Quantifying the Rain-Shadow Effect
Results from the Peak District, British Isles

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Mountains affect the distribution of clouds and precipitation. For example, Houze (2012, his Fig. 3) showed a variety of physical mechanisms for orographically enhanced precipitation. Many mountain ranges commonly show large gradients in precipitation across them: the Andes, Himalayas, Cascade Mountains of Washington State, Sierra Nevada of California, and the Rocky Mountains as a whole. The most common explanation for these gradients is rain (or precipitation) shadowing. Rain shadows are described in geography, climatology, and meteorology textbooks (e.g., Marshak 2008, p. 733; Ahrens 2009, p. 156; Ackerman and Knox 2015, 136–137; Petersen et al. 2017, p. 162), as well as the Glossary of Meteorology (Huschke 1959; Glickman 2000), as being caused by ascending air and precipitation on the windward side of a mountain range followed by descending air and a reduction in precipitation on the leeward side (i.e., the shadow).

Yet, the rain-shadow effect does not appear widely in the scientific literature. A search through the American Meteorological Society’s (AMS) Journals Online website turns up only four articles with “rain shadow(s)” or “precipitation shadow(s)” in the title: Brady and Waldstreicher (2001), Ralph et al. (2003), Siler et al. (2013), and Siler and Durran (2016). Expanding to other publishers through the Web of Science, only 27 more articles have “rain shadow” in the title, mostly just using the term, pertaining to paleoclimates, stable isotopes in precipitation, geomorphology, or ecology. Only three pertain to the dynamics and cloud microphysics of the rain shadow. Expanding the search to the more general topic “orographic precipitation” shows that most articles focus on the enhancement of precipitation on the windward side, rather than the reduction of precipitation on the leeward side. Even the most recent summary of mountain weather and forecasting only has five brief citations to precipitation shadows within its 750 pages (Chow et al. 2013).

At first glance, an explanation for the rain shadow is easily demonstrated and intellectually satisfying:
air goes up on the windward side producing clouds and precipitation, and air goes down on the leeward side inhibiting clouds and precipitation. Upon deeper reflection, however, such an explanation may not be so obvious, especially when attempting to quantify the magnitude of the rain-shadow effect for a given location on different time scales.

WHAT IS A RAIN SHADOW AND HOW CAN IT BE QUANTIFIED? The Glossary of Meteorology website defines a rain shadow as “A region of sharply reduced precipitation on the lee side of an orographic barrier, as compared with regions upwind of the barrier” (http://glossary.ametsoc.org/wiki/Rain_shadow). How to quantify the rain-shadow effect from this definition poses several problems.

1) No time scale is mentioned in this definition. Is this definition applied instantaneously within a storm, applied to storm-total precipitation, or applied to climatological data? Or, is the time scale irrelevant for the application of this definition? Certainly the published literature refers to rain shadows at all time scales, from instantaneous radar imagery (e.g., Brady and Waldstreicher 2001) to storm-total precipitation (e.g., Ralph et al. 2003; Sindosi et al. 2015) to average seasonal and annual precipitation amounts (e.g., Nieto Ferreira et al. 2013; Kenworthy 2014; Lenaerts et al. 2014; Narkhedkar et al. 2015) to geological time scales (e.g., Galewsky 2009). Such diversity of usage would imply that there is no agreement on the necessity of a time scale to classify a reduction in precipitation across a mountain range as a rain shadow.

2) What about the spatial scale of the reduction of precipitation? How far away from the mountain crest does the rain-shadow effect extend? It would seem that a rain shadow would have to persist farther downstream than just the immediate descent in the lee of the mountains, although this is not explicitly stated. An extensive minimum in precipitation downstream of the mountain would require mountain-wave breaking and the entrainment of dry air aloft, which would be a function of the height of the mountains, the static stability profile, and the moisture profile. As such, applying any distance criteria might be a function of the specific mountain range or synoptic pattern.

3) What does “sharply reduced” mean when trying to quantify the rain shadow? If a windward site received 4 mm of rain and a leeward site received 3 mm of rain, would that qualify as a rain shadow?

4) What if there were less precipitation on the lee side for reasons other than the classic up–down mechanism? In other words, the physical mechanism for the rain shadow is not explicitly stated in the definition. For example, Smith et al. (2009) found that the water lost as a result of precipitation during orographic ascent over the island of Dominica was insufficient to explain the lesser climatological precipitation in the lee. Instead, the shallower trade-wind inversion and reduced instability on the lee side were responsible for the reduced precipitation. Is this still a rain shadow?

These questions raise the specter that the seemingly obvious definition is challenging to apply when faced with real data, a point we explore next.

THE PEAK DISTRICT AND ITS RAIN SHADOW. To further this point about the definition lacking quantification, consider one location that has been recognized as a classic rain-shadow locality: the Peak District of the Pennines range, United Kingdom (e.g., Garnett 1956; Milner 1968; Chaun and Lockwood 1974; Wheeler 1990, 2013). Wheeler (2013) writes, “One term alone dominates the precipitation patterns of [northeast England]: ‘rain shadow’.” A large east–west gradient in annual-average precipitation extends across the United Kingdom and Ireland (Fig. 1), consistent with the dominant westerly flow associated with classic wet British weather. Manchester, which is west of the Peak District, receives about 1,200 mm of rain each year. Fifty-six kilometers to the east at Sheffield, about 700 mm of rain falls each year. Although Manchester and Sheffield city centers are both about 30 m above sea level, the majority of the intervening high terrain of the Peak District lies 300 m above sea level, with the highest point, Kinder Scout, at 636 m above sea level. Although some rain shadows, such as those of the Andes and Himalayas, may feature an order of magnitude decrease in precipitation across them (e.g., Barros et al. 2006; Viale and Núñez 2011; Lenaerts et al. 2014), the Peak District only experiences about a 40% reduction. Although the Peak District has modest elevations in comparison to mountain ranges that host more extreme rain shadows, a persistent westerly flow and large gradient in precipitation across the Peak District would suggest a strong rain-shadow effect.

For example, a classic rain-shadow event occurred on the morning of 5 December 2015 (Fig. 2). On
this day, west-southwesterly flow brought rain to northwestern England and Scotland for many hours (e.g., Fig. 2a), but little precipitation fell on the east side of the Pennines, with the strongest gradient in 10-h accumulated precipitation lying north of Manchester and Sheffield (Fig. 2b). The repeated occurrence of this pattern over many precipitation events could easily explain the gradient in precipitation across the United Kingdom. However, even a cursory look at weather events passing over the United Kingdom readily shows that not all precipitation events exhibit a rain shadow.

First, not all weather events may be associated with reduced precipitation in the lee. Sometimes, precipitating systems show little change in intensity as they pass over the Peak District (e.g., Jaroszweski et al. 2015). In other cases, precipitation may increase toward the east. For example, westerly flow during the warm season often exhibits growing convective storms from west to east, producing more precipitation toward the east (e.g., Thielen and Gadian 1996; Bennett et al. 2006). Even for a single mountain range under westerly flow, there may be substantial along-mountain variability of the rain-shadow effect (e.g., Viale and Nuñez 2011; Shi and Durran 2015), and the magnitude of the rain-shadow effect may depend on the synoptic pattern (e.g., Browning et al. 1975; Sweeney and O’Hare 1992; Siler et al. 2013; Mass et al. 2015; Siler and Durran 2015, 2016). For example, Siler et al. (2013) and Mass et al. (2015) showed that storms with a strong rain-shadow effect were associated with precipitation in the warm sector, whereas storms with a weak rain-shadow effect were associated with the passage of warm and occluded fronts. Siler and Durran (2016) found that the reason for these weak rain shadows was the reduced leeside mountain waves caused by the low-level stable air that precedes the warm front.

Second, precipitating systems sometimes weaken as they move eastward as a result of the weakening of forcing for ascent on the synoptic scale or mesoscale, rather than the systems weakening due to orographic forcing. The United Kingdom being near the climatological jet exit region makes such an explanation possible in some cases, albeit at a larger horizontal scale than the cross-mountain scale. Thus, even if less precipitation occurred in the lee, the rain shadow may not necessarily explain it.

Third, the airflow over the mountains may not be captured as a simple flow up and over the mountains. Stable low-level flow on the upwind side may be blocked and not traverse the mountains, as reviewed...
The downstream impact of the leeside descent may be enhanced by wave breaking over the terrain and entrainment of dry air, enhancing the downstream length of the rain shadow. More importantly, different air masses may bring different weather to the west and east sides of the Peak District. Specifically, the eastern United Kingdom may be more susceptible to dry, but snowy, air masses originating from the European continent in winter (e.g., Ogden 1997; Pike 1999) and more unstable air masses from Europe during summer (e.g., Lewis and Gray 2010). In contrast, the western United Kingdom is more susceptible to moister air masses originating from the North Atlantic Ocean. So, any precipitation gradients across the mountains may simply be because of access to different air masses. As another example, consider the Rocky Mountains. Although a rain shadow is the traditional explanation for the dryness in the western Great Plains (e.g., Rosenberg 1987), this may not explain all of the reduction in precipitation over central North America (e.g., Harrington 2008). Flow in the lee over central North America may experience either moist air because of return flow from the Gulf of Mexico (e.g., Crisp and Lewis 1992; Weiss 1992) or dry air because of cold-air incursions from the Arctic (e.g., Schultz et al. 1997, 1998) compared to the moister air masses originating from the North Pacific Ocean and making landfall on the west coast of North America. Again, the lee side is often under the influence of different air masses than those on the west side of the mountains. In another example, Sato (2005) showed that arid regions downstream of the Tian Shan Mountains were present, even without the upstream mountains, suggesting no rain-shadow effect there. Instead, Sato (2005) found that what made the strong gradient remarkable was not the leeside reduction of precipitation, but the windward enhancement of precipitation. Should this situation correctly be called a rain shadow?

All of these scenarios for how weather systems evolve over the United Kingdom differ from the classic rain shadow with a uniform steady westerly flow impinging on the Peak District and wringing moisture out during orographic ascent, leaving drying in its lee. Thus, these different scenarios raise the question of how important the rain-shadow effect is to explaining the climatological distribution of precipitation across the United Kingdom (Fig. 1).

Fig. 2. Radar mosaics showing (a) radar rainfall rates (mm h\(^{-1}\)) at 0815 UTC 5 Dec 2015 and 850-hPa geopotential height at 1200 UTC and (b) radar-derived 10-h accumulated precipitation during 0800–1800 UTC 5 Dec 2015.
Does the rain shadow occur during all precipitation events? If not, how important is it, and when does it occur? How many days of the year is the rain-shadow effect actually operating to explain the climatological distribution of rain across England? This study represents an attempt using precipitation-gauge statistics to quantify the rain-shadow effect and to provide an answer to the public about how important the rain shadow actually is. Thus, the purpose of this study is to critically examine the definition of a rain shadow, highlighting the ambiguity in its definition and the ambiguity in providing quantitative information to evaluate the rain-shadow effect using the example of the Peak District. This study does not address the physical mechanisms for the rain shadow.

**DATA AND METHODS.** The dataset consists of the daily precipitation amount (mm) from 54 weather stations within 20-km radii of the Sheffield and Manchester city centers, recorded over the 30-yr period 1 January 1981–31 December 2010 (Fig. 3). The daily 24-h period is from 0000 to 2359 UTC. These data are obtained from the Met Office’s Integrated Data Archive System (MIDAS). To establish the geographic distribution of precipitation across the Peak District, each of the 54 weather stations is identified as being located in one of four regions: Manchester (25 stations), Sheffield (11 stations), the Manchester side of the Peak District (7 stations), or the Sheffield side of the Peak District (11 stations) (Fig. 3). The amount of precipitation from each station in each region is averaged together to produce a regional average for each day.

These 54 stations were determined because they had over 5000 observations in 30 yr (45.7% of the total number of days). We chose 5000 observations because some stations were not operating or reporting during the whole 30-yr period. If we limit the dataset to stations where 90% or more of possible observations existed over the 30 yr, then we would have only 11 stations in Manchester and 4 in Sheffield, too few to produce a reliable measure of whether the lee side had experienced a region of widespread rain or not. Importantly, when a station was operating, the dataset indicated nearly perfect reporting from that station. By lowering the threshold of station longevity, we were able to include more stations into our measure of how widespread the precipitation was or was not. Such an indication ensures that our results are representative and not merely a result of incomplete sampling due to a small number of stations. The averaging of the precipitation amount into four regions further ensures that the data are robust, despite some missing station data.

The prevailing wind direction is determined...
from the 850-hPa wind direction from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) at 1200 UTC for each day. The 850-hPa level equates to about 1.4–1.5 km, which is above the crest height of the Peak District. Westerly days are classified by a wind direction of 225°–315° at the closest grid point to Manchester (53.25°N, 2.25°W), and easterly days are classified by a wind direction of 45°–135° at the closest grid point to Sheffield (53.25°N, 1.5°W). Westerly winds prevail over the Peak District on about 57% of the days (207 out of 365 days yr\(^{-1}\)), indicating the dominance of westerly winds on British weather. In contrast, only 8% of the days (28 days yr\(^{-1}\)) have easterly flow.

To test the possible occurrence of a rain shadow, we perform three tests.

**Test 1: Does it rain more on the upwind side of the Peak District?** The first test is to compare the daily average precipitation amount for each region to establish the distribution of precipitation across the Peak District as a function of westerly or easterly flow. A distinct pattern in the distribution of precipitation occurs under both westerly and easterly flow (Table 1). In each case, the lowest amount of precipitation is recorded in the city region on the lee side of the range, the highest amount of precipitation is recorded in the region of the Peak District first exposed to the wind flow, and the second highest amount of rainfall is recorded in the city region that first encounters the prevailing wind direction (Table 1). The difference between regions of highest and lowest daily precipitation is greatest under westerly flow. When the flow is westerly, 1.5 mm (50%) more average daily precipitation occurs on the Manchester side of the Peak District compared to the Sheffield side. In comparison, under easterly flow, 0.8 mm (40%) more average daily precipitation occurs on the Sheffield side of the Peak District compared to the Manchester side. Overall, westerly flows produce more daily precipitation than easterly flows.

**Table 1.** Overall daily average precipitation amounts (mm) recorded under westerly and easterly flows over the 30-yr period (Jan 1981–Dec 2010).

<table>
<thead>
<tr>
<th>Location</th>
<th>Manchester</th>
<th>Peak District (Manchester)</th>
<th>Peak District (Sheffield)</th>
<th>Sheffield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westerly flow</td>
<td>3.9</td>
<td>4.5</td>
<td>3.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Easterly flow</td>
<td>1.5</td>
<td>2.0</td>
<td>2.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>
mean precipitation across the domain. In isolation, the results from this first test are consistent with the expectations of a rain-shadow effect for both westerly and easterly flow.

Test 1: Rainfall rates in Manchester under a prevailing westerly flow and an enhancement in the number of days of precipitation in the Peak District and Sheffield under a prevailing easterly flow (Tables 2 and 3). Out of the annual average of 207 westerly flow days, precipitation was recorded in Manchester on 154 occasions and in Sheffield on 121 occasions (Table 2), equating to an annual difference of 33 days each year in which Manchester receives precipitation and Sheffield does not (16% of all westerly flow days). In comparison, under the 28 easterly flow days each year, there are

CHOICE OF PRECIPITATION DURATION

Because the definition of a rain shadow does not specify a time scale, using rain gauge data requires selecting a time scale. So, what should be chosen? One-hour precipitation amounts? Twenty-four-hour precipitation amounts? Because precipitation occurrence is fractal (e.g., Olsson et al. 1993; Harris et al. 1996; Kiely and Ivanova 1999), no natural time scale exists upon which to perform this analysis. The actual usage of the expression “rain shadow” in the literature provides no insight into this dilemma. Examples of rain shadows being referred to on short time scales exist (e.g., instantaneous radar imagery as in our Fig. 2), as do rain shadows of storm-total precipitation (comparable to our 24-h data). Rain shadows can also be inferred from precipitation climatologies of rainfall from radar, satellite, or gauge data (as in our Fig. 1). Thus, our choice of a 24-h rainfall dataset is not inconsistent with the definition of rain shadow, and our choice is not inconsistent with how it is used practically in the literature.

Reviewers raised the concern whether our results would be different if more frequent rainfall data were used. Consider the following. If it rains continuously for 24 h (0000–2359 UTC) on the upwind side and no rain falls on the leeside, then all of the twenty-four 1-h periods would qualify as rain shadows, too. Thus, using 24- or 1-h rainfall data would yield no difference. Of course, it may only rain for 6 h within that 24-h period such that identifying a rain shadow with 1-h data would determine that 6 h of the day were associated with a rain shadow. Alternatively, if it were to rain on the lee side for 3 of those 6 h, then the rain shadow would only have existed for 3 out of the 6 h, but would not be classified as a rain shadow using our approach with 24-h data. So, our calculation could be performed by hour-long intervals by saying that x% of hours with westerly flow qualify as a rain shadow, where x ≤ 24 h. The 24-h values can be thought of as a conservative limit of the percentage of time with a rain shadow. Furthermore, our statement that 17% of days have a rain shadow for the 24-h period is correct within the context of the question that we have asked with the data we have used, which was about the number of days during which a possible rain shadow was occurring.

To redo the analysis with 1-h data, the number of hours of rain shadows over the course of the year (from 1-h data) would be more or less consistent with the number of days of rain shadows per year (from 24-h data). There would be a small difference because many rain-shadow days with 24-h data would not have rain shadows for all 24 h, whereas other non-rain-shadow days would have some hours of hourly rain shadows. Thus, we believe that the results may change quantitatively with hourly data, but likely would not be qualitatively different.

Does talking about the rain shadow hour by hour make any sense? The finer the increment of time, the more challenging determining the existence of a rain shadow becomes from point rainfall measurements, especially when scattered showers are occurring. Does a rain shadow even have any meaning under this environment? Even if it were raining in Manchester and dry in Sheffield, only a dynamic analysis could ascertain the reason why. There is the added complication that as the data become hourly, at least for the Pennines, the number of stations decreases. The analysis could be performed, but it would be difficult to compare with the analysis from the 24-h data. Not that a rain shadow could not be defined for hourly data, but a convincing argument is more easily made that the rain shadow is more likely operating with multi-hour accumulated rainfall.

Finally, the 24-h data were just meant to be representative of the type of calculation that one could do to demonstrate this point. A different threshold would produce different results to a different question with a different interpretation. Using a different interval would be a different study than what we intended. Although using a finer-resolved rainfall data interval would produce a quantitatively different result, whether the result would be substantially different is unclear. We encourage readers to explore these issues with their own rainfall datasets with different temporal resolutions for other regions of the world. Thus, we argue that the time resolution of the rainfall is an open point for debate and any suitably defensible choice is entirely reasonable.

Thus, we argue that performing this calculation with 1-h rain gauge data would not yield qualitatively different results. What is optimal? Three hours? Six hours? There is no single best answer. We hope that discussing these issues out in the open will be beneficial to the overall discussion of how to identify and quantify a rain shadow.
on average 2 days each year in which precipitation is recorded in Sheffield but not in Manchester (7% of all easterly flow days) (Table 3). Thus, as measured by the frequency of precipitation, the results of the second test seem to support the idea that the rain shadow (as defined in this study) is not particularly common in westerly flow and is even rarer in easterly flow (cf. 33 vs 2 days yr$^{-1}$).

Tests 1 and 2 are the types of bulk precipitation amount and frequency statistics that are often employed to explain rain shadows. For example, these bulk climatological data are often used to explain the rain-shadow effect from west to east across the United Kingdom (e.g., Hill 1983; Sweeney and O’Hare 1992; Hand 2005).

Test 3: When it rains on the upwind side, is it also raining on the downwind side? In a third—and more rigorous—test of the rain-shadow effect, the number of individual days where a rain-shadow effect might have been occurring was calculated. For this analysis, only daily rainfall data that were available for both the Manchester and Sheffield regions on a particular day were used, reducing the size of the dataset slightly (i.e., 207 days yr$^{-1}$ of westerly flow down to 197 days yr$^{-1}$, and 28 days yr$^{-1}$ of easterly flow down to 26 days yr$^{-1}$).

For this analysis, we define a rain shadow as a day where it rained on the windward-side stations, but not on the leeward-side stations. This definition is consistent with the simple conceptual models of the rain shadow found in textbooks that show precipitation on the windward side and none on the leeward side (e.g., Marshak 2008, p. 733; Ahrens 2009, p. 156; Ackerman and Knox 2015, p. 137; Petersen et al. 2017, p. 162). Plus, the absence of precipitation on the leeward-side stations would be characterized as a sharp reduction of precipitation across the topography, consistent with the AMS Glossary of Meteorology. Of course, the rain-shadow effect could still be operating with less precipitation occurring downwind, perhaps caused by so-called spillover precipitation [i.e., hydrometeor drift over the crest onto the leeside; e.g., Sinclair et al. (1997); Colle (2004)]. We acknowledge that ours is a restrictive definition of a rain shadow and that other reasonable choices could have been made, but we adopt

| Table 2. Precipitation occurrence in each of the four regions under westerly flow. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Manchester      | Peak District   | Peak District   | Sheffield       |
| No. of days when precipitation  | 4,616           | 4,357           | 4,153           | 3,643           |
| was recorded across the region  |                 |                 |                 |                 |
| Percentage of precipitation    | 74%             | 70%             | 67%             | 58%             |
| days under westerly flow each   |                 |                 |                 |                 |
| year                           |                 |                 |                 |                 |
| Avg No. of days of precipitation| 154             | 145             | 138             | 121             |
| per year under westerly flow    |                 |                 |                 |                 |

| Table 3. Precipitation occurrence under easterly flow across the Peak District. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Manchester      | Peak District   | Peak District   | Sheffield       |
| No. of days when precipitation  | 340             | 349             | 433             | 384             |
| was recorded across the region  |                 |                 |                 |                 |
| Percentage of precipitation    | 41%             | 42%             | 51%             | 45%             |
| days under easterly flow each   |                 |                 |                 |                 |
| year                           |                 |                 |                 |                 |
| Avg No. of days of precipitation| 11              | 12              | 14              | 13              |
| per year under easterly flow    |                 |                 |                 |                 |
this conservative approach as a starting point.

Specifically, for a westerly rain-shadow effect, we count the number of days with rain in Manchester but no rain in Sheffield. For an easterly rain-shadow effect, we count the number of days with rain in Sheffield but no rain in Manchester. The result is a count of the number of days where the rain-shadow effect could conceivably be occurring. Moreover, just because precipitation falls on the upstream location but none falls in the downstream location does not necessarily mean that the rain-shadow effect is responsible (as discussed earlier).

For the 197 days yr⁻¹ with westerly flow, 57% of all westerly flow days were associated with rain at both Manchester and Sheffield (Table 4). These days were most common during the cool season with a minimum in the spring (Fig. 4a). Only 17% of westerly flow days occurred where the rain-shadow effect could be operating (Manchester with rain and Sheffield with no rain). These days were concentrated in the warm season (Fig. 4a).

In contrast, only 2.3% of

**Table 4. Average number of days per year with or without rain in Manchester and Sheffield under westerly flow. Percentages out of the total number of 197 days appear in parentheses. Percentages do not add up to 100% because of round-off errors.**

<table>
<thead>
<tr>
<th>Sheffield avg No. of days per year with zero precipitation amount</th>
<th>Manchester avg No. of days per year with nonzero precipitation amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 (22.8%)</td>
<td>34 (17.3%)</td>
</tr>
<tr>
<td>4.6 (2.3%)</td>
<td>113 (57.4%)</td>
</tr>
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</table>

Fig. 4. Monthly distribution of days per year under (a) westerly and (b) easterly flows. RShf represents rain in Sheffield, NRShf represents no rain in Sheffield, NRMan represents no rain in Manchester, and RMan represents rain in Manchester. In (a), the black bars represent days per year when the rain-shadow effect was possible. In (b), the gray bars represent days per year when the rain-shadow effect was possible.
westerly flow days showed no rain in Manchester and rain in Sheffield, a result opposite to the rain-shadow effect—what Roe and Baker (2006) call the reverse rain shadow. These results suggest that, for all westerly flow days, the non-rain-shadow days were nearly 5 times more likely than rain-shadow days using our definition.

For comparison, 36% of the 26 days yr$^{-1}$ with easterly flow were associated with rain at both Manchester and Sheffield (Table 5). These days were maxima in the winter and spring (Fig. 4b). Only 10% of easterly flow days occurred where the rain-shadow effect could be operating (Sheffield with rain and Manchester without rain). Interestingly, however, 4.2% of easterly flow days occurred with rain in Manchester and no rain in Sheffield, a result opposite to the rain-shadow effect. Thus, for all easterly flow days, the non-rain-shadow days were 9 times more likely than rain-shadow days. A look through some of these easterly flow events indicates that the synoptic pattern is typically characterized by a strong equivalent-barotropic low pressure system to the south or west of the United Kingdom. Deep easterly flow is prevalent, and precipitation is associated with bands wrapped around the cyclone. In these situations, the precipitation is affected little by the orography.

In this third test of the rain-shadow effect, our results were consistent with those from the second test (Table 6). Specifically, westerly winds were more likely to produce precipitation than easterly winds (75% vs 46%), westerly winds were more likely to exhibit a rain shadow than easterly winds (17% vs 10%), and westerly winds were less likely to exhibit a reverse rain shadow than easterly winds (2.3% vs 9.1%). Although the ratio of rain-shadow days to reverse-rain-shadow days was larger for westerly flow than easterly flow (7.4 vs 2.4), the ratio of days with rain at both Manchester and Sheffield to rain-shadow days in westerly and easterly flows was relatively similar (3.3 to 3.5). This result seems to suggest how relatively common the reverse-rain-shadow days under easterly flow were, given their tendency to appear at a higher rate than for reverse-rain-shadow days under westerly flow.

Only 34 days a year possessed both westerly flow and the requisite precipitation pattern (Manchester with rain and Sheffield with no rain) to be consistent with the rain-shadow effect. Although a rain-shadow effect can be seen on 34 days each year in which Manchester receives rainfall and Sheffield does not, this observation goes only part of the way toward accounting for the regional differences in precipitation across the Peak District each year.

**DOCUMENTARY.** The findings of this analysis are incorporated into a documentary entitled Chasing Sheffield’s Rain Shadow, which is available on YouTube (www.youtube.com/watch?v=3eaVn7JQpOQ). This documentary was created in partial fulfilment of the lead author’s master of science dissertation in science communication at the University of Sheffield. The documentary explores the origins of Sheffield’s rain shadow and features interviews with meteorology experts from both sides of the Peak District, with the goal of engaging with and educating the public on the Sheffield rain shadow. Some of the quantitative information in the documentary has been updated and double-checked for this publication since recording, but the results and storytelling are robust, nonetheless.

**TOWARD A DEEPER UNDERSTANDING OF THE RAIN SHADOW.** This research explores how to quantify the impact that the rain shadow has on individual precipitation events across the United Kingdom. Other analysis approaches could be reasonably taken with different criteria chosen for the sharp reduction in precipitation on the leeside, and the analysis could be extended to other regions both north and south of the Peak District. Would they also show similar relationships? Under what synoptic conditions is the rain-shadow effect most and least prominent? For example, one might imagine

| Table 5. Average number of days per year with or without rain in Manchester and Sheffield under easterly flow. Percentages out of the total number of 26 days appear in parentheses. |
|-------------------------------------------------|-------------------------------------------------|
| Manchester avg No. of days per year with zero precipitation amount | Manchester avg No. of days per year with nonzero precipitation amount |
| Sheffield avg No. of days per year with zero precipitation amount | 13 (50%) | 1.1 (4.2%) |
| Sheffield avg No. of days per year with nonzero precipitation amount | 2.6 (10%) | 9.3 (35.8%) |
situations such as the northern England floods of Christmas 2015 (Barker et al. 2016) where widespread rain on the synoptic scale showed little favoritism for one side of the Peak District over another. Indeed, Siler and Durran (2015) have argued that warm fronts are less likely to produce a strong rain shadow.

What would high-resolution mesoscale modeling show for rain-shadow events? Are there systematic biases in numerical model output related to the rain-shadow effect (e.g., Colle et al. 2000)? Anecdotal evidence from our real-time model simulations at ManUniCast.com (Schultz et al. 2015) suggests the rain-shadow effect is underrepresented in the model output in some cases. Do leeside mountain waves produce strong descent immediately to the lee of the Peak District that enhances the gradient in precipitation, or does leeside stability affect the distribution of precipitation (e.g., Brady and Waldstreicher 2001; Smith et al. 2009)? What roles do precipitation spillover and multiple ridges play in the rain-shadow effect (e.g., Sinclair et al. 1997; Colle 2004, 2008)? What is the importance of upstream blocking (airmass transition across mountains), gravity wave breaking, convection, and vertical wind shear?

Finally, what do other mountain ranges around the world show? Other regions around the world show more dramatic rain shadows than the Peak District, and an intercomparison between the different ranges to quantify the different factors affecting the rain shadows in different geographical contexts would be an interesting application of this work, a point raised by Barros and Lettenmaier (1994).

These and other questions could form the basis for future research on rain shadows. Such work would go a long way to exploring beyond the simple textbook explanation for the weather patterns across the Peak District, as well as other mountain ranges.

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### REFERENCES


Bennett, L. J., K. A. Browning, A. M. Blyth, D. J. Parker, and P. A. Clark, 2006: A review of the initiation of


Thielen, J., and A. Gadian, 1996: Influence of different wind directions in relation to topography on the


