Meteorology and climate inspire secondary science students

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ABSTRACT As part of its National Science and Engineering Week activities in 2009 and 2010, the University of Reading organised two open days for 60 local key stage 4 pupils. The theme of both open days was '*How do we predict weather and climate?*' Making use of the students' familiarity with weather and climate, several concepts of relevance to secondary science were investigated. The open days also provided an opportunity for more than 30 research staff from the university to interact with the students. Feedback from students and teachers was extremely positive. This article shows how meteorological science can be used to illustrate elements of the secondary science and mathematics curricula.

Meteorological science has always struggled to find a suitable permanent home within the key stage 3 (KS3; ages 11–14 years) and KS4 (ages 14–16 years) National Curriculum for England and Wales (available on the QCDA website at curriculum.qcda.gov.uk). Currently, the curriculum for science at KS4 contains some elements of climate science (sections 2.4a and b), while most meteorology is dealt with in the geography curriculum. At KS3, weather and climate is dealt with in section 3f of the geography curriculum. At KS4, most of the syllabuses for geography GCSE qualifications emphasise the broad social, environmental and political context of weather and climate (see, for example, AQA, 2008) and not the scientific basis. Working in a university department specialising in weather and climate science, we feel that this distinction in the curriculum has a strong influence on students as they progress through the education system to study atmospheric science or meteorology at first degree or postgraduate level. Anecdotally, many students who would wish to study our undergraduate courses simply do not have the required science background, particularly in physics.

UK scientists, through both the university sector and public bodies such as the Met Office, have played and continue to play a major role in understanding and predicting our changing climate. In addition, environmental science has also made a substantial contribution to the UK economy over the past 20 years (NERC, 2006). Almost all of the meteorological and climate scientists currently working in the UK have a strong background in physics and/or mathematics. We feel that if we can inspire and enthuse secondary students about physics and mathematics by demonstrating their relevance to exciting and topical areas such as weather and climate, they are more likely to continue their studies in these areas.

The purpose of this article is to show that meteorological and climate science, despite its inherent complexity, lends itself very naturally as a tool to teach secondary level physics and mathematics. We see the inclusion of more elements of meteorology and climate science in the secondary science curriculum as being of mutual benefit to both the secondary and the higher education sectors. For the secondary sector, climate science provides a high-profile example of ways in which science and mathematics are useful in the real world. For the higher education sector, encouraging more school students to be enthusiastic about physics, in particular, might encourage them to choose to study physics at A-level and then physics-based subjects at university. This is particularly important given the recent decline in the numbers of students taking physics at A-level (Research Councils UK, 2008; Times Higher Education, 2008). The activities described below have been designed to highlight the idea that a combination of observations and predictive equations, based on our understanding of how the atmosphere behaves, are necessary to produce weather and climate forecasts.

Aims and objectives of the open days

With the above motivation in mind, a number of open days have been held at the University of Reading. These had three broad objectives:

1. to engage local schoolchildren in physics and mathematics and the university experience in general;
2. to develop novel activities and materials useful for secondary science and mathematics education;
3. to provide an opportunity for school outreach for many academic and research staff in our department and to encourage them to participate in future outreach events.

Activities provided and learning outcomes

In order to meet the objectives outlined above, the open days were organised around three main hands-on science activities for students to participate in during the day. The broader context of the activities was explained to students both at the beginning and the end of the day. On the day, the students were split into four equal groups. Two groups jointly participated in a radiosonde launch followed by a measurement-taking activity at the atmospheric observatory; this combined activity took 1 hour to complete. While this activity was going on, the other two groups took part in additional experiments. One group carried out a density current experiment in the fluids laboratory and the other group took part in the 'forecast factory' activity. Each of these activities lasted approximately 30 minutes. Throughout the day, all groups rotated to each of the different activities (i.e. groups taking part in the radiosonde launch swapped with the groups involved in the other activities) so that all of the students took part in each activity once during the day. All of the activities were designed to be as interactive as possible for the students. The open days concluded with a weather forecast given by Nigel Roberts of the Joint Centre for Mesoscale Meteorology at the University of Reading, which is jointly funded by the Met Office and the Natural Environment Research Council.

Below we provide a brief outline of the activities we organised and their overall learning outcomes in the context of secondary science and mathematics. Detailed instructions and worksheets for all of the activities can be downloaded from our outreach website (www.met.reading.ac.uk/outreach). It is important to emphasise that almost all the activities (apart from the weather balloon launch) could be performed with very modest equipment that is available to most secondary schools.

Activity 1: Making measurements of the atmosphere

Before we can understand how weather 'works', we must take good-quality, frequent observations of temperature, humidity, pressure, wind, etc. Observations of the weather are the lifeblood of weather forecasting. We can not tell how things will evolve over the next few hours or days if we do not know what is happening 'now'. It is not good enough, however, simply to take measurements in our own backyard; it is absolutely essential that high-quality observations are taken widely around the world, both at the surface and through the depth of the atmosphere.

Weather services around the world take surface observations every hour, on the hour, if they can; in addition, weather balloons are released at least once a day. The data these radiosondes provide are critical for forecasting. Very frequent observations of atmospheric pressure, temperature, relative humidity and wind direction and speed are relayed instantly by a radio transmitter to a receiver on the ground as the balloon ascends and also as it drifts back to Earth on a parachute after the balloon bursts. (NB: The radiosonde is typically not recovered as it often lands many miles away from the launch site.) This provides a real-time profile of how these measures change as the instrument package ascends to about 15 km or more. The data are fed automatically into the computer-based forecast model, and are also transmitted rapidly around the world for other forecast centres to use.

In this activity, students were introduced to the various ways that meteorological measurements are made and were given the opportunity to try out some of the techniques themselves. The activities carried out by the students are described below, with the relevant knowledge, skills and understanding from the KS4 Science National Curriculum shown in brackets.

The focus of the activity was the live launch of a radiosonde lifted by a helium-filled balloon (Figure 1). Atmospheric pressure, temperature and humidity data from the radiosonde were

Figure 1 Launching a radiosonde

relayed in real time back to the students. The data from the radiosonde provides a vertical profile of measurements throughout the depth of the atmosphere. The data were taken away by the students so that they could plot graphs of how the temperature and humidity changed with height. This allowed the students to identify dry and cloudy layers of the atmosphere and link this with the cloud observations taken during the visit. The total change in temperature from the surface to the lowest value aloft divided by the distance between them indicates the 'lapse rate' of temperature. This is a measure of how rapidly or slowly the air temperature changes with height.

In addition to the balloon launches, observations of weather elements at the surface were taken. All students had the chance to measure and to log values of temperature, humidity, wind direction and speed, and cloud type and amount. This was done at a few separate times to appreciate that changes occur in all or most of these measures, even over short periods (Sections 1.1a, 1.2b, c and d: '*collect data from primary and secondary sources, working safely in groups and evaluating methods of collection of data*').

Extensive follow-up activities for students are also included in a resource pack given to teachers. This information includes records of daily data from the university's Atmospheric Observatory, as well as values of maximum and minimum temperature, total precipitation and wind direction and speed over long time periods. Students are encouraged to construct averages and to evaluate changes in the various observations over long time periods (Sections 1.1b and 2.4b: '*examining local changes in atmospheric variables and interpreting these changes with available data*').

Activity 2: Density current experiment in the fluid laboratory

Density currents form when fluids of differing densities come into contact. Predicting how air masses of differing density will interact in the atmosphere is key to forecasting the weather and climate. In this activity, students predict the speed of a density current using a theoretical calculation. They then perform an experiment in the fluid laboratory to test the prediction derived from theoretical considerations. The aims of this activity are to teach the students how fluids of differing densities interact with one another and the implications of these interactions in the atmosphere. The activities carried out by the students are described below.

First, the students were asked to recall the equation for calculating the density of a fluid. Ways in which the density of a fluid can be changed were discussed (Section 3a: '*recall, interpret and apply scientific information*'). The concept of density currents was introduced through everyday examples such as ice cubes melting in warm drinks and the separation of oil and vinegar in salad dressings, and then density currents in the atmosphere were described, such as sea breezes and cold air outflow from thunderstorms (Section 1c: '*explanation of phenomena using scientific theories, models and ideas*'). Next, the equation used to predict the speed U of a steady, energy-conserving density current was introduced to the students:

$$U = \tfrac{1}{2}\sqrt{gD(\Delta\rho/\rho)}$$

The variables used in the equation and their units were discussed with the students. Here ρ is the density of the less dense fluid, $\Delta\rho$ is the difference between the densities of the more dense and less dense fluids, g is the gravitational acceleration ($g \approx 9.8\,\mathrm{m\,s^{-2}}$) and D the original depth of the less dense fluid. The students measured D and used the equation to predict the speeds of various density currents (Section 3c: '*using mathematical language and symbols*').

A 'lock gate' experiment was designed and carried out to test the theoretical prediction (Section 1b: '*testing ideas and developing theories*'; Section 2a: '*planning and testing a scientific idea*'). Students filled the fluid tank with fresh water and calculated the volume. The amount of salt needed to create a given salinity was calculated and added behind the lock gate along with some dye (Section 3c: '*use of scientific and mathematical language and symbols*'). The lock gate was opened and the time taken for the density current to reach the end of the tank (as observed by movement of dye; Figure 2) was timed (Section 1a: '*scientific data collection*'; Section 1a: '*collection of data from primary sources*'). The speed of the density current was calculated and compared with the theoretical prediction. Finally, reasons for differences between the theoretical and observed speeds were discussed (Section 2d: '*evaluate methods of collection of data and consider their validity and reliability as evidence*').

Figure 2 The density current experiment

Activity 3: Richardson's forecast factory: using human computers to forecast temperature.

A key element of current meteorological and climate science is the development of numerical models of the atmosphere (Holton, 1992). These models attempt to simulate the behaviour of the climate system by representing the atmosphere as discrete elements of fluid at particular locations around the Earth and solving equations that govern the evolution of the fluid elements. Modelling the atmosphere using numerical methods was first conceived by a polymath British atmospheric scientist, Lewis Fry Richardson, in the 1920s (Lynch, 2007). Although unable to put his idea into practice, Richardson conceived a giant 'forecast-factory' in which thousands of human computers would process equations relevant to the fluid motion in a particular region of the atmosphere. By communicating their forecast and its outcome to other computers, a forecast of the overall future state of the atmosphere could be made.

In this activity, we used Richardson's forecast factory as a starting point to explain the idea of numerical weather and climate prediction to the students. The activities carried out by the students are described below, with the relevant knowledge, skills and understanding from the KS4 mathematics National Curriculum in brackets. In general, the activity was relevant to many of the key concepts of the curriculum, including applying mathematical methods to real-world situations, understanding limitations to the use of the given mathematical model and understanding its cultural and historical roots.

First, 16 students were seated in an ordinary classroom at desks arranged in a 4 × 4 grid. Each student was accompanied by a member of academic or research staff from the university. Information was given to the students to allow them to understand and predict the future temperature at their location from the local flow and horizontal gradients of temperature. To predict the future temperature, students solved what is known as the advection equation for temperature:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = 0$$

This equation forms part of the system of equations used to make real weather forecasts. Terms in this equation that use the partial derivative symbol ∂ essentially represent gradients of temperature (T) with respect to time (t) and x and y distance. Unlike laboratory experiments, weather forecasts always involve several unknown variables and consider these variables in multiple dimensions. Hence mathematical techniques much more advanced than typically used at school level are required. Realising this helps students to appreciate why weather forecasts have a reputation (often undeserved) for being unreliable. The first term on the left-hand side of the equation is the rate of change of temperature with time. This term depends on the advection of temperature in the east–west (x) and north–south (y) directions by the wind (which has components of u and v in the x and y directions, respectively). The advection terms are calculated by multiplying horizontal temperature gradients by the corresponding wind components.

We can convert this equation into a form that is easily solved using a computer (using a forward, finite-difference approximation to the partial derivatives) as follows:

$$T^{n+1} = T^n - \frac{\Delta t}{\Delta x}\left(u^n\left[T_x^n - T_{x-1}^n\right] + v^n\left[T_{y+1}^n - T_y^n\right]\right)$$

In this equation, superscripts indicate the time level and subscripts indicate the horizontal position. The terms Δt and Δx represent the 'time-step' and distance between grid-points, the grid spacing. We chose to make the grid spacing uniform in both x and y to make the problem simpler. Computers are ideally suited to solving this kind of problem, which involves keeping a record of temperature at 16 points on the x–y grid and at several different time levels. However, with some planning and many people, it is possible to solve the finite-difference form of the equation using only paper, pencil and calculator.

To complete this 'pencil and paper' solution, the students were given input values of wind and temperature and asked to predict the future evolution of temperature by substituting the input values into specially designed computation sheets (Sections 3.1b and c and 3.2f: '*rules of arithmetic, proportional reasoning, vectors in two-dimensions*'). Each solution of the equation on the computation sheets represented a prediction of the temperature a short time-step into the future. To make further predictions, the students were then required to gather information about the updated temperature at points close to them on the grid. After four time-steps, the predictions made by the students were collected and compared with those produced by a computer using the same equation as those solved by the students (Section 2.1, 2.2 and 2.3: '*representing, analysing, and interpreting and evaluating broad relevance in key processes*'). The activity was run four times during the open day and, in all cases, the predictions made by the students compared well with those of the computer (Figure 3).

Student, teacher and participant evaluation

Following the open days, we conducted extensive evaluation of our activities using questionnaires. We focused on three aspects:

- the experience of student attendees;
- the observations of their accompanying staff;
- the impact on academic participants in the activity.

Figure 3 Students and staff participating in the 'forecast-factory' experiment

In general, the evaluation of all three groups was very positive. The ratings by students and teachers who attended the events in 2009 and 2010 are shown in Figure 4.

All of the teachers who attended the event indicated that they would like to attend a similar event next year during National Science and Engineering Week (NSEW). Students attending the event also gave extensive feedback. Some of the highlights of their comments were:

I learnt about how weather is forecasted and the calculations behind it. I also learnt about density.

I may consider taking a career in science and engineering.

I learnt calculations to work out the density and temperature in the atmosphere.

Many of the comments emphasised the mathematical and scientific aspects of the open day activity.

We also evaluated the participation of our research scientist volunteers in the event. Of those surveyed, fewer than 5% had participated in an NSEW activity before, and all of those surveyed said they would probably or definitely participate in a similar event in the future.

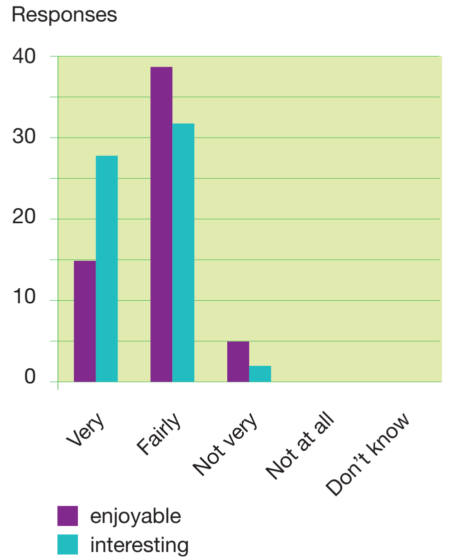

Figure 4 Evaluation of the open days by students and teachers

Widening participation in higher education

The open days also had an additional widening participation aim to try to increase participation in higher education by under-represented groups. These groups are capable of achieving at higher education level but – owing to cultural, social or economic reasons – may not consider university to be an option. The University of Reading programme of outreach activities in the sciences is delivered through a number of activities and events. Working with university departments, academic staff and trained student science ambassadors, we also try to engage wherever possible with other national and regional initiatives to maximise the impact of the activity.

Subject-focused hands-on experience in a higher education environment is crucial when engaging with young people within the widening participation agenda. Not only do they enthuse and provide an experience not possible within a classroom, they demonstrate potential career paths with science subjects and help to dispel stereotypes and misconceptions about sciences and higher education, not only for pupils, but also for the teaching staff advising these young people about career options and higher education choices. The open day sessions were interactive, required a high degree of participation by the pupils, and provided an 'application' for the mathematics and physics taught in school. They are designed not just to interest pupils and engage them in the sciences by imparting information, but also to build confidence in their own abilities and ultimately to raise their aspirations to ensure that, for those that are capable, higher education seems like a viable option. For some of these pupils, getting an insight into a university department has a positive impact that is often followed by a more focused and driven approach in the classroom. This, combined with the added benefit of teachers being better informed about the possibilities at higher education with science subjects, can assist in ensuring that students aspire to the highest levels with the best possible support.

The broader context for meteorology and school science

The position of meteorological science within the secondary curriculum is an issue of continuing concern for many within meteorological research. We are by no means the first or only group to attempt to design activities that might help to encourage schools to use meteorology in their science activities. In particular, the professional body for meteorology in the UK, the Royal Meteorological Society (www.rmets.org), has an active and dynamic education section that regularly organises events of this kind. In this article, we hope to have demonstrated both some new and useful techniques for using meteorological science in secondary education and that this is an interesting and useful approach in general. To our knowledge, our forecast factory activity in particular is a novel way to communicate the mathematical basis of weather and climate prediction to a general audience.

We have produced more detailed descriptions of the activities undertaken on the open days that would allow teachers to repeat these activities in their own classrooms with limited resources. Included in our pack of resources for teachers are follow-on activities and worksheets. Materials developed for the open day are freely available to all schools or university departments who wish to put on similar events: visit our outreach website (www.met.reading.ac.uk/outreach) or email our outreach coordinator (outreach@met.reading.ac.uk) for more details.

Acknowledgements

We thank Research Councils UK for providing funding for our activity through their NSEW award scheme. We also thank the enthusiastic support and contribution of our academic colleagues who helped to make our open days a success.

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