been essential to the impact on the insurance industry are:

1. **Our leading role in the development of high resolution global climate models capable of simulating high impact events** such as tropical cyclones *and* – crucially – the global drivers of variability and change in these events. This work was made possible by our strategic partnership with the Met Office on high resolution modelling beginning with the HiGEM project, continuing UK-Japan Climate Collaboration (2005-09) and up to the present under the NERC-Met Office Joint Weather and Climate Research Programme High Resolution Climate Modelling (HRCM) programme (in which the UPSCALE project, mentioned in part 2, is a key part.)

2. **Our fundamental research activities on high impact weather and climate events** (e.g. **Vidale 1** and **Vidale 3**). This research has provided new insights into the drivers of variability and change in high impact events, including the nature of global teleconnections. It has enabled improved interpretation of the very sparse observational record for tropical cyclones.

3. **Targeted research and analysis to address insurance industry questions and provide information in a form that can be used by the industry for risk assessment.** Throughout 2007-2012 we have processed climate model and re-analysis data in order to "feature track" Tropical Cyclones (using a methodology developed by NCEO). This involved processing many hundreds of years of model data; for comparison, the typical observation-based database used in industry only comprises 50 years worth of data. Our synthetic tracks were then re-formatted to the common format used at Willis (e.g. the format of the IBTRACKS observational database). We analysed all these outputs alongside the traditional datasets, whenever possible, for evidence of unknown relationships, e.g. correlated TC risk under different phases of interannual or decadal variability. We also studied large-scale factors that modulate TC location and variability in each basin; the latter are not available in observational data sets. Many of the questions driving our regional analyses were raised at regular meetings with Willis clients that operate in those parts of the world, and by discussion with Willis brokers, who need to make operational decisions each year and want to acquire better supporting tools. As part of the knowledge exchange activities, our WRN Fellow summarised findings in each area in "Fact Sheets" that were distributed and discussed with brokers.

4. **The KTP project has provided a direct link between NCAS research and Willis needs.** A major focus of this project (details of which were provided in Section 2) has been our contribution to the development of the TC Lab, for example we have implemented a set of "climatological event filters", which allow the user to select targeted portions of a hazard dataset when computing Exceedence Probability Curves (EPCs), for a particular year and region. The TC Lab displays model-derived information (reports, maps, charts) on a computer screen in the same way that brokers are currently used to with observational information. Estimates of vulnerability can be combined with this information to produce return curves, as well as estimates of losses, in monetary terms.

As described in Section 2, the NCAS relationship with Willis is a long term strategic partnership which has been supported by Willis, NCAS, the University of Reading and the Technology Strategy Board. The expertise gained through the interaction with the WRN on tropical cyclones is currently being applied to extra-tropical windstorms. One of the difficulties in assessing the skill of models and validating their results is the lack of solid historical data. Solvency II requires insurers to justify that the models they use are fit for purpose. One of the best ways to do this is to examine historical windstorm events (and their footprint) and compare the modelled losses to actual losses recorded by the industry. A catalogue of observed extreme European windstorms is being jointly developed by NCAS, the University of Exeter and the Met Office. The catalogue will be freely available for use within the scientific and insurance communities. There is high interest in this extreme European windstorm catalogue, evidenced by the funding of the project partners by the WRN, and pledged funding from the Lighthill Risk Network (a research network whose core industry members are AON, Catlin, Guy Carpenter and Lloyd's).

4. Evidence and sources to corroborate the impact

1. Letter from the TSB supporting the NCAS-Willis KTP.

2. Letter from Head of Proprietary Modelling, Willis Global Analytics.

3. NERC commissioned report by DTZ “High Resolution Climate Modelling and the Reinsurance Industry”

4. Speech by David Willetts on “Science and the City” at Willis on 7 March 2012 highlighted the importance of the Willis collaboration with NCAS activities, and in particular the “huge potential in combining high performance computing and analytics to improve existing models: the better the model, the better the business decision”. – Transcript available http://news.bis.gov.uk/content/Detail.aspx?ReleaseID=423640&NewsAreaID=2

5. Contacts for further information

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Prof. P.L. Vidale

Case study code and title

NCAS_9 Air Quality in Extreme Events (Public Health)

1. Summary of the impact (maximum 100 words)

Summertime air pollution episodes continue to cause major health impacts despite decades of public investment in technologies such as catalytic converters; summer 2003 led to thousands of additional deaths in Europe attributable to ozone and particulates. NCAS demonstrated that trees in the UK emitted unexpectedly large amounts of isoprene during the hottest periods, catalysing the formation of additional smog. The research stimulated public debate on the impacts of a warmer climate, contributed to several Government reports and resulted in a change in Defra reporting of biogenic emissions, embedding the knowledge into all future Government policy evaluations of air pollution.

2. Nature of the impact

In the UK air pollutants reduce lifespan on average by 8-14 months, and by up to 9 years for the most vulnerable groupings, inducing respiratory and pulmonary diseases that affect disproportionately the elderly and children, with health costs estimated to be comparable to that of alcohol misuse. The connection between heatwaves and air pollution and their impacts on the population reached wide attention during summer 2003, a period that lead to several thousand additional deaths throughout Europe attributable to the ozone and fine particulates (e.g. Stedman *et. al*. Atmos. Env. 2004). Although far from unique in terms of occurrence, the event catalysed public debate on the effects of air pollution, the possible impacts of a warmer climate and the effectiveness of past and future Government policy for pollution control.

A key finding from the research of Lewis and others at NCAS (Composition Directorate) was that biogenic volatile organic compounds were released in substantial quantities from vegetation in the UK on the hottest days in summer. The key chemical observations of biogenic species and ozone were made by researchers from NCAS Composition. The emissions of biogenic VOCs are very important in atmospheric chemistry since they rapidly promote the formation of photochemical ozone. The presence of natural isoprene during heatwaves was shown by Lee et al. to have offset some of the benefits that had accrued from policies to reduce man-made VOCs from sources such as combustion and solvent usage. Using the unique NCAS Composition measurements of VOCs, and supporting data, NCAS scientists calculated the impacts of biogenics on air quality. The reporting of this finding was widely debated in the media at the time[1], and was used as one of the first clear examples of how climate change, which is likely to result in more summers like 2003, may produce unexpected impacts on the UK.

The research data collected by NCAS Composition was sought by the evidence team at the Department for Environment Food and Rural Affairs (Defra), the Government department responsible for ensuring UK compliance with European legislation, and specifically the air quality Directive 2008/50/EC. Over the next few years Defra met regularly with Lewis and Lee, and research and modelling was adapted to inform policy, resulting in peer reviewed publications. These and other academic publications were part of the evidence base used by Defra to guide the terms of reference and recommendations of two substantial Government reports in to future air quality. These outputs from Government, which include numerous policy recommendations and practice changes, have taken the original research and, during this assessment period, delivered policy and societal impact.

The first Defra expert report on the impacts of climate change on air pollution was published in 2008[2] and the second reporting on ozone in the UK in 2009[2]. Both made substantial references to the original underpinning research, highlighting the impacts that new understanding of natural emissions may have on national air quality, and how climate change may exacerbate this process. Both Government reports made extensive reference to the need to improve the representation of biogenic species in UK emissions models, in light of the NCAS research[4]. This recommendation was taken forward by other air quality practitioners and private sector organisations who simulated impacts of UK air quality under a range of scenarios, and independently estimated the impacts of

natural emissions on ozone formation. Whilst no statutory requirement exists for the inclusion of biogenic VOCs in Government inventories, updates to the reporting of isoprene within National Inventories were made, embedding the original research finding in future policy scenario modelling and policy formulations.

The benefit to Government has been clear scientific evidence for the causes of continuing peak summertime ozone pollution, and an enhanced appreciation of the limitations of EU control policies in high temperatures periods. The inclusion of biogenic species in a representative manner in predictive models now provides the UK Government with an improved capability to forecast air quality in the short term, and provide better advice to citizens (for example through Met Office air quality forecasts given to the public)[5]. It has also improved evaluations of how the UK atmosphere may respond in the future to changes in emissions, both natural and as a result of policy change. Since controlling man-made emissions is a costly activity, the benefits of improved prediction are felt in both health and financial domains. A wider appreciation of UK summertime isoprene emissions is now also apparent in urban planning policies relating for example to urban tree planting.

3. How the Centre contributed to the impact

NCAS delivers unique capabilities to measure and model air quality processes in the UK, and in particular assesses how individual chemical sources may impact on air pollution in the future.

A key interdisciplinary goal of NCAS is to understand how short-term atmospheric impacts, such as photochemical pollution episodes, may change in the future as a result of Government and EU policy and climate change, and to identify cost-effective measures to improve public health impacts.

NCAS invests around £1.5M in national capability for air quality research including state of the art observations, modelling and laboratory studies of fundamental processes. This is supplemented by NERC responsive funding. The impact reported here arises from a combination of national capability and thematic programme support.

The research from NCAS was used by Defra as a key part of the evidence guiding two Government reports. Through these reports, incorporating policy recommendations and practice changes, the impacts of the research have primarily been realised.

4. Evidence and sources to corroborate the impact

References to public debate (not exhaustive) prior to Government reports

1. News stories:
    a. The Observer front-page story ‘Summer heat to spark killer fog of ozone’.
    b. The Daily Telegraph. ‘Heatwave Britain – when trees turn toxic’.
    c. BBC 1 TV News (1pm, 10pm). ‘Summer ozone’
    d. BBC Radio 4, ‘Costing the Earth’
    e. The Guardian, ‘Do trees pollute the atmosphere?’
    f. Relevance of the research to future policy independently highlighted at BAAS, Cheltenham Science festival, and Climate Change Management articles.
2. Government reports and meetings referencing research (within impact period):
    a. Defra, - ‘Air Quality and Climate Change – A UK perspective’, ISBN 0-85521-172-5, 2008. See for example Section 3 in executive summary, or chapter 4 on VOCs. http://archive.defra.gov.uk/environment/quality/air/airquality/publications/airqual-climatechange/documents/fullreport.pdf
    b. Defra, - Air Quality and Climate Change policymakers summary’, see page 18-20, Air Quality and Climate Change’, 2008, http://archive.defra.gov.uk/environment/quality/air/airquality/publications/airqual-

climatechange/documents/summary.pdf

3. Defra reports and meetings:

   a. Defra, - Expert meeting to consider biogenic emissions and air quality, 2009, see http://uk-air.defra.gov.uk/reports/cat11/0903231041_Ozone_in_the_United_Kingdom_-_Agenda.pdf , and then subsequent links to presentations including from National Atmospheric Emissions Inventory on updating biogenic inventory.

   b. Defra, - 'Ozone in the United Kingdom'. Published 2009. ISBN 978-0-85521-184-4. See for example Defra recommendations relating to reporting of biogenic VOCs in Annex 1 and Annex 2. http://archive.defra.gov.uk/environment/quality/air/airquality/publications/ozone/documents/aqeg-ozone-report.pdf

4. Policy recommendation specifically associated with biogenic VOCs with reference to this research, also in Executive Summary: (http://archive.defra.gov.uk/environment/quality/air/airquality/publications/airqual-climatechange/documents/contents-execsumm.pdf)

5. Policy and wider air pollution impacts, House of Commons environmental audit committee report: www.publications.parliament.uk/pa/cm200910/cmselect/cmenvaud/229/22906.htm#a11

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