ManUniCast: a real-time weather and air-quality forecasting portal and app for teaching

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Numerical modelling is the cornerstone of modern environmental prediction. Whether it is weather, air-quality, hydrological, ecological or climate predictions, the basic principles of constructing and running numerical models are pretty much the same. A great success story in environmental prediction is weather forecasting. In particular, the success of human forecasters is closely tied to the model output, demonstrating the value that knowledge of model biases and human experience brings to improving upon the numerical guidance (Doswell, 2004; Novak et al., 2014; Sukovich et al., 2014). Thus, if we wish to teach environmental prediction (or weather forecasting, specifically) to students, then exposure to modelling tools and output is necessary.

In an educational setting, weather forecasting offers many benefits to students. Weather forecasting is the number-one attraction for students who take atmospheric-science classes (Knox and Ackerman, 2005). Besides its popularity with students, active learning through repeated practice is the best way for students to gain experience and improve (Roebber and Bosart, 1996). Specifically, Hilliker (2008) and Suess et al. (2013) showed that students in a general education course and geology majors who participated in a forecast contest could improve as they developed more experience. Thus, repeated exposure to weather forecasting tools appears to benefit student learning. Weather forecasting also encourages critical-thinking skills, involving the highest levels in the cognitive domain of Bloom’s taxonomy (e.g. application, analysis, synthesis, evaluation). In addition, forecasting contests and discussions of the current weather in the classroom can motivate student learning (Harrington et al., 1991; Skeeter, 2006; Barrett and Woods, 2012), inspire better grades (Hilliker, 2008) and result in better forecasts (Market, 2006; Bond and Mass, 2009; Suess et al., 2013). Finally, weather discussions help close the gap between the knowledge-seeking professors and the goal-seeking students (Roebber, 2005), because an otherwise sterile set of equations illustrating complicated physical concepts comes alive when being used to illustrate the current weather in the news or outside the window.

Despite the importance of environmental prediction models and the clear educational benefits of working with such models, their output is often difficult to access. One particular problem is that raw weather data and forecast model output in Europe are often highly restricted compared with that in the USA, where governmental weather data and model output are freely available on many websites. Although numerous US universities run real-time models that are freely available online (Mass and Kuo, 1998; Table 1), no atmospheric-science department in the UK did when the first author began teaching meteorology in the UK in 2010. As such models are the basis of modern environmental predictions, UK students’ inability to even see such output on a daily basis, let alone work with it, is a severe disadvantage in preparing them for a future career where the use of such models is commonplace.

To make a positive step towards accessible environmental model output that can be viewed and interrogated by students, we have developed ManUniCast, a real-time and archived weather and air-quality modelling system, web-based portal, and mobile app. ManUniCast provides real-time weather and air-quality forecasts made by a state-of-the-art model free to students and the general public. By making this resource freely available, our aim is to have as wide a distribution as possible to students. The purpose of this article is to describe ManUniCast’s development and implementation, as well as suggest educational and outreach opportunities for its use.

### Weather Research and Forecast (WRF) and WRF with Chemistry models

ManUniCast uses two different, but closely related, modelling systems. ManUniCast weather predictions are produced by version 3.4.1 of the Advanced Research Weather Research and Forecast model (WRF-ARW;
Skamarock and Klemp, 2008; Skamarock et al., 2009), which is an open-source model maintained by scientists at the National Center for Atmospheric Research (NCAR) and designed for free use by all members of the meteorological community (http://www.wrf-model.org). Principal users of WRF-ARW include many universities worldwide, as well as the US National Oceanic and Atmospheric Administration (NOAA).

The ManUniCast air-quality predictions are produced by version 3.4.1 of the WRF with chemistry (WRF-Chem; Grell et al., 2005; Fast et al., 2006) model, with modifications made at the University of Manchester (Archer-Nicholls et al., 2014). WRF-Chem is a fully coupled atmospheric chemistry model with meteorological predictions that are produced from the same physics as WRF-ARW.

The ManUniCast weather predictions consist of two domains connected through one-way nesting: the first domain covering the majority of western Europe and much of the eastern North Atlantic Ocean at a 20km grid spacing (Figure 1), and the nested second domain covering the United Kingdom and Ireland (excluding the Shetland Islands) at a 4km grid spacing (Figure 2). The ManUniCast air-quality predictions are made using a single domain covering the UK, Ireland, the North Sea, much of France and Germany and the Low Countries at 12km grid spacing. We display only the results for the centre of the domain (matching the spatial coverage of the 4km weather domain) in order to minimise the influence on our forecast from the chemical boundary conditions.

All three domains have 45 vertical levels and produce forecasts for 54h, starting daily from the 1800 UTC NOAA Global Forecast System (GFS) model forecasts at 0.5° latitude–longitude grid spacing. The GFS provides both the initial conditions for ManUniCast from the 1800 UTC global analysis, as well as the lateral boundary conditions at 3h intervals from the forecast. The GFS assimilates global datasets using the gridpoint statistical interpolation scheme (Kleist et al., 2009). However, due to the WRF simulations having a ‘cold start’ with no data assimilation, all cloud and precipitation fields must develop within the first few hours of model operation. This model spin-up limits the accuracy of the forecasts in the first 6h or so.

The chemical initial conditions are taken from the previous day’s 24h forecast. The chemical boundary conditions are taken from MOZART-4/MOPITT global chemistry model forecasts at 2.0° × 2.5° latitude–longitude grid spacing (Emmons et al., 2010; http://www.acd.ucar.edu/acesp/forecast/). Chemistry emissions are taken from the UK National Atmospheric Emissions Inventory (NAEI; http://naei.defra.gov.uk) and Netherlands Organisation for Applied Scientific Research TNO emissions inventory (Denier van der Gon et al., 2010). The evolution of emissions on monthly, daily and hourly time scales is constructed from scaling factors that estimate climatological observations. More details on the physical parameterisations can be found at http://manunicast.seaes.manchester.ac.uk/model.html.

The models are run daily at 0005 UTC on RedQueen, the high-performance computing cluster at the University of Manchester (http://ri.itservices.manchester.ac.uk/redqueen/). Weather forecasts are generally available by 0700 UTC and chemistry forecasts by 1300 UTC.

Web portal

The web portal allows access to the output. The portal displays not only output from the recent forecasts, but also the forecasts back to June 2013, when some of the earliest test simulations were being run. Only three steps are required to produce a simple graphic: (i) identify the date of the forecast (defaults to the most recent run), (ii) select the forecast domain (Europe weather, UK weather, UK air quality), and (iii) select the plot type and variables. Further instructions can be found on the Getting Started part of the web page.

ManUniCast produces output of various types: horizontal maps of over 30 different meteorological quantities (Table 1) and over 30 different air-chemistry and composition quantities (Table 2), cross-sections, skewT-logp diagrams, and time series at a location (also known as meteograms) (Figure 3). Currently, skewT-logp diagrams and meteograms are available at 36 sites around the UK and Ireland (Figure 4).

ManUniCast also provides several different parameters: planetary boundary-layer height, forecast rainfall patterns in the form of simulated radar-reflectivity factor at a CAPPI (constant altitude plan position indicator) 1km above ground level, and simulated satellite images. Simulated reflectivity is derived using a Rayleigh approximation on the output from the Thompson microphysics scheme within the WRF model (Thompson et al., 2008) and then interpolated to 1km above ground level. The simulated reflectivity is also used to calculate
simulated radar-derived rainfall rate, similar to that offered by the Met Office (Kitchen and Illingworth, 2011). Simulated satellite images are derived from the total cloud (liquid water plus ice) water paths and then scaled to a grey-scale colour table to provide a first-order approximation of the reflection and transmission processes that would occur in an actual cloud without having to run a complex radiative transfer model.

The approach to plotting in ManUniCast was markedly different to most meteorological plotting packages. To help students visualise the relationship between different quantities, the portal allows the ability to overlay as many as five different quantities, then dynamically make them more opaque or more transparent. The layering order can also be rearranged, which can aid students with the visualisation of relationships between different products. Users can also switch quickly between the European and the UK weather domains to either zoom in on or expand their perspective without having to reselect the products being plotted.

Once graphics are loaded into the web browser, users can animate hourly output from the 54h forecasts at animation speeds from 1 to 20 frames s⁻¹ (dependent on the user’s browser and hardware capabilities). Users can select from one of a number of different background images, including latitude–longitude contours, terrain height, UK county boundaries, roadways, and rail lines.

ManUniCast’s meteogram feature is also unique, as several surface weather variables (temperature, dewpoint, relative humidity, wind speed and direction, pressure, and precipitation) can be layered on top of each other via an interactive JavaScript plotting interface. Variables can be added and removed easily, with dynamic axes created with each variable. This functionality allows for exploration of meteorological variables through time, such as examining the relationship with wind speed and direction along with pressure changes during a frontal passage. Each dynamically created meteogram can also be saved with the user’s preference of variables.

The site is built with responsive web design principles so that its layout changes automatically according to the viewer’s devices (e.g. different layout for tablet PCs and desktops). Finally, to facilitate the production of graphics for lecture presentations or student homework assignments, one-click buttons allow users to download images or animated graphics interchange format (GIF) files to their computer.

**Mobile app**

To encourage even easier access to the model output, a mobile app was constructed. Output from the three forecasts is provided
strongest winds (about 100–150km in width). A time series of meteorological quantities at Exeter (closest location in Figure 4 to Dawlish) shows the passage of the low centre, the 10m winds reaching peak values exceeding 15ms\(^{-1}\) during 5 February, and several centimetres of rainfall (Figure 3(c)).

Example: 2–3 April 2014 pollution event

To illustrate ManUniCast’s chemistry output, we present images from the pollution event at the start of April 2014, which covered a large area of southeast England in smog (Figure 6). At 1800 UTC on 2 April through a smaller number (five to eight) of composite plots of two or three of the most commonly requested quantities (Figure 5). The limited number of pre-designed composite images keeps the app easy to use, especially for non-scientists. At this point, only an iPhone and iPad app exist, although we hope to offer an Android app in the future. We are unaware of anyone else who has a free app for weather and air-quality forecasts from a real-time forecasting model.

Example: 5 February 2014 flood

To illustrate ManUniCast’s meteorological output, we present some images from the cyclone that washed away the railway line at Dawlish, shutting down traffic between Exeter and Plymouth (Figures 1 and 2). At 0000 UTC on 5 February 2014, ManUniCast's 30h forecast showed a 950hPa low centre southwest of Ireland (Figure 1), whereas the Met Office surface chart at this time showed a 947hPa low in almost the same location (not shown). Winds exceeding 24ms\(^{-1}\) were south and southwest of the low centre in a location similar to that of a sting jet (Figure 1). By 0800 UTC, the low made landfall in Ireland and winds exceeding 20ms\(^{-1}\) reached southwest England (Figure 2). The 4km grid spacing allows fine-scale features in the wind field to be resolved and shows the narrow spatial scale of the region of strongest winds (about 100–150km in width). A time series of meteorological quantities at Exeter (closest location in Figure 4 to Dawlish) shows the passage of the low centre, the 10m winds reaching peak values exceeding 15ms\(^{-1}\) during 5 February, and several centimetres of rainfall (Figure 3(c)).
2014, ManUniCast’s 24h forecast showed a region of high (50–70 ppbv) nitrogen dioxide (NO₂) mixing ratios over the North Sea, which was carried over England by the westerly flow (Figure 6(a)). At the same time, the hourly NO₂ measurement at St Oysth (51.8° latitude, 1.05° longitude; part of the Department for Environment, Food and Rural Affairs (Defra) Automatic Urban and Rural Network) was 50 ppbv (not shown). The elevated NO₂ concentrations led to increases in the nitrate content of particulates: PM₂.₅ nitrate mass loadings exceeded 30 μg m⁻³ (Figure 6(b)), contributing to total PM₂.₅ mass loadings of over 70 μg m⁻³ during this period (Figure 6(c)).

Outreach activities

Another motivation for ManUniCast is that it serves as an outreach tool for talking to students and the public about how forecasts are made. ManUniCast has been used for outreach activities at science fairs, open days, and public lectures. The history of numerical weather forecasting is an amazing story, one that is not as well known as it should be. Furthermore, members of the public are sometimes amazed when they find out the amount of science that goes into making such forecasts. Educational information on how weather forecasts in general, and ManUniCast forecasts specifically, are made can be found at http://manunicast.seaes.manchester.ac.uk/how.

The air-quality forecasts can also be used for outreach. For example, ManUniCast provides more detailed background information on the methodology of how air-quality forecasts are made, including the individual components of the air-quality forecasts that go into the air-quality products issued by Defra (http://uk-air.defra.gov.uk/air-pollution/daqi?view=more-info). Thus, interested users of Defra’s forecasts can see which particular components may be contributing most to the air-quality forecast at that time.

Uses in teaching

We see ManUniCast’s tremendous potential to the academic community for teaching and research: indeed, it has already been used in weather discussions in meteorology classes at Manchester. Furthermore, ManUniCast’s predecessor has been used successfully by students for evaluating the relative strengths and weaknesses of model output as part of a writing assignment on a meteorological case study.

Analysing and interpreting model output led to the following positive educational goals for students:

- learning how such models are constructed and run, and working with model output;
- recognition that all models are wrong, but some are useful;
- being able to identify those weather and air-quality phenomena that can be forecast well from those that cannot, whether it be due to resolution or
unaccounted for physical or chemical processes;
• understanding that a model simulation may have specific variables it forecasts well and variables it forecasts less well.

Present and future educational uses include:
• weather discussions in atmospheric science, atmospheric physics and meteorology lectures at all academic levels from introductory courses to postgraduate-level courses;
• a resource for forecasting competitions (e.g. Schultz et al., 2013);
• atmospheric-science field courses run across the UK;
• data for undergraduate research projects;
• training postgraduate students on model use and simulation, leading to dissertation projects;
• non-credit-bearing weather discussions.

We encourage others to use ManUniCast in their teaching activities and welcome sharing of educational resources on numerical weather prediction contest in multi-leveled meteorology classes. The mobile app was created by TappCandy of York.

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References
Archer-Nicholls S, Lowe D, Utembe S et al. 2014. Gaseous chemistry and aerosol mechanism developments for version 3.5.1 of the online regional model WRF-Chem. Geosci. Model Dev. 7: 2557–2579.
Barrett BS, Woods JE. 2012. Using the amazing atmosphere to foster student learning and interest in meteorology. Bull. Am. Meteorol. Soc. 93: 315–323.
Bond NA, Mass CF. 2009. Development of skill by students enrolled in a weather forecasting laboratory. Weather and Forecasting 24: 1141–1148.
Denier van der Gon HAC, Visschedijk A, van der Brugh H et al. 2010. A high resolution European emission data base for the year 2005, a contribution to UBA – Projekt PAREST: particle reduction strategies. TNO Report TNO-034-UT-2010-01895 RPT-ML. Netherlands Organisation for Applied Scientific Research: Utrecht.
Dobson CA. 2004. Weather forecasting by humans—heuristics and decision making. Weather and Forecasting 19: 1115–1126.
Emmons LK, Walters S, Hess PG et al. 2010. Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). Geosci. Model Dev. 3: 43–67.
Fast JD, Gustafson WI, Easter RC et al. 2006. Evolution of ozone, particulates, and aerosol direct forcing in an urban area using a new fully-coupled meteorology, chemistry, and aerosol model. J. Geophys. Res. 111(S): D21305, doi:10.1029/2005JD006721.
Grell GA, Peckham SE, Schmitz R et al. 2005. Fully coupled ‘online’ chemistry within the WRF model. Atmos. Environ. 39: 6957–6975.
Harrington JA, Cerveny RS, Hobgood JS. 1991. Competitive learning experiences: the role of weather forecasting contests in geography programs. J. Geogr. 90(1): 27–31.
Hilliker J. 2008. Assessment of a weather forecasting contest in multi-leveled meteorology classes. J. Geosci. Educ. 56(2): 160–165.
Inness PM, Dorling S. 2011. Operational Weather Forecasting. John Wiley & Sons: London, 248 pp.
Kitchen M, Illingworth A. 2011. From observations to forecasts – Part 13: The UK weather radar network – past, present and future. Weather 66: 291–297.
Kleist DT, Parish DF, Derber JC et al. 2009. Introduction of the GSI into the

Figure 6. The 24h WRF-Chem ground-level forecasts for 1800 UTC 2 April 2014: (a) NO2 mixing ratio (ppbv), (b) PM2.5 nitrate mass loadings (μgm–3) and (c) PM2.5 total mass loadings (μgm–3). Each plot also includes wind barbs (full barb and half-barb denote 10ms–1 and 5ms–1, respectively).
Organisation of orographic convection by mountain waves above Cross Fell and Wales

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Orographic cumulus forms when air is lifted to its level of free convection by forced ascent or convergence from heating (Banta, 1990). Convection can also interact with waves, forming convection waves above plains (Höhndorf, 1937a; 1937b; Kuettner et al., 1987). Convective updraughts behave as an obstacle or oscillator to undisturbed stable-air flow, and the resulting waves influence the location of convection, with the waves and convection interacting in a ‘chicken and egg’ process, or mutually reinforcing feedback. Mountain waves, by interacting with precipitating cloud, have been shown to be significant for weather forecasting (Reinking et al., 2000).

Mountain waves also occur above convective rolls present above mountains (Bradbury, 1990), being launched by a process similar to convection waves, where the mountain waves modulate the strength of convection (Hosler et al., 1963; Orville, 1965; Tang et al., 2012) and the convection partly forces the waves (Worthington, 2002, 2006). Worthington (2014) suggests there are two types of mountain wave: classic ‘type 1’ mountain waves are forced directly by high ridge-like mountains; ‘type 2’ are forced indirectly, for example above convection, rotors and turbulence in the lower boundary layer, with the flow only becoming mostly wave-like above a mountain-wave launching height (Shutts, 1997). Type 1 and 2 waves are different from the type 1 and 2 rotors described by Hertenstein and Kuettner (2005).

Cross Fell in northern England is known for a type 1 mountain-wave windstorm, the Helm Wind, in northeasterly airflow (Manley, 1945). However, type 2 convective mountain waves also occur at Cross Fell in southwesterly winds (Worthington, 2005). On 17 March 2004 (Worthington, 2005), convective rolls revealed by cloud streets started upwind of Cross Fell and then developed wave-like across-wind structure, probably caused by mountain waves. Here, another...