Institution: University of Leeds		
Unit of Assessment: B10, Mathematical Sciences		
Title of case study: Direct use of new data analysis and diagnostics by the Met Office in the prediction of locally extreme and high-impact UK weather		
Period when the underpinning research was undertaken: September 2012 to present.		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Douglas Parker	Professor	1997-present
Period when the claimed impact occurred: 2018 onward.		
Is this case study continued from a case study submitted in 2014? N		

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

New diagnostic methods developed at Leeds [1] are being used by the Met Office [A,B,C] to exploit crowd-sourced data [D] and to provide forecasters with maps showing, at unprecedentedly high resolution, the UK surface-weather conditions. The products feed directly into Met Office forecasts and alerts of extreme events [A,B,C]. One example [B] shows how a successful flood alert would not have been possible without these products.

Exploiting the observational work [1], we devised a predictor of tornado probability [1,2]. Clark, who is employed as a scientist at the Met Office and registered as a part-time PhD student supervised by Parker, has shared the methods with Met Office senior forecasters through research-to-operations seminars. The methods enabled forecasters to estimate the probabilities of UK tornadoes on a case-by-case basis [C], increasing confidence in the alerts they have provided to the public.

2. Underpinning research (indicative maximum 500 words)

The research developed in Leeds used novel observational analysis techniques [1] to explain the atmospheric conditions that are conducive to the development of tornadoes on intense UK cold fronts [1,2].

The innovative methodology in [1] was the application and automation -- for the first time in the UK and, to the best of our knowledge, internationally -- of a real-time bias-corrected analysis technique for observations from a dispersed network of surface-weather data. The research was able to evaluate the limits of the possible analysis, in particular demonstrating (for the first time) the extent to which fine structures and derivatives of fields, including calculation of convergence and vertical vorticity fields, could usefully be made [1,α,D]. The data analysis takes observations on a spatial network of weather stations separated by, on average, 5-20 kilometres (typically with higher resolution where it is most needed, in highly-populated areas), and interpolates them onto a 5 km grid for the whole of the UK. The research in [1,α,D] demonstrated that boundaries such as fronts or shear lines, and the associated vorticity and convergence, could be resolved accurately in the gridded fields on these 5 km scales. For comparison, prior methods gave forecasters only the maps of raw station data, at resolutions of around 30km; the fronts and shear lines had to be drawn on charts by hand; and, derived quantities like vorticity and divergence were not available to the forecasters at all from surface observations.

The research [1,2] identified, for the first time, the atmospheric fluid-dynamical conditions causing cold-frontal tornadoes. Tornadoes occur preferentially in conditions of strong post-frontal winds oriented at a high angle relative to the front [1]. The high-resolution observations demonstrate that the development of pre-tornadic vortices is consistent with theoretical fluid-dynamical models, giving confidence that the results are robust and enabling forecasters to have good conceptual understanding of a weather situation (so-called “situational awareness”).

In subsequent research [2] we significantly improved the analysis of conditions favourable for tornadoes on UK cold fronts, increasing the sample of cases from 15 to 114. A quantitative tornado probability, p(TN), has been derived on the basis of two parameters: frontal shear vorticity and the normal component of post-frontal winds. This represents a more quantitative version of the results in [1] from a bigger dataset and wider range of parameters. UK forecasters are testing and using the quantitative tornado probability diagnostic, and it has influenced forecasts [C].

This research was initiated by a secondment of Clark from the Met Office to the University of Leeds in the period September-November 2012, with the aim of gaining fundamental scientific understanding of atmospheric dynamics associated with UK windstorms. The resulting paper [1] included, for the first time in the UK, gridded surface fields from the surface data; the paper was effectively a pilot study demonstrating that it is possible to obtain useful parameters by sophisticated analysis of data from a network of sites. Clark subsequently registered for a part-time PhD at the University of Leeds, during which time he extended the analysis to include data from the crowd-sourced Weather Observation Website (WOW) [α,D].

3. References to the research (indicative maximum of six references)
Staff conducting the underpinning research from the submitting unit are highlighted in bold font.

[1]. Clark M.R., **Parker D.J.** 2014. On the mesoscale structure of surface wind and pressure fields near tornadic and nontornadic cold fronts. *Monthly Weather Review* **142**(10), 3560-3585. https://doi.org/10.1175/MWR-D-13-00395.1

[2] Clark M.R., **Parker D.J.** 2020. Synoptic and mesoscale controls for tornadogenesis on cold fronts: A generalised measure of tornado risk and identification of synoptic types. *Quarterly Journal of the Royal Meteorological Society,* in press. https://doi.org/10.1002/qj.3898

Supplementary reference to third-party authors:

[α] Clark M.R., Webb J.D.C., Kirk P.J. 2018. Fine-scale analysis of a severe hailstorm using crowd-sourced and conventional observations. *Meteorological Applications* **25,** 472-492. https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/met.1715

4. Details of the impact (indicative maximum 750 words)
New automated data analysis based on our methods [1] is yielding maps of prevailing UK surface-weather conditions, which are used by UK forecasters on a daily basis to predict high-impact weather [A]. Clark extended [α,D] the published methods [1] to develop an automatic analysis of Weather Observation Website (WOW) data (i.e. “crowd-sourced” home-based automatic weather stations) plus a subset of the official Met Office surface station data (~80 stations that report back to HQ in real time, out of a total of ~300 UK stations). The approach significantly increases the effective spatial resolution of the maps that can be derived from official Met Office stations. Prior to this work, forecasters had access to only charts showing quantities observed Met Office station locations, on a spatial resolution of around 30 km. The new charts are mapped on a grid of 5 km resolution and we have shown [1,α,D] that they capture derived features of vorticity and convergence accurately. The increased resolution significantly increases the value of the weather forecasts provided to customers (e.g. emergency responders), because 5 km is the most “user-relevant” scale, e.g. that of a town.

The products are maps of surface-weather conditions, constructed from the bias-corrected WOW data. The analyses are created every 10 minutes, about 12 minutes behind real time. They are one of a number of trial products (the others being mainly radar-based) supplied to Met Office Ops Centre since early 2018, as part of the Nowcasting project (led by Met Office Chief Meteorologist [A]). The maps show forecasters the prevailing conditions of pressure, winds and temperatures, and derived fields including convergence and vorticity on the 5 km grid scale. In particular, the horizontal convergence from the gridded wind field helps forecasters pinpoint the most likely locations of convective storm initiation on days when impactful storms are anticipated. These products are now being used operationally by forecasters and have improved [A,B] their ability to provide successful [B,D] short-term alerts of severe UK weather: the surface maps *"represent a step-change in the level of information on surface conditions, and their spatial variability, available to the UK's operational weather forecasters … the new maps are used on days when thunderstorms or other mesoscale severe weather phenomena are anticipated to help analyse the most likely locations for occurrence of high-impact weather, including severe local winds, thunderstorms and flash floods." [A].*

The automated generation of these products follows the methodologies developed in the research at Leeds [1]. Through his position in the Met Office, Clark was able to work with colleagues, including operational forecasters, to promote the new methods, and to integrate them into operational forecasting practice at the National Severe Weather Warning Service (NSWWS).

One example of the WOW analyses helping to inform the NSWWS decision-making process occurred on 27 May 2018 [B,D]. "*The development of severe convection was finely balanced with [Numerical Weather Prediction] NWP output showing the potential for convective release but tending away from realising severe developments. During that afternoon, the WOW analyses showed increasing thermal contrast and surface convergence across parts of the Midlands and this, combined with satellite imagery developments, aided in the decision to increase the likelihood of the warning – resulting in an AMBER weather warning being issued across the Birmingham area. This warning was then available on the Met Office website and app and was send directly to emergency responders in the affected areas. This highlighted the increasing likelihood of impacts from severe thunderstorms such as flooding and allowed emergency responders to stand up operations in preparation for rescue operations*" [B]. In the event, flash flooding occurred in Birmingham as predicted.

The use of the maps of surface weather conditions in research [1] has explained the conditions leading to UK cold-frontal tornadoes [1,2]. "*Previously, there has been no guidance available to UK meteorologists, as to whether a tornado may form on a given cold-front, … on the basis of your research with Matt Clark, we now have a quantitative predictor of tornado probability, backed up by evidence and physical understanding*" [A]. The predictive tools emerging from this work [2] are now also being used and tested by UK forecasters [A,C] to assess the likelihood of these tornadoes and to influence the forecasts and alerts which are issued. The probability of tornadoes, p(TN), has been computed and tested in two cases by the Chief Forecaster on duty, and used alongside other evidence to influence the Met Office internal forecast-discussion and daily briefing, the outcome of which is the daily written brief to all forecasters [A]. The information increases the "situational awareness" of forecasters, alerting them to the possibility of tornadoes and enabling them to respond to the changing situation. "*By explaining, for the first time, 'how' and 'why' tornadoes form in a given weather system, meteorologists are much better prepared to anticipate events in advance, to interpret and challenge the results of numerical weather prediction models, and to communicate their confidence in a given forecast*" [A]. For example, the genesis of tornadoes is explained in [1,2] in terms of wind patterns recognised by the forecaster, and in terms of fluid-dynamical mechanisms understood by a forecaster, such as horizontal shear instability.

In one event of 10th December 2019, this information was used to influence the judgement of forecasters [C] of the prevailing elevated tornado risk, one day in advance of the event. The Chief Forecaster was able to use the results of the research [2] to calculate a tornado probability of p(TN) ~ 0.5, and this was supported by other measures developed for US tornadoes. This knowledge increased the forecasters' situational awareness, prompting them to consider the tornado risk in greater detail and, as a result, the "internal guidance" circulated among Met Office forecasters on 9th December 2019 noted the risk of high-impact winds. In the event, a tornado did occur.

As a result of the research [1,2], Clark is regularly consulted by the Met Office forecast office to advise the forecasters directly when they anticipate a risk of UK tornadoes, for instance in winter cold-front situations. Since 2018 Clark has advised Met Office forecasters [A] about 5-10 times per year on the impending risks of tornadoes, usually through use of internal networking-platforms within the Met Office. In this manner the research is increasing the wider capabilities of the staff in the Met Office: Clark, a Met Office scientist is using his experience developed in the research with Parker [1,2] and his PhD studentship at the University of Leeds, to advise and train the Met Office forecasters [A] on the impending risks of tornadoes.

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

[A] Letter from Met Office Chief Meteorologist explaining the value of the new products and how they are being used since 2018.

[B] Letter from Met Office Chief Forecaster during the 27 May 2018 event, to explain how the products influenced his successful guidance on that day.

[C] Letter from Met Office Chief Forecaster who calculated the diagnostic of the model data from some winter events.

[D] Kirk PJ, Clark MR, Creed E. 2020. Weather observations website. *Weather.* https://doi.org/10.1002/wea.3856