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Journal:	*Weather*
Manuscript ID:	Draft
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
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Keywords:	numerical weather prediction, ManUniCast, forecasting, air quality, mobile app

ManUniCast: A Real-Time Weather and Air-Quality Forecasting Portal and App for Teaching

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Submitted to *Weather*

26 September 2014

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ABSTRACT

ManUniCast is a real-time weather and air-quality forecasting portal developed for education and outreach at the University of Manchester. The web portal manunicast.com displays model output from a WRF simulation with 20-km horizontal grid spacing over the North Atlantic and Europe, including a 4-km nest over the UK and Ireland. The portal also displays output from a WRF-Chem simulation at 12-km grid spacing over the UK. The portal displays over 60 different meteorological, chemical and composition quantities. Both the portal and an accompanying mobile app are free. Educational opportunities for incorporating ManUniCast into existing courses are discussed.

Numerical modeling 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 all the same. A big 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 modeling 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 Seuss 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 out 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 to that in the United States where governmental weather data and model output are freely available on many web sites. 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. Because 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 to preparing them for a future career where the use of such models is commonplace.

To make a positive step toward 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 modeling system, web-based portal, and mobile app. 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 the development and implementation of ManUniCast, as well as suggest educational and outreach opportunities for its use.

WRF and WRF-Chem

ManUniCast uses two different, but closely related, modelling systems. The weather predictions of ManUniCast 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., 2008), 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 United States National Oceanic and Atmospheric Administration (NOAA).

The air-quality predictions of ManUniCast are produced by version 3.4.1 of the Weather Research and Forecast Model with Chemistry (WRF-Chem; Grell et al. 2005, Fast et al., 2006) 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 weather predictions of ManUniCast 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 20-km grid spacing (Figure 1), and the nested second domain covering the United Kingdom and Ireland (excluding the Shetland Islands) at a 4-km grid spacing (Figure 2). The air-quality predictions of ManUniCast are made using a single domain covering the UK, Ireland, the North Sea, much of France and Germany and the Low Countries at 12-km grid spacing. We only display the results for the centre of the domain (matching the spatial coverage of the 4-km weather domain) to minimize the influence on our forecast from the chemical boundary conditions.

All three domains have 45 vertical levels and produce forecasts for 54 hours, starting daily from the 1800 UTC NOAA Global Forecast System (GFS) model forecasts. The GFS provides both the initial conditions for ManUniCast from the 1800 UTC global analysis, as well as the lateral boundary conditions at 3-hour intervals. Because the model is given a “cold start” with no data assimilation, all cloud and precipitation fields must develop within the first few hours, limiting the accuracy of the forecasts in the first 6 hours or so.

The chemical initial conditions are taken from the previous day's forecast. The chemical boundary conditions are taken from MOZART-4/MOPITT global chemistry model forecasts (Emmons et al., 2010;

http://www.acd.ucar.edu/acresp/forecast/). Chemistry emissions are taken from the UK National Atmospheric Emissions Inventory (NAEI; http://www.naei.defra.gov.uk) and 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 not only displays output from the recent forecasts, but also displays forecasts back to June 2013 when some of the earliest test simulations were being run. 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, skew*T*–log*p* diagrams, and time series at a location (also known as meteograms) (Figure 3). Currently, skew*T*–log*p* 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) 1 km 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 1 km above ground level. The simulated reflectivity is also used to calculate simulated radar-derived rainfall rate, similar to what is offered from the MetOffice (Kitchen and Illingworth, 2011). Simulated satellite images are derived from the total cloud (liquid water plus ice) water paths and then scaled to a gray-scale colour table to provide a first-order approximation of the reflection and transmission processes that would occur in an actual cloud without having run a complex radiative transfer model.

The approach to plotting in ManUniCast was markedly different to most meteorological plotting packages. To help students visualize 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 visualization 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 54-hour forecasts at animation speeds from 1 to 20 frames per second (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.

The meteogram feature is unique to ManUniCast as well, 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 relation with wind speed and direction along with pressure changes during frontal passage. Each dynamically created meteogram can also be saved with the user's preference of variables.

The site has been designed in *responsive web design* so that the layout of the site automatically changes 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 gifs to their computer.

Mobile App

To encourage even easier access to the model output, a mobile app was designed. Output from the three forecasts is provided through a smaller number (5–8) of composite plots comprised 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 exists, 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 the meteorological output from ManUniCast, we present some images from the cyclone that resulted in the washing out of the railway line at Dawlish, shutting down traffic between Exeter to Plymouth (Figures 1 and 2). At 0000 UTC 5 February 2014, ManUniCast's 30-h forecast showed a 950-mb low centre southwest of Ireland, whereas the Met Office surface chart at this time showed a 947-mb low in almost the same location. Winds exceeding 24 m s^{-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 20 m s^{-1} breached southwest England (Figure 2). The 4-km 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 100–150 km 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 10-m winds reaching peak values exceeding 15 m s^{-1} during 5 February, and several cm of rainfall (Figure 3c).

Example: 2–3 April 2014 Pollution Event

To illustrate the chemistry output from ManUniCast, we present images from the pollution event at the start of April 2014, which covered a large area of south-east England in smog (Figure 6). At 1800 UTC 2 April 2014, ManUniCast's 24-h forecast showed a region of high (50–70 ppbv) nitrogen dioxide (NO_2) mixing ratios over the North Sea, which was carried over the England by the westerly flow (Figure 6a). At the same time, the hourly NO_2 measurement at St Oysth (51.8° Latitude, 1.05° Longitude; part of the Defra Automatic Urban and Rural Network) was 50 ppbv (not shown). The elevated NO_2 concentrations led to increases in the nitrate content of particulates: PM2.5 nitrate mass loadings exceeded 30 µg m^{-3} (Figure 6b), contributing to total PM2.5 mass loadings of over 70 µg m^{-3} during this period (Figure 6c).

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. Such educational information 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. Thus, interested users of DEFRA forecasts can see which particular components may be contributing most to the air-quality forecast at that time.

Uses in Teaching

We see tremendous potential for ManUniCast to the academic community for teaching and research. Indeed, ManUniCast has already been used in weekly weather discussions at Manchester and ManUniCast's predecessor has been used successfully to get students evaluating the relative strengths and weaknesses of model output as part of a writing assignment on a meteorological case study.

Analyzing and interpreting model output lead to the following positive educational goals:

- Learning how such models are constructed and run, and working with 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, and
- Understanding that a model simulation may have specific variables it forecasts well and variables it forecasts less well.

Future educational uses could 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, and
- Non-credit-bearing weekly weather discussions.

We encourage others to employ ManUniCast in their teaching activities and welcome sharing of educational resources on numerical weather prediction. When coupled with a textbook such as *Operational Weather Forecasting* (Inness and Dorling 2013), a class specifically focused on environmental prediction could help educate the meteorologists and environmental scientists of the future.

Acknowledgements

ManUniCast was funded by a grant from the Higher Education Academy Subject Centre for Geography, Earth and Environmental Sciences Learning and Teaching Development Fund with additional support from the Faculty of Engineering and Physical Sciences and the Research Infrastructure Team from IT Services, underpinned by the University Computationally Intensive Research Ecosystem. We thank Tony Brown and Alison Hamilton for their support of this project. Educational content was coauthored with the assistance of Fiona Lomas and Katy Mulqueen. Hardware and technical support was provided by Michael Bane, Simon Hood, George Leaver, and Chris Paul. ManUniCast uses the Weather Research and Forecasting (WRF) and WRF-Chem model, a state-of-the-art numerical weather prediction system designed for community use and supported by the National Center for Atmospheric Research, which is sponsored by the U.S. National Science Foundation. The mobile app was partially funded by the Learning Through Research Project, Teaching and Learning Support Office, Directorate for the Student Experience, University of Manchester, and partially through a University of Manchester Teaching Excellence Award to Schultz. The mobile app was created by TappCandy of York.

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Table 1: Quantities forecast within the weather domains of ManUniCast.

- Temperature
- Dewpoint temperature/mixing ratio
- Relative humidity
- Horizontal wind speed and direction
- Vertical wind speed
- Geopotential height
- Sea-level pressure
- Level of free convection
- Lifting condensation level
- Most unstable convective available potential energy
- Maximum convective inhibition
- Maximum radar reflectivity
- Simulated radar reflectivity at 1 km
- Radar-derived rainfall rate
- Hourly accumulated precipitation
- Total accumulated precipitation
- Planetary boundary layer height
- 320 K potential vorticity
- Precipitable water
- Simulated satellite imagery
- Absolute vorticity
- Potential vorticity
- Moist potential vorticity
- Potential temperature
- Equivalent potential temperature
- Layer thickness from 1000 mb
- Petterssen frontogenesis
- Cloud water mixing ratio
- Cloud ice mixing ratio

Table 2: Quantities forecast specific to the air-quality domain of ManUniCast.

Ammonia (NH_3) mixing ratio
Carbon monoxide (CO) mixing ratio
Cloud condensation nuclei numbers at 0.2%, 0.5%, and 1% supersaturations
Dinitrogen pentoxide (N_2O_5) mixing ratio
Formaldehyde (HCHO) mixing ratio
Hydrogen peroxide (H_2O_2) mixing ratio
Hydroxyl radical (OH) mixing ratio
Sulphur dioxide (SO_2) mixing ratio
Nitrate radical (NO_3) mixing ratio
Nitric acid (HNO_3) mixing ratio
Nitric oxide (NO) mixing ratio
Nitrogen dioxide (NO_2) mixing ratio
Nonmethane volatile organic carbon (NMVOC) mixing ratio
Ozone (O_3) mixing ratio
Peroxyacylnitrate (PAN) mixing ratio
PM1 and PM2.5 black carbon mass loadings
PM1 inorganics mass loading
PM1 and PM2.5 organic particulate mass loadings
PM2.5 ammonium mass loading
PM2.5 sodium mass loading
PM2.5 chloride mass loading
PM2.5 sulfate mass loading
PM2.5 nitrate mass loading
PM10 dust mass loading
PM10 sea salt mass loading
Total PM2.5 and PM10 mass loadings
Total aerosol concentration

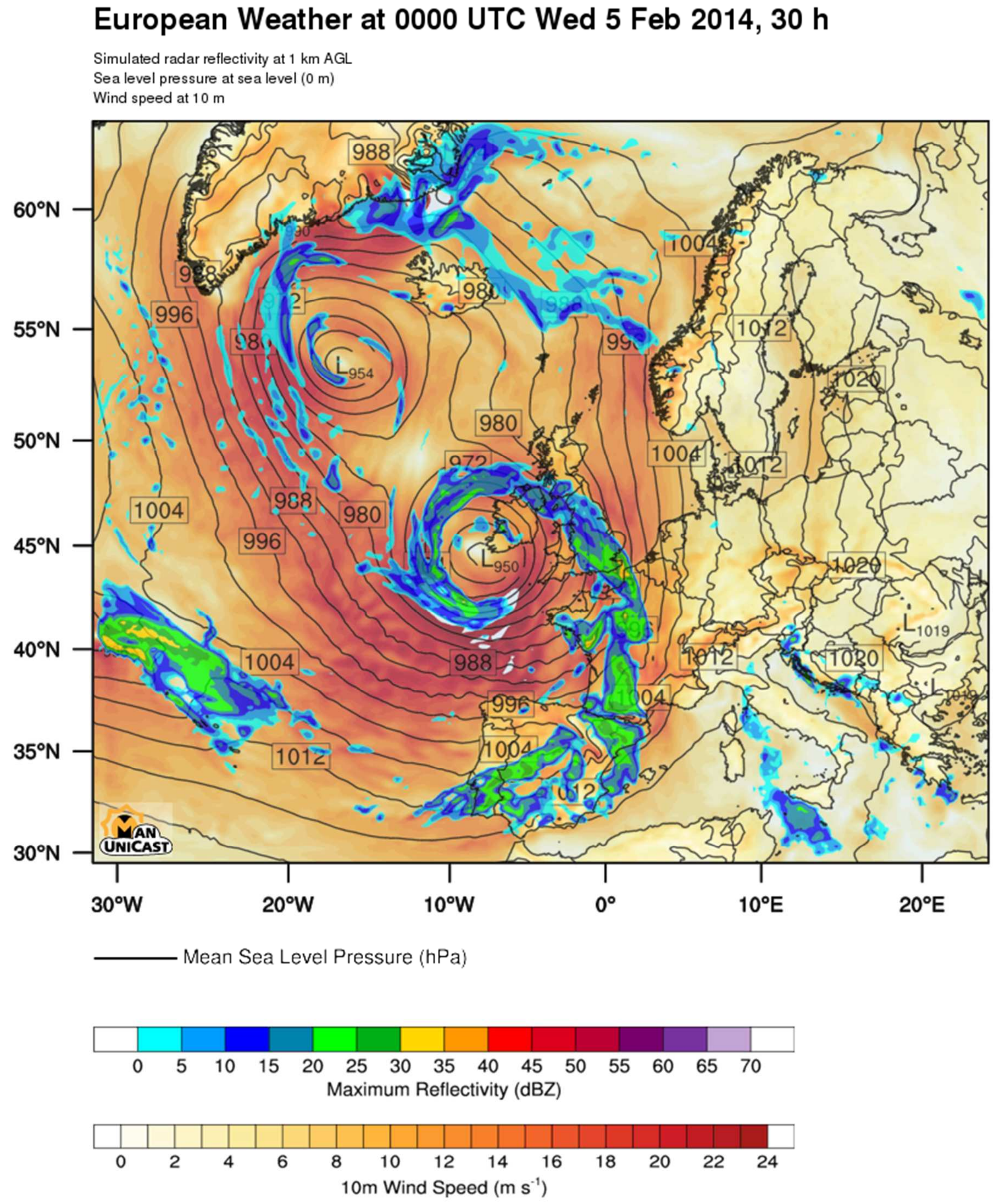

Figure 1. 30-h WRF forecast for 0000 UTC 5 February 2014 on the domain with 20-km horizontal grid spacing: mean sea-level pressure, 10-m wind speed, and simulated maximum radar reflectivity.

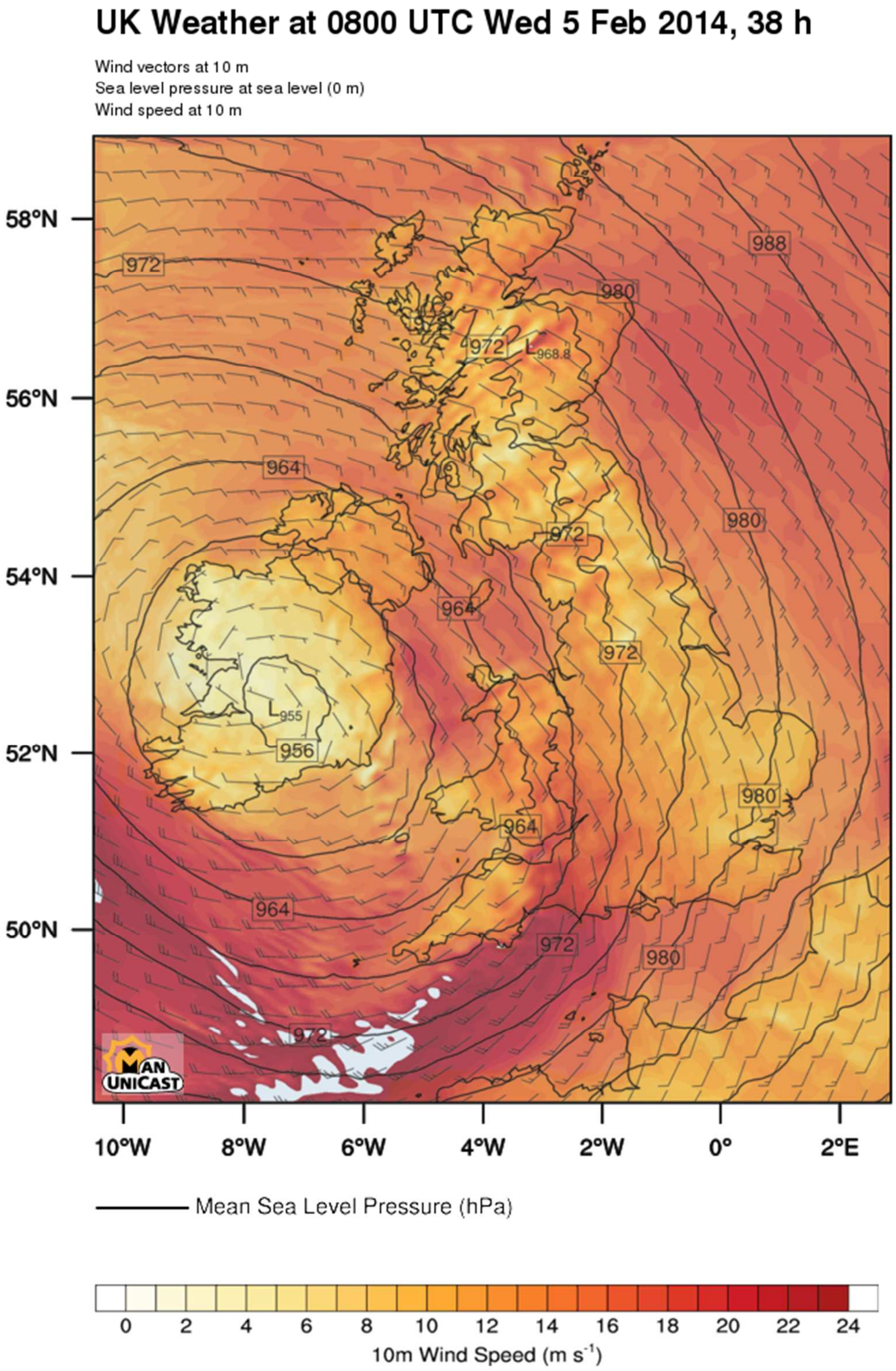

Figure 2. 38-h WRF forecast for 0800 UTC 5 February 2014 on the domain with 4-km horizontal grid spacing: mean sea-level pressure, 10-m wind speed, and wind barbs (full barb, and half-barb denote 10 and 5 m s^{-1}, respectively).

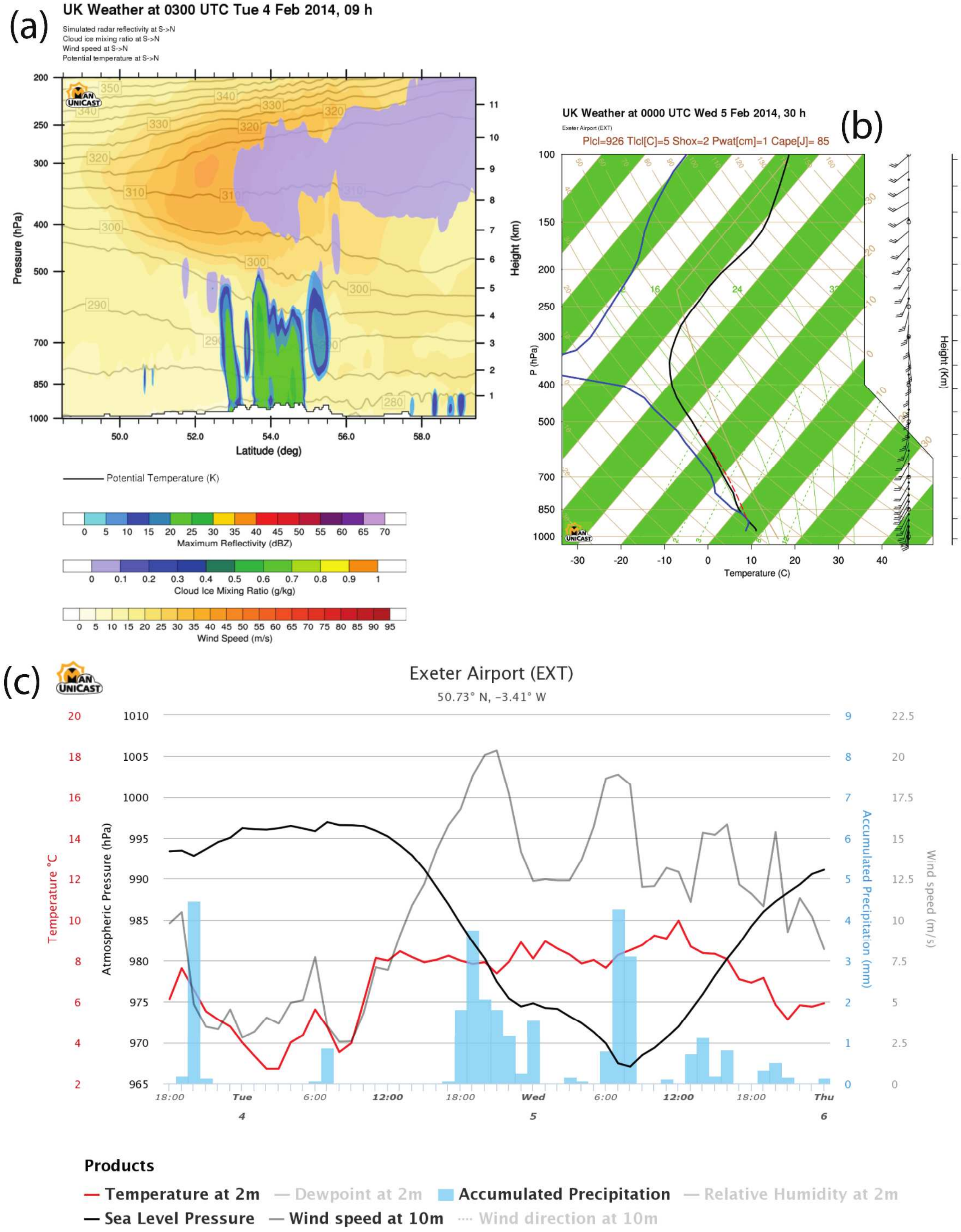

Figure 3. Examples of a (a) cross section, (b) skew*T*–log*p*, and (c) meteogram.

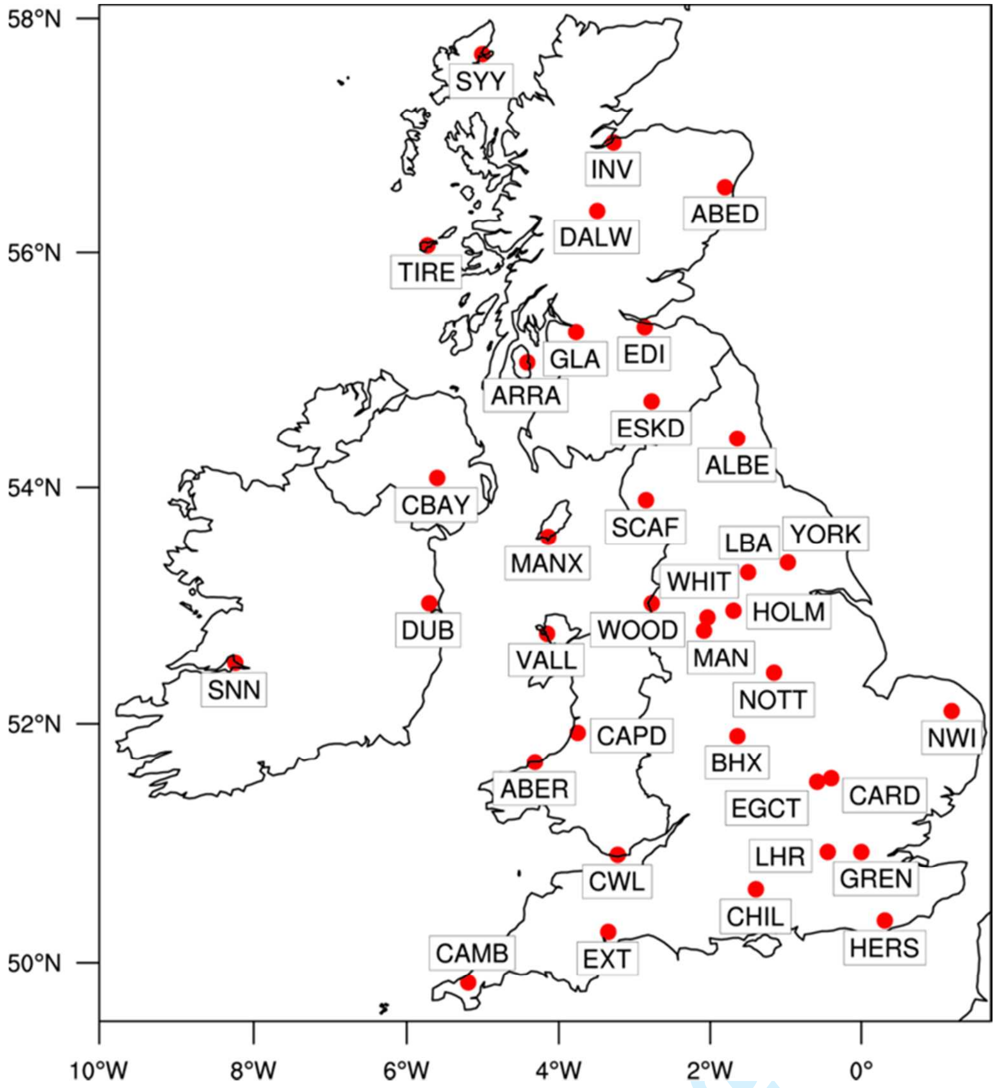

Figure 4: Locations of surface meteograms and skew*T*–log*p* diagrams. ABED = Aberdeen, ABER=Aberporth, ALBE=Albermare, ARRA=Isle of Arran, BHX= Birmingham Airport, CAMB=Camborne, CAPD=Capel Dewi, CARD=Cardington, CBAY=Castor Bay, CHIL=Chilbolton Observatory, CWL= Rhoose Cardiff-Wales Airport, DALW=Dalwhinney, DUB=Dublin Airport, EDI=Edinburgh Airport, EGCT=Cranfield Airport, ESKD=Eskdalemuir, EXT=Exeter Airport, GLA=Glasgow Airport, GREN=Royal Observatory, Greenwich, HERS=Herstmonceux, HOLM=Holme Moss, INV=Inverness Airport, LBA=Leeds/Bradford Airport, LHR=London/Heathrow, MAN=Manchester Airport, MANX=Isle of Man, NOTT=Nottingham Weather Centre, NWI=Norwich Airport, SCAF=Scafell Pike, SNN=Shannon, SYY=Stornoway Airport, TIRE=Tireee, VALL=Valley, WHIT=Whitworth Observatory, University of Manchester, WOOD=Woodvale, YORK=York.

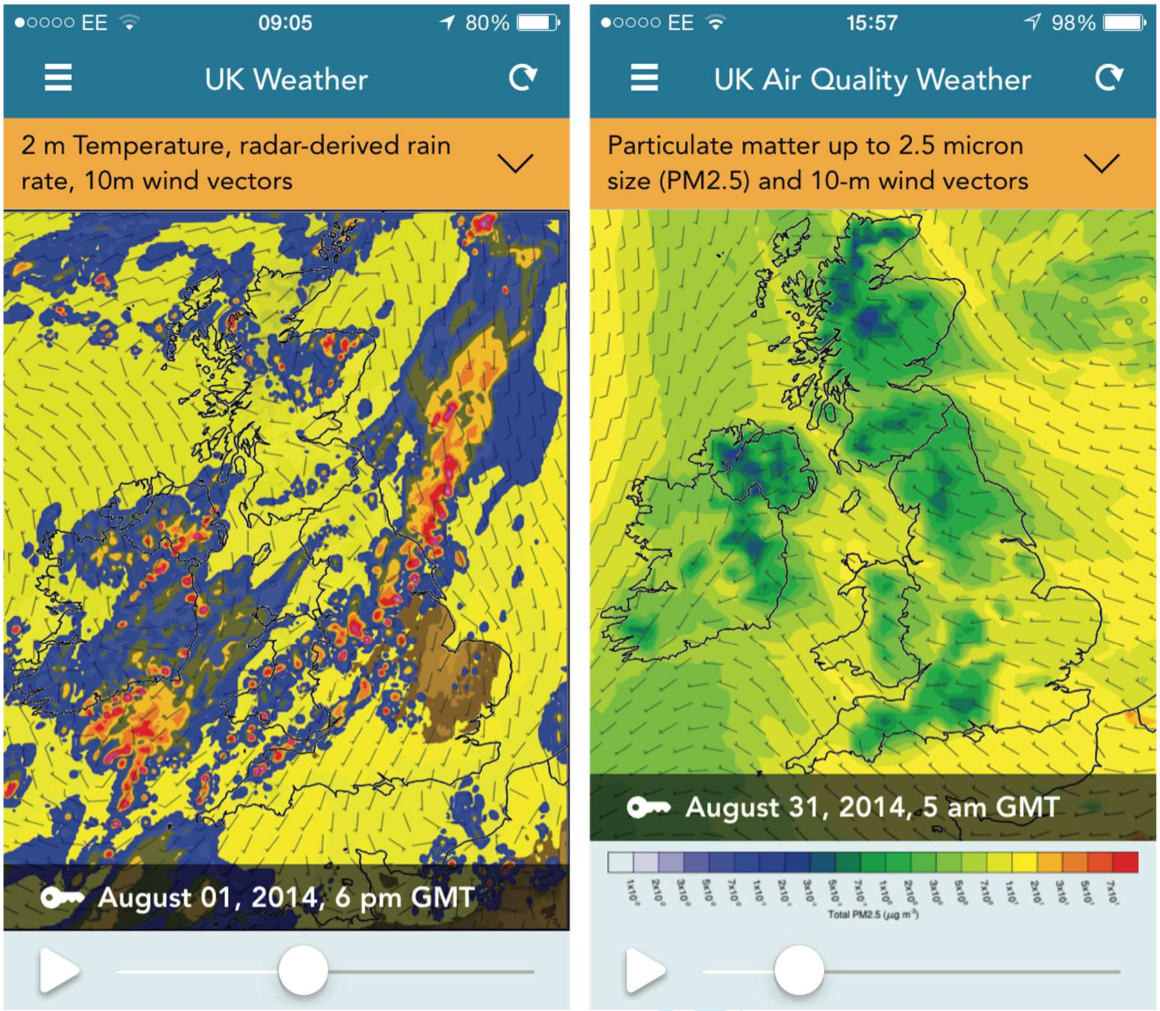

Figure 5. Screenshots from the ManUniCast iPhone app.

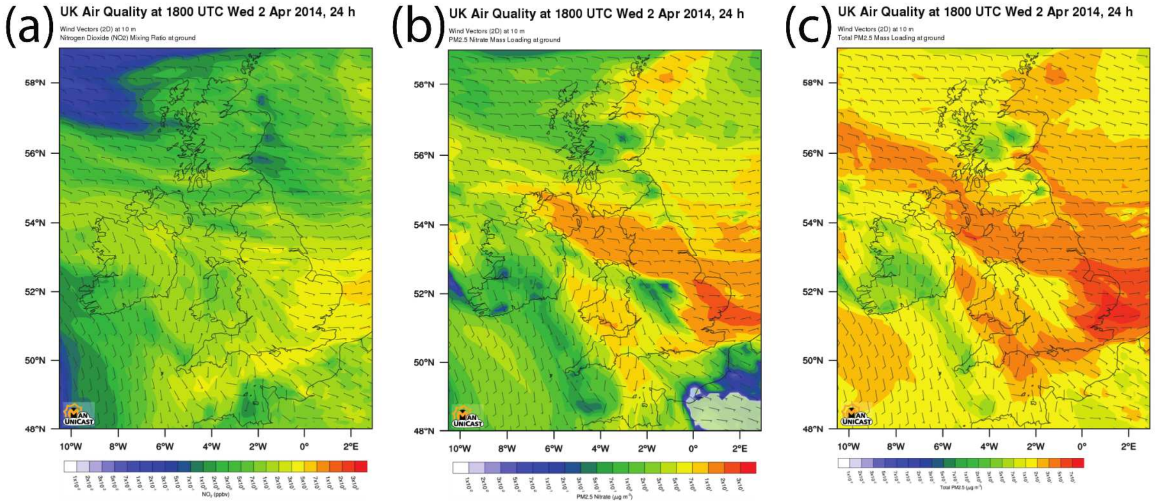

Figure 6. 24-h WRF-Chem ground-level forecasts for 1800 UTC 2 April 2014: (a) NO_2 mixing ratio (ppbv), (b) PM2.5 nitrate mass loadings (μg m^{-3}), and (c) PM2.5 total mass loadings (μg m^{-3}). Each plot also includes wind barbs (full barb and half-barb denote 10 and 5 m s^{-1}, respectively).