Accepted Article

Atmospheric Rivers don't explain UK Summer Extreme Rainfall

Adrian J. Champion,[1] Richard P. Allan,[1] David A. Lavers,[2]

Corresponding author: Adrian J. Champion, Department of Meteorology, University of Reading, Reading, RG6 6AL, UK. (a.j.champion@reading.ac.uk)

[1]Department of Meteorology, University of Reading, Reading, UK.

[2]Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, USA

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2014JD022863

©2015 American Geophysical Union. All Rights Reserved.

Abstract. Extreme rainfall events continue to be one of the largest natural hazards in the UK. In winter, heavy precipitation and floods have been linked with intense moisture transport events associated with atmospheric rivers (ARs), yet no large-scale atmospheric precursors have been linked to summer flooding in the UK. This study investigates the link between ARs and extreme rainfall from two perspectives: 1) Given an extreme rainfall event, is there an associated AR? 2) Given an AR, is there an associated extreme rainfall event?

We identify extreme rainfall events using the UK Met Office daily raingauge dataset and link these to ARs using two different horizontal resolution atmospheric datasets (ERA-Interim and 20th Century Re-analysis). The results show that less than 35% of winter ARs and less than 15% of summer ARs are associated with an extreme rainfall event. Consistent with previous studies, at least 50% of extreme winter rainfall events are associated with an AR. However, less than 20% of the identified summer extreme rainfall events are associated with an AR. The dependence of the water vapor transport intensity threshold used to define an AR on the years included in the study, and on the length of the season, is also examined. Including a longer period (1900-2012) compared to previous studies (1979-2005) reduces the water vapor transport intensity threshold used to define an AR.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

1. Introduction

Extreme rainfall continues to be one of the greatest natural hazards in the UK. A number of recent extreme rainfall events have led to widespread flooding highlighting the vulnerability of the UK to this hydrohazard. Aside from flooding, extreme rainfall can lead to hazardous driving conditions and disruptions to other travel. With extreme rainfall events expected to change in intensity and frequency with climate change [*Gregerson et al.*, 2013; *Kendon et al.*, 2014], understanding the causes of these extreme rainfall events is of particular importance.

Previous studies have shown a strong relationship between winter flooding over the UK and Atmospheric Rivers (ARs) [*Lavers et al.*, 2012], synoptic features which have also been associated with winter flooding in the remainder of Europe [*Lu et al.*, 2013; *Lavers and Villarini*, 2013a], the US [*Lavers and Villarini*, 2013b; *Ralph et al.*, 2006; *Neiman et al.*, 2011], and South America [*Viale and Nuñez*, 2011]. *Dacre et al.* [2015] show this enhanced moisture transport is formed by the cold front of an extratropical cyclone sweeping up water vapour in the warm sector as it catches up with the warm front. This results in a narrow band of high water vapour content forming ahead of the cold front at the base of the warm conveyor belt airflow. The UK study of *Lavers et al.* [2011] used river flow-gauge data and was focussed on basins in the west of the country. The present study exploits raingauge data for the whole country to identify events that may potentially lead to flooding in other regions.

Previous studies have shown that 70% of the winter precipitation in the UK can be attributed to extra-tropical cyclones [*Hawcroft et al.*, 2012]. Whilst there can be small-

©2015 American Geophysical Union. All Rights Reserved.

scale processes that lead to an increase in the precipitation intensity (e.g. orographic enhancement), the scale of the conditions that lead to winter precipitation, e.g. fronts, is of the scale of 1000s of km and can last several days. Hence, winter precipitation is typically widespread and for a prolonged period [*Hand et al.*, 2004]. Therefore, it can be expected that extreme winter events are also associated with a large-scale process associated with cyclones. For example, an AR could be providing the "feeder" moisture for heavy precipitation associated with a seeder-feeder mechanism [*Bergeron*, 1965; *Browning*, 1974]. This is where upper-level precipitation (seeder) falls through lower-level orographic precipitation (feeder), here an AR, causing an increase in the precipitation intensity. There have been a large number of studies that have shown the significant role orography has on the enhancement of precipitation associated with ARs in the US [*Neiman et al.*, 2013; *Smith et al.*, 2010; *Ralph et al.*, 2006; *Dettinger et al.*, 2004] and elsewhere in the world [*Viale and Nuñez*, 2011].

Summer precipitation, however, is generally dominated by small-scale (less than 10s of km), short-lived (a few hours) precipitation [*Hand et al.*, 2004], with flash floods (those lasting only a few hours) dominating the flood record. This type of precipitation is more commonly associated with convective events which can lead to extremely high rainfall rates. There are a number of dynamical processes that lead to convective precipitation [*Bennett et al.*, 2006] which typically occur on relatively small spatial scales. Therefore it is not clear whether ARs are associated with such events, since ARs are defined as a large-scale region of atmospheric convergence, while the processes that cause the summer events are typically much smaller in scale.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

If the atmospheric precursors are better known, this could contribute towards better prediction of flash floods, thus reducing their potential impact on the UK. The aims of this paper are to investigate whether ARs can be used to explain summer extreme rainfall events over the UK, and to examine how the threshold for defining an AR depends on the season and number of years used in the study.

2. Data and Method

2.1. Atmospheric Datasets

Two atmospheric datasets were used in this study, ERA-Interim [*Dee et al.*, 2011] and the ensemble mean of the 20th Century Reanalysis (20CR) [*Compo et al.*, 2011]. ERA-Interim is a high-resolution (0.7° latitude by 0.7° longitude) re-analysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF) that spans from 1979 until the present day; the period up until the end of 2013 was used in this study. The 20CR is a lower-resolution (2.0° latitude by 2.0° longitude) re-analysis ensemble product from the National Oceanic and Atmospheric Administration (NOAA) covering a much longer period, 1871-2012; only the period 1900-2012 was used in this study. 1900 was chosen as the start year due to the availability of the raingauge data (discussed later).

The higher resolution of the ERA-Interim data increases the likelihood that fields with small spatial scales associated with ARs, e.g. specific humidity, are identified; the longer period of the 20CR allows for trends in AR occurrence to be investigated. It should be noted that 20CR only assimilates surface observations of synoptic pressure, monthly sea surface temperature and sea ice distribution [*Compo et al.*, 2011], therefore the synoptic details are quite likely less accurate although the temporal continuity is greater, compared

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

to the ERA-Interim. The number of ARs identified in each dataset, and their association with known flooding events, are presented in the next Section.

2.2. Atmospheric Rivers Identification

We apply a comparable method to *Lavers et al.* [2013] to detect ARs. Vertically integrated horizontal water vapour transport (IVT) is calculated by integrating the zonal and meridional moisture fluxes through each atmospheric layer between 1000hPa and 300hPa, as described in Equation 1, where u and v represent the wind field in the zonal and meridional directions respectively, q is the specific humidity and p is the pressure at different pressure levels. The integral was calculated using two layers, one between 1000hPa and 750hPa and another between 750hPa and 300hPa. For ERA-Interim this involved integrating 11 vertical levels between 1000hPa and 750hPa (at 25hPa intervals) and 10 vertical levels between 750hPa and 300hPa (at 50hPa intervals). For 20CR, where the output has a constant vertical interval of 50hPa, there were 7 vertical levels between 1000hPa and 750hPa and 9 vertical levels between 750hPa and 300hPa. This was calculated as a global field for every model time-step. This does not take into account any contributions below 1000hPa, which could be addressed by using surface pressure instead of 1000hPa. 1000hPa was used here for comparison to previous studies.

$$IVT = \left[\left(\frac{1}{g} \int_{1000}^{300} qudp \right)^2 + \left(\frac{1}{g} \int_{1000}^{300} qvdp \right)^2 \right]^{1/2}. \quad (1)$$

The IVT values (kg m^{-1} s^{-1}) between 50°N and 60°N at 4°W are examined and the 85th percentile of the daily maxima at 1200 UTC is taken as the threshold for defining an AR, as used in previous studies [*Lavers et al.*, 2013]. The limits of 50°N and 60°N

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

were chosen for direct comparison to *Lavers et al.* [2013]. Whilst this may result in some filaments of enhanced IVT that occur on the southern coast of the UK being missed, the limits were retained for comparison to previous studies. It was also found that between 20% and 25% of identified ARs occur north of 58°N, where there is very little landmass and very few raingauges. This may result in a number of ARs being identified that do not have an effect on the precipitation over land. However, as before, the limits were retained for comparison to previous studies.

When the globally pre-calculated IVT field has exceeded the 85th percentile threshold between the limits of 50°N and 60°N at 4°W, the IVT field is tracked back to see whether this threshold is met for at least 20 degrees in longitude and must be persistent for 18 hours, 3 time-steps, to meet the criteria for the persistent AR definition. Only a 4.5° latitude displacement (between time steps) to the north or south of the initial IVT maximum at 4°W was allowed. By assuming that the maximum IVT represents the mid-point of the AR (at 4°W), and that ARs have been considered to be on the order of 1000 km wide [*Neiman et al.*, 2008], a 4.5° movement (which is approximately equal to 500 km) means that even if the central location of the AR moves by 4.5°, the AR may still be present over a specific location.

Finally we ensure that each AR is unique by ensuring there are 4 time-steps (1 day) in-between identified IVT exceedances. A region of moisture convergence that fits all these criteria is then labelled as an independent AR. An example of a region of IVT that meets the AR definition for the UK is shown in Figure 1 from the ERA-Interim dataset, along with the fields that are used to calculate IVT: specific humidity (q), zonal wind (u) and meridional wind (v) (all shown at 850hPa).

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Brönnimann et al. [2012] note that individual members of the 20CR are better able to represent extremes compared to the ensemble mean which is used here. This caveat is therefore considered when interpreting differences between the reanlaysis products. *Brönnimann et al.* [2012] also show that the ensemble variance of extreme winds decreases after 1950. This suggests that the variance of the IVT values selected would similarly decline; this is not considered in the present study since trends are not assessed.

2.3. Extreme Rainfall Identification

To determine whether ARs over the UK can be linked to extreme rainfall events, daily raingauge totals from the NERC Centre for Environmental Data Archival (CEDA, *Met Office* [2012]) were used to identify extreme rainfall events. The locations of all the gauges included in this study are shown in Figure 2 (top). Whilst it is known that intense summer rainfall is typically convective [*Hand et al.*, 2004], occurring on timescales shorter than a day (typically hours), daily data were used to due a lack of a nationwide hourly raingauge data.

To identify an event as extreme, a peaks-over-threshold (POT) method was used. The threshold used was the top-decile (90th percentile) of the maximum rainfall observed over the UK for all days for the period of the dataset (1979-2013 for ERA-Interim and 1900-2012 for 20CR), for each season considered. In addition, only days when precipitation was observed are included, using a value of 2.54mm as the lower daily threshold. This method is similar to the one used by *Rutz et al.* [2014], with their lower threshold being based on the resolution of their dataset. The intensity resolution of the dataset used here is 0.2mm. However, this resulted in a very low top-decile, and it was decided to use a

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

similar threshold as used by *Rutz et al.* [2014]. The top-decile calculated for each season is shown in Table 1.

Other methods [*Davison and Smith*, 1990] have suggested selecting only a certain number of events for the period of study, such as the POT method. The POT method identifies a set number of events for the period, i.e. using POT1 an average of 1 event per year would be extracted, however multiple events could come from the same year. Using POT2 and POT3 an average of 2 and 3 events per year respectively would be selected. These are applied separately to winter and summer. These thresholds are shown alongside the thresholds calculated earlier in Figure 3. This method was considered suitable for datasets where the number of events of interest is low (e.g. when river flow-gauge data exceeds the banks and therefore causes flooding). However, in this case where the number of events of interest is higher it was decided that these thresholds identified too few extreme events. Hence the top-decile method was used to identify extreme events as being of interest.

The raingauge dataset had already undergone a number of quality control checks by the UK Met Office. However, it was necessary for further quality checks to be made to remove further problems identified in the dataset. The number of raingauges included in this study varies significantly for different periods. For the period 1900-1960, the number of operational raingauges (post quality control) were relatively few (typically 100-300). After 1960 there was a large increase in the number of operational raingauges to over 4000. For the period 2001-2011 there were a number of data quality issues due to changes to the data quality flags, used to identify data as potentially incorrect. This could not be resolved in this study; thus the number of raingauges included for this study during this period was around 1000.

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

These variations in the number of raingauges included may result in the number, or intensity, of the extreme events being identified changing. This was investigated and it was found not to have a significant effect; the most extreme events in a year were still being recorded by a raingauge somewhere in the UK. In the analysis, when multiple raingauges recorded an extreme event on the same day it was only classed as a single event. Therefore the variation in the number of raingauges is not considered to have a significant effect on the results. Studies have also shown that percentile indices potentially introduce inhomogeneities into the time series [*Zhang et al.*, 2005], although this is more important for climate change detection and monitoring which is not the focus of the present study.

An AR was considered to be associated with an extreme rainfall event if the AR was first detected up to a day before the extreme rainfall event. *Lavers et al.* [2012], who used river flow-gauge data, allowed 3 days between an AR and flood event. This to allow for the catchment response time, the time it takes for rain falling across the catchment to feed into the rivers and potentially result in flooding. The 1-day period used here is also the same used by *Rutz et al.* [2014], who also used raingauge data in their study.

The sensitivity of the results to the length of this period was tested, up to 5 days, and is discussed in more detail alongside the main results in Section 3.2. On average, for each day the period was extended by, an extra 1% of AR events had an extreme rain event associated with them. Given an extreme rain event, an additional 2% per day the period was extended by had an AR associated with them. This study also uses the end date of the identified AR, allowing an extreme rainfall event to be associated with an AR until the final day it is identified. The sensitivity of the results to the end date of an identified

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

AR was not tested. This study was not able to take into account any positional errors in the locations of the ARs in the re-analysis.

3. Results

3.1. Threshold Selection

In previous studies [*Lavers et al.*, 2013], the threshold to define an IVT as an AR was chosen as the 85th percentile of IVT identified at 4°W for the period 1979-2005 at 1200 for October to March (ONDJFM). In this study, more recent years were available (up until 2013 for ERA-Interim and 2012 for 20CR). The extra years available were used to test the dependence of the threshold value on the period over which it was calculated. It is known that there is variability between seasons and years on the prevalence of extreme rainfall [*Burt and Howden*, 2013; *Jones et al.*, 2013]. This suggests there will be variability in the IVT intensities depending on the years chosen to calculate the threshold, and on the season being investigated. The dependence of the threshold on the length of the season used, i.e. an extended winter/summer (ONDJFM/AMJJAS) or a shortened winter/summer (DJF/JJA), was also investigated.

Initially the study looked at the winter period to compare to known previous thresholds [*Lavers et al.*, 2013] who used the period 1979-2005 and for an extended winter. Table 2 shows the 85% IVT values for two different periods, 1979-2005 and 1979-2013, for both an extended winter (ONDJFM) and a shortened winter (DJF). The results for both the ERA-Interim and 20CR datasets is shown to also highlight the difference between datasets with two resolutions. For 20CR an additional period, 1900-2012, is included to investigate potential impacts of annual variability.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

By including the most recent data (2005-2013 for ERA-Interim and 2005-2012 for 20CR) there are small differences in the winter threshold value of IVT, although the effect on the number of ARs identified is very small. There is much more pronounced difference for 20CR if the whole period available is used (1900-2012); the values are around 5% lower than either the 1979-2005 or 1979-2012 periods. This study did not investigate which years caused the decrease in the IVT threshold value but the results do highlight the annual variability as expected earlier. There is also a marginal dependence on whether an extended or a shortened season is used. However, this again would only result in a difference of a few ARs. These results are consistent for both ERA-Interim and 20CR, although lower thresholds are calculated for 20CR.

The results for summer, Table 3, highlight a number of differences to the results seen for winter (Table 2). In contrast to the winter results, the threshold value of IVT is similar for ERA-Interim and 20CR. For winter, the 20CR thresholds were around 10% lower than the ERA-Interim values. For summer the thresholds calculated never differ by more than 2%, a similar magnitude of difference as seen in the winter investigation into the effect of the length of the season and the years included. The reason for these differences could not be determined in this study.

This effect is also highlighted when comparing the summer IVT thresholds to the winter thresholds. For ERA-Interim there is typically a reduction of around 5% in the summer threshold compared to the winter threshold (with the exception of the 1979-2013 JJA value). The 20CR results however show an increase in the threshold value for summer compared to winter, differing by up to 10%. The dependency of the results on model resolution are similar to *Hagos et al.* [2015] who found a decrease in the frequency of AR

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

events with model resolution. The causes of the differences observed here are outside the scope of the present study but merits further investigation.

As observed in the winter results, there is very little difference in the summer threshold values of IVT between the 1979-2005 period and the 1979-2013 (for ERA-Interim, 1979-2012 for 20CR) period. However, in contrast to the winter results, the summer threshold value of IVT for the longer 1900-2012 period is very similar to both the 1979-2005 or 1979-2012 periods in 20CR. The same small dependence on the season length, as seen in winter, is also seen for summer. Again, in contrast to the winter results, the extended seasons show a reduction in the threshold value of IVT, compared to the increase seen in winter.

The threshold investigation has shown that for winter, by including the whole period available (1900-2012), there is a reduction in the threshold value of IVT. This is not seen for summer. As stated earlier, it is predicted that the variance of the IVT threshold decreases during this period, particularly after 1950. A study into whether this is the case would be an interesting extension to this result. The threshold investigation has also shown that the two different resolution datasets have similar threshold values of IVT for summer. For winter around a 10% difference is seen. It is worth remembering the results from *Brönnimann et al.* [2012] that the ensemble mean of 20CR (used here) does not represent extremes as well as individual members. Thus the average IVT threshold may be artificially lowered as the most extreme IVT values are not captured, compared to ERA-Interim. Any implications these results may have in determining the main cause for moisture availability over the UK in the summer is discussed in the next Section.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

3.2. Relevance to UK Extreme Rainfall

Lavers et al. [2012] linked AR events to winter flooding using a POT1 method on flow-gauge data in nine river basins to identify flooding events. The present study focusses on extreme rainfall as observed from raingauges to capture events that might not be captured by flow-gauge data, e.g. overland flow. Not all of these events will lead to flooding, nor will all flooding events be captured due to a number of events being over short timescales (hours) and very localised, such as summer flash floods caused by convective events. This study will also not look at events with less extreme rainfall intensities but which last for a number of consecutive days that may also lead to flooding. However, the use of raingauges can provide useful insights into the causes of extreme rainfall in the UK, and potentially identifying overland flow.

The results are analysed from two perspectives. The first is: *Given an extreme rainfall event is there an associated AR?*. These results are shown in the left panel of Figure 4. For a flood event to be attributed to an AR the criteria used by *Lavers et al.* [2012] was to allow an AR to be present up to 3 days prior to the flood. In this study, due to the raingauge response being almost instantaneous, the approach taken by *Rutz et al.* [2014] is used where the AR must be present on the same day or a maximum of 1 day previously, although this only reduces the number of associated events by up to 4%. The second perspective examines how many extreme rainfall events occur given there's an AR, answering the question as to whether an AR can be used as an indicator of an extreme rainfall event occurring; these results are also shown in the right panel of Figure 4. The location of the raingauges that had events linked to ARs is shown in the bottom panels of

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Figure 2, for both winter (left) and summer (right). The locations are the same for both perspectives considered.

The results for the first perspective (given there's an extreme rainfall event is there an associated AR, left panel Figure 4) show that for a short winter (DJF), 65% of the extreme rainfall events identified had an AR associated with them. These values are very similar to those found by *Lavers et al.* [2012], although that was for an extended winter and for a smaller sample of 9 river basins. The results for an extended winter show a smaller percentage, around 50%. The results between ERA-Interim and 20CR are very similar, an interesting result given the longer period the 20CR data is examined over, 1900 to 2012. This is also similar if different periods of the 20CR data are chosen, e.g. 1979-2012.

The results for summer show a very different result, with fewer than 20% of the extreme rainfall events identified, regardless of season length of data set, being associated with an AR. Whilst a reduction in the connection was expected due to the more convective, and therefore localised, nature of extreme rainfall events in summer (hence the further reduction in the short summer), this shows a very large reduction in the connection. The thresholds for defining both an extreme rainfall event and an AR are both lower in the summer, although the relation is considerably weaker.

This suggests that ARs are not a good indicator of summer extreme rainfall possibly due to the relatively small scale summer convection compared to the large-scale nature of ARs. The sensitivity of the results to the length of time between the identified AR and an associated extreme rainfall event showed that for every day the period was extended

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

by (up to 5 days tested), the number of extreme events that had an AR associated with it went up by 2-3%. This result was independent of the season, or the length of the season.

The second perspective taken in this study is: *Given an AR is there an extreme rainfall event* (right panel Figure 4)? It is immediately clear that for summer, and winter, the percentages are much lower than the results for the prior perspective. These results suggest that whilst extreme rainfall events, in winter, can be associated with ARs, there are far more ARs (using the definition of *Lavers et al.* [2012]) than extreme rainfall events, where an extreme rainfall event is defined by being in the top-decile of all rainfall events over the whole of the UK. Further results (not shown) indicate that it also not necessarily the most extreme summer rainfall events that are identified by ARs, suggesting that there are other factors that are more important in determining the severity of summer rainfall events. The same sensitivity test to the period between an AR and an extreme event was performed and showed that for each day the period was extended the number of events went up by only 1-2% (up to 5 days tested).

The location of the raingauges which had events associated with ARs identified in ERA-Interim (Figure 2 for both winter (bottom left) and summer (bottom right)) also highlight two conclusions that agree with previous studies. The first is that almost all of the raingauges are located on the west coast of England, Scotland and Wales with only two raingauges being identified in the east of the UK. However, there is little variation between the north and the south of the UK. The second is that they are also predominantly associated with areas of high orography. This agrees with previous work on linking ARs to flooding in river basins in the north-west of Britain [*Lavers et al.*, 2012] and the importance

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

of orographic forcing on the enhancement of precipitation associated with landfalling ARs [*Neiman et al.*, 2013].

4. Conclusions

This study has examined the link between extreme daily rainfall in the UK and intense moisture transport episodes associated with ARs during the winter and summer seasons. The study has produced similar results to the flow-gauge study of *Lavers et al.* [2012], demonstrating a connection between ARs and winter extreme raingauge events, although the percentages are reduced for an extended winter. However, the results have shown that ARs cannot be used to explain summer extreme rainfall events, with less than 20% of summer extreme rainfall events having an AR associated with them. The results have also highlighted the importance of orography in the connection between ARs and extreme rainfall events. This study examined whether ARs could be defined as a precursor to extreme rainfall events. The results showed that many more ARs are identified than are associated with extreme rainfall events, with less than 10% of ARs in the short summer being associated with an extreme rainfall event.

Whilst these results suggest that ARs are not particularly useful for the summer, there are a number of factors that ought to be taken into account. The first is the short timescale over which summer extreme rainfall events typically occur, which is hours rather than days. Therefore the raingauge dataset used in this study, a daily dataset, may not capture many of the extreme rainfall events, and it could be that many of the ARs identified do cause extreme rainfall however on much shorter timescales. The second factor is that due to quality control issues the number of raingauges between 2002 and

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

2008 were significantly reduced, compared to surrounding years. Also, for the case of 20CR, the number of gauges before 1960 is significantly smaller.

The results also show that for for both seasons (and shortened and extended), more of the extreme rainfall events were associated with ARs identified in 20CR than in ERA-Interim. The periods over which the relationship was tested were very different, 35 years (1979 to 2013) for ERA-Interim and 113 years (1900 to 2012) for 20CR. This suggests the correlation may be affected by natural variability, i.e. the effect of wet seasons and dry seasons, however this is not tested in this study. This result could also be strongly affected by the quality control issue of the raingauge dataset mentioned earlier.

The results for winter showed a reduction (5%) in the threshold value of IVT when a much longer period of 1900-2012 compared to a period of 1979-2005, or 1979-2012, was used in the 20CR data. This reduction was not seen for the summer. The difference between the periods 1979-2005 and 1979-2013 (for ERA-Interim, 1979-2012 for 20CR) was very small. The effect of the resolution of the dataset on the threshold value of IVT was shown to be more pronounced in winter than in summer. In winter, the threshold values of IVT were around 10% lower in 20CR than in ERA-Interim. For summer, the threshold values of IVT were very similar. It was also seen that by using an extended winter caused an increase in the threshold value of IVT, whereas a reduction was seen for summer. The summer thresholds were also around 5% lower than in winter. Taking into account the representation of extremes in the 20CR ensemble mean [*Brönnimann et al.*, 2012], this implies that different processes are operating depending on the season. It also highlights the potential variability in the threshold value of IVT depending on the season, and years included, in the study.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

This preliminary study considered the connection between atmospheric rivers and ungridded daily raingauge data observations. The limitations to this work include the use of daily raingauge data to try to observe hourly rainfall events in the summer months, the choice of the threshold value to define an event as extreme and that ARs are defined at 4° West and the raingauges are taken over the whole country. However, the results show an agreement to *Lavers et al.* [2012] as to how many winter events are associated with an AR and also show that far fewer summer events are associated with an AR. The results also highlight that a lot more ARs are identified than extreme rainfall events. Future work will be to use an hourly raingauge dataset to identify more convective events in the summer months, and to use alternative moisture identification methods, such as the ones used by *Lavers and Villarini* [2013a] and *Rutz et al.* [2014].

Acknowledgments. The authors would like to acknowledge the constructive comments from all the reviewers in improving this paper. This research is part of the SINATRA project which is supported by the United Kingdom NERC Flooding From Intense Rainfall programme (grant NE/K00896X/1). The ERA-Interim dataset was made available from the European Centre for Medium-Range Weather Forecast (ECMWF) via the ECMWF Data Server (http://www.ecmwf.int). The 20th Century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. Support for the Twentieth Century Reanalysis Project dataset is provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Atmospheric Administration Climate Program Office. The rainguage dataset was downloaded from the NERC Centre for Environmental Data Archival (http://www.ceda.ac.uk).

References

Bennett, L., K. Browning, A. Blyth, D. Parker, and P. Clark (2006), A review of the initiation of precipitating convection in the united kingdom, *Q.J.R.Met. Soc.*, *132*, 1001–1020.

Bergeron, T., *On the Low-level Redistribution of Atmospheric Water Caused by Orography.* Meteorologiska Institutionen, 1965.

Brönnimann, S., O. Martius, H. von Waldow, C. Welker, J. Luterbacker, G.P. Compo, P.D. Sardeshmukh, and T. Usbeck (2012), Extreme winds at nothern mid-latitudes since 1871, *Met. Zeit.*, *21*, 13–27, doi10.1127/0941-2948/2012/0337.

Browning, K. (1974), Mesoscale structure of rain systems in the British Isles, *J. Meteorol. Soc. Japan*, *52*, 314–327.

Burt, T., and N. Howden (2013), North atlantic oscillation amplified orographic precipitation and river flow in upland britain, *Water Resources Research*, *49*(6), 3504–3515, doi:10.1002/wrcr.20297.

Compo, G., J. Whitaker, P. Sardeshmukh, N. Matsui, R. Allan, X. Yin, B. Gleason, R. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R. Crouthamel, A. Grant, P. Groisman, P. Jones, M. Kruk, A. Kruger, G. Marshall, M. Maugeri, H. Mok, . Nordli, T. Ross, R. Trigo, X. Wang, S. Woodruff, and S. Worley (2011), The Twentieth Century Reanalysis Project, *Q.J.R.Meteorol. Soc.*, *137*(654), 1–28, doi: 10.1002/qj.776.

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

Accepted Article

Dacre, H., P. Clark, O. Martinez-Alvarado, M. Stringer, and D. Lavers (in press), How do atmospheric rivers form?, *Bull. Am. Met. Soc.*, doi:10.1175/BAMS-D-14-00031.1.

Davison, A., and R. Smith (1990), Models for exceedances over high thresholds, *J. R. Stat. Soc.*, *52B*, 393–442.

Dee, D., S. Uppala, A. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. D. andM. Fuentes, A. Geer, L. Haimberger, S. Healy, H. Hersbach, E. Hlm, L. Isaksen, P. Kllberg, M. Khler, M. Matricardi, A. McNally, B. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thpaut, and F. Vitart (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Q.J.R.Meteorol. Soc.*, *137*, 553–597, doi: 10.1002/qj.828.

Dettinger, M., K. Redmond, and D. Cayan (2004), Winter Orographic Precipitation Ratios in the Sierra Nevada - Large-Scale Atmospheric Circulations and Hydrologic Consequences, *J. Hydrometeor.*, *5*, 1102–1116.

Gregerson, I., H. Srup, H. Madsen, D. Rosbjerg, P. Mikkelsen, and K. Ambjerg-Nielsen (2013), Asessing future cliamte changes of rainfall extremes at small spatio-temporal scales, *Climatic Change*, *118(3–4)*, 783–797, doi:10.1007/s10584-012-0669-0.

Hagos, S., L. Leung, Q. Yang, C. Zhao, and J. Lu (in press), Resolution and Dynamical Core Dependence of Atmospheric River Frequency in Global Models simulations, *J. Clim.*, doi:10.1175/JCLI-D-14-00567.1.

Hand, W., N. Fox, and C. Collier (2004), A study of the twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting, *Meteorol. Appl.*, *11*,

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

15–31.

Hawcroft, M., L. Shaffrey, K. Hodges, and H. Dacre (2012), How much northern hemisphere precipitation is associated with extratropical cyclones?, *Geophys. Res. Lett.*, *29*, L24,809, doi:10.1029/2012GL053866.

Jones, M., H. Fowler, C. Kilsby, and S. Blenkinsop (2013), An assessment of chnages in seasonal and annual extreme rainfall in the UK between 1961 and 2009, *Int. J. Clim.*, *33*(5), 1178–1194, doi:10.1002/joc.3503.

Kendon, E., N. Roberts, H. Fowler, M. Roberts, S. Chan, and A. Senior (2014), Heavier summer downpours with climate change revealed by weather foreacst resolution model, *Nature Climate Change.*, *4*, 570–576, doi:10.1038/nclimate2258.

Lavers, D., and G. Villarini (2013a), The nexus between atmospheric rivers and extreme precipitation across europe, *Geophys. Res. Lett.*, *40*(12), 3259–3264.

Lavers, D., R. Allan, E. Wood, G. Villarini, D. Brayshaw, and A. Wade (2011), Winter floods in Britain are connected to atmospheric rivers, *Geophys. Res. Lett.*, *38*, L23,803, doi:10.1029/2011GL049783.

Lavers, D., G. Villarini, R. Allan, E. Wood, and A. Wade (2012), The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation, *J. Geophys. Res.*, *117*, D20,106, doi:10.1029/2012JD018027.

Lavers, D., R. Allan, G. Villarini, B. Lloyd-Hughes, D. Brayshaw, and A. wade (2013), Future changes in atmospheric rivers and their implications for winter flooding in Britain, *Environ. Res. Lett.*, *8*, 034010, doi:10.1088/1748-9326/8/3/034010.

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

Lavers, D. A., and G. Villarini (2013b), Atmospheric rivers and flood over the central united states, *J. Clim.*, *26*, 7829–7836.

Lu, M., U. Lall, A. Schwartz, and H. Kwon (2013), Precipitation predicability associated with tropical mositure exports and circulation patterns for a major flood in france in 1995, *Water Resources Research*, *49*(10), 6381–6392.

Neiman, P., F. Ralph, G. Wick, J. Lundquist, and M. Dettinger (2008), Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations, *J. Hydrometeor.*, *9(1)*, 22–47.

Neiman, P., L. Schick, F. Ralph, M. Hughes, and G. Wick (2011), Flooding in Western Washington: The Connection to Atmospheric Rivers, *J. Hydrometeor.*, *12*, 1337–1358, doi:10.1175/2011JHM1358.1.

Neiman, P., F. Ralph, B. Moore, M. Hughes, K. Mahoney, J. Cordeira, and M. Dettinger (2013), The Landfall and Inland Penetration of a Flood-Producing Atmospheric River in Arizona. Part I: Observed Synoptic-Scale, Orographic, and Hydrometeorlogical Characteristics, *J. Hydrometeor.*, *14*, 460–484.

Ralph, F., P. Neiman, G. Wick, S. Gutman, M. Dettinger, D. Cayan, and A. White (2006), Flooding on california's russian river: Role of amotpsheric rivers, *Geophys. Res. Lett.*, *33*(13), L13,801, doi:10.1029/2006GL026689.

Rutz, J., J. Steenburgh, and F. Ralph (2014), Climatological characteristics of atmospheric rivers and their inland penetration over the western united states, *Mon. Wea. Rev.*, *142*, 905–921.

©2015 American Geophysical Union. All Rights Reserved.

Smith, B., S. Yuter, P. Neiman, and D. Kingsmill (2010), Water Vapor Fluxes and Orographic Precipitation over Northern California Associated with a Landfalling Atmospheric River, *Mon. Wea. Rev.*, *138*, 74–100.

Met Office (2012), Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current). NCAS British Atmospheric Data Centre, November 2014. http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0

Viale, M., and M. Nuñez (2011), Climatology of Winter Orographic Precipitation over the Subtropical Central Andes and Associated Synoptic and Regional Characteristics, *J. Hydrometeor.*, *12*, 481–507, doi:10.1175/2010JHM1284.1.

Zhang, X., G. Hegerl, F. Zwiers, and J. Kenyon (2005), Avoiding Inhomogeneity in Percentile-Based Indices of Temperature Extremes, *J. Clim.*, *18*, 1641–1651, doi:10.1175/JCLI3366.1.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

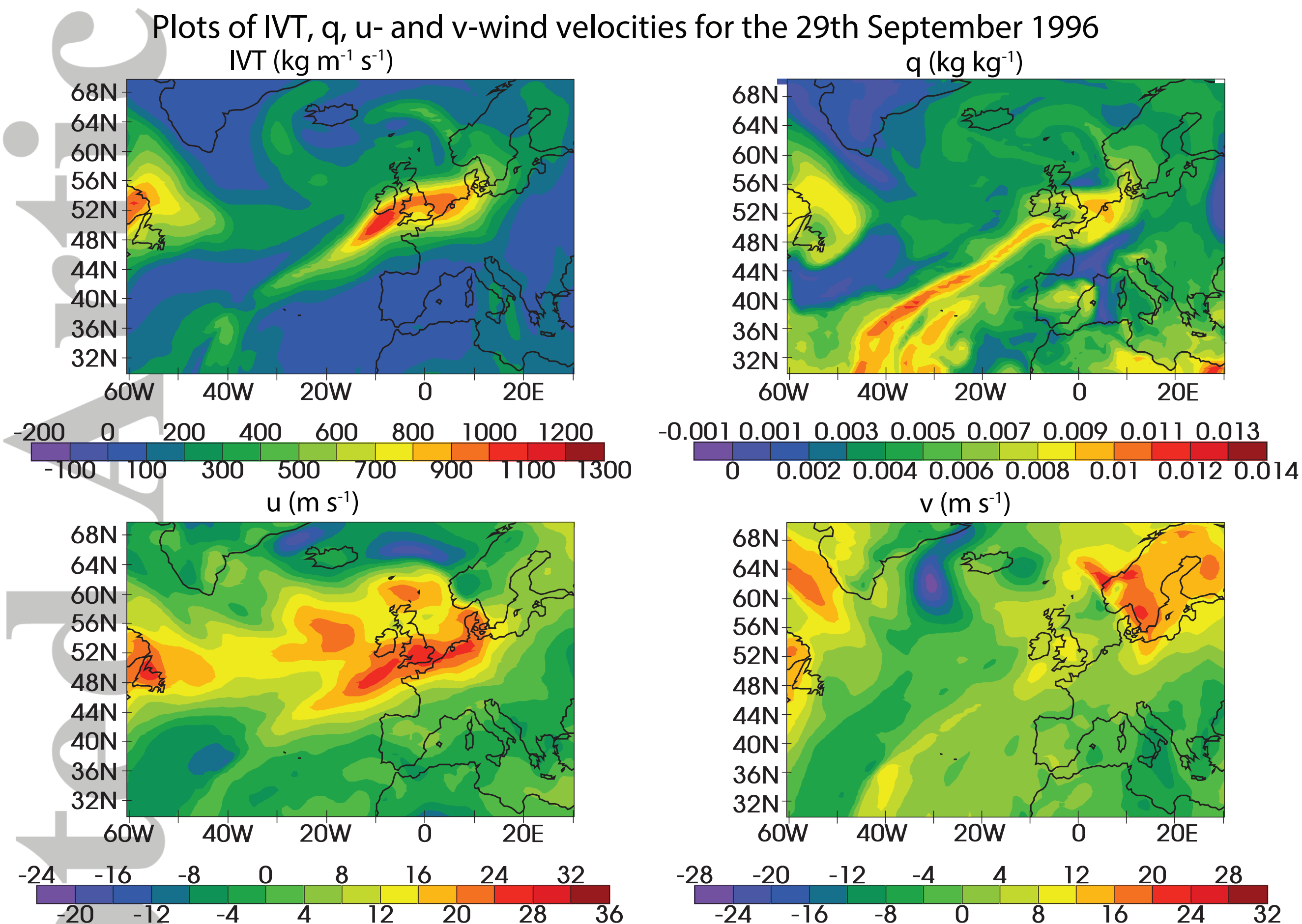

Figure 1. Plots of the vertically integrated horizontal water vapour transport (IVT, top left), 850hPa specific humidity (q, top right), 850hPa zonal winds (u, bottom left) and 850hPa meridional winds (v, bottom right) for the 29th September 1996 at 1200 from ERA-Interim. This date was chosen as being associated with both an atmospheric river and an extreme rainfall event.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

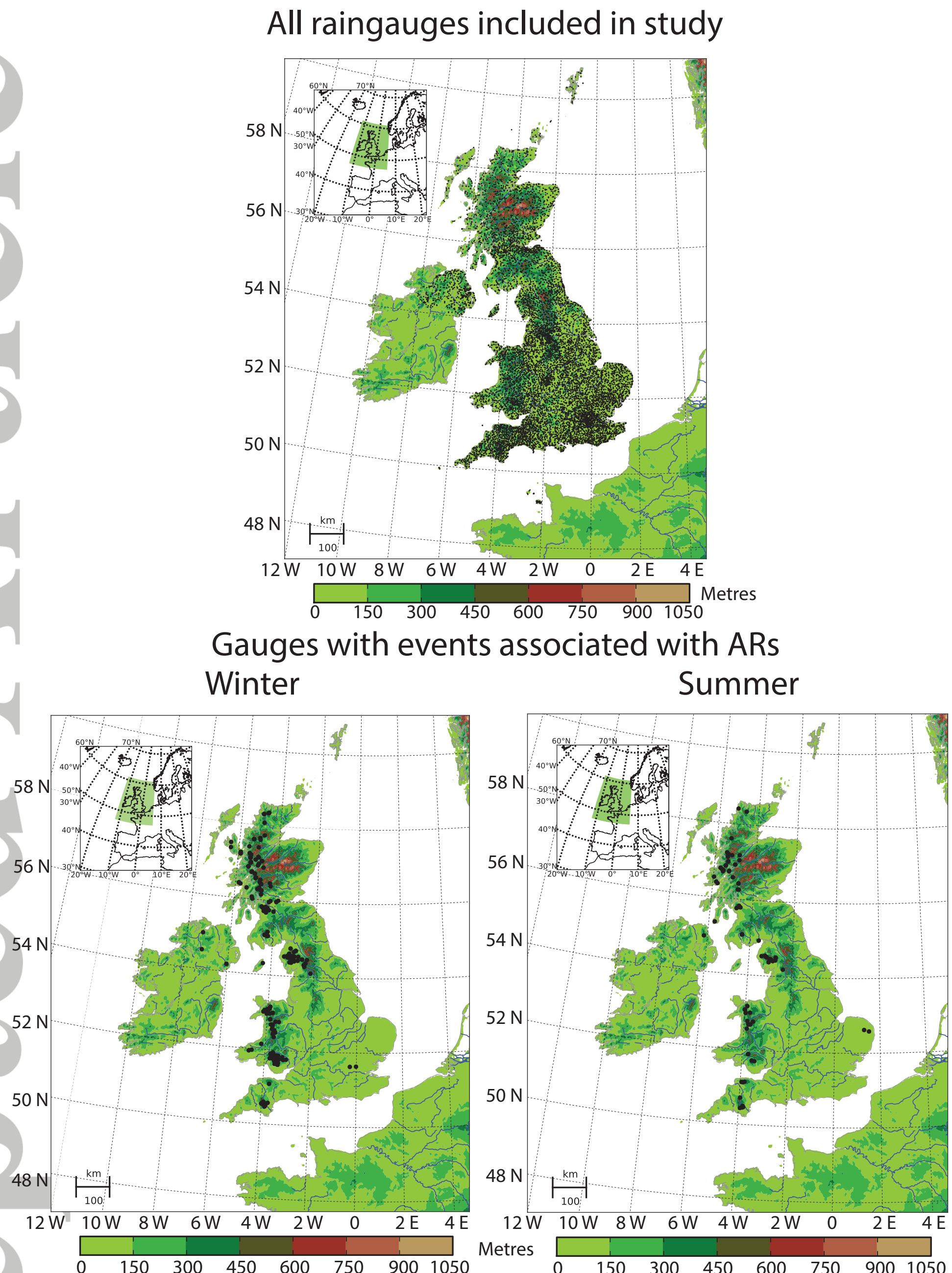

Figure 2. Terrain maps of the UK showing the location of all the NERC MIDAS raingauges used in this study (top) and those gauges where an extreme rainfall event was associated with an AR (bottom) identified in ERA-Interim for both an extended winter (left) and an extended summer (right).

©2015 American Geophysical Union. All Rights Reserved.

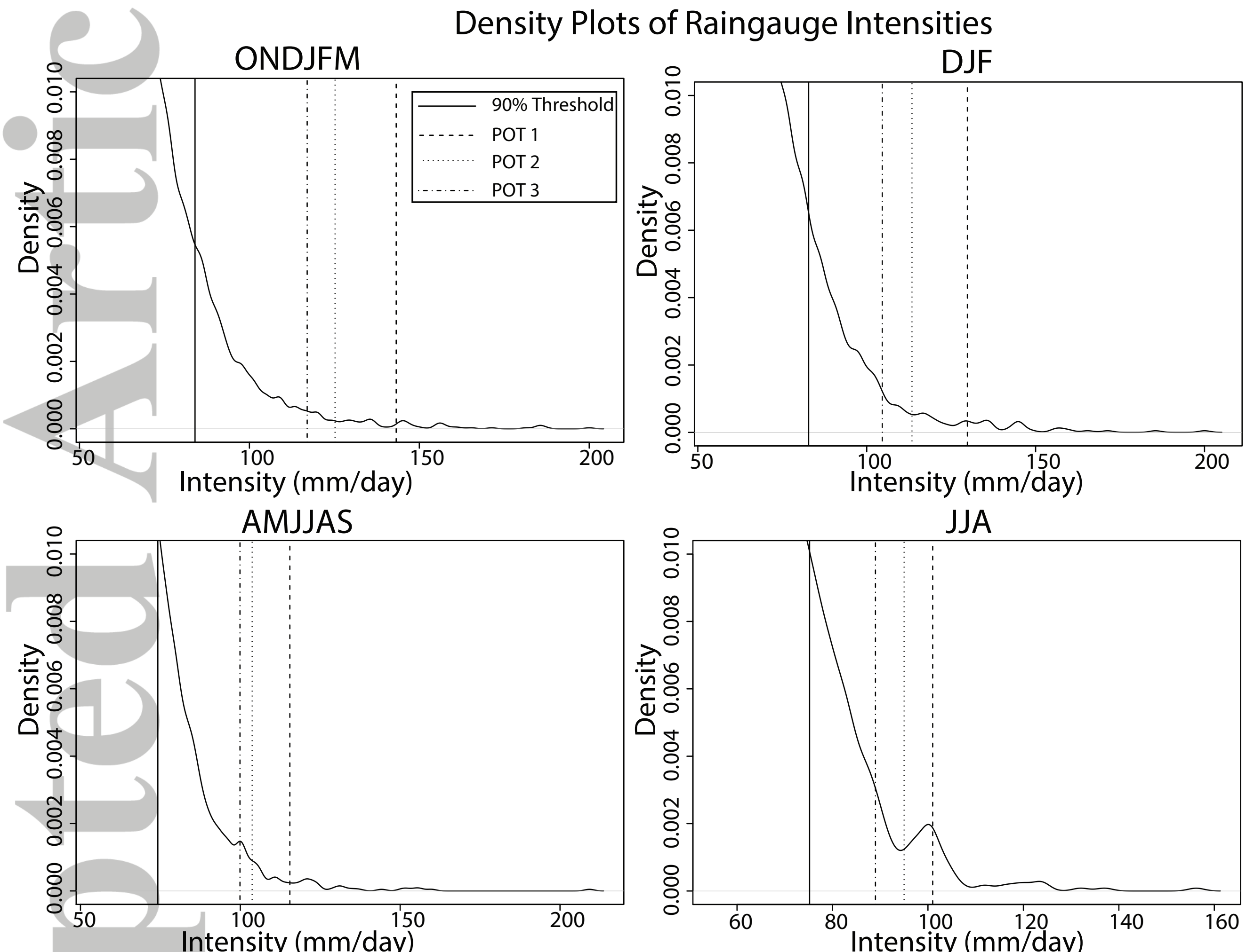

Figure 3. Density plots of the raingauge intensities for winter (top) and summer (bottom) and for a short season (right) and long season (left) for the ERA-Interim period (1979-2013). The top-decile is shown with a solid line, POT1 with a dashed line, POT2 with a dotted line and POT3 with a dot-dashed line.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

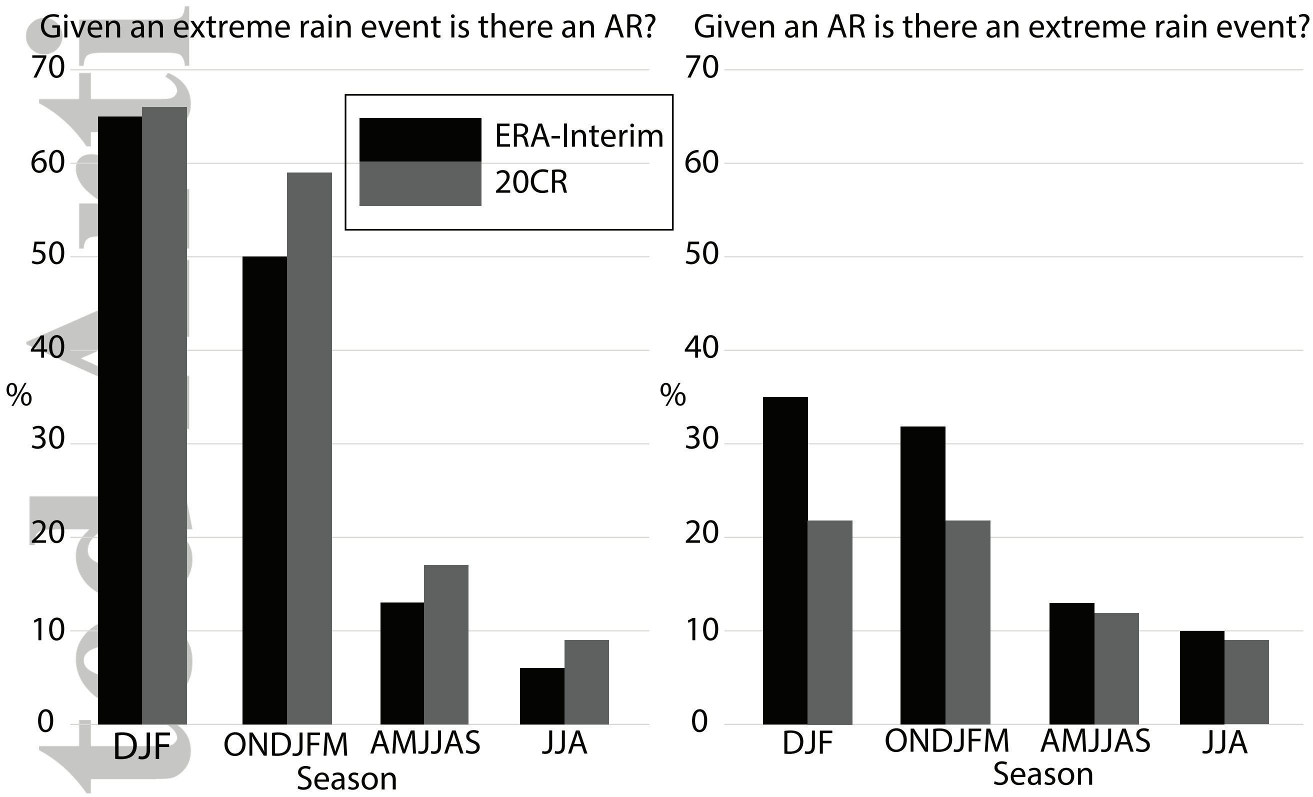

Figure 4. The percentage (to the nearest integer) of extreme rainfall observations that have an AR associated with them (left) and the percentage of ARs that have an extreme rainfall observation associated with them (right) for both ERA-Interim (black) and 20CR (grey) for both winter and summer, shortened and extended.

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Accepted Article

Table 1. The top-decile threshold based on daily maximum observations where the observed amount exceeds 2.54mm/day for each season investigated, for the periods 1979-2013 (ERA-Interim evaluation period) and 1900-2012 (20CR evaluation period). All units are mm/day.

Season	1979-2013 (ERA-Interim)	1900-2012 (20CR)
ONDJFM	84.0	78.0
DJF	82.8	79.3
AMJJAS	74.2	76.5
JJA	75.2	81.3

©2015 American Geophysical Union. All Rights Reserved.

Table 2. The value of the 85% of winter IVT values identified at 4°W for ERA-Interim and 20th Century Re-Analysis using two different periods and for an extended winter and a shortened winter. The numbers in brackets show the number of ARs identified. Notes: 1) As used by *Lavers et al.* [2013]. 2) 1979 - 2012 for 20CR. All units are kg m^{-1} s^{-1}.

Years	Months	ERA-Interim	20th Century Re-Analysis	Notes
1979 - 2005	ONDJFM	511.6 (223)	460.2 (186)	1
1979 - 2005	DJF	507.1 (112)	451.1 (84)	
1979 - 2013	ONDJFM	504.7 (137)	457.7 (294)	2
1979 - 2013	DJF	493.4 (262)	443.4 (141)	2
1900 - 2012	ONDJFM	NA	434.5 (992)	
1900 - 2012	DJF	NA	424.7 (507)	

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.

Table 3. The value of the 85% of summer IVT values identified at 4°W for ERA-Interim and 20th Century Re-Analysis using different periods and months. The numbers in brackets show the number of ARs identified. Notes: 1) Same period as used by *Lavers et al.* [2013] for winter. 2) 1979 - 2012 for 20CR. All units are kg m^{-1} s^{-1}.

Years	Months	ERA-Interim	20th Century Re-Analysis	Notes
1979 - 2005	AMJJAS	472.0 (138)	465.7 (179)	1
1979 - 2005	JJA	486.9 (82)	488.1 (104)	
1979 - 2013	AMJJAS	474.6 (227)	469.4 (264)	2
1979 - 2013	JJA	487.3 (116)	487.7 (128)	2
1900 - 2012	AMJJAS	NA	452.5 (897)	
1900 - 2012	JJA	NA	478.7 (454)	

Accepted Article

©2015 American Geophysical Union. All Rights Reserved.