INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **32**: 967–974 (2012)
Published online 25 March 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.2321

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Short Communication

Is the changing precipitation regime of Manchester, United Kingdom, driven by the development of urban areas?

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ABSTRACT: Precipitation measurements made at three weather stations and one composite record from the Manchester region and the Isle of Man have been analysed over the period 1899–2008. Large positive trends over the last 40 years were identified for the three records within 50 km of Manchester whilst the Isle of Man measurements revealed no such trend. The recent increase in rainfall at the urban or urban-influenced sites was significantly and negatively correlated with NO_x emissions recorded in Manchester whilst local temperature and atmospheric circulation indices appeared to be largely unrelated. Sea surface temperature in the precipitation source region was also significantly related to annual precipitation levels. Further evidence for an urban influence was investigated but an analysis of back trajectories (BTs) showed only a slight increase in rainfall on the days where the trajectories tracked back past an urban centre. However, the discovery of a weekly cycle in the precipitation increase suggests that an urban influence should not be ruled out. The complicated factors driving this distinctive rainfall trend require further investigation so that water resources and flood impacts can be managed more effectively in the future. Copyright © 2011 Royal Meteorological Society

KEY WORDS rainfall; urban precipitation; back trajectories

Received 28 September 2010; Revised 20 December 2010; Accepted 11 February 2011

1. Introduction

Understanding precipitation in a changing climate is a key challenge for climatology as water availability changes and periods of extreme precipitation are among the highest impact events that can be foreseen (IPCC, 2007). This issue is made more difficult because of the high variability of rainfall over small distances and the difficulty that weather and climate models face in making precipitation predictions and projections into the near and long-term future.

Despite these limitations, regional climate analyses and projections for the north-west of England produced by the UK Climate Impacts Programme (UKCIP) bring up some points worthy of note. They find that precipitation in England and Wales has not changed significantly over the last 240 years but within this there is a lot of seasonal variability (Jenkins *et al*., 2008). The seasonal trends manifest themselves as winter increases in precipitation (largely from rainfall event size increase) and summer decreases in precipitation. UKCIP projections for the future (Murphy *et al*., 2009) show similar patterns: annual levels remaining largely unchanged but with winter increases ('central probability projection' of 16% increase for north-west England in 2050) and summer decreases ('central probability projection' of 22% decrease for north-west England in 2050).

Looking to smaller scales within this region, Barrett (1964) examined local variations in the precipitation regime of the Manchester area of the UK using data from 17 local stations between two time periods: 1890–1924 and 1925–1959. Barrett found a large, positive increase in precipitation (∼17%) in the latter period in three stations to the north and west of the city, derived mostly from summer increases. This trend decreased when moving outwards from the city centre and became negative at 15 km distance. It is, however, unclear how these patterns have changed more recently in Manchester or how well the UKCIP analyses represent the city.

Barrett speculated over an urban influence on the regional rainfall changes but had no data to test that hypothesis. More recently, though, Collier (2006) has discussed the impact of urban areas, in terms of building heights and aerosol emissions, on weather and precipitation in general whilst Carraça and Collier (2007) have used a numerical model to show how high-rise buildings in Greater Manchester can initiate convective cells. We can very briefly summarise the urban impact on rainfall thus: the increased local temperature (i.e. the urban heat island), the change in land use/surface height and aerosol emissions can all lead to increased precipitation

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likelihood. However, the thermal effect of aerosols on precipitation is not clear (Ming *et al*., 2010) and any impact on cloud physics and the subsequent promotion or suppression of precipitation is sensitive to pollution type and concentration and weather conditions (Raes *et al*., 2000; van den Heever and Cotton, 2007; Carrio, *et al*., 2010).

So, given the importance of the regional UKCIP projections discussed above and the changes in the urban environment and monitoring since 1959, we propose that the Barrett (1964) analysis requires updating. This is the aim of this short communication.

2. Data and method

To achieve this aim we are using data from the Met Office Integrated Data Archive System (MIDAS) Land Surface Observation Stations Data archive. Precipitation records were obtained for the period 1899–2008 from two stations in and near Greater Manchester: Lyme Park (2.05 °W; 53.3 °N) and Wall Grange (2.05 °W; 53.08 °N). These stations are 20 km south-east and 50 km south of Manchester city centre respectively. These data were used to analyse trends and to identify rain days for an analysis of precipitation origin. Data were also analysed from Douglas, Isle of Man (4.5 °W; 54.15 °N) as a control site, which is around 150 km north-west of Manchester, i.e. within the same synoptic regime but largely isolated from the urban influence.

Most of the 17 stations analysed by Barrett (1964) were closed in the 1950s and 1970s (Met Office, personal communication) so whilst a larger dataset would have been preferable, the data we have is nonetheless adequate for our investigation. However, to determine how applicable our results are to Manchester itself, we have compiled a 'city centre' composite record using data from stations within 10 km of the city centre that have at least 20 years of data.

To identify the origin of the moist air parcels that resulted in the precipitation on the rain days, we use back trajectories (BTs) run from the British Atmospheric Data Centre trajectory model (http://www.badc.nerc.ac.uk). The model produces three-dimensional air parcel paths from ECMWF re-analysis wind data held on a 2.5° × 2.5° latitude-longitude grid. The BTs cover the period 1970–2008 (i.e. when the re-analysis data is most reliable) and were initiated from a height of 850 hPa, which has been used in previous studies as an appropriate height to identify precipitation sources in the UK (Russell *et al*., 2008). The BTs were run for 2 days, which is long enough to determine their track over any industrialised areas.

NO_x data from Manchester Town Hall for the period of availability, 1987–2007, and national NO_x levels for 1970–2007 were also used. These data were obtained from the UK Air Quality Archive (http://www.airquality.co.uk/) and the National Atmospheric Emissions Inventory (http://www.naei.org.uk/), respectively. NO_x is a useful proxy for industrial activity as it is produced via fuel combustion, biomass burning and production processes.

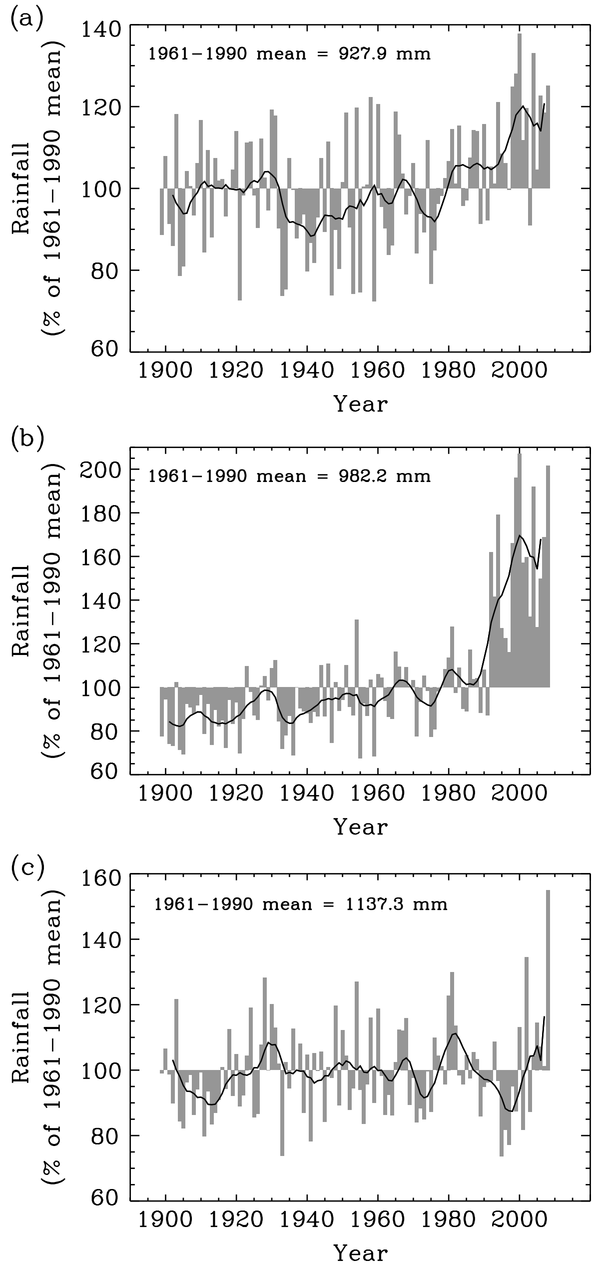

Figure 1. Annual precipitation relative to the 1961–1990 annual mean, which is indicated on each plot, from: (a) Wall Grange, (b) Lyme Park and (c) Douglas. Note that the y-axis is different on each plot. A 5-year running mean is plotted for each site.

3. Precipitation regime

Figure 1 shows the annual precipitation levels from the three stations. Wall Grange and Lyme Park (Figure 1a, b) show clear positive trends from the 1970s to 2008 of 7.7 and 24 mm year^{-1}, respectively. Most of the increase has come from rain days delivering more precipitation: in the first half of the Lyme Park record, rain days delivered a mean of 4.5 mm; more recently (1990–2008), the average rainy day delivered more than 6 mm of precipitation. Douglas (Figure 1c) shows no such trend, although 2008 was the wettest year in the record. However, Douglas received over 10% more precipitation than the other two stations before 1980. There is only weak evidence in the Douglas and Lyme Park datasets of the precipitation increase after 1924 that Barrett (1964) described and the reverse appears to be true for Wall Grange. None of these stations, though, are within the 15 km radius where Barrett observed that trend and our data only goes back to 1899.

Figure 2 presents the composite 'city centre' precipitation record, which shows a similar recent trend (9.2 mm $year^{-1}$) and interannual variability to Wall Grange and Lyme Park (correlation coefficients of $r = 0.89$ and $r = 0.91$ respectively, both significant at the less than 1% level). This gives us confidence that similar driving factors are at work in these closely located stations and that our conclusions can be applied to the city centre as well as the Wall Grange and Lyme Park stations. There is, again, no evidence of the post-1924 precipitation increase in this record.

Seasonal trends can be seen in Figure 3. Wall Grange (Figure 3a) shows a positive trend in recent years in winter and, less so, in autumn. Summer also shows a strong positive trend over the last 10 years, though this was from a low starting point compared to that season in the first half of the 20th Century. These patterns are broadly in line with the UKCIP analyses discussed in the Section 1. The Lyme Park data (Figure 3b) show strong positive trends in all seasons since the mid-1970s, which is in contrast to the UKCIP conclusions discussed previously. This implies that the background climate changes are not the only driver of the precipitation trend seen at Lyme Park. The Douglas data (Figure 3c) show no trends of note in any season and have the lowest interannual variability of all three stations.

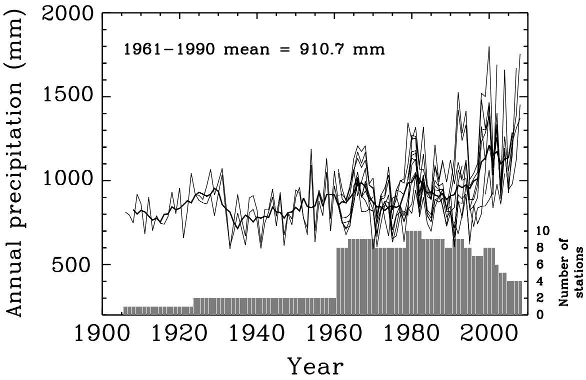

Figure 2. Composite annual precipitation plot for the Manchester city centre area. The data comes from the following stations: Chorlton-cum-Hardy (1906–1970), Davyhulme (1924–2008), Weaste (1961–2001), Sale: Carrington Lane (1961–2002), Prestwich (1961–1988), Heaton Park (1961–2007), Ringway (1961–2004), Fallowfield: Platt Fields Park (1961–1993), Gorton (1964–2008), Audenshaw (1979–2001) and Denton (1979–2008). A 5-year running mean is plotted and the number of stations used in each year is indicated by the bar chart at the bottom of the plot.

4. Why is there a large precipitation increase at Lyme Park?

Figure 4 places the Lyme Park data in context with factors that could be driving the trend. Table I shows how well these factors are correlated with the annual precipitation records at the three sites. Whilst this exercise gives no indication of how these factors may have combined to influence the precipitation regime, it nonetheless uncovers a strong and significant negative correlation between NO_x (for the UK and Manchester emissions data) and Lyme Park precipitation. The correlation between the Wall Grange precipitation and NO_x data is also significant. This could be seen as a clear link between the urban emissions decrease and local precipitation increase. Indeed, there is no significant relationship between the seemingly more obvious drivers of precipitation, i.e. circulation indices or regional temperature (Figure 4a–c). It is also probable that temperature changes at the precipitation source region (Figure 5) will have a large influence. Indeed, for the period of data availability (1946–2008) there is a correlation coefficient of $r = 0.32$ (significant at the less than 1% level) between the Lyme Park precipitation and mean sea surface temperature from HadSST2 (Rayner *et al.*, 2006) for the region 40–60 °N and 10–30 °W.

However, the concurrent negative trend in NO_x and the positive trend in precipitation could be purely coincidental if unrelated climate signals and clean air initiatives began to have an impact at the same time. Indeed, until very recently (Thompson *et al.*, 2010), the Northern

Table I. Spearman's rank correlation coefficients for the precipitation data and measures of atmospheric circulation, temperature and NO_x.

	Lyme Park	Wall Grange	Douglas
NAO	0.17 (0.14)	0.16 (0.13)	0.01 (−0.01)
SOI	−0.17 (−0.16)	−0.06 (−0.07)	0.01 (−0.22)
Temperature	0.13 (**0.35***)	−0.01	−0.08 (−0.20)
NO_x (UK, 1970–2007)	**−0.66****	**−0.46****	−0.15
NO_x (Manchester, 1987–2007)	**−0.51***	−0.34	−0.25

Bold values with a single asterisk (*) are significant at the less than 5% level, those with a double asterisk (**) are significant at the less than 1% level. Values in brackets are correlation coefficients calculated over the same time period as the UK NO_x data (i.e. 1970–2007).

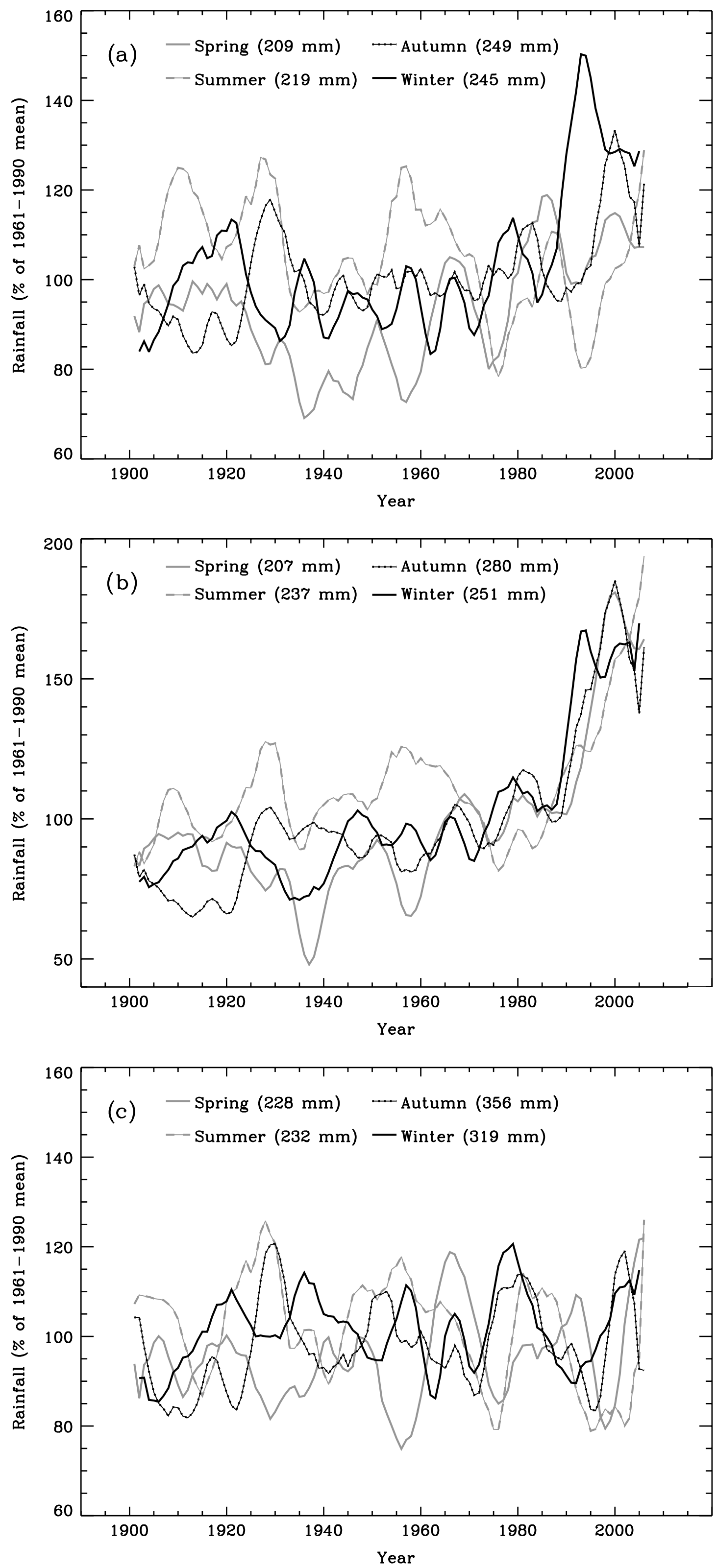

Figure 3. Seasonal precipitation totals relative to the 1961–1990 seasonal means (listed on the plot after the season name) from: (a) Wall Grange, (b) Lyme Park and (c) Douglas. Note that the y-axis is different on Figure 3b.

Hemisphere temperature rise that occurred at approximately the same time as the Manchester area precipitation increase/NO_x decrease was thought to be driven by aerosol concentration in this region. There is clearly some interconnectedness here.

The key causal link between aerosol concentration and precipitation is that the higher particle levels in the early years of the record may have suppressed rainfall downstream of the city. This can occur because increased cloud condensation nuclei (CCN) results in more, smaller

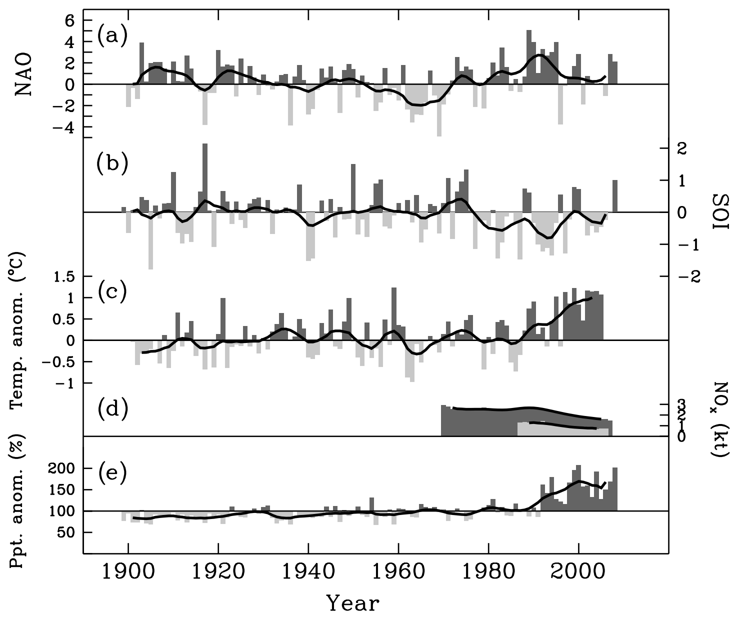

Figure 4. (a) North Atlantic Oscillation index; (b) Southern Oscillation Index; (c) temperature anomaly (in °C relative to the 1961–1990 mean) for the area 53–53.5 °N, 2–2.5 °W; (d) national NO_x levels in kilotonnes (dark grey) with Manchester NO_x levels in 1.0×10^{-8} g m^{-3} (light grey) plotted for comparison and (e) precipitation anomaly (in % relative to the 1961–1990 mean) from the Lyme Park rain gauge. The data presented in (a)–(c) are used subject to the attribution © Climatic Research Unit, University of East Anglia.

cloud droplets forming that do not fall as rain where they otherwise would. As the pollution levels decrease past a certain threshold, the cloud droplets grow larger nearer to the pollution source and, therefore, precipitation levels increase. If Lyme Park is at the optimum distance from the emissions source to be subject to this effect then this would explain why the larger trend is observed there. Such a complicated aerosol–precipitation relationship was presented by van den Heever and Cotton (2007), who also noted the importance of the overlying weather patterns in determining the impact of the pollution on individual days.

The higher NO_x-precipitation correlation coefficients could also be a facet of the shorter time period available. However, when we calculate the correlation coefficients for the same, shorter period for which we have national NO_x data, all remain insignificant apart from Lyme Park precipitation *versus* temperature (Table I), indicating that recent temperature changes may have also influenced the rainfall levels and that urban heat island effect may lead to more local precipitation.

5. Precipitation origin and urban influence

To assess if there is an urban influence on precipitation at these sites we determined whether the air parcels that delivered the rain travelled over any major urban areas. To do this, Figure 5 shows the typical origin area for air parcels arriving at each of the three sites at 850 hPa at 12 UTC on days when rain was recorded. The most striking result is that most of the 'rain day' BTs arrive from the west over a relatively narrow latitudinal range over the Atlantic.

Within this precipitation air parcel analysis we identified the 13 largest urban areas in the UK and Ireland, which are centred on London, Birmingham, Manchester, Leeds, Glasgow, Dublin, Newcastle, Liverpool, Nottingham, Sheffield, Bristol, Belfast and Edinburgh. It was found that 42% of 'rain day' BTs from Lyme Park passed within 25 km of a major urban centre. This figure was 25% for Wall Grange and 14% for Douglas. These 'urban rain days' accounted for 40, 25 and 12% of the total rainfall at the three sites respectively. This implies a strong urban influence on the Lyme Park precipitation record and a weak influence on the Douglas record. Indeed, the majority of the Lyme Park 'urban rain day' BTs travelled over some of the UK's largest cities (i.e. Birmingham, Manchester, Leeds and Liverpool) whilst 'urban rain day' BTs for Douglas are associated with smaller cities (i.e. Dublin and Belfast).

However, this analysis provides no clear evidence that the increase in rainfall seen at Lyme Park since the 1970s can be attributed to the influence of urban environments. Whilst there is a positive trend in the mean rainfall on 'urban rain days' in the analysis period (1970–2008) for Lyme Park, this is also true for 'non-urban rain days'. Indeed, the largest change in this period is an increase in the amount of rainfall on 'non-urban rain days' of approximately 15 mm year^{-1}. This trend is, to a lesser extent, also seen at Wall Grange: 5 mm year^{-1}.

This pattern may, however, be consistent with a reduction in precipitation suppression due to decreasing aerosol concentration in general rather than on specific days as we assumed in this analysis. For example, our analysis does not consider larger scale weather patterns, the height of the BTs when they 'encounter' a city,

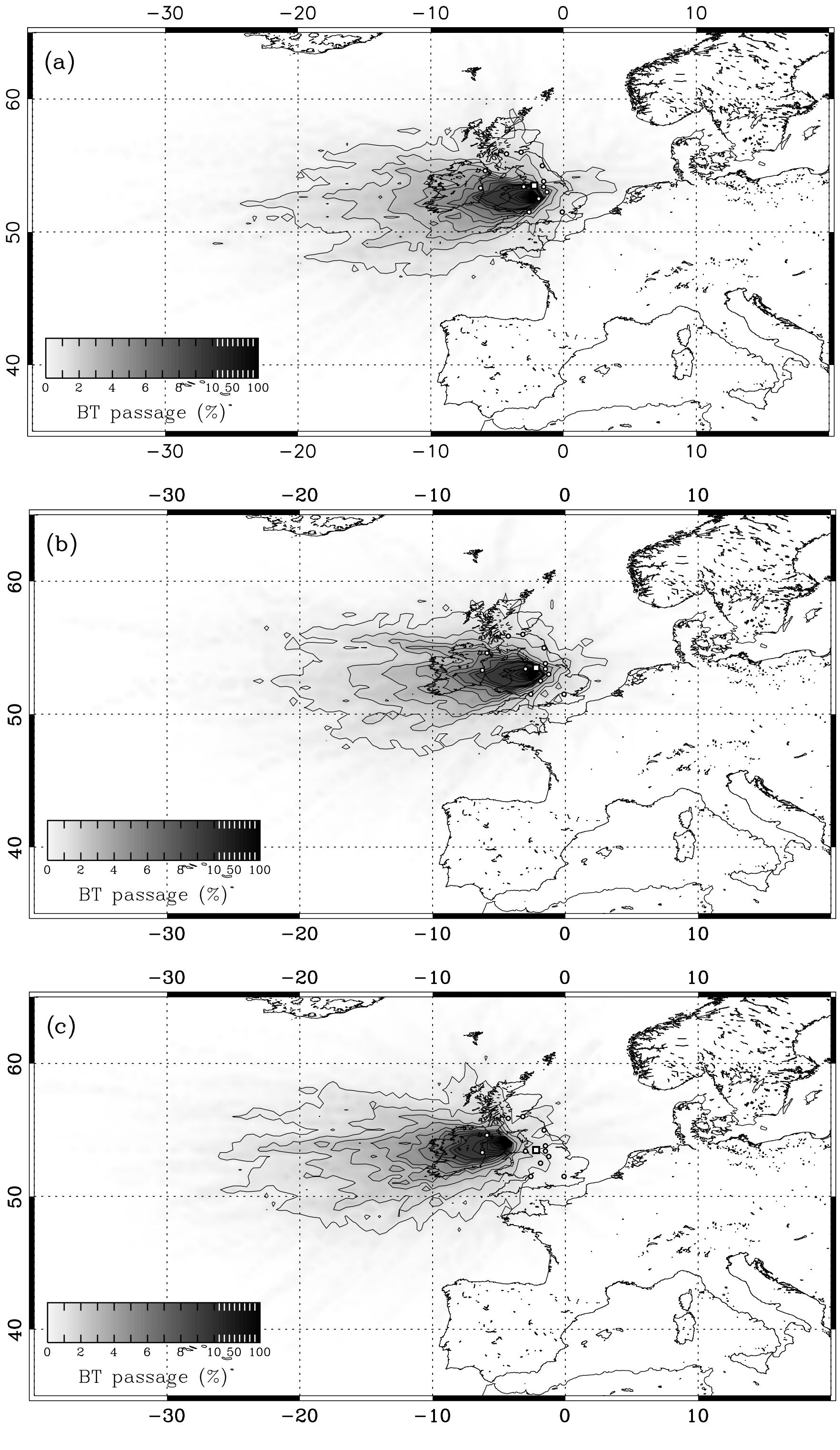

Figure 5. Percent of ‘rain day’ BTs passing through each point of a 0.5° × 0.5° latitude-longitude grid initiated from: (a) Wall Grange, (b) Lyme Park and (c) Douglas. The shading scale is nonlinear to highlight the variability below 10%. The black circles (or a square for Manchester) with white centres show the location of the 13 major urban areas in the UK and Ireland listed in Section 4.

surface temperature variations or the aerosol dispersion characteristics or concentration levels, which will all be different on different days. These factors could combine in such a way as to increase the precipitation levels around Manchester in the way that we have observed but a much more complex methodology would be required to investigate this.

6. Precipitation cycles and urban influence

Table II shows that the precipitation increase at Lyme Park occurred completely on weekdays: mostly Mondays, Wednesdays and Fridays. Weekends, conversely, show a very slight negative trend. This is of interest as any urban influence on meteorology is likely to demonstrate some sort of weekly cycle in line with industrial work and emission patterns. The theory of a weekly cycle in rainfall/weather patterns and its urban link has been investigated for decades (Ashworth, 1929) but a definitive connection is elusive. For example, Cerveny and Balling (1998) reported weekly cycles in several atmospheric phenomena, some of which one would assume would be insensitive to urban influence, whilst Schultz *et al*. (2007) failed to find evidence of such a cycle in a methodical investigation of rainfall data across the United States. It is also unclear as to whether this weekly cycle would be evident local to the emissions source or on much larger scales (Bäumer and Vogel 2007). Despite this uncertainty, there is still an interesting pattern in the Lyme Park data that is consistent with a strong aerosol-precipitation link and this requires further investigation.

7. Conclusions

We have analysed precipitation data from the Manchester region of the UK and identified a distinctive trend in recent years. We investigated whether the changing precipitation regime was driven by the development of urban areas and, in short, we have presented data that is not inconsistent with this being the case. Indeed, the key lines of evidence presented here (i.e. the Lyme Park precipitation increase from less than to more than the Douglas levels after ∼1980, the precipitation increase across all seasons, the reduction in urban emissions, the frequency of 'urban rain day' BTs and the weekly cycle) leads us to hypothesise that the trend seen at Lyme Park (and, to a lesser extent, Wall Grange and Manchester 'city centre') is caused by a reduction of precipitation suppression. This hypothesis requires further testing.

A back trajectory analysis designed to identify precipitation increases associated with moist air parcels that track back over urban centres found no convincing link. Indeed, the opposite was found to be true but, given the complex nature of the proposed link between aerosol emissions and the precipitation changes, this method may have been too simplistic. The other major driving factor of the precipitation trend was found to be the sea surface temperature in the precipitation source region.

This analysis, whilst not conclusive, certainly demonstrates that the precipitation regime of Manchester is dynamic and would be an ideal location for further investigation of urban influences. To understand the driving factors of the precipitation patterns more conclusively, modelling experiments are required to untangle the effects of the various features and to represent the role and dispersion of aerosol in a way that the observations used here cannot achieve. A detailed analysis of satellite observations, alongside more emissions and precipitation data, would also help in understanding the recent changes. Such experiments would be welcome in order to help predict and prepare for the future changes in precipitation for this area.

Table II. Trend, in mm year^{-1}, for annual precipitation for 1970–2008 recorded on different days of the week for the three stations.

	Lyme Park	Wall Grange	Douglas
Monday	8.7	1.2	0.2
Tuesday	0.9	1.0	0.8
Wednesday	4.9	1.3	0.1
Thursday	0.2	1.2	−0.2
Friday	5.3	0.7	−0.5
Saturday	−0.1	1.3	−0.8
Sunday	−0.2	0.6	−0.9

Acknowledgements

We are grateful to the two anonymous reviewers of this paper, who made insightful comments that significantly improved the analysis and discussion. Thanks are also due to Dr David Schultz (University of Manchester) for his help in planning this work and to the Manchester Science Festival for inspiring the initial investigation of rainfall measurements around Manchester.

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