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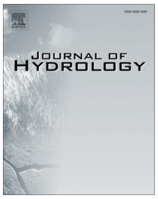

The contribution of atmospheric rivers to precipitation in Europe and the United States

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SUMMARY

Atmospheric rivers (ARs) are narrow corridors within the warm conveyor belt of extratropical cyclones in which the majority of the poleward water vapour transport occurs. These filamentary synoptic features are responsible for extreme precipitation and flooding in Europe and the central and western United States, and also play an essential role for water resources in these areas. Using gridded precipitation products across Europe and the continental United States and the ERA-Interim reanalysis, we investigate the fraction of precipitation from 1979 to 2012 that is related to ARs in these regions. The results are region- and month-dependent, with the largest contribution generally occurring during the winter season and being on the order of 30–50%. This is particularly true for Western Europe, the U.S. West Coast, and the central and northeastern United States. Our results suggest that ARs are important agents for water supply in Europe and the United States. We have also examined whether there have been changes over time in the fractional contribution of ARs to seasonal rainfall using zero-inflated beta regression. We find that there has been a decrease in the average AR-contribution over the Mediterranean region and over the central United States.

1. Introduction

Extratropical cyclones are an important mechanism of precipitation in the extratropics (Stewart et al., 1998), and have been shown to play a key role in mid-latitude extreme precipitation events (e.g., Pfahl and Wernli, 2012). A recent study by Hawcroft et al. (2012) investigated the proportion of precipitation associated with extratropical cyclones using reanalysis and satellite-based precipitation products. In particular, they showed that in parts of Europe and North America more than 70% of total precipitation could be attributed to extratropical cyclones. Another study by Catto et al. (2012) investigated the amount of precipitation related to fronts, features which form an integral part of extratropical storms, and concluded that up to 90% of precipitation was associated with fronts in the main storm track regions of the Northern Hemisphere (North Pacific and North Atlantic). These results highlight the important role that extratropical cyclones play in the mid-latitude water budget.

The poleward transport of sensible and latent heat occurs in the extratropical cyclone's warm conveyor belt (WCB). At low altitudes (< ~2.5 km) in the pre-cold-frontal region within the WCB a combination of high moisture content and the low-level jet (LLJ) results in a narrow region responsible for the vast majority of the water vapour (or latent heat) transport; this region is called an *atmospheric river* (AR). The AR region has been known for some time (Browning and Pardoe, 1973), and research has found strong relationships between ARs and heavy rainfall and flooding in the mid-latitudes, in particular over western North America (e.g., Ralph et al., 2006; Neiman et al. 2011; Ralph and Dettinger, 2012), the central United States (Moore et al., 2012; Nakamura et al., 2013; Lavers and Villarini, 2013a), South America (e.g., Viale and Nunez, 2011), the British Isles (Lavers et al., 2011, 2012), and continental Europe (Lavers and Villarini, 2013b). For example, in the Russian River basin in northern California Ralph et al. (2006) found that the seven recorded floods (from 1998 to 2006) were caused by ARs; in Europe Lavers and Villarini (2013b) showed that areas, such as Scotland and the Iberian Peninsula, had 7 of the top 10 daily annual maxima precipitation events related to ARs.

In the western United States research has considered the role ARs have in precipitation occurrence, as opposed to considering the precipitation from the whole of extratropical cyclones, as in Hawcroft et al. (2012). Dettinger et al. (2011) estimated that over

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1998–2008 ARs were responsible for 20–50% of California's precipitation and streamflow. Furthermore, this precipitation was delivered in a few AR storms, highlighting the importance of ARs for water supplies in California. Rutz and Steenburgh (2012) investigated the AR contribution to precipitation across the western United States (over 1998–2008) using ARs identified as far south as 24°N (to include Baja Peninsula), and by including high-elevation snowpack telemetry sites. They found good agreement with the results of Dettinger et al. (2011), and found that including ARs crossing the Baja Peninsula led to increased AR fraction over the southwestern United States. More recently, Rutz et al. (2014) expanded on these previous two studies providing information about the climatological characteristics of ARs and their inland penetration.

A literature review uncovered no studies that have attempted to characterize the contribution of ARs to precipitation over Europe or the eastern half of the United States. Moreover, the research related to AR contributions to the water budget has focused only on limited time periods (i.e., a decade or so). To address these research gaps, we focus on the period 1979–2012 (34 years) with the goal of evaluating the importance of ARs to precipitation over Europe and the continental United States. Finally, despite the importance of ARs as a source of terrestrial moisture, we currently do not know whether there has been a change (either positive or negative) in the fractional contribution of ARs to seasonal precipitation over Europe or the continental United States. Here we will provide insight on this issue by developing zero-inflated beta regression models.

2. Data and methods

The specific humidity, and the zonal and meridional wind fields were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (ERAIN) reanalysis at a $0.7° \times 0.7°$ resolution over 1979–2012 (Dee et al., 2011). The vertically-integrated horizontal water vapour transport (hereafter, integrated vapour transport, IVT) was calculated from 1000 hPa to 300 hPa in an Eulerian framework (e.g. Neiman et al., 2008). The IVT fields were used in AR detection algorithms developed for Europe in Lavers and Villarini (2013b), and for the central United States in Lavers and Villarini (2013a). We applied a modified version of the European algorithm for the western United States. A brief description of the algorithm in the three regions is given below.

Initially we computed IVT thresholds that are used to identify AR occurrence. For Europe (between 30°N and 70°N near 10°W) and the western United States (between 25°N and 50°N along the coast) a latitude-dependent IVT threshold was calculated as follows. At 1200 UTC on each day from 1979 to 2012 we extracted the maximum IVT (between 30°N and 70°N near 10°W; between 25°N and 50°N along the U.S. West Coast) and binned it into 5-degree latitude bins. The median of the IVT in each latitude bin was used as the threshold value for ARs identified in that region. The IVT thresholds in each band in Europe are given in Supplementary Table 1; for the western United States the IVT thresholds are given in Supplementary Table 2. For the central and eastern United States a threshold was determined by extracting the maximum IVT at 1200 UTC on each day from 1979 to 2012 between 110°W and 70°W near 40°N, and then calculating the median value; the IVT threshold was $367.8\ \mathrm{kg\ m^{-1}\ s^{-1}}$.

To identify ARs striking the western European boundary between 30°N and 70°N at 10°W, we applied a modified version of the algorithm described in Lavers and Villarini (2013b) at each ERAIN six hour time step from 1979 to 2012. We calculated the IVT at grid points spanning between 30°N and 70°N along 10°W and retained the maximum IVT value and location. If the maximum IVT value exceeded the IVT threshold for that particular latitudinal bin, the grid point was recorded. We then searched for the maximum IVT along each meridian from 10°W to 30°W, and tracked the location of the grid points where the IVT threshold (taken from 10°W) was exceeded. We also searched for the maximum IVT along each meridian from 10°W to 25°E recording the locations where the IVT threshold was exceeded. Finally, we determined whether the extracted points satisfied the criterion of an appropriate length scale. If 30 continuous longitude points (with no more than a 3° latitude displacement between each set of points) exceeded the threshold (on average across the domain this is roughly equal to 1500 km), we considered it an AR time step. We also ran the above AR algorithm at 5°E (using the same IVT thresholds from 10°W) to identify ARs that would not be detected at 10°W (thus more closely capturing AR penetration into Europe). The only difference in the algorithm was that the maximum IVT between 30°N and 70°N along 5°E was identified, and then we searched for the maximum IVT along each meridian from 5°E to 15°W and 5°E to 25°E.

To identify ARs striking the western United States between 25°N and 50°N, the following methodology was used at each ERAIN six hour time step from 1979 to 2012. We calculated the IVT at grid points spanning between 25°N and 50°N (along the coast) and retained its maximum value and location. If the maximum value exceeded the threshold for that particular region, the grid point was recorded. We then searched for the maximum IVT along each meridian up to 20° westwards from the coast, and tracked the location for the grid points where the IVT threshold (taken from the coast) was exceeded. We also searched for the maximum value along each meridian from the coast to 100°W recording the locations where the threshold was exceeded. Finally, we determined whether the extracted points satisfied the criterion of an appropriate length scale. If 30 continuous longitude points (with no more than a 3° latitude displacement between each set of points) exceeded the threshold, we considered it as an AR time step.

For the central and eastern United States the following methodology was used at each six hour time step in the ERAIN reanalysis over the study period; this is a slightly modified version of the algorithm presented in Lavers and Villarini (2013a). We calculated the IVT at grid points spanning 66°W and 110°W along 40.35°N and retained its maximum value. If the IVT at 40.35°N exceeded the threshold, we searched for the maximum value along each parallel from 40°N to 25°N, and tracked the location for the grid points where the IVT threshold was exceeded. We also searched for the maximum IVT along each parallel from 40°N to 50°N, and tracked the location for the grid points where the threshold was exceeded. If 13 continuous longitude points (with no more than a 3° longitude displacement between each set of points) exceeded the threshold, we considered it as an AR time step. Furthermore, any days when a North Atlantic tropical cyclone was present between 25°N and 50°N, and 110°W and 70°W were excluded from the analysis.

For Europe we retrieved daily observed gauge-based precipitation produced by the ENSEMBLES project (Haylock et al., 2008) at a $0.25° \times 0.25°$resolution (E-OBS version 7.0 data set). Data from 1979 to 2012 were used and these represent daily accumulations from 00UTC to 00UTC. Over the United States we used the Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Daily Precipitation (http://www.esrl.noaa.gov/psd/data/gridded/data.unified.daily.conus.html) as the reference dataset. Data from 1979 to 2012 were used and represent daily accumulations at 12UTC at a $0.25° \times 0.25°$ resolution. This dataset is based on precipitation measurements from the National Oceanic and Atmospheric Administration (NOAA)'s National Climate Data Center (NCDC) daily COOP stations, daily accumulations from hourly precipitation