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Exceeding Climate Thresholds: Extreme Weather Impacts on the Environment and Population of Greater Manchester

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Abstract:

Extreme weather events, such as floods, heatwaves and heavy snowfall, can have severe consequences for the local environment and population. Future projections of climate change indicate that the North West region is likely to experience an increasing frequency and intensity of meteorological extremes. Consequently, it is important that the region enhances its preparedness for such events. This paper uses archive evidence and historical Met Office data for the case study area of Greater Manchester, to explore the impact of past extreme events on the local environment and/or population. These temporal analogues offer a valuable tool for understanding how projected future climate change may impact on the region. Such information can be used to inform decision-making with respect to climate risk assessment and the implementation of climate change adaptation strategies.

Keywords:
climate, analogue, extreme event, urban, Greater Manchester

Introduction

Extreme weather events can have significant negative impacts for both the local environment and population, and are accountable for a disproportionately large amount of climate-related risk. In addition to causing extensive physical damage, these events can have severe consequences for society and the economy. For example, the June/July 2008 floods in the UK are estimated to have caused £3000 m worth of damage (Association of British Insurers, 2009). The impact of rapid fluctuations in meteorological conditions and the occurrence of weather events which fall at the limits of the distribution for a particular climate variable are felt most acutely in those areas where the human and environmental systems are already marginal (e.g. heavily populated urban areas, coastal/soil erosion zones). For example, during the 2003 heat wave when average daily temperatures in Manchester exceeded 20°C in August on 8 near-consecutive days (compared to the 1971-2000 daily average of 16.1°C), unhealthy living and working spaces (internal temperatures >30°C) were experienced in buildings situated in the Manchester city region and surrounding suburbs (Wright *et al*, 2005). The affect of this on the productivity and health of building occupants would be considerable, given that the comfort design criteria specify that no more than 1% of occupied hours should exceed 28°C (CIBSE, 2006). In contrast, the heavy snowfall and extreme low temperatures (less than –10°C in Manchester during the night time) experienced during winter 2009/10 are reported to have cost the local economy £24m in 24 hours (MEN, 2010). A number of recent flood events around the UK have also highlighted the vulnerability of urban areas to flooding, specifically pluvial flooding (Pitt, 2007). This is exemplified in Greater Manchester by the localised flooding events in Heywood during the summers of 2004 and 2006 (Douglas *et al*, 2010). The impact of these events included physical damage, with 50% of local residents subjected to internal flooding needing to evacuate homes for up to eight months, and negative health impacts for those affected, included liver problems, asthma, stress and depression (Douglas *et al*, 2010).

Future projections of climate change (e.g. UKCP09) indicate that, in addition to shifts in average climate variables, the North West region is likely to experience an increasing frequency and intensity of extreme climate events, such as floods, heat waves and storms (Murphy *et al*, 2009). To understand the implications of this changing climate for Greater Manchester it is sensible to look to past events to provide an indication of how, and where, extreme events manifest themselves. Temporal analogues, which can be defined as past events during which the meteorological conditions experienced are reflective of those that are predicted to occur in the future, offer a valuable resource to aid understanding of how past events have affected the local environment and population. Although a single extreme event can offer only limited insight to the impacts that may be experienced in the future, the lessons that can be learned from the event could be used to help shape future policy response.

Future climate conditions can be reported with respect to these historical events in terms of the frequency and severity of recurrence, within the scientific limitations of error and uncertainty associated with climate forecasting. For example, the 2003 European heat wave cited above, which is considered an extreme event (exceeds 90th percentile) under current climate conditions becomes comparable to median climate conditions for the period 2071-2100 (Beniston, 2004; Beniston and Diaz, 2004). Such analogues are a useful communication tool for policy makers, stakeholders and the general public because they are based on real events and the likelihood that such events will become increasingly common in the future. They can also provide the type of quantitative information which is required for informed risk evaluation and adaptation planning.

This paper provides an overview of the past, current and future climate of Greater Manchester, with respect to both average and extreme conditions. Historical meteorological records from the UK Met Office are evaluated in the context of quantitative climate thresholds, which are indicative of extreme events for the case study area of Greater Manchester. The larger city-region is examined as opposed to an individual authority to allow for consideration of climate impacts which cross administrative boundaries. Temporal analogues, coincident with the exceedance of one or more of the quantitative extreme event thresholds, are examined to determine the impact of extreme weather-related events on human health/wellbeing, urban infrastructure and service delivery. The implications of increasing frequency and intensity of extreme events in the future are discussed.

The Climate of Greater Manchester

The Met Office station at Manchester International Airport (Ringway) offers the only suitably long, uninterrupted record of observed meteorological data in Greater Manchester. Daily meteorological data for Manchester Airport were extracted from the British Atmospheric Data Centre (BADC) for the period 1961-2009. With respect to average conditions (1961-1990) these data indicate an annual daily maximum temperature of 12.8°C (17.5°C in summer; 6.7°C in winter), a daily minimum temperature of 6.2°C (12.8°C in summer; 1.5°C in winter), a mean annual precipitation total of 808 mm and 42 frost days per annum. However, there is a significant NE-SW climate gradient evident across the region, which corresponds to the change in elevation (Figure 1). The airport, which is relatively low lying in the context of Greater Manchester as a whole, will record higher temperatures and lower precipitation totals than the regional average. This means that average conditions and indices of meteorological extremes will be spatially variable across the case study area, both in terms of how they are quantified but also in terms of the timing, frequency and impacts of extreme events and the response of the environment and population to them.

There is evidence that the climate of this region has already experienced some significant changes over the past 4 decades (Table 1). Increases in temperature, particularly during the winter months, are marked, and the data suggest that maximum temperatures are rising more rapidly than minimum temperatures. Seasonal changes in rainfall are also apparent, with the summer months becoming drier (although this trend is not significant at the 95% level) and the winter months considerably wetter.

Table 1: Percentage changes in key climate variables in north west England, 1961-2006. (Adapted from Jenkins et al, 2008).

	Spring	Summer	Autumn	Winter	Annual
Mean temperature (°C)	1.44*	1.45*	1.07*	1.81*	1.40*
Daily maximum temperature (°C)	1.67*	1.63*	1.13*	1.93*	1.55*
Daily minimum temperature (°C)	1.25*	1.31*	1.03*	1.70*	1.29*
Days of air frost	–5.9*	–0.1*	–3.2*	–13.1*	–24.4*
Total precipitation (% change)	6.3	–13.2	5.6	43.0*	8.8
Days of rain > 1mm	0.4	–1.1	2.9	6.8	7.5

*significant at the 95% level

In the future, the temporal trends in climate variables experienced since the 1960s are projected to continue and could, for some variables, intensify (Murphy *et al*, 2009). For example, by the 2050s under the Medium emissions scenario mean daily winter temperatures for the North West are predicted to increase by 0.8 to 3.3°C and summer temperatures by an even greater 1.1 to 4.7°C (Murphy *et al*, 2009). The warmest day of the summer (99th percentile) under this scenario will be between 4 and 5°C warmer than that experienced during the period 1961-1990. As

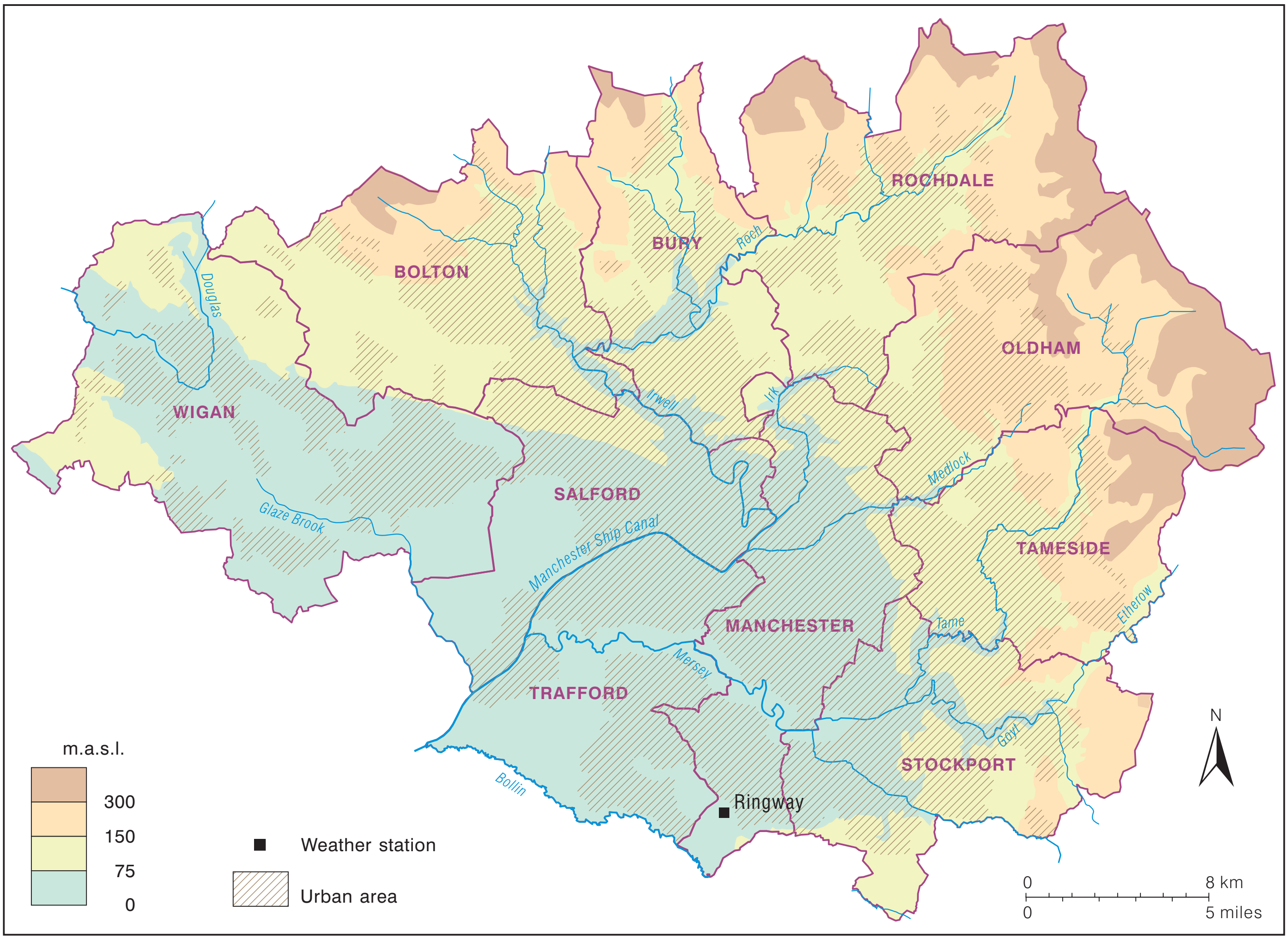

Figure 1: Greater Manchester: physical geography, Local Authority boundaries and principal weather stations.

a consequence, 2050s Manchester will experience peak summer temperatures similar to present day cities in Holland and Belgium. By the 2080s peak summer temperatures could be equivalent to Berlin, Frankfurt and Rome.

In contrast, the number of frost days in the winter is very likely to decrease as a result of the overall warming trend, particularly in urban areas (McCarthy *et al*, in press). The winter minimum temperature rise across the region, even under the Low scenario, indicates that there will be very few places in the region with average minimum temperatures remaining below freezing.

The seasonal discrepancy in precipitation trends is predicted to continue, with summer precipitation totals decreasing by as much as 36% relative to the 1961-90 baseline, while winter precipitation could increase by up to 26% (Murphy *et al*, 2009). Aside from seasonal changes in precipitation patterns, increases in rainfall intensity are thought to be likely throughout the year. The number of depressions moving across the UK from the North Atlantic is expected to increase leading to the possibility of more frequent and more intense storm events. Therefore, although summers look set to become drier, intense high volume rainfall events could become more common. However, there remains much uncertainty over predicting associated details, such as the path of storm tracks and wind speeds.

Quantifying Extreme Weather Events

To examine changes in the frequency of extreme event occurence, extremes for a range of climate variables have been classified according to a set of quantitative thresholds, using the historical (1961-1990) Manchester International Airport Met Office data (Smith and Lawson, 2012; see Table 2).

Table 2: Indicators used to identify extreme weather events from historical Meteorological Office records (after Smith and Lawson, 2012).

Weather Event	Extreme Events Identified As:
High Temperature	$T_{max} \geq 29.2\,°C$; $T_{min} \geq 22\,°C$
Low Temperature	$T_{max} \leq -2.4\,°C$
High Precipitation	Ppn ≥ 24.6 mm/day
Low Precipitation	Consecutive Dry Days (CDD) ≥ 15
Heavy Snowfall	snow amount ≥ 6 cm/day
High Windspeeds	Gale Days (mean wind speed reaches or exceeds 34kn for a period of 10 mins)

Trends in the occurrence of extreme temperature conditions over the past 5 decades (1961-2009) reflect the changes in average climate variables (Table 1). Extreme high temperature events, defined as days when the maximum daily temperature is greater than or equal to 29.2°C, have increased in frequency from 0.2 to 1.5 per year between 1961 and 2000. In contrast, the frequency of extremely cold days exhibits a declining trend since the 1960s, when over three days per year experienced a maximum daily temperature of less than or equal to –2.4°C, compared to less than 1.5 events per year during the past two decades.

Notably, there is a tendency for clustering of extreme events during particular years. This corresponds to occasions when unusual synoptic conditions gave rise to a prolonged heat wave event or a severe cold snap. For example, the majority of classified extreme high temperature days during the last two decades occurred during the unusually hot summers of 1995 and 2003, while the low temperature extremes since 2001 are confined to the winters of 2008/09 and 2009/10.

Future projections of temperature suggest an increase in both average and extreme temperature conditions for the North West region. Therefore, analogous past extreme events, such as the 2003 heatwave, can be used to establish the implications of future climate warming on the region. In contrast, low temperature-related climate impacts, such as transport delays, road traffic accidents and falls due to snow and ice, are likely to diminish in the future as average winter temperatures increase.

The quantification of precipitation extremes is suggested to be highly variable across Greater Manchester (Smith and Lawson, 2012). The 24.6 mm precipitation threshold defined using Manchester International Airport data would be an over-cautious parameter for the Pennine fringe area to the north east of the region, where a daily precipitation total of 38.6 mm and over is regarded as a more reliable indicator of flood occurrence. Furthermore, unlike temperature extremes, the occurrence of an extreme precipitation event at Manchester Airport is not necessarily indicative of an extreme event elsewhere in Greater Manchester, due to the significant spatial variability of precipitation patterns. This marked difference over a relatively small spatial area is largely a result of the prevailing weather conditions and the altitudinal variation of the region (Figure 1).

There is an absence of a temporal trend in the frequency of extreme rainfall events across the precipitation monitoring network. However, this does not necessarily imply that flood events have become more or less frequent but may instead be due to the use of daily total data, which are disguising brief but intense precipitation episodes which are the primary cause of pluvial flooding. Heavy snowfall events (daily snowfall ≥6 cm), on the other hand, do exhibit a significant change in frequency over time. Over the past 5 decades the number of extreme snowfall events per annum has declined by almost three quarters, which can be attributed to the warming winter climate. There is also evidence that snowfall events are becoming less extreme. Prior to the heavy snowfall that occurred during winter 2009/2010 the historical Met Office dataset has no record of any events where snowfall exceeded 10 cm since 1984, in spite of events of this magnitude being not uncommon during the 1960s, 70s and early 80s.

Lack of precipitation resulting in drought conditions is harder to quantify compared to some of the other climate extremes, as it is brought about by a long term deviation from the average climate conditions as oppose to an abrupt anomaly. Defining a low precipitation extreme event as a period with 15 or more consecutive dry days, the Met Office data indicate that that the number of summer droughts has increased consistently decade on decade since 1961. This is in agreement with previous research which has shown summer precipitation amounts have declined over time (Osborne and Hulme, 2002; Jenkins *et al*, 2008). Given that the average level of rainfall during the summer throughout the region is anticipated to decrease, the local population and environment are likely to become increasingly exposed to drought conditions. For example, the dry conditions of the 2003 summer, when the precipitation total in Manchester was less than half of the 1961-1990 mean JJA rainfall amount, will be replicated in 9 out of 10 summers by the 2080s, under the High emissions scenario (Murphy *et al*, 2009).

The frequency of extreme storm/wind events since 1961 exhibits a significant downward trend. There are over three times fewer events, using the criterion in Table 2, between 2000 and 2009 relative to the 1961-1970 period.

This is at odds with the UK-wide increase in windstorms suggested by other research (Alexander *et al*, 2005; Jenkins *et al*, 2008). However, the low numbers of such storms, the unreliability of direct wind speed observations and the different methods of defining a severe storm event confound the ability to draw definite conclusions about temporal patterns of windstorm events. The Manchester International Airport Met Office data also display no evidence of an overall trend in the magnitude of storm events, with incidents of windspeeds exceeding 60 knots occurring in all five decades between 1961 and 2009.

Impacts of Extreme Events

To establish the impacts of these extreme events, a temporal analogue approach was used. This involved a detailed archive search of a range of source materials including:

- Media reports in all local papers throughout Greater Manchester.
- Association of Greater Manchester Authorities (AGMA) – Strategic Flood Risk Assessments
- The Environment Agency – Catchment Management Plans
- Greater Manchester Fire and Rescue Service – Flooding Call-Out Records
- Association of British Insurers – Major Weather Incidents in the UK Dataset
- North West Public Health Observatory – Hospital Admissions Statistics
- Consultation with Mike Goodwill, NHS North West
- Consultation with Alan Goodman, Met Office Regional Advisor, Northwest England
- Data supplied by all 10 Local Authorities in Greater Manchester who were asked to collate data from their civil contingencies, education, highways, social services, drainage, media and archive departments.

The archive search was carried out independently of the Met Office data analysis to avoid biasing the results. As a result of this consultation a database of weather related events in Greater Manchester for the period 1961-2009 was constructed. These were then matched to the incidences of extreme events, as classified according to the historical Met Office data (Table 2), to establish what the impact of these events was for the local population, infrastructure and environment.

Temperature Extremes

With respect to a quantitative index of extreme temperature events, a cross comparison between the historical Met Office data and the archive database of extreme events reveals that for every day when T_{max} was recorded as being greater than 30.9°C there was a reported negative impact in the archive evidence. The 2003 event is well-documented for the impact it had on the vulnerable population (Stedman, 2004; Kovats and Hajat, 2008) and infrastructure (Wright *et al*, 2005; Dobney *et al*, 2009). Locally, the impacts, as extracted from the archive search, included photochemical smog levels more than double the health guidelines at 5 sites in Wigan and an incident of convective storm damage at Manchester International Airport. Train services were also severely disrupted due to restricted speeds and cancellations in the Bolton area. The July 2006 heatwave, during which the maximum temperature experienced at Manchester International Airport was marginally lower than the 2003 heatwave (31.3°C compared to 31.6°C), was responsible for an estimated 140 excess deaths across the region (MEN, 2006). As with the 2003 event, local infrastructure was also effected, trains were delayed due to the risk of rail buckling, particularly on the west coast main line, and road surfaces suffered heat damage. Rural areas were not immune to the impacts of the heatwave, and there were numerous reports of moorland fires around the region during the 2006 event.

Prior to 2000, events in 1990 and 1995 were also deemed exceptional with respect to summer temperatures. The maximum daily temperature record at Bolton was set on August 3rd 1990, when temperatures reached 32.1°C. This has never been surpassed, however, it should be noted that observations at this station were terminated at the end of 1995. Impacts of these events included poor air quality and high pollen counts, both of which had implications for population health and wellbeing. There was a surge in heat-related hospital admissions and an increased mortality rate. The combination of high temperatures with prolonged dry conditions during both of these incidents meant that hosepipe bans were enforced and moorland fires were more prevalent.

Other notable heat-related impacts include three drownings in mill ponds/reservoirs during July 1983 (T_{max} at Manchester International Airport was 31.6°C on 12th July), as people turned to swimming as a way to keep cool. Heatwave-induced fire damage also occurred to infrastructure including a chemical plant in Littleborough (1983) and a paper warehouse in Warrington (1976) (Markham, 1995). The heatwave in 1976, when temperatures reached a maximum of 32.2°C at Manchester International

Airport, was responsible for a trebling of the death rate in the over 65s and caused a heat induced hay fever epidemic (pollen count 322 at Salford) (Markham, 1995).

All of these events correspond to periods when daily T_{max} exceeded 30.9. The costs (physical, societal and economic) associated with these extreme heat events are indicative of the costs of future events of this magnitude, which are predicted to become increasingly frequent. Understanding the risks associated with these events can help decision and policy makers to plan and prepare for future events, and combined with information about where the heat hazard is greatest (Smith *et al*, 2011), provide a useful tool for resource distribution and allocation. However, it should be noted that heat-related impacts were also reported in the archive sources when T_{max} was below this threshold, although often to a lesser extent.

Low temperature extreme events have in the past caused significant disruption within Greater Manchester, particularly to transport networks. The last two winters (2008/09 and 2009/10) are both categorised as extreme cold events according to the criterion in Table 2. The minimum temperature at Woodford[1] during the night of 6th/7th January 2010 is the coldest on record (–17.6°C). The prolonged period of freezing conditions and heavy snowfall caused treacherous conditions on roads and pavements, which resulted in numerous accidents and falls. Minor roads were particularly badly affected, as these were left untreated due to limited road salt supplies. Manchester International Airport was forced to close on more than one occasion due to the low temperatures and heavy snowfall.

The number of emergency hospital admissions for falls involving ice and snow increased substantially during the winter of 2009/10, rising from 149 in winter 2006/07 (which was a warmer than average winter: +2.7°C anomaly compared to the 1961-1990 average) to 3,170 admissions during winter 2009/10 (Mason *et al*, 2010). However, emergency hospital admissions in winter for transport accidents and respiratory conditions do not show any correlation with winter temperatures. The number of falls caused by ice and snow puts increased pressure on Accident and Emergency facilities and hospital beds, which has economic consequences as well as impacts for service delivery. Schools in the region are also particularly vulnerable to freezing conditions, as a result of the aforementioned travel issues but frequently due to burst pipes.

The last very serious cold related event pre 2008/09 was in December 1995, when temperatures at Manchester International Airport dipped to –12°C. This was combined with freezing fog. During this episode the RAC received 3000 calls for help from stranded car drivers, planes had to be diverted from the airport and the railway between Crewe and Manchester was closed. Hospitals were under pressure due to the increased number of falls on ice, with some patients needing to be transferred because of the demand on hospital beds. In addition, 2000 council houses in Ardwick were without heating as a result of the community boiler freezing.

The archive evidence references the impacts of a number of low temperature events throughout the 60s, 70s and 80s. Disruption to transport networks is a recurrent outcome when T_{max} is less than or equal to –2.4°C. However, it is the occurrence of daily T_{min} below –9°C that are consistently reported as having a negative impact on the population and environment in the archive evidence. In addition to the transport delays, reports of drowning (e.g. 4th Dec 1962 and 4th Jan 1993), flooding due to burst pipes (e.g. 16th Jan 1982 and 3rd Jan 1979) and, pre-1970, power outages (e.g.22nd Jan 1963 and 8th Feb 1969) are also common.

While the historical Met Office data suggest that the number of extreme cold-related events has decreased over time, particularly so since the 1960s, the reporting of the impacts of these events has remained consistent. This implies that the ability of snow/ice to disrupt services has not diminished, despite a reduction in the frequency of the hazard. This highlights the importance of preparedness and robust contingency planning for future incidences of such events.

Precipitation Extremes

Flooding is suggested by the archive evidence to be the dominant climate impact within the region across all decades, and is found to be attributable for 37-55% of extreme events between 1961 and 2009. In contrast to the Met Office data, there is some suggestion from the database that flood events are becoming more frequent (Figure 2). This is especially true for pluvial flooding events, which have become notably more prevalent since the 1990s. The majority of past pluvial flood events occurred between April and September. For example, the summer 2006 flooding is attributable to storm formation due to warm, humid air conditions, which was responsible for over 30 mm of rain within 1 hour in Rochdale. Although the seasonal steer towards summer events may appear to contradict evidence that summer precipitation totals are decreasing, it is the

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[1] Records in Woodford began in 2003 as a replacement for Manchester International Airport

tendency toward brief but very intense rainfall episodes that is driving this trend. For example, Jenkins *et al* (2008) found a significant increase in the number of severe storms over the UK as a whole since the 1950s, and this is likely to be partially attributable to the increase in pluvial flooding since 1998. These climatic changes, coupled with changes to land use over time, such as urban infill trends, which increase surface runoff (Lawson and Lindley, 2008), put pressure on drainage systems and can make particular areas ever more vulnerable to flood damage.

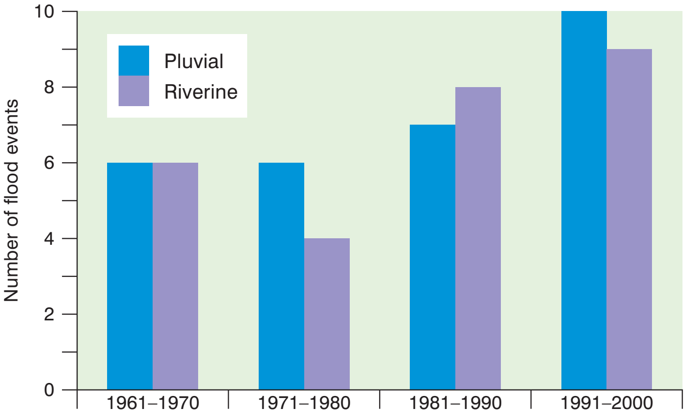

Figure 2: Number of flood events by type (pluvial, fluvial) per decade from 1961-2009 derived from archive searches.

The archive evidence indicates that the frequency of riverine flooding also displays an upward trend (Figure 2). However, the severity of the impacts of these events appear to be somewhat lessened, particularly so for the south of the region (Mersey catchment) (Smith and Lawson, 2012) since the opening of the Sale and Didsbury temporary flood storage basins in the 1970s.

Relating the archive evidence to the Met Office data from Manchester Airport suggests that daily precipitation totals in excess of 38 mm resulted in flooding which had impacts for human health/well-being and/or infrastructure, or caused severe disruption to services. Examples of the impacts of these flooding events in Greater Manchester include cancellation of football matches, power failure (July, 2007; monthly precipitation total 200% of 1961-1990 average; July/August 1999, daily precipitation up to 101.9 mm), flooding of homes and businesses (e.g. July 1973, recorded precipitation at Manchester Airport of 64.7 mm; August 1981, recorded precipitation at Manchester Airport of 95.9 mm; June 1987, recorded precipitation at Manchester Airport of 48.1 mm; August 2004, recorded precipitation at Manchester Airport of 69.2 mm; July 2006, recorded precipitation at Manchester Airport of 44 mm) and disruption to transport networks, road, rail and metrolink (e.g. December 1964, recorded precipitation at Manchester Airport of 54.6. mm; July/August 2002, recorded precipitation at Manchester Airport of 38.3. mm; August 2004, recorded precipitation at Manchester Airport of 69.2 mm). In addition to the direct impacts of extremely heavy precipitation episodes, the indirect consequences for the local population can be equally severe. People whose homes are affected by flood damage, for example, can suffer large amounts of disruption due to the need to evacuate and find temporary accommodation. This, along with the often lengthy procedure of processing insurance claims can cause anxiety, stress and depression for the affected population (Douglas *et al*, 2010).

While the 38 mm threshold is a useful indicator of an extreme precipitation event which is highly likely to manifest itself as flooding, many flood events extracted from the archive evidence occurred when the daily precipitation at Manchester Airport was in the region of 25-30mm and even lower. This is due to prolonged periods of rain causing total saturation of soils and pressure on the drainage system, the high spatial variability of precipitation and the aggregated nature of the dataset used (daily total). The north of the region, which is of a higher altitude, experiences a different climate to Manchester Airport. Consequently, conditions at the airport may not reflect what is happening elsewhere in Greater Manchester, particularly for variables such as precipitation which are spatially non-uniform. To reflect this, the Met Office has a denser network of precipitation monitoring stations, and it is therefore logical to use a more geographically comparable precipitation station for identifying localised extremes. By taking account of this, extreme events in the north of the region can be more easily identified for cross comparison with the archive evidence (Smith and Lawson, 2012). Moreover, the daily aggregate data often fail to pick up on very intense precipitation episodes, which may occur on a half-hourly to hourly temporal scale. This can be extremely difficult to forecast but finer temporal resolution data may provide insights into a more appropriate fine temporal scale threshold.

The archive evidence revealed very few records of drought in Greater Manchester. The dry conditions in 1984 and 2003, which were reported, led to low reservoir levels and restrictions on water use (e.g. hosepipe bans). On both of these occasions the 15 consecutive dry days criterion (Table 2) was met. However, the drought conditions were likely to be the result of longer term low precipitation during the preceding weeks/months. There were frequent occasions when the low precipitation criterion was met, according to the Met Office data, but no drought was identified in the archives. This may be due to the perceived lack of severity or immediacy of drought conditions for the region compared to other extreme weather events, which means they are more likely to go unreported in the sources consulted. For instance, anecdotal evidence suggests that moorland wildfires are on the increase (Bolton MBC) but there is insufficient information from the archive evidence to substantiate this claim.

Storminess and Wind Extremes

The number of storm events per year, identified from the archive sources, was relatively stable between 1961 and 2000, but their frequency appears to have increased during the past decade. The impacts of these events frequently include disruption to transport and power supply, structural damage and, in the worst cases, death. For example, a deep area of low pressure during March 2008 was responsible for gusts of up to 60 mph in Greater Manchester which caused significant damage to buildings and trees within the region, and also resulted in the closure of the M6 over the Thelwall viaduct. An intense depression during February 1990, when the maximum gust speed recorded at the airport was in excess of 80 mph, resulted in the deaths of three people in Wigan. Since 1961, every day with a maximum gust speed in excess of 70 mph was reported as having a negative impact in the archive evidence. However, on a number of occasions, days when wind speeds were defined by the Met office as Gale Force (force 8 on the Beaufort scale: speeds in excess of 20 mph over a period of at least several minutes) also resulted in impacts. Not surprisingly, the impact of storm events is more serious when the high wind speeds are combined with other inclement weather conditions, such as lightning and heavy precipitation. There is some indication, however, that the impacts of storm and wind events have become less severe in recent years. This is possibly due to improved building standards and arboreal services.

Conclusions

Here we have examined the impact of past extreme events on the population and environment of Greater Manchester using quantitative indices of 'extreme conditions' derived from Met Office data (Table 2). This type of information is invaluable for local decision makers and stakeholders as it allows them to assess local risk according to information given in short term weather forecasts, but also in longer term climate projections. This is turn can form the basis of climate adaptation strategies and contingency plans for when extreme conditions occur.

The overarching conclusions which may be drawn from the archive evidence are that human health in terms of serious injury or death is most severely affected by extreme storm/wind events and flooding. Mental health, in particular, is most severely affected by flood impacts. Infrastructure damage is also most frequently caused by extremes in precipitation and wind, while fog and low temperatures are more disruptive to transport networks. While the process of collating the archive evidence base has been rigorous and has drawn on a broad range of resources, there are several external factors which may limit the completeness of the extreme events database. Namely, that the press is inconsistent in recording weather related events. As well as depending on the whims of journalists, the recording of such events will also be influenced by the amount of other newsworthy events at the time. In addition, some of the Local Authority officers consulted experienced difficulty in obtaining records of past weather related events from within their respective departments. The recording of past weather related impacts by Local Authorities is haphazard, a weakness that should ideally be addressed if climate change adaptation is to be a priority for the future.

When used in conjunction with projections of future climate change (e.g. UKCP09), the extreme threshold indices will help to determine the probabilities of extremes occurring in the future and identify the elements or areas most at risk. For example, heavy precipitation events which have in the past caused detrimental flooding in Greater Manchester (e.g.flooding in Heywood in 2004 and 2006; Douglas *et al*, 2010), may occur as frequently as 1-4 times per year by the 2050s under the High emissions scenario (Cavan, 2010). This information can subsequently be used to prioritise and target climate adaptation strategies, with the important caveat that extraneous factors are nonstationary (Wilby *et al*, 2009). For example, improvements to adaptive capacity (e.g. changes to surface cover properties, policy interventions) may mean that society and the environment become increasingly resilient to extreme climate events, and therefore the thresholds may have to be re-evaluated and adjusted accordingly.

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