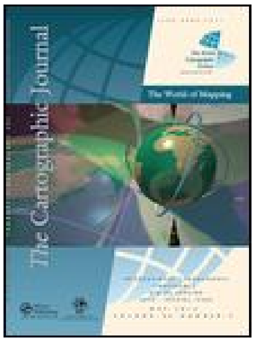
# *Cartograms for use in forecasting weather driven natural hazards*



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# Cartograms for Use in Forecasting Weather-Driven Natural Hazards

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**ABSTRACT**
This paper evaluates the potential of using cartograms for visualizing and interpreting forecasts of weather-driven natural hazards in the context of global weather forecasting and early warning systems. The use of cartograms is intended to supplement traditional cartographic representations of the hazards in order to highlight the severity of an upcoming event. Cartogrammetric transformations are applied to forecasts of floods, heatwaves, windstorms and snowstorms taken from the European Centre for Medium-range Weather Forecasts (ECMWF) forecast archive. Key cartogram design principles in standard weather forecast visualization are tested. Optimal cartogram transformation is found to be dependent on geographical features (such as coastlines) and forecast features (such as snowstorm intensity). For highly spatially autocorrelated weather variables used in analysing several upcoming natural hazards such as 2m temperature anomaly, the visualization of the distortion provides a promising addition to standard forecast visualizations for highlighting upcoming weather-driven natural hazards.

**KEYWORDS**
Cartogram; data visualization; weather forecasts; early warning; natural hazards

## Introduction

Maps are one of the fundamental ways to describe both the human sphere and the Earth's physical geography (Hennig, 2014). Spatial communication and decision-making are known to be enhanced through the use of maps (Arciniegas *et al.*, 2011) and visual representations lead to more holistic and intuitive decision-making (Sloman, 1996). Maps are used routinely in weather forecasting to communicate the upcoming weather and to support forecaster decision-making (Gigerenzer *et al.*, 2005; Keeling, 2010; Fairbairn and Jadidi, 2013; Zabini *et al.*, 2015). However, it is well understood that maps can both foster or hinder understanding of what is trying to be communicated depending on their composition and interpretation (Hennig, 2014) and this is also true in many aspects of weather forecast communication (Demuth *et al.*, 2012).

Cartograms are created by transforming a map based on some numerical or statistical information, usually with a static geographical shape at the centre of interest, but with the remaining geographical areas scaled in proportion to the numerical/statistical data. For example, the globe could be scaled according to available freshwater resources, which would show the European continent larger in comparison to Northern Africa. Cartograms have become very popular in a number of different disciplines, including social, political, agricultural and epidemiological applications, as a way of supplementing existing maps to highlight particular features, e.g. the availability of arable land (Kaspar *et al.*, 2011; Hennig, 2014; Nusrat and Kobourov, 2016; Nusrat *et al.*, 2018). There is a learning curve in being able to use and interpret cartograms because of the distortion compared to the typical geographic representation of the data (Tobler, 2004). However, this is a similar challenge to the use and interpretation of different map projections (Battersby, 2009) in which some distortions can be considered acceptable if key properties are conserved. Hence cartograms have the potential to be a key supplement in understanding the world when users are familiarized with their look and meaning.

The concept of a *weather forecast value chain* considers that there is a chain from forecast producer to forecast consumer and value is added at each step. A key step in this chain is that of producing effective forecast visualizations or summary statistics from raw weather model output in order to support forecasters and other users in their decision-making. Experimenting, showcasing and developing novel forecast visualization is particularly important for large weather forecasting centres, such as the European Centre for Medium-Range Weather Forecasts (ECMWF). The visualization techniques to support the forecast user community must keep

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pace with the continuous developments in forecasted variables, archived forecast timestreams and statistical products. Forecast users are particularly keen for innovation in forecast visualization to assist with providing warnings of upcoming weather-driven natural hazards (Haiden *et al.*, 2016; Hewson, 2017).

Forecasters need a variety of different information in interpreting natural hazard forecasts including understanding the location, severity, likelihood and timescale of an event (Table 1). However, effective forecast visualization has many challenges; forecasts are very complex with many variables and timescales to display, usually involving data from probabilistic and/or multi-model forecasts (Demeritt *et al.*, 2010; Ramos *et al.*, 2010; Spiegelhalter *et al.*, 2011; Cloke *et al.*, 2013; Rautenhaus *et al.*, 2015; Davis *et al.*, 2016; Quinan and Meyer, 2016). Finding optimal ways to present forecast information and associated uncertainties is challenging, but good solutions can be found if developed in collaboration with decision-makers (Cox *et al.*, 2013; Pappenberger *et al.*, 2013). Forecasting also usually means time pressure in the decision-making, which typically has a negative impact on objective decision performance (Zakay, 1982; Zakay and Wooler, 1984). In addition, cartographic visualization methods and user preferences vary between different nations and regions (Duhr, 2004). Table 1 shows a taxonomy of cartogram properties and how they relate to forecast information (edited from Nusrat and Kobourov (2015) and Schulz *et al.* (2013)).

In this paper, the suitability of a variety of cartogrammetric transformation techniques in the representation of upcoming weather-driven natural hazards is explored. Key design principles are considered and a sensitivity analysis of these undertaken using key examples of forecasts of weather-driven natural hazards.

## Methods and data

In this section, the methodology used to create the cartograms is first described, followed by an explanation of the design of the sensitivity analysis and the case study data used.

### *Cartogram techniques*

The cartogram generation technique applied in this paper is a diffusion-based method for producing density equalizing maps (Gastner and Newman, 2004, modified by Hennig, 2013). This method has previously been applied in a range of fields including the mapping of natural hazard risk (Hennig, 2014). It is based on diffusion equations as a transformation which emulates the process of a flowing liquid from higher to lower densities to smooth out differences (Gastner and Newman, 2004). This technique was selected as the most suitable from a large number of possibilities (Nusrat and Kobourov, 2016) as it preserves topology (meaning two regions are neighbours only if they are neighbours in the original map); it has a high statistical accuracy (modified areas represent the corresponding statistics); and the resulting cartogram is contiguous (it is not shape preserving) but also creates recognizable regions (Guseyn-Zade and Tikunov, 1994). These attributes, alongside the free availability, mean that the technique is now widely applied (Nusrat and Kobourov, 2016).

The original method was applied to administrative units such as countries and regions, but Hennig (2013) proposed a gridded version of the method. The quantitative indicator of each grid cell is resized whilst each grid cell preserves its relative position to its neighbours. The unit in the transformation is therefore not an area of arbitrary size, but a section of a map in which each area has the same geographical context (Hennig, 2013, 2014). Gridded cartograms have advantages over conventional cartograms as they can distort information on an accurate but neutral areal unit (Hennig, 2014). Hennig (2014) also added various other design criteria, for

**Table 1.** Taxonomy of cartograms to evaluate suitability of maps modified after Nusrat and Kobourov (2015) and Schulz *et al.* (2013).

| Task | Description of task | Example based on a display of precipitation anomalies (dry/wet) over Europe |
|---|---|---|
| Detect Change | Detect change in size relative to a baseline map (this is a central feature for cartograms) | Detect whether 'England' has shrunk or increased in size which would mean the precipitation anomaly is below or above normal respectively |
| Locate | Search or find a location | Locate 'England' |
| Recognize | Recognize shape of region | Be able to distinguish the region 'England' from its neighbours |
| Identify | Search for an attribute or characteristic focused on a single object | Identify whether 'England' is predominantly dry or wet |
| Compare | Find similarities and difference between attributes | Compare two regions by size |
| Find top *k* | Find *k* entries with maximum (or minimum) values given an attribute | Find which regions are driest |
| Filter | Find data that satisfy some criteria about a given attribute | Find regions which are wetter than 'England' |
| Find adjacent | Identify neighbours | Find all regions bordering 'England' |
| Cluster | Find clusters or objects with similar attributes | Find regions that are similarly 'dry' to 'England' |
| Summarize | Find patterns and trends to convey the big picture | Are the precipitation anomalies driven by convective storms? |

example, country borders or administrative borders, to allow faster orientation. Map orientation aligns with widely used conventional map projections and the prime meridian is not always in the centre unless it aids interpretation. A colour scheme is used to support the information.

### *Cartogram sensitivity testing*

The sensitivity testing involves perturbing the parameters of cartogram distortion and analysing the effects on the readability of the forecasts from ECMWF. The aim is to provide useful supporting information for a forecast in order to enhance the understanding of forecast attributes, including event severity, timing and location. The sensitivity analysis considers several aspects of a cartogram that can be varied focusing on properties which are currently used within the setting of the global weather forecasting environment, including spatial autocorrelation; the range of values which are displayed (e.g. which minimum and maximum temperature); the value to which sea points are set (e.g. minimum, maximum or median value of the map), the inclusion of geographic features such as rivers, cities or borders and the geographic extent selected to display. All these choices impact upon the final look of a cartogram and therefore have an influence on the taxonomy properties listed in Table 1.

### *Data*

ECMWF produce a range of different weather forecasts (see www.ecmwf.int). A key product is the *medium-range forecast* which consists of an ensemble of 52 individual forecast members forecasting 15 days ahead in time and which is created twice a day. Ensemble forecasting is a probabilistic forecasting method which quantifies the uncertainty that is inherent in all weather forecasts by perturbing the initial state and the model physics. One forecast member is called the *high resolution forecast* and has a horizontal resolution of ~9 km (correct at October 2018). This member is important because it is created using the most accurate estimation of the initial state of the atmosphere. This is complemented by 51 ensemble forecast members at a lower spatial resolution of ~18 km (correct at October 2018). This provides a range of possible future weather scenarios. Twice a week, this ensemble is extended to 46 days providing a *monthly forecast.* The medium range and monthly forecasting systems are complemented by a *seasonal forecast* which predicts large-scale weather patterns up to 13 months ahead.

ECMWF updates its modelling system up to 3 times a year, and for the analysis undertaken here, the forecasting system which was operational on the date of the extreme event is used. A full history and description of the ECMWF forecasts are provided by Persson (2015) and further information on the model system evolution can also be found at ECMWF (2017b). ECMWF forecasts are available for a large number of weather and earth system variables relevant for natural hazards, such as precipitation, temperature, snowfall and soil moisture. These variables are visualized in many different ways to enable the forecast user to interpret the forecasts effectively and communicate them to decision-makers (more information on the charts currently provided can be found on ECMWF (2017a).

Weather forecasts are assessed by statistics related to their performance; this considers aspects of accuracy and reliability, termed *skill*. ECMWF forecast skill has continuously improved and the forecasts have proven to be useful for identifying upcoming extreme events (Haiden *et al*., 2016). ECMWF has developed particular tools in order to aid decision-making from uncertain forecasts including the Extreme Forecast Index (EFI) (Dutra *et al*., 2013; Alfieri *et al*., 2014; Zsótér *et al*., 2015; Lavers *et al*., 2016). The EFI compares a forecast with a climatic distribution (constructed from some kind of long-term average) and expresses the difference as a value between −1 and 1. Larger anomalies in the weather forecast are represented by values further away from zero. ECMWF archives forecasts of extreme weather events across the globe and documents and analyses forecast performance in a Severe Event Catalogue (ECMWF, 2017c). Several events have been chosen from this catalogue for analysis in this paper (listed in Table 2) in order to consider the influence of cartogram construction on the interpretation of a range of the variables and products used in forecasting for weather-driven natural hazards.

## Results

This section considers the influence of several cartogrammetric parameters on the cartogram effectiveness including the spatial autocorrelation of the variable (measuring the similarity between neighbouring objects), the range of values which are displayed (e.g. which minimum and maximum temperature), the value to which sea points are set (e.g. minimum, maximum or median value of the map), and the inclusion of geographic features such as rivers, cities or borders and geographic extent.

**Table 2.** Data and forecasted weather variable or index used in the visualizations of cartograms.

| Natural Hazard | Weather variable or index forecasted | Additional Description | Event(s) | Lead time (time range into the future) displayed |
|---|---|---|---|---|
| Flooding | Total Precipitation (mm) | Total precipitation (includes all types of rainfall and snowfall added together) | **F1**: Flooding of the River Seine in June 2016 | 3 days and 18 hrs |
| | | | **F2:** Severe and unseasonal rainfall in southern Thailand in January 2017 | 6 hrs |
| Heatwave | Extreme Forecast Index (EFI) of 2 metre temperature | Index measuring the severity of an extreme temperature event (very high or very low temperature) derived from ensemble forecast | **H1:** Heatwaves in Western Europe in September 2016 | 3 days–10 days |
| Heatwave | Time average ensemble mean of 2 metre temperature anomaly | Average of the ensemble mean over a given time period e.g. 1 week with respect to a given climate to calculate anomalies | **H2:** Heatwave in south-eastern Australia in February 2017 | 7 days–15 days |
| Windstorm | Wind gust at 10 m | Short burst of increased wind speed at 10 metre height | **W1:** Windstorm in Australia in September 2016 | 3 days |
| | | | **W2:** Windstorm in France in March 2017 | 3 days |
| Snowstorm | Extreme Forecast Index (EFI) of snowfall | Index measuring the severity of an extreme snowfall event (very high or very low snow) derived from ensemble forecast | **S1:** Snowstorm in Sweden in September 2016 | 0–24 hrs |
| | | | **S2:** Snowstorm in east coast USA in March 2017 | 0–24 hrs |

Note: Details for all events are available in the severe event catalogue of ECMWF (https://software.ecmwf.int/wiki/display/FCST/Severe+Event+Catalogue).

## *Influence of spatial autocorrelation of a variable*

Figure 1(a,b) shows a cartogram constructed for event **H2** (Australian Heatwave) in order to highlight the severity of the forecasted natural hazard. In the figure, the cartogram including distortion is displayed at the top, the benchmark (standard) forecast map below, for the time averaged ensemble mean of the 2 m temperature anomaly. State borders are displayed on the cartograms and it is clear to see that the area of increased temperature is noticeably enlarged. The ocean is set to the median value and thus the land mass only shows a minimum distortion. The hot area is clearly more dominant and can be easily geographically pinpointed.

The cartograms for an extreme windstorm event in Australia in September 2016 (event **W1**) are shown in Figure 1(c,d). The map as would be expected has distinct similarities to Figure 1(a,b) as it is an extreme natural hazard event over Australia. However, temperature has a high spatial autocorrelation whilst wind gust has a far lower autocorrelation and has more localized areas of extremes. In this example, it is again clear that the area

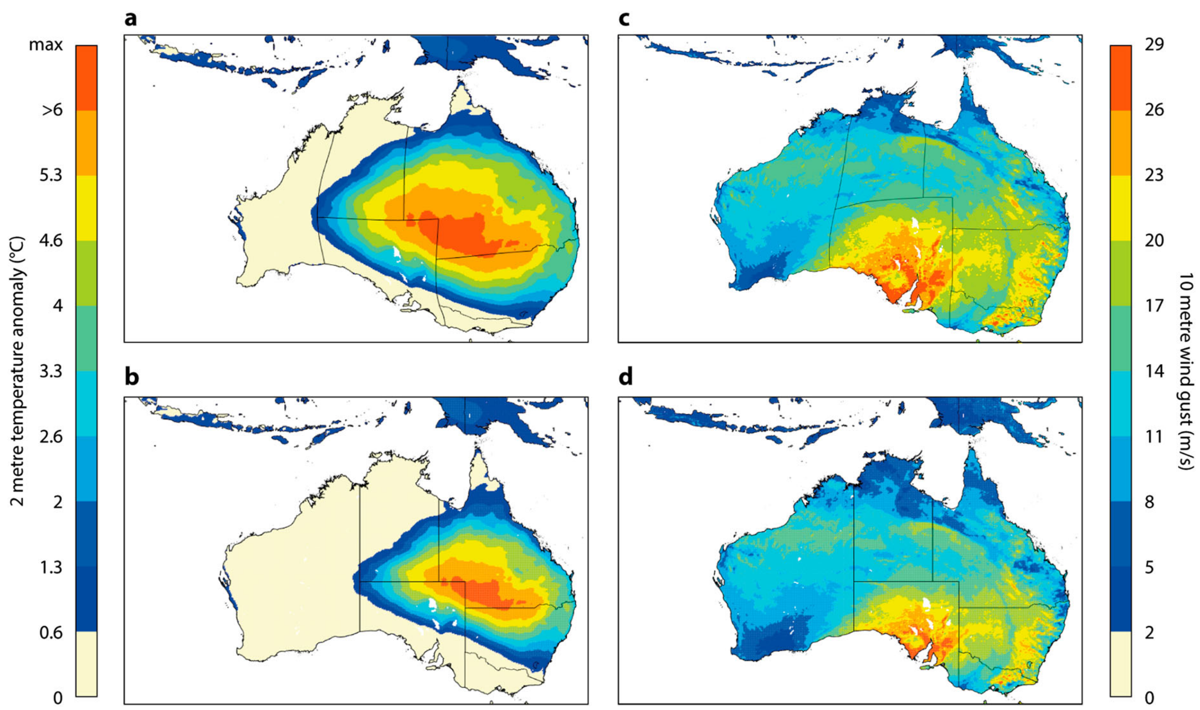


**Figure 1.** (a, b) Time average ensemble mean (2 m temperature anomaly) over Australia in February 2017 (event **H2**). The temperature scale displays an anomaly above the average. The higher the value the hotter in comparison to the climate. (c, d) Wind gust at 10 m for an extreme windstorm event in Australia in September 2016 (event **W1**). The top figures (a, c) are distorted, whilst the bottom figures (b, d) show the benchmark forecast and thus shows an undistorted map.

of interest in the South of Australia is clearly enlarged which is useful for an overall picture of upcoming hazard. However, there are also smaller areas of high windspeed and these are less clearly pronounced because they are embedded in other values. The lower the spatial correlation of a variable the more difficult it is to detect change and the more difficult it is to compare or find the top k (sixth entry in the taxonomy of Table 1). Being unable to identify the windiest region thus makes it more difficult to summarize the map. Other related findings from this example are that the variable wind speed shows a much finer structure with less clear boundaries making any enlarged area far less visible.

### *Influence of variable scale minimum and maximum values*

Any static map is constrained by the range of values selected for display. Maps that consider the EFI require the specification of a minimum and a maximum value. This range will influence the distortion of the cartogram and this is demonstrated by changing the minimum value of the EFI. It should be noted that even on standard maps, changing the minimum and maximum values changes the appearance and focus of the map.

Figure 2 shows the influence of the minimum value of the EFI for the extreme weather event of the snowstorm in Sweden/Russian in September 2016 (event **S1**), and wind gust at 10 m for an extreme windstorm event in France in March 2016 (event **W2**). Each weather event is more pronounced in the cartogram when using a lower minimum threshold which leads to a larger value range (Figure 2(a,e)). With lower minimum thresholds change detection can be seen to be clearly reduced, whilst recognition of regions is increased. This is demonstrated by the dark red area of extreme snowfall in Figure 2 which gets progressively smaller from Figure 2(a–d) (and a similar behaviour is noticeable for wind gust in Figure 2(e–h)). This red area is displaying the same values of EFI, but because the range of values (maximum minus minimum thresholds) determines the magnitude of the distortion, the distortion is reduced for higher minimum thresholds. In addition, spatial autocorrelation plays a significant role which can be seen when comparing the EFI of snowfall, which has high spatial autocorrelation (Figure 2(a–d), left hand panels), to wind gust, which has a lower spatial autocorrelation (Figure 2(e–h), right hand panels), the latter of which shows a less visible change.

### *Influence of value for sea*

All areas with missing values require the map designer to take a decision on how to assign a value. This is particularly the case for areas which have been masked out such as the sea. In Figures 1 and 2, the sea values were set to the median. This preserves the geographic shape of the land mass as there is a minimal distortion of the sea values. If in contrast the sea is set to the minimum value, the land masses expand substantially to compensate (with decreasing sea values the land mass expands proportionally) which can be seen in Figure 3. Figure 3 shows three different settings: in the top panels (Figure 3(a,e)), the sea is set to maximum value observed on land; in the second row of panels (Figure 3(b,f)), the sea is set to the average value observed over land; and in the third row of panels (Figure 3(c,g)), the sea is set to the minimum value observed over land. The bottom panels (Figure 3(d,h)) are undistorted for comparison. The Thailand example **F2** (right hand panels of Figure 3) is the most striking with land area increasing with a decrease of the sea value (as expected). The result can be so extreme that the extreme precipitation feature fills the entire plot (Figure 3(g)) and that no other cartographic features remain visible. In the Thailand example, all land points have a value (meaning there are no missing values). This is not the case for the Snowstorm in the East coast of USA **S2** (left hand panels in Figure 3), where there are areas on land with no values. In this setting, the distortion is less sensitive to the setting of the sea value, and although land areas still grow between Figure 3(a–c), the missing values result in a weaker distortion. This points to the necessity in comparing cases with and without missing values in order to exemplify this behaviour. Although the differences in Figure 3 are striking there are no clear advantages or disadvantages of a particular cartogram setting for sea areas overall, and it must be considered carefully depending on the phenomenon, variable and geographic location under consideration. Certainly for large land masses, the impacts of extreme distortion can make the cartogram indecipherable when minimum values are selected for sea areas, however, for more complex coastlines a low value may be more desirable.

### *Influence of geographical features*

In the previous examples (Figures 1–5), country or state borders were displayed on the cartograms to orientate the reader. However, there are a number of additional geographical features that can be added in order to enable more effective decision-making. In Figure 4, rivers and cities are added to a significantly distorted map in order to provide additional orientation. Whilst cities seem to contribute to the ability to interpret the map, at first glance

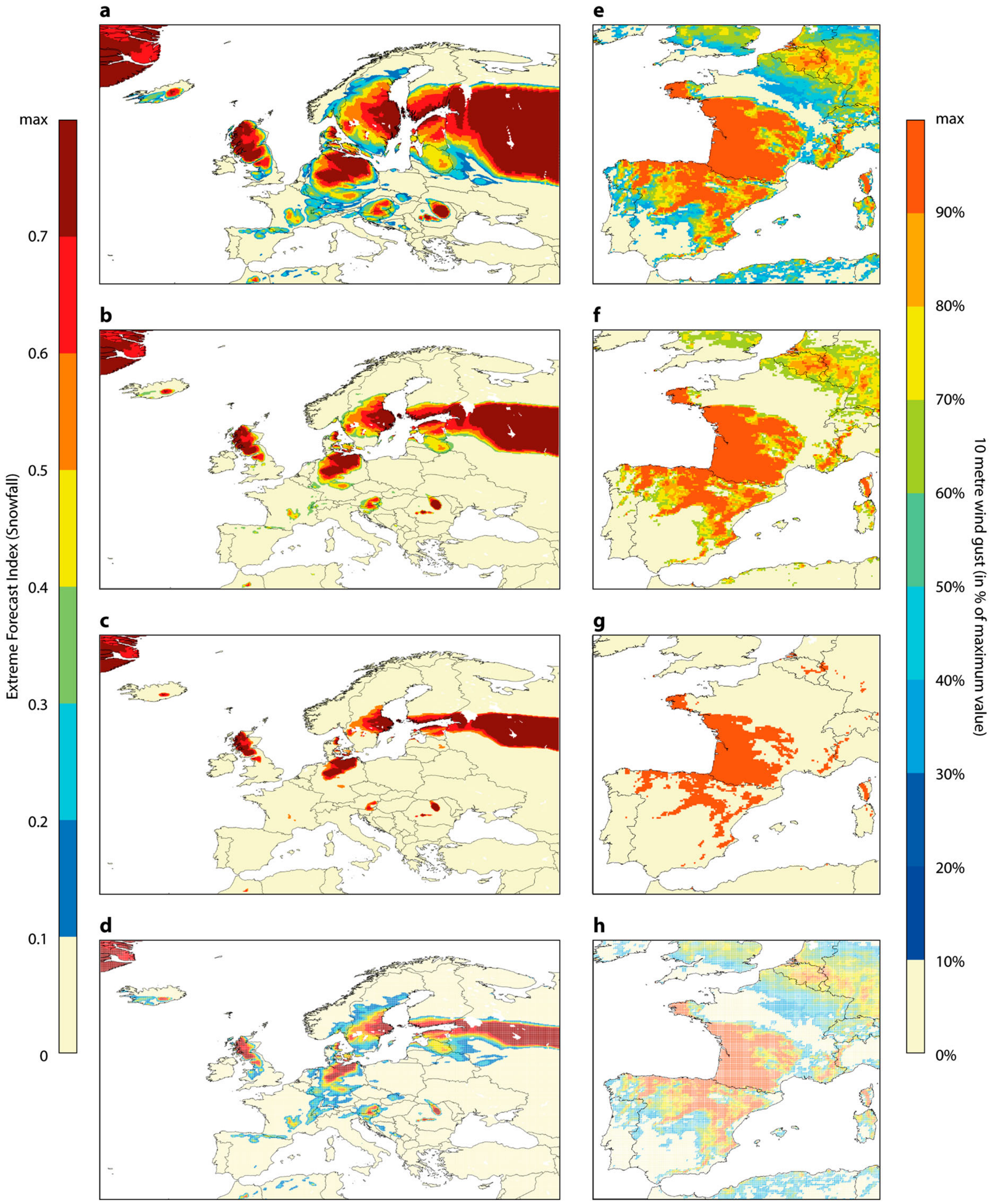


**Figure 2.** (a–d) Extreme Forecast Index (Snowfall) for Snowstorm in Sweden/Russia in September 2016, event **S1**; lead time displayed: 0–24 hrs.; (a) EFI minimum at 0.1; (b) EFI minimum at 0.3; (c) EFI minimum at 0.5 (e–h); (e–h) wind gust at 10 m for an extreme windstorm event in France in March 2016 (event **W2**). Values are expressed in % of maximum wind gust. Lead time displayed: 3 days; (a) minimum at 20%; (b) minimum at 50%; (c) minimum at 80%; (d, h) are the undistorted maps.

it may seem that the rivers seem to help much less because their shapes and outlines are less familiar in general. However, based on the authors' practical experience of natural hazard forecasting it is usually the case that for a forecaster familiar with a particular river this may be more useful. Figure 4 shows the case of extreme precipitation in France in June 2016 (event **F1**) which led to flooding on the River Seine. In this case, the amount of precipitation falling upstream of Paris and the affected parts of the Seine is of key consideration. In Figure 4(a) the upstream area becomes more clearly visible in comparison to the undistorted version (Figure 4(b)). In this case, as the river is a continuous feature and the labelling was kept constant, the labelling of 'Seine' is distorted away from the centre of the plot. This potentially makes the flood hazard less clear, and therefore a correction to ensure river labels remain at prominent locations would be required. Other geographical features such as river catchment outlines could also help in this context.

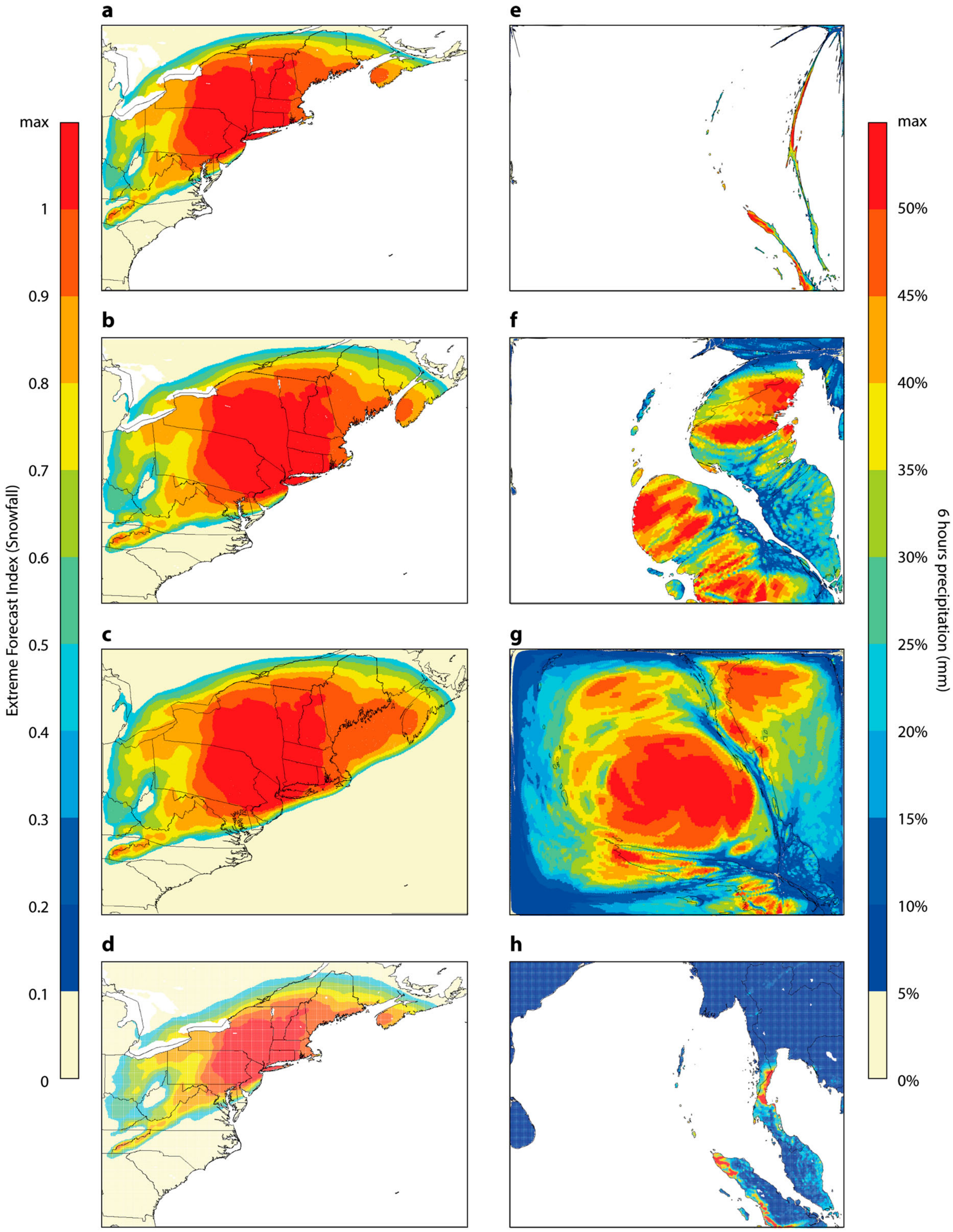


**Figure 3.** (a–d) Extreme Forecast Index (Snowfall) for Snowstorm in East coast of USA in March 2017 in September 2016 (event **S2**); lead time displayed: 0–24 hrs. (e–h) Extreme precipitation in southern Thailand in January 2017 (event **F2**); lead time displayed: 6 hrs. (a, e) sea value set to maximum; (b, f) sea value set to average; (c, g) sea value set to minimum, (d, h) undistorted maps.

## *Influence of geographic extent*

In the examples considered above, the cartograms have focussed on a particular geographic region of interest. However, there is an impact of the choice of geographic extent, i.e. size of the geographic domain, on the interpretability of the cartogram. A larger area would theoretically allow a better overview and thus better orientation for the user, however when forecasting the weather other events of interest often occur at the same time, which may result in multiple distortion centres. Figure 5 focuses on a heatwave in Western Europe (event **H1**) and shows distorted maps for a restricted part of Western Europe and also the full Western Europe

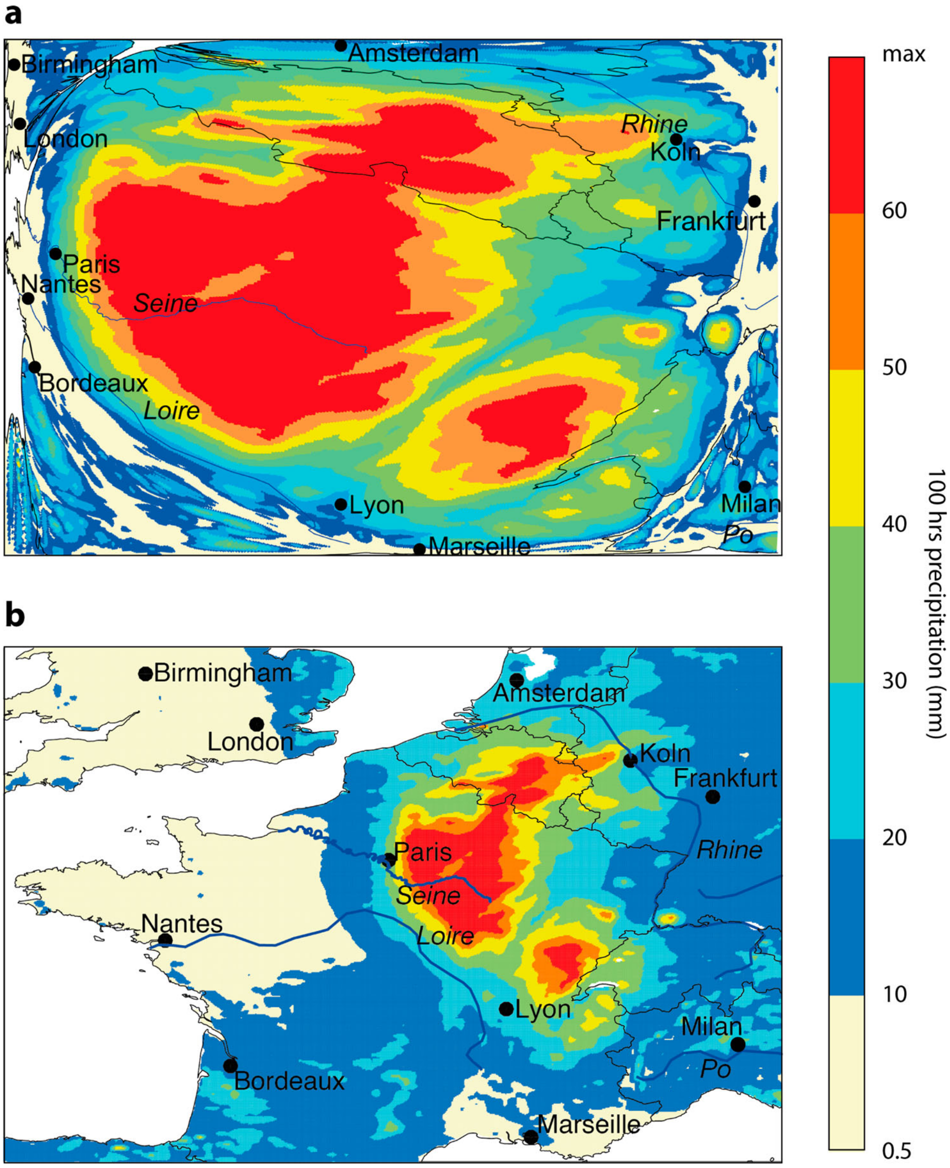


**Figure 4.** Extreme precipitation in France in June 2016 (event **F1**); (a) is the distorted figure whilst (b) is the undistorted figure.

domain. In this example to fully interpret the heatwave extent and characteristics, a user would need the full map, however, for a user in Lisbon, the restricted map may be adequate. In the first case, the distorted map highlights the relevant temperature features in a relevant way, although increased distortion may be desirable in order to amplify regions with extreme values. In the case of the user in Portugal, the distortion is of lesser use. Of course, some of this may be due to the fact that smaller areas are likely to have a smaller range of values. Overall, the extent of the geographic domain selected can dominate over any distortional features of the cartogram.

## Discussion and conclusions

Forecast visualization of weather-driven natural hazards is complex and using maps forms a key part of the interpretation, analysis and decision-making in such forecasting. Here cartogrammetric transformations were considered as a way to aid interpretation, and the suitability of the techniques for visualizing forecasts has been evaluated. Although previously some have criticized the readability of cartograms (e.g. Roth *et al.*, 2010), the aim here was to test some key design principles to overcome these concerns (Nusrat *et al.*, 2018), particularly considering the visualization and decision-making tasks currently used in weather and natural hazard forecasting, and considering key properties intrinsic to weather forecasting such as the spatial autocorrelation of variables.

### *Influence on interpretation tasks*

There are some key interpretation tasks for which the cartograms show added value over traditional maps. Visualizing weather hazard variables that have higher spatial autocorrelation results in a more visible distortion

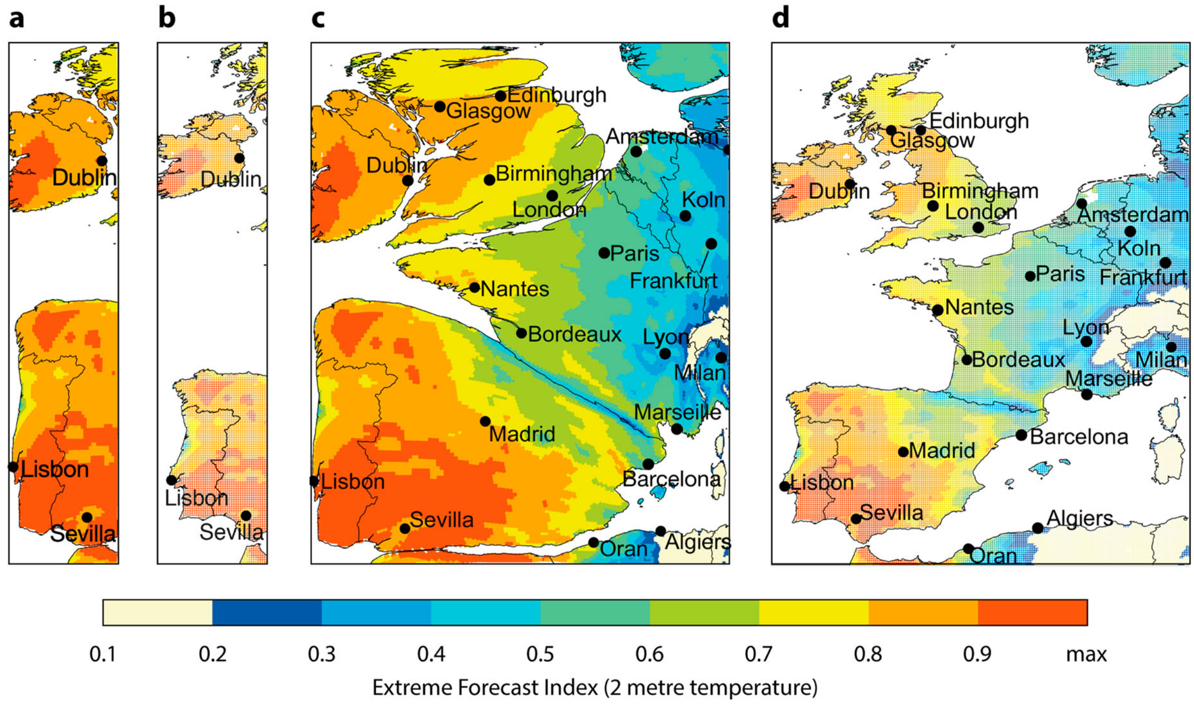


**Figure 5.** Extreme Forecast Index (2 m Temperature) for Heatwaves ibn Western Europe, event **H1**; lead time displayed: 3–10 days; (a, b) geographical area restricted to extreme western part of the continent; (c, d) western Europe; (b, c) undistorted maps.

in the cartogram and thus may lead to earlier detection and warnings of the upcoming natural hazard. Cartograms may then be more suitable in terms of representation for spatially autocorrelated variables such as temperature and less so for model outputs such as wind gust. With decreasing spatial autocorrelation in variables, cartograms do not support the ability to detect change better, find similarities or convey the big picture messages in comparison to undistorted projections. Weather forecast variables often have a large numeric range. For example, in Europe on a given day there may be minimum temperatures of −10 degree Celsius in some locations, whilst there could be maximum temperatures of +30 degree Celsius in other locations. The larger the range the smaller the local distortion of similar neighbouring values, whilst there will be a larger distortion globally as the cartogrammetric representation is driven by differences in values. This may aid the interpretation on a trans-European scale and allow the big picture to be conveyed, but would hinder more localized interpretation, which is also often a key part of communicating weather forecasts.

Forecasts are often visualized using cut-off threshold values of a variable, in particular, when the interpretation focuses on extremes. For example, for heatwaves it is often standard practice to display only the area of anomalous weather, to enable a clearer and easier to interpret map. For cartogrammetrically transformed maps this means that decreasing the range will lead to a less visible distortion, but this still may be a useful distortion in comparison to the standard map. Another typical feature of weather forecast maps is the masking (hiding) of sea values. Although global weather forecasts have no geographical boundaries, values over the sea are often not displayed when they are considered to have little relevance. For example, 2 m temperature or precipitation are often only displayed over land in order to focus attention on where the impacts are, whereas wind is often also displayed over sea to illustrate the large-scale patterns which enable a better understanding of the meteorological situation. This masking of the sea does, however, present a challenge in terms of cartograms as it directly impacts upon how the land mass is distorted. If the sea is set to the average value of the map, then the land mass is largely undistorted. If it is set to the minimum, the land becomes proportionally larger and if set to a maximum then proportionally smaller (always subject to the actual values over land). Different cartogram settings are likely to be best for different types of natural hazard event and weather variable characteristics, particularly in an early warning and decision-making framework. For example, if a land mass completely fills the mapping area because it has very extreme values, then the forecaster will be immediately alerted to an event, but this will only work if the forecaster is familiar with the map in the first place, underlining the importance of providing familiarization training for forecasters.

It has been demonstrated elsewhere that with increasing task complexity the use of maps with specific properties can enhance decision-making performance (Smelcer and Carmel, 1997). Here specific geographical properties were considered such as the addition of cities, rivers and varying geographic extent which have the potential to provide helpful anchoring points, in particular, if forecasters are unfamiliar with the cartogrammetric projections.

However, there is a distinct interplay between the various properties. For example, as found in the results presented above, the extent to which a variable is spatially autocorrelated affects how much distortion may be required to adequately detect change. However, a variable with low spatial autocorrelation will require more distortion, perhaps by setting the sea and/or land values to minimum. Other interactions are, for example, that if focussing upon a large geographic area (global or continental scale) greater distortions may be desired to amplify regions with extreme values. This can provide a way of quickly identifying at risk areas which merit closer investigation by a forecaster.

### *Future considerations*

This study was designed to cover a core series of examples which demonstrate how maps are currently used, and how cartograms could potentially be used, within the daily routine of the forecasting of natural hazards. The cartograms were considered in the context of forming additional information for the forecaster, rather than replacing current information. There are many aspects that were beyond the scope of this initial exercise and which should be tested in further studies: for example, displaying the temporal evolution of forecasts with a coherent cartogrammetric transformation and interactive displays, displaying the uncertainty in the forecasts, displaying risk rather than hazard which would require considerations of vulnerability and exposure. The latter could have been particularly useful during the 2017 hurricane season in the Caribbean, where small, densely populated islands were difficult to identify in undistorted maps. Another next step will be to work with a wider group of forecasters to evaluate the implementation of the cartograms in different real weather scenarios in the forecasting environment, to consider the forecast-specific and geographic-specific aspects of cartogram generation. Work is also needed to integrate the cartograms into forecaster training programmes alongside the large suite of current maps and other forecast visualizations, and to provide long-term familiarity benchmarks for the cartograms. Another consideration might be advanced studies using eye tracking methodologies may help to support the potential value of cartogram introduction to forecast visualization (e.g. Fuchs *et al.*, 2009; Garlandini and Fabrikant, 2009). It might also be useful to consider cartograms as a forecast model diagnostic tool to help determine, for example, where there may be problems with the forecast model, by distorting areas of a forecast map which have large increments (error corrections).

Forecast decision-making will remain a complex process, and maps, whether cartograms or not, will only form one part in it, often other pieces of knowledge will contribute and compete. Effectiveness of maps in this process includes several aspects (Eikelboom and Janssen, 2015) from doing the right thing the right way, improving the quality of the data, enabling the stakeholder to execute what was intended and ensure that the information fits the capability and demands of the decision-maker (Budic, 1994; Goodhue and Thompson, 1995; Jonsson *et al.*, 2011) However, this study has provided initial evidence that cartograms can provide added value over standard maps in the forecasting context.

### *Conclusions*

This study has evaluated the potential of using cartograms to visualize and aid interpretation of forecasts of weather-driven natural hazards, particularly in the context of global weather forecasting and early warning systems. Cartogrammetric transformations were applied to examples of floods, heatwaves, windstorms and snowstorms taken from the global ECMWF forecast archive and used to analyse some key aspects of the interpretation of the forecasts. Results are promising, showing added value in detecting extreme phenomena but also show that the utility of the cartogram is dependent on cartogram design principles. The optimal cartogram transformation is dependent on geographical features (such as coastlines) and forecast features (such as snowstorm intensity), and thus familiarization training for forecasters is essential. It was found, in particular, that for highly spatially autocorrelated weather variables used in analysing several upcoming natural hazards such as 2 m temperature anomaly, the visualization of the distortion provides a promising addition to standard forecast visualizations for highlighting upcoming weather-driven natural hazards.

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