3.1 A PROBABILISTIC VEHICLE OVERTURNING MODULE: ASSESSING THE RISK OF DISRUPTION DUE TO VEHICLES OVERTURNING ON THE UK ROAD NETWORK DURING HIGH WIND EVENTS

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1. INTRODUCTION

Weather forecasting is a dynamic field which has recently been advancing towards using model ensembles to provide probabilistic forecasts as well as providing an assessment of the potential impact of a particular event. The impacts can include, but are not limited to, transport disruption, infrastructure damage and loss of property. The Met Office National Severe Weather Warning Service (NSWWS) uses a matrix to define the warning colour of an event (yellow, amber or red) through a combination of likelihood and impact (Figure 1) (Neal et al., 2013). The impact section of this matrix is relatively hard to quantify as there are numerous factors at play which influence the level of impact expected. Knowledge of the number of people in the affected area as well as amount of infrastructure is taken into account. For example a high intensity storm hitting London would be a high impact event however if the same storm hit northern Scotland the impact would be lesser.

The Natural Hazards Partnership (NHP) is an effort to bring together the leading public sector agencies in the UK in order to prepare, respond and review the hazards which impact the UK. The NHP was established in 2011 and is a collaborative partnership between 12 technical and scientific organisations** including the Met Office as well as five stakeholders*** including the UK Cabinet Office. The overall aim of the NHP is to give coordinated and coherent advice to the government and the resilience community to help prioritise where to deploy responder services.

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** NHP organisations: Met Office, Environment Agency, Natural Environment Research Council (NERC), British Geological Survey (BGS), UK Space Agency, Public Health England (PHE), National Oceanography Centre (NOC), National Centre for Atmospheric Science (NCAS), Health & Safety Laboratory (HSL), Ordnance Survey, Scottish Environment Protection Agency (SEPA) and the Centre for Ecology & Hydrology (CEH)

*** NHP stakeholders: UK Cabinet Office, The Scottish Government, Welsh Government, Department for Environment Food and Rural Affairs (DEFRA) and the Government Office for Science.

The NHP has four main activities. The daily hazard summary assessment is issued everyday to stakeholders and covers a number of hazards including flooding, geological hazards and weather. The aim is to provide an all hazards summary to help increase the UK's ability to respond to, and be prepared for multi-hazard events. The NHP also contributes to the National Risk Assessment (NRA) of the UK by providing scientific overviews of natural hazards and advising on new risks as well as supplementing advice on current known risks. Partners have been developing pre-prepared science notes for each hazard. These contain background information and the key aspects of a hazard that may need to be taken into account ahead of and during an emergency.

The final activity is the Hazard Impact Model (HIM), this uses the data and expertise of the NHP partners to identify areas which are most vulnerable to hazards. The aim is to model where impacts are likely to occur and the risk of disruption using a combination of hazard, vulnerability and exposure. The HIM is currently in its research and development phase and at present consists of three 'modules' each specialising in modelling risk due to a particular hazard. The current modules are surface water flooding, landslides and the vehicle overturning model. This paper focuses on the Vehicle OverTurning (VOT) model which is the showcase module of the HIM.

The definitions of hazard, vulnerability , exposure and risk which are used in the NHP and the HIM are outlined below for clarity.

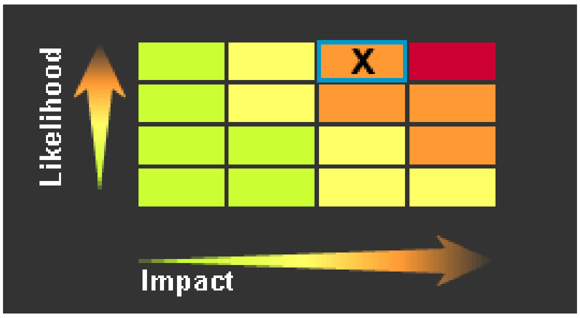

Figure 1 | The NSWWS matrix. This event has a high likelihood and medium impact therefore an amber, be prepared warning is issued (Met Office, 2014).

- *Hazard*: 'natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage' (UNISDR, 2009).
- *Vulnerability*: 'characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard' (UNISDR, 2009).
- *Exposure*: 'people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses' (UNISDR, 2009).
- *Risk:* a function of a hazardous environment and the vulnerability of the exposed elements (Birkmann, 2007)

1.1 *The wind work package*

Part of the Met Office's remit in the NHP is the wind work package. This investigates the affects of high winds on a number of assets across the UK, the effects of high winds impacting the road network and the VOT model itself are at the forefront of this work.

Understanding wind, its hazards and impacts is extremely important especially as wind related domestic property damage in the UK exceeds £340m annually with over 200,000 properties being damaged (Association of British Insurers, 2005). Up to 80 - 85% of natural disaster economic losses in the world have been attributed to extreme winds and accompanying events (Tamura, 2009). Understanding wind hazards is essential for the protection of life and property with increasing damage costs and more of the population living along exposed coasts we need to better define and understand winds and its damage potential (Levitan and Frieland, 2003).

The aim of the wind work package is to encompass a number of assets across the UK, which are affected during high wind events into an overall wind impact model. The model will calculate the risk of damage and/or disruption to these assets to give an idea of areas most likely to be impacted. This will give first responders prior warning to an event and allow them to make decisions based on impact.

2. THE VEHICLE OVERTURNING MODEL

The Vehicle Overturning (VOT) model is a probabilistic model which uses the high resolution Met Office Global and Regional Ensemble Prediction System (MOGREPS-UK) to forecast the wind gust and direction over the UK (Mylne, 2013). The inputs in to the VOT model are hourly 2km gridded wind gust and direction fields which update every six hours. The ensemble has 12 members and a lead time of T+36 hours (1.5 days).

The model uses the Integrated Transport Network (ITN) truck road network layer from Ordnance Survey (OS) MasterMap. This network consists of all major transport routes in the UK including all motorways and the majority of A-roads. The network consists of ~72,000 'links', these are road sections up to 2km long however can be significantly shorter depending on road features e.g. a roundabout consists of a number of 'links' between junctions.

2.1 *VOT Model Hazard*

The VOT model's hazard component uses wind gust thresholds established by Birmingham University (Baker et al. 2008). These thresholds indicate the accident gust speeds required for a vehicle to be overturned. They were established using a simple mechanical model and took in to account the aerodynamic parameters of each vehicle type (e.g. vehicle weight, area and height) and a number of aspects of the road structure (e.g. camber and curvature). Wind speed curves were developed; these highlighted the worst case scenario wind gust accident thresholds for four vehicle types: Unloaded heavy goods vehicles (UHGVs), unloaded Light Goods Vehicles (LGVs), Cars and Loaded heavy goods vehicles (LHGVs). The wind gust values established by this report were 23m/s, 26m/s, 35m/s and 36m/s respectively. These thresholds are used to calculate the probability of wind gust values (from MOGREPS-UK) exceeding vehicle overturning thresholds for each section of the road network. These probability values are output between 0 and 1; with 0 indicating that no member has wind gust values which pass the particular threshold and 1 indicating that all 12 members have wind gust values which exceed the threshold for that particular road section. This method is carried out on each section of the ITN road network.

2.2 *VOT Model Vulnerability*

The vulnerability section of the VOT model consists of four elements. Each element is equally weighted between 0 (least vulnerable) and 1 (most vulnerable) using Equation 1 (Balica et al, 2012). This was determined to be the best option as there is no defensible method for assigning weights to these factors (Cutter et al, 2003).

$$\delta = \frac{d - d^{min}}{d^{max} - d^{min}} \quad (1)$$

where *d* is the element value, d^{min} is the minimum element value over all road sections and d^{min} is the maximum element value over all road sections.

1. *Altitude of Road Section*: The mean altitude of the road section was derived from a 90m digital elevation model (DEM). Here it is assumed that high altitude roads are more likely to experience higher wind gusts that those at a lower altitude. These values are then normalised using Equation 1.

2. *Number of Lanes*: This is used as a proxy for carriageway width and indicates the road sections' ability to absorb the effects of a hazard. It is assumed that single lane carriageways are less able to absorb the effects of an overturned vehicle and are more likely to be closed than those with multiple lanes. Should a vehicle overturn on a carriageway with a high number of lanes certain lanes may close however traffic is still able to pass the incident reducing the impact on the surrounding road network. Single lane carriageways therefore have the highest vulnerability (value of 1) and the largest carriageways, sections of the M25 (motorway around London) have six lanes, have the lowest vulnerability (value of 0). Values in-between are normalised between 0 and 1.

3. *Aspects of Infrastructure*: This provides additional information on which roads have an enhanced susceptibility to high winds. This data is from the OS 1:250,000 scale OS Travel Map and ITN layers. A road section in a tunnel has a vulnerability value of 0 (least vulnerable) as the tunnel shields the road from the wind. Sections which are a part of a slip road or roundabout have a value of 0.2 as vehicle speed is reduced and therefore the vehicle overturning moment is reduced. Sections which are part of a bridge or highlighted by the Highways Agency as 'Locations with Very High Blow-Over Risk' are considered the most vulnerable and are assigned a value of 1. All other sections have a value of 0.6 or moderately vulnerable. These values have been subjectively determined based on an understanding of the road network being modelled and how wind gusts are likely to interact with the network and vehicles.

4. *Direction of wind*: As well as determining vehicle overturning thresholds Baker et al (2008) found that the wind direction was important and that vehicle have a critical overturning angle of 70° to the road orientation. This is the angle at which a vehicle is most liable to be overturned should the wind be strong enough. Using ArcGIS software the mean orientation of each road section was determined allowing the critical wind direction to be calculated. A buffer zone of 30° either side of this critical angle was applied to capture model limitations in resolving wind direction. Using the MOGREPS-UK wind direction field each model member and each road section is checked to ascertain whether the wind direction is within these critical angles (value of 1) or not (value of 0).

These four factors are then averaged together to give an overall vulnerability value between 0 and 1. This results in two road network maps of the UK (Figure 2). Vulnerability elements 1, 2 and 3 are static whereas element 4 (wind direction) changes frequently. If different members of the same model run do not agree on whether the wind is within the critical angles or not, the values from both maps are taken in proportion. For example three members have a wind direction not within the critical angles (e.g.

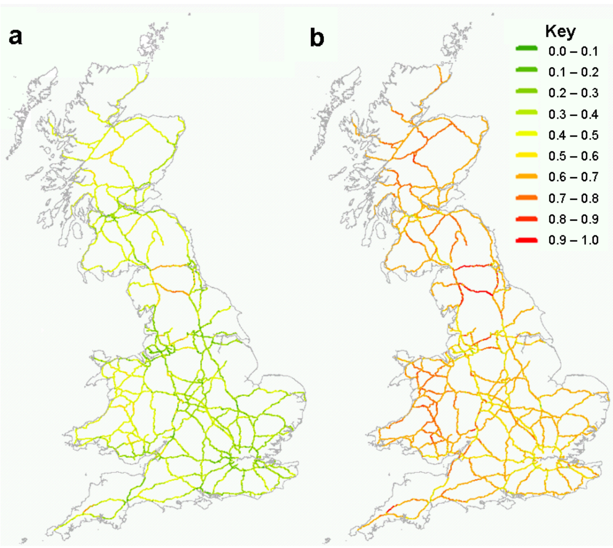

Figure 2 | Vulnerability maps of the UK for the VOT model. a) Map used when wind direction is not within the critical angles. b) Map used when wind direction is withing the critical angles.

each has a value from Figure 2a of 0.5) and the other nine members have a wind direction within the critical angles (e.g. this value is 0.75 from Figure 2b). The overall vulnerability value for that road section and time step is ((0.5*3)+(0.75*9))/12 = 0.6875.

2.3 *VOT Model Exposure*

The exposure part of the VOT model consists of the number of vehicles using the road network. The greater the number of vehicles on the road the larger the disruption should a vehicle overturning incident occur as the more vehicles are impacted. No live traffic flow data is available therefore Annual Average Daily Flow (AADF) data was used from the Department of Transport (2011). This data indicates the number of vehicles which drive along a stretch of road on an average day in the year. Vehicle count points are at approximately every junction on the major truck road network and provide average daily flow information for each road and vehicle type.

As some routes have proportionally more freight vehicles than others it was decided to use the vehicle type data from the AADF data to separate vehicle types in accordance to the four thresholds used in the model (UHGV, LGV, Car and LHGV). By using vehicle specific flow data, routes which have a high proportion of freight vehicles would be identified as having a higher risk particularly at wind gust speeds which exceed just the UHGV threshold. To conform to the hourly model time steps the AADF data was converted to the mean number of vehicles per hour per vehicle type. This hourly data was then statistically forced with data from the Department of Transport (2013) showing changes in traffic flow on monthly, daily and hourly time scales (Figure 3). The same statistics are applied to the entire road network as data at a smaller spatial resolution to this is currently not available. From this data three exposure fields were generated:

1. Number of UHGVs per hour per road section normalised between 0 and 1 using Equation 1. This is used when the UHGV wind gust threshold (23m/s) has been exceeded.

2. Number of UHGVs plus the number LGVs per road section normalised between 0 and 1 using Equation1. This is used when both the UHGV and LGV wind gust thresholds (23m/s and 26m/s respectively) have been exceeded.

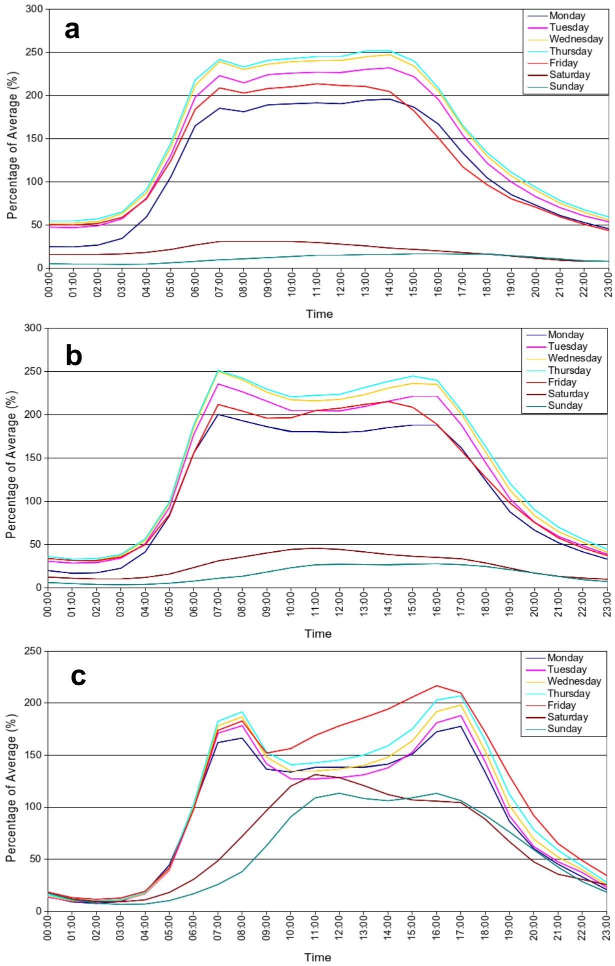

Figure 3 |Temporal change in the vehicle exposure values over day of week and hour of day from Department for Transport (2013) data. Plots all show January data, other months differ slightly. 100% is the AADF value from the Department if Transport (2014). a) Temporal changes in UHGV distribution. b) Temporal changes in UHGV + LGV distribution. c) Temporal change in all vehicle distribution.

3. Number of all vehicles per hour per road section normalised between 0 and 1. This is used when the UHGV, LGV and Car wind gust thresholds (23m/s, 26m/s and 35m/s) have all been exceeded.

A fourth exposure value has not been created (to coincide with LHGV wind gust threshold (36m/s)) as cars make up a very large proportion of the total vehicle population compared with the number of loaded HGVs within the same population. Due to this there would be very little difference in the two exposure fields and therefore at this stage in model development separating these fields is not deemed necessary. Also the two wind gust thresholds for Cars (35m/s) and LHGVS (36m/s) are very similar so combining exposure seems appropriate for this initial methodology.

2.4 *VOT Model risk output*

Each of the three components of the VOT model is weighted equally. The three normalised values (between 0 and 1) are multiplied together to give an overall risk value between 0 and 1. The risk value itself is termed 'risk of disruption', this endeavours to communicate that the model is forecasting the impact of a vehicle overturning event causing disruption to the surrounding road network. High risk road sections are generally those likely to experience high wind gusts, have a high vulnerability and a large amount of traffic on them.

The model output is currently visualised using four different services: an ArcGIS web map service, Open Layers, QGIS and Online Visual Weather, they all allow the user to animate through the 36 hourly time steps and also zoom into the map to look at the roads in more detail.

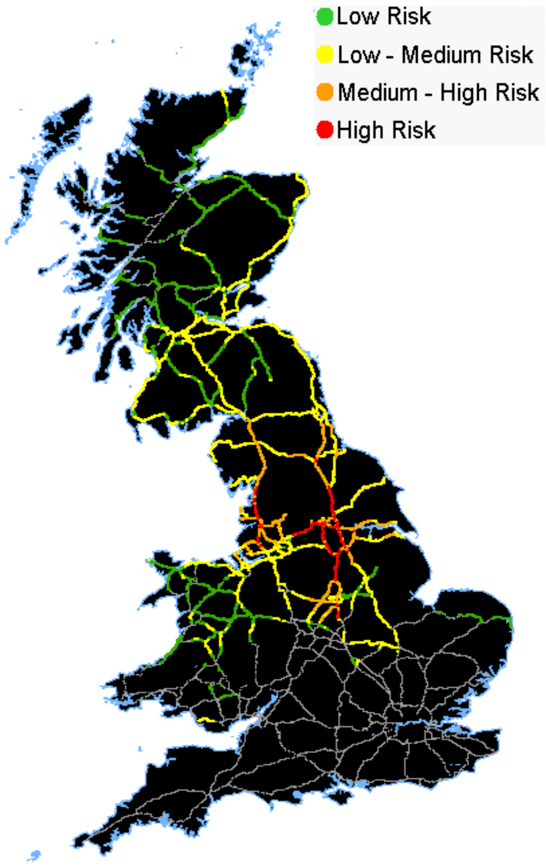

Figure 4 | VOT Model output example from 5th December 2013 storm 11:00am showing the maximum risk value calculated by the model. Output shown is from the model run at 15Z on 7th December 2013 at T+19 hours. Key indicates the level of risk forecast on the road network.

3. MODEL VERIFICATION

Verification is a very important part of any model. It allows an analysis of the model as to whether the areas forecast at being high risk are correct and of any impacts that occur. However impact verification is difficult, a high risk road highlighted by the VOT model does not mean that a vehicle will overturn it means that the risk of disruption is high. This is a combination of factors including wind gusts being strong enough to cause a vehicle to overturn. Driver behaviour is also impossible to model and predict and this may be a factor in an overturning event. Should a wind warning be issued some drivers will pull over and wait until the strong winds have passed before continuing their journey, hence mitigate against an overturning. Due to this the false alarm rate, a high risk road being forecast and no overturning incident, may prove to be high. Until a suitable methodology for verification is decided upon, case study verification has been adopted as an initial assessment of the VOT model.

3.1 *27th/28th October 2013 storm*

This storm event was the first time the VOT Model was run as a probabilistic model in real-time. The output (Figure 5) highlights the areas most a risk of disruption during the storm. The highest risk areas are around London, between 02Z and 05Z, as here the exposure value is high due to large traffic volumes. The model also tracks the path and footprint of the storm well, agreeing with observations of the storm track. The impact of the storm was mitigated against with trains and flights being cancelled in advance however a number of impacts were reported in the media, all occurring in the south of the UK. These included four vehicles overturning on or near highlighted roads (not all roads are currently included in the module), a large number of felled trees and structural damage in the south of the country (Figure 6). All the impacts were within the regions highlighted by the module suggesting it produced a realistic forecast of the area at risk of disruption due to the storm.

3.2 *5th December 2013 storm*

The wind gusts forecast on 5th December (Figure 7) can be seen to exceed 55 knots (28m/s) this exceeds both the UHGV and LGV wind gust thresholds. The majority of MOGREPS-UK members also agreed on the wind gust strength being high therefore the

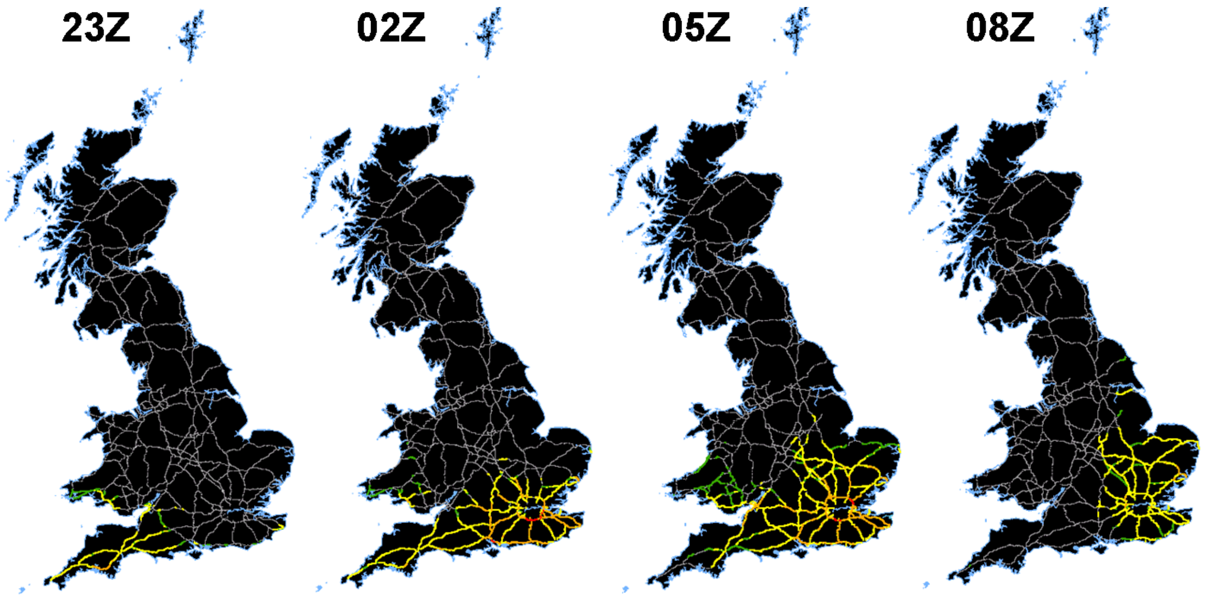

Figure 5 | VOT Model output from the 27th/28th October 2013 storm. Colours show the maximum risk of disruption forecast by the model at three hour intervals as the storm moved across the country. The risk value was calculated using a combination of hazard, vulnerability and exposure values as detailed in the text. Key indicates the risk attributed to each colour. Times are in UTC. Data shown is from the 09Z model run on 27th October 2013

probability of the wind gusts exceeding the vehicle thresholds was high. The VOT model showed a high risk of disruption signal during the event on the main motorways carrying vehicles from north to south (Figures 4 and 8). For this event the mitigation that took place for the 27th/28th October 2013 storm was not repeated resulting in a number of impacts across Scotland and the north and central England. For the purpose of this model the most relevant of these were overturned vehicles, total of 28 separate events were found using media reports and

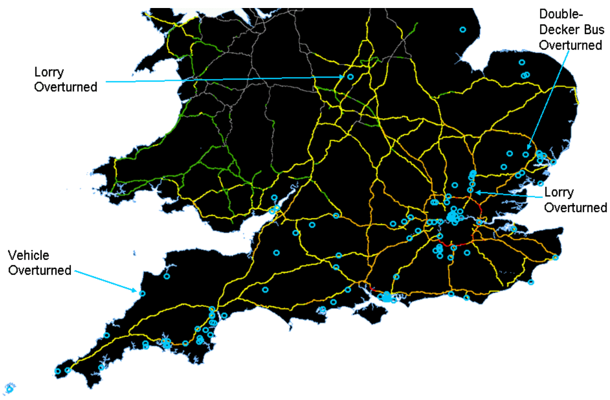

Figure 6 | Wind related impacts from the 27th/28th October 2013 storm. Blue circles indicate location of impact. Impacts and locations sourced from media reports. Vehicle overturning events are indicated. Background VOT map is the maximum risk value from all time steps for the 09Z model run on 27th October 2013.

twitter feeds. Of these 23 were overturned HGVs, three were overturned vans and two where described as 'vehicles' with no further description of type. The locations of the incidents are mainly on roads indicated to have a medium to high risk of disruption suggesting that the model is forecasting risk of disruption well during high wind events (Figure 8).

4. CONCLUDING REMARKS

Verification of the VOT model is continuing currently on a case study basis however the hope is to develop a more time effective method which will allow continual verification in the near future using impact data from partner agencies. Consistency between model runs has also been investigated, the model has so far demonstrated that there is a good correlation in risk of disruption values between model runs. Slight differences do occur due to small changes in the ensemble member wind gust values however this is expected. Once verification has successfully been carried out, and given a positive result, the model will be available to operational meteorologists to consult with during high wind events to aid decision making.

The other two modules currently in development by the NHP partners for the HIM are all still in the early research and

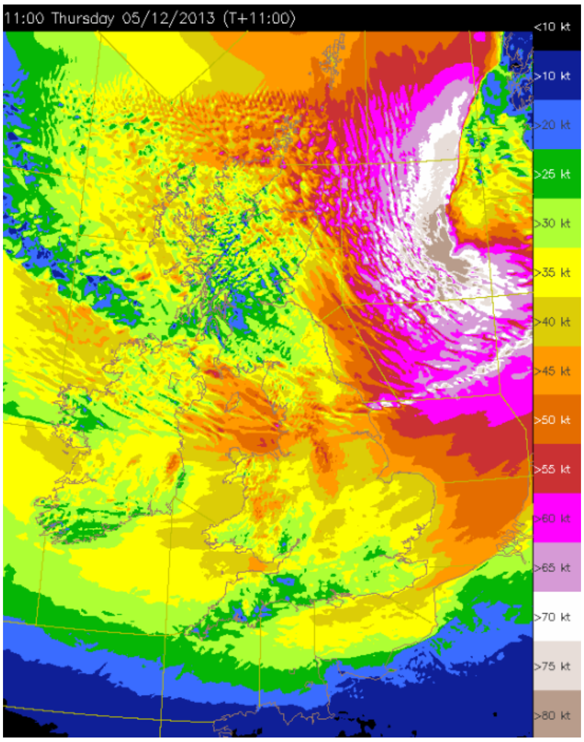

Figure 7 | Model wind gust output from the Met Office Unified Model for 5th December 2013 11:00am. For comparison with Figure 4.

development stage. One aim of the NHP is to expand the wind work package with additional modules on leisure activities and buildings, these are currently under development. Another aim is to add more hazards to the HIM. Current ideas to expand the HIM include snow and ice and health impacts of aerosols and temperature, these ideas will be explored as to whether data is available to create these model and also if they are appropriate to the HIM.

The NHP has already gained international recognition for its work on risk assessment of natural hazards. UNISDR (2013) highlighted the NHP as a model 'other nations may wish to adopt'.

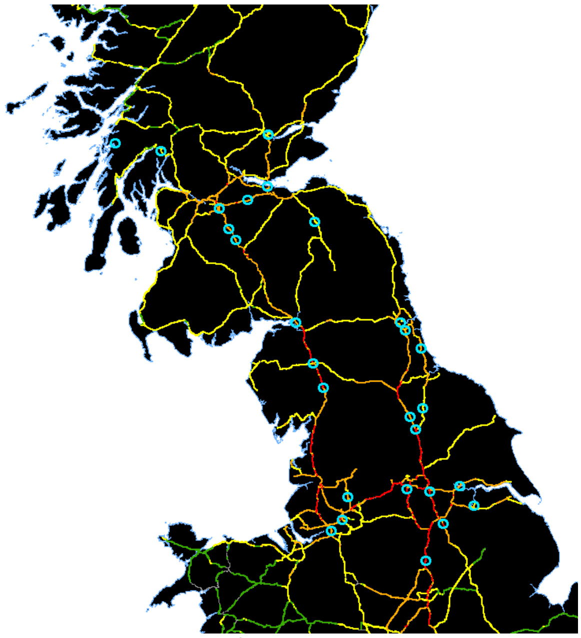

Figure 8 | Locations of overturned vehicles during the 5th December 2013 storm, indicated by the blue circles. Overturning events and locations collected from media reports and twitter feeds. Background VOT map is the maximum risk value from all time steps for the 15Z model run on 4th December 2013.

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