Institution:

University of Leeds

Unit of Assessment:

7, Earth Systems and Environmental Sciences

Title of case study:

Case study 9: Predicting turbulence – improved weather forecasts and £1.25 million annual savings for MoD

1. Summary of the impact (indicative maximum 100 words)

Research carried out at the University of Leeds has led to the development of a system for predicting severe air turbulence at airports and elsewhere. The research modelled highly localised 'rotor streaming' turbulence which is too small-scale to predict using today's numerical weather prediction models. The Met Office now uses the highly efficient 3DVOM computer prediction model, based on the Leeds research, to improve its operational weather forecasting, especially for providing warnings of 'gustiness' to the public and airports and to highlight risks of overturning of high-sided vehicles. In addition, the model is used by forecasters to predict dangerous turbulence at Mount Pleasant Airport in the Falkland Islands, and has led to the prevention of around five flight diversions per year at an estimated cost saving of £1.25 million.

2. Underpinning research (indicative maximum 500 words)

Certain airports, especially those located in the lee of a hill or mountain, are prone to a particular type of atmospheric turbulence often called 'rotor streaming' by meteorologists. Strong winds passing over and around a hill generate pockets of highly turbulent 'spinning' air, which are dangerous for aircraft. When atmospheric conditions for rotor streaming occur, flights may be diverted to a safer airport.

Although rotor streaming has been recorded many times since the 1950s, meteorologists have had limited success in predicting this phenomenon. Even the high-resolution weather models of the UK's Met Office, which run on supercomputers, have been unable to resolve the details of these turbulent eddies, which typically are very small (a few hundred metres) in scale.

In 1999 the Ministry of Defence (MoD) commissioned a Leeds team led by **Stephen Mobbs** to develop a new forecasting system for turbulence at the new Mount Pleasant Airport (MPA), Falkland Islands, which suffered from problems of expensive flight diversions. The work was funded on the basis of **Mobbs**' expertise on airflows over mountains (e.g. **[1]**). Following a successful first phase, the MoD continued to support the development of the forecasting model in three additional phases over a period of about four years (1999-2004), and the research was further supported by funding from the Natural Environment Research Council (NERC) between 2002 and 2007.

Mobbs and colleagues from Leeds spent two years taking atmospheric measurements in the Falkland Islands and in Scotland **[2,3]**. Some of this work required the team to modify the design of sensitive barographs so they could measure the effect of lee waves on the drag force on hills. These instruments were deployed in the Falklands and in the UK; readings from these instruments helped the researchers to understand the parameters and dynamics of rotor streaming and diagnose the physical processes that were the cause of the severe turbulence at MPA.

Such detailed ground-based and aircraft observations generated a detailed understanding of this localised turbulence which allowed the researchers to develop a computer prediction model, later called 3D Velocities Over Mountains (3DVOM) **[5]**. Analysis of this data over several years also led to new and more detailed understanding of turbulent airflow over hills **[4]**.

Model refinement, testing and validation

As part of the wider development of the predictive model, **Mobbs** and his colleagues carried out an 18-month experiment in collaboration with the Met Office. The study focused on the Pennines in northern England to address turbulence encountered by flights to and from the chain of MoD

airfields in North Yorkshire, as well as wind hazards on the A1 trunk road **[5]**. Both the Leeds research group and the Met Office team contributed equally to the collection of field data and modelling using 3DVOM. The team also studied capabilities of the 3DVOM system to forecast turbulence in steeper mountains, carrying out experiments in Switzerland in 2003 **[6]**. This work demonstrated that techniques developed for the Falkland Islands could be effectively adapted to similar turbulence situations elsewhere.

By 2007, 3DVOM had been integrated into the Met Office's suite of forecasting models; the Met Office was able to improve its turbulence forecasting to airports using the new technology (see Section 4).

Key researcher:

Stephen Mobbs, Professor of Atmospheric Dynamics (1995-present) in the School of Earth and Environment, University of Leeds.

3. References to the research (indicative maximum of six references)

1. Vosper, S.B., Castro, I.P., Snyder, W.H., and **Mobbs**, S.D. (1999) Experimental studies of strongly stratified flow past three-dimensional orography, *Journal of Fluid Mechanics*, 390, pp. 223-249
2. Burton, R.R., Vosper, S.B. and **Mobbs**, S.D. (2006) Underlying structures in orographic flow: An analysis of measurements made on the Isle of Arran, *Quarterly Journal of the Royal Meteorological Society,* **132**, 457-1466. DOI: 10.1256/qj.05.192.
3. **Mobbs**, S.D., Vosper, S.B., Sheridan, P.F., Cardoso, R., Burton, R.R. and Arnold, S.J. (2005) Observations of downslope winds and rotors in the Falkland Islands, *Quarterly Journal of the Royal Meteorological Society,* **131**, 329-351. DOI: 10.1256/qj.04.51.
4. Ross, A.N., Arnold, S., Vosper, S.B., **Mobbs**, S.D., Dixon, N. and Robins, A.G. (2004) A comparison of wind-tunnel experiments and numerical simulations of neutral and stratified flow over a hill, *Boundary-Layer Meteorology*, **113**, 427-459. DOI: 10.1007/s10546-004-0490-z.
5. 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, *Quarterly Journal of the Royal Meteorological Society*, **133**, 1353-1369. DOI: 10.1002/qj.110.
6. Lewis, H.W., **Mobbs**, S.D. and Lehning, M. (2008) Observations of cross-ridge flows across steep terrain, *Quarterly Journal of the Royal Meteorological Society*, **134**, 801-816. DOI: 10.1002/qj.259.

Key funding and grants

The research outputs listed above were funded from a variety of sources, including the following key grants (NERC grants are awarded on the basis of rigorous peer review):

- Natural Environment Research Council (NERC): £77,355 for "Flow over complex terrain using adaptive numerical methods" (1997-2000).
- Royal Society: £9916 for "Measurement of Orographic Drag" (1997-1998).
- NERC: £162,831 for "Stable boundary layer flow over hills" (1998-2002).
- NERC: £9,016 for "A microbarograph array for detection of travelling internal gravity waves" (1997-2000).
- Ministry of Defence: £325,082 for "Rotor forecasting at MPA" (1999-2000).
- Ministry of Defence: £78,985 for "Rotor forecasting at MPA" (2001-2002).
- Ministry of Defence: £48,000 for "Development of a rotor forecasting system" (2003-2004).
- Ministry of Defence (via Met Office): £48,950 for "Rotor forecasting at MPA" (2001-2002).
- NERC: £133,693 for "Unsteady flow over complex terrain" (2002-2005).
- NERC: £203,610 for "Observations and Modelling of Rotors" (2003-2007).

All grants were awarded to **Mobbs** as Principal Investigator. The MoD does not provide

evaluations of its commissioned research; however, the repeated funding is indicative of the quality of the Leeds research and its application to the MoD's requirements.

4. Details of the impact (indicative maximum 750 words)

Improved weather forecasts – protecting people

The 3DVOM predictive computer model is now fully integrated into the operational forecasting of the Met Office in the UK, aided by the transfer of Dr Simon Vosper (Research Fellow, 1995-2001) from **Mobbs'** Leeds research group to the Met Office in 2004-05. It provides meteorologists with predictions of vertical wind speed, which they can integrate into their forecasts.

The 3DVOM software was initially deployed in 2005 for forecasting hazardous turbulence in the Falkland Islands, especially around MPA. However, following additional studies and testing by the Leeds group, the Met Office extended its operational use of 3DVOM to four UK meteorological domains: south-west England (Dartmoor and Bodmin moor), north Wales (Snowdonia), northern England (the Pennines and the Lake District) and eastern Scotland (the Grampians) **[A1,A2]**. In 2007 the domains of Northern Ireland and eastern Ireland were added. Since this application of 3DVOM to the UK, duty forecasters have been able to use the model's output to produce warnings of hazardous turbulence for both the MoD and civil aviation authorities across the country, allowing them to adjust flight plans accordingly **[B]**.

Since 2010 the 3DVOM system has been run four times per day serving 5 UK areas, Eire and the Falklands, giving forecasters refreshed model predictions every six hours. Direct users include all the Aviation and Defence forecasters within the Met Office Head Quarters (Exeter), all the outstations (e.g. Falkland Island) and within the Defence sites (*c*.5). 3DVOM predictions for low-level winds, combined with outputs from other forecasting models, are also used by forecasters to assess the risk of overturning for high-sided vehicles on exposed routes, such as the A1 trunk road to the east of the Pennines. Forecasts of 'gusts' in public weather forecasts and warnings issued by the Met Office are based on 3DVOM output **[B]**.

Commercial benefits – reducing costly diversions from Mount Pleasant Airport

MPA was constructed in the Falkland Islands in the 1980s following the conflict there to service the military garrison. It is often afflicted by severe turbulence, which prevents incoming aircraft from landing. Aircraft from the UK fly to MPA via Ascension Island, over seven hours flying time away. If flights to MPA are unable to land they are diverted to distant airports in South America, at least three hours away. Here the crew must rest for more than 12 hours and the passengers must be accommodated during this time. Such diversions are costly: rough estimates suggest diversion costs for a flight are somewhere around £250,000, based on additional aviation fuel costs, airport charges and unscheduled overnight accommodation for 300 passengers **[C,D]**.

Clearly it is preferable for flights to remain at Ascension until weather conditions at MPA improve; ideally accurate weather and turbulence forecasts are required at least 12 hours in advance of take-off from the Ascension stopover. Since the implementation of 3DVOM for Falkland Islands forecasting by the Met Office in 2005, the system has helped to avoid approximately five diversions per year, with a cost saving to the MoD of around £1.25 million per year **[B,D]**.

The 3DVOM turbulence forecasts have also helped to protect military personnel at MPA, for example in a case described by the Principal Met Officer at MPA*: "I did have a case last year when a VVIP was on board the airbridge, and I advised all in this region that the vertical motion was of great concern as we were forecasting very strong cross winds and rotors during the usual airbridge arrival time. I briefed CBF [Chief of British Forces] along with many operators, and we managed to delay the aircraft until the wind backed westerly, to reduce any diversion risk"* **[B]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. Papers to the Met Office Working Group for the Operational Suite (WGOS): A1 *Proposed implementation of the 3DVOM lee-wave forecasting system*, 2006. A2 *Implementation of two additional 3dVOM domains*, 2007.

This report pre-dates the REF assessment, but is included to provide evidence that the program was integrated within the MET Office Operational Suite.

B. Letter from MET Office (dated 01/02/2013) detailing the Met Office usage of 3DVOM.

C. Letter from MET Office (dated 13/06/2013) regarding requests for clarification on savings estimates. Within this letter, the MET Office provides an extract from email correspondence between MET Office personnel and the Senior Operational Meteorologist at Met Office Falkland Islands dated 11 April 2013: "*I'm not sure if you're interested or not but the last few runs of the 3DVOM for the Falklands has produced some very strong signals. In all my time forecasting down here, I don't think I've ever seen a signal that was in essence "off the scale" in terms of strengths of up/down drafts. As a result of the output from the 3DVOM and a recent air bridge encounter with severe up/down drafts, nobody is willing to take chances and as such the airfield is essentially now closed to all aircraft until 0300Z tomorrow morning, when the wind becomes westerly and the risk has diminished.*"

D. Further corroboration can be obtained from the Head of Atmospheric Processes and Parameterizations, Met Office.