Weekly to multi-month persistence in sets of daily weather patterns over Europe and the North Atlantic Ocean

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Full title: Weekly to multi-month persistence in sets of daily weather patterns over Europe and the North Atlantic Ocean

Short title: Weekly to multi-month persistence of European weather patterns

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Abstract

Persistence in time series of daily weather pattern (WP) classifications can provide useful information such as on the memory of broad-scale atmospheric circulation. Despite this, research of WP persistence has lagged behind that exploring their frequencies of occurrence. We develop two methods for identifying persistence in a 167-year time series of WPs defined over the North Atlantic-European domain. The first is an empirical counting technique used to find periods of persistence amongst sets of WPs, with the definition of persistence more relaxed than just consecutive occurrences. We then condition this method on the driest WPs to see if persistence can be used to identify historical drought. The second method uses a Markov model to assess if WP transition probabilities change when conditioned on information up to 20 days prior, without the need for estimating the large number of parameters usually required for high-order Markov chains. Results are compared with a benchmark ensemble of synthetic time series generated using first-order transition probabilities. We show that there were multi-month periods when small sets of WPs dominated, and some of these periods coincided with notable meteorological events, including droughts and storms, such as the mid-1990s drought in northern England and the Burn's Day Storm over southern Scotland in 1990. Some WPs also behave as 'attractors', showing increased probability of reoccurrence despite other WPs occurring in-between. However, we find no link between the persistence statistics of each WP and their flow characteristics, except for those featuring an easterly flow over the UK, which are amongst the most persistent. The benchmark simulation ensemble is unable to reproduce many of the key persistence statistics of the observations, confirming that the persistence is a physical phenomenon. Finally, we discuss the potential processes underpinning WP persistence, such as the effects of large-scale circulation patterns and land-surface feedbacks.

1. Introduction

A weather pattern classification comprises a group of weather patterns (WPs; also called weather types, circulation types or circulation patterns), each representing distinct states of atmospheric circulation over a given domain and time-scale (usually daily). They are a useful way of reducing the complexity of the atmosphere and making general predictions of local-scale weather variables such as temperature or precipitation. There is a wide range of research using WP classifications, including in historical and future climate change studies (Donat *et al.*, 2010a; Gómez-Gesteira *et al.*, 2011; Lorenzo *et al.*, 2011; Brigode *et al.*; Fereday *et al.*, 2018), weather prediction (Ferranti *et al.*, 2015; Neal *et al.*, 2016; Vuillaume and Herath, 2017) and in establishing links with a variety of hydro-climatic variables (Trnka *et al.*, 2009; van den Besselaar *et al.*, 2009; Donat *et al.*, 2010b; Giuntoli *et al.*, 2013; Ramos *et al.*, 2013; Wilby and Quinn, 2013; Nied *et al.*, 2014; Prein *et al.*, 2016; Richardson *et al.*, 2018); see Huth *et al.* (2008) for a full review and for references to literature pre-2008.

Uniting the majority of these studies is their focus on WP frequencies of occurrence. By analysing how the frequencies of the WPs change over time or during particular hydro-meteorological events, it is possible to identify changes in circulation or those WPs most commonly associated with a type of extreme weather. For example, various authors have studied how WP frequencies change during floods or droughts in the UK (Wilby, 1993; Phillips and McGregor, 1998; Wilby, 1998; Fowler and Kilsby, 2002; Fleig *et al.*, 2011; Burt and Ferranti, 2012; Pattison and Lane, 2012; Wilby and Quinn, 2013; Richardson *et al.*, 2018).

WP persistence has been much less researched and has focussed on changes and trends in mean persistence over time (Stefanicki *et al.*, 1998; Werner *et al.*, 2000; Kysely, 2002; Kysely and Domonkos, 2006; Kysely and Huth, 2006; Kysely, 2007; Blenkinsop *et al.*, 2009; Cahynová and Huth, 2009; Casado *et al.*, 2009; Kučerová *et al.*, 2017). Missing from the literature is analysis of the longest persistent sequences of WPs and the implications for

atmospheric circulation and hydro-climatic variables. Furthermore, persistence has not to our knowledge been explored in a modelling context except by Fayos and Fayos (2007). Using the objective Lamb Weather Type classification (Lamb, 1972; Jenkinson and Collison, 1977), they developed a neural network forecast model to predict a WP based on the previous five days of WPs. Quantifying persistence in a statistical framework is a useful exercise as it could form the basis of a WP forecast model. Another motivation for this study is to explore a more relaxed definition for persistence. WP persistence has always been defined in previous works as uninterrupted sequences of a single WP (or WP cluster) and as a result these sequences are relatively short, typically with a mean of one week or less (Werner *et al.*, 2000; Kysely, 2002; Kysely and Domonkos, 2006; Kysely and Huth, 2006; Cahynová and Huth, 2009; Casado *et al.*, 2009). An exception found by Kučerová *et al.* (2017) is for some classifications during the summer over the eastern Mediterranean, which show a mean persistence of up to 52 days, which the authors state reflects the classifications' unrealistic temporal behaviour. We propose a less strict assumption, allowing for limited numbers of different WPs to break up occurrences of the WP(s) under consideration. This means much longer sequences that are broadly characterised, but not exclusively dominated, by one or more WPs could be identified, with little change in local climatic conditions.

We shall explore the persistence of a 167-year daily WP series from a Met Office classification (Neal *et al.*, 2016) using two methods. The first is an empirical counting method used to identify monthly to seasonal persistence in groups of WPs, which will be linked to UK precipitation and notable meteorological events. The second method focuses on shorter-term (up to three weeks) persistence in a novel Markov-model framework used to quantify the likelihood of WPs occurring given their occurrence up to 20 days prior. Results will be compared to a benchmark ensemble of WP time series. Section 2 outlines the WP and

precipitation data and the two methods for quantifying WP persistence. Section 3 presents the results and discussion points and Section 4 provides conclusions.

2. Data and methodology

Data

We use a WP classification introduced by Neal *et al.* (2016) comprising 30 WPs defined objectively using daily mean sea level pressure (MSLP) anomalies over the North Atlantic Ocean and much of Europe. Specifically the domain is 30°W-20°E; 35°-70°N, with a spatial resolution of 5°. The WP definitions were derived by clustering 154 years (1850 through 2003) of daily MSLP anomaly fields from the European and North Atlantic Daily to multi-decadal climate variability (EMULATE) data set (Ansell *et al.*, 2006) into 30 distinct states using simulated annealing. Using these definitions, a time series of WPs was created by assigning daily MSLP anomaly fields from EMULATE to the closest matching WP via the sum-of-squared-differences. The series was extended from 2004 to 2016 using 1200 UTC SLP fields from the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis data set (Dee *et al.*, 2011). We use the entire series from 1850 to 2016, referring to the classification as MO-30 and to individual WPs as WP_i , for $i = 1, \dots, 30$. MSLP definitions for the WPs are shown in Figure 1. WPs are ordered according to their historic occurrence between 1850 and 2003: WP1 through WP11 are more common in the summer (April to September) than in the winter (October to March) half-years and vice versa for the remaining WPs (Richardson *et al.*, 2018). MO-30 has previously been used to show the contribution of atmospheric circulation to historical and projected European precipitation variability (Fereday *et al.*, 2018), to predict periods of increased likelihood for UK coastal flooding (Neal *et al.*, 2018) and in analysing aspects of UK precipitation and meteorological drought (Richardson *et al.*, 2018). For precipitation we use the Met Office HadUKP data set from

1931 to 2016 (Alexander and Jones, 2000). We standardise the data for the nine regions (Figure 2) by $\mathbf{Z} = \mathbf{X} - \tilde{x}$, where $\mathbf{X}$ is the distribution of daily precipitation for a particular month and region and $\tilde{x}$ is the median of $\mathbf{X}$.

An empirical counting method for identifying long-term WP persistence

The first step in analysing WP persistence is to count on how many consecutive days each WP occurs. Annually, for 24 individual WPs the median persistence is just one day (Figure 3). The remaining six WPs have a median persistence of two days. The maximum persistence of any WP over the whole 167 years is 18 days for WP27, followed by 17 days for WP28. These are the only WPs characterised by easterly flow over the UK; this will be discussed in Section 3. Persistence is also linked to seasonality, with out-of-season WPs less likely to persist compared to the annual average (not shown).

The length of persistence for individual WPs might be suitable for linking with short-term events such as flooding, but not for events that evolve on longer time-scales, such as drought. To identify longer-term persistence, we therefore develop an empirical counting (EC) method, considering sets of WPs, denoted S , that are treated as a single WP. For different sets of n WPs, EC searches the MO-30 time series to find persistent periods of length at least v days containing WPs in the set. We consider that it is likely that long-duration dry and wet events will not be exclusively composed of whichever WPs are in the set under consideration - there will be days on which a different WP occurs that may not be dry or wet (and may indeed be the opposite to the majority of WPs during the event). However, if the number of these days is sufficiently low then the period under consideration may still be dry or wet overall. Therefore, EC permits a certain percentage, $\alpha\%$, of days to be WPs outside the set. Sets of two and three WPs out of the 30 WPs in MO-30 have 435 and 4,060 unique, unordered combinations, respectively. It is feasible to compute persistence periods for each of

these combinations. For higher-order WP combinations, the task becomes far more expensive in terms of time and computational burden: four- and five-WP sets have 27,405 and 142,506 unique combinations, respectively. Therefore, EC is extended to $n > 3$ by introducing a second set of n_f fixed WPs, S_f . For $n < 4$, $S_f = \emptyset$, the empty set. We define a persistence period as a time period of at least v days where $(100 - a)\%$ of WPs are in S or S_f . Each WP in S and at least one WP in S_f must occur over this period. Using $S_f \neq \emptyset$ for $n > 3$ WPs then allows identification of much longer periods of persistence, as occurrences of WPs in S broken up by occurrences of WPs in S_f will not terminate a persistence period. Moreover, it enables the searching of hypothetically promising sets of more than three WPs while drastically reducing the total number of combinations to process.

The algorithm for EC is as follows, using $n = 2$ and $n_f = 3$ as an example:

1. Define a set of three fixed WPs $S_f = \{W_1 = i, W_2 = j, W_3 = l\}$ and a set of two WPs $S = \{W_4 = m, W_5 = o\}$ for $i, j, l, m, o = 1, \dots, 30$, with $i \neq j \neq l \neq m \neq o$.
2. Set time $t = 0$, the length of the moving window in days, v , and the percentage of days per moving window allowed to be WPs not in S or S_f as $a\%$.
3. Take the $t, \dots, t + v$ days of the WP time series. If $(100 - a)\%$ of WPs in this window are in S or S_f , each WP in S occurs at least once and at least one WP from S_f occurs, then define a new persistence period of length v days and proceed to Step 4. If not satisfied, set $t = t + 1$ and repeat.
4. Set $t = t + 1$ and take the $t, \dots, t + v$ days of the WP time series. If $(100 - a)\%$ of WPs in this window are also in S or S_f , each WP in S occurs at least once and at least one WP from S_f occurs, then the length of the persistence period becomes $v^* = v + 1$ days. Repeat this step until less than $(100 - a)\%$ of WPs in S and S_f are in the window, at least one WP from S does not occur or no WPs in S_f occur.

5. The persistence period is terminated. Trim the persistence period at either end such that the period must begin and end with a WP in either S or S_f .
6. Set $t = t + 1$ and return to Step 3 until the entire time series has been searched.
7. Choose a new $S^* \neq S$ and repeat from Step 3 until every combination of WPs has been processed.

A persistence period of v^* days will not necessarily contain at least $v^*(100 - \alpha)\%$ days featuring the WPs in S or S_f , but each of the v -day windows within the period will have at least $v^*(100 - \alpha)\%$ days of these WPs. EC effectively treats all WPs in the sets as the same WP, and therefore the identification of multi-WP persistence periods does not necessarily mean that the individual WPs persist within that period. It is possible that a period could consist of many single-day occurrences of WPs in S and/or S_f .

For each identified persistence period, the observed precipitation anomalies, Z_o , and expected precipitation anomalies given the WPs, Z_e , are calculated. The expected precipitation anomalies for each v -day persistence period are calculated as follows.

1. Let $\mathbf{Y}$ be the time series of precipitation anomalies for a particular region.
2. Set the month, M , as that corresponding to the middle day of the persistence period, and let the season, s , comprise M and the two months either side.
3. For each day in the persistence period, $T = t, \dots, t + v$, generate $Q = 10,000$ draws with replacement, $\mathbf{y}_T = (y_{1,T}, \dots, y_{Q,T})$, from the conditional distribution of precipitation anomalies given the WP occurring in s , $\mathbf{Y}_{s,WP}$,
4. Over all days, sum the generated samples to obtain a distribution of expected precipitation anomalies, $\mathbf{Z}_e = \sum_{T=t}^{t+v} \mathbf{y}_T$.

The observed persistence period precipitation is the sum of the daily anomalies, Y_T , over the period, given by $Z_o = \sum_{T=t}^{t+v} Y_T$. While Z_e can be estimated for the same period that MO-30 is available for (1850 to 2016), Z_o is only available from 1931.

We consider two sets of parameters for EC. First, to test for monthly persistence amongst small sets of WPs, we choose $n = 3$ WPs, $v = 30$ days and $a = 10\%$. As $n < 4$ no fixed WPs are required, so we let $S_f = \emptyset$. This parameter combination is denoted EC30. These are strict criteria: to be satisfied, three WPs will have to dominate 30-day periods with only three days permitted to be other WPs. The second parameter combination is chosen to seek multi-month persistence. After trying various numbers of WPs in S and S_f , a suitable compromise between number of WPs and length of persistence is identified as follows. We set $n = 3$ WPs, $n_f = 3$ WPs, $v = 60$ days and $a = 20\%$ (the same ratio of v and a as for EC30). We name this parameter combination EC60. Choosing to investigate the link between persistence and drought, we then select the three driest WPs according to UK mean daily precipitation (Richardson *et al.*, 2018) and define $S_f = \{\text{WP6}, \text{WP17}, \text{WP25}\}$. This choice reflects both frequently occurring summer WPs (WP6) and less frequent, wintry WPs (WP17 and WP25). As the three driest WPs, they are unsurprisingly characterised by anticyclonic conditions over the UK (Figure 1).

A Markov model for quantifying persistence

As EC is not a statistical model, it is difficult to use results arising from its application in further applications such as forecasting. Therefore, we take another approach to quantify persistence in MO-30, underpinned more formally by a statistical model. A common way of modelling discrete data is using Markov processes (Norris, 1997) to quantify the probability of state (in this case WP) transitions. As before, we let W_t represent a particular WP i on day t . Therefore, the first-order Markov assumption is:

$$\Pr(W_t | W_{t-1}, W_{t-2}, \dots, W_1) = \Pr(W_t | W_{t-1}),$$

i.e. the probability of a WP occurring is only dependent on the WP of the previous day. The transition probabilities are given by the transition matrix, $\mathbf{P}$, with each element calculated as $p_{ij} = \Pr(W_t = i | W_{t-1} = j)$, for $i, j = 1, \dots, 30$. The most likely transition for any WP is the same-state transition and the seasonality is also evident, with the lower-numbered, summer WPs more likely to transition between themselves and vice-versa for the winter WPs (Figure 4). To increase the number of days influencing each transition, higher-order Markov chains could be considered. However, the number of parameters needed to estimate Markov models increases exponentially with the order, and the sample size of some multi-day transitions could be very small, making their transition probability estimates highly uncertain. Fortunately, for persistence, consideration of all possible transitions to a high order is not necessary; only the return of the WP system to its initial state is of interest. For example, in the second-order case, rather than considering $\Pr(W_t = i | W_{t-1} = j, W_{t-2} = l)$, $i, j, l = 1, \dots, 30$, it is sufficient to consider $\Pr(W_t = i | W_{t-1} = j, W_{t-2} = i)$. Instead of 30 permutations given by the values l could take, only one is necessary, that given by i .

We generalise this idea to higher orders by considering $u \geq 1$ occurrences of $W_t = i$ in the k -day period prior to the final transition of W_{t-1} to W_t . This conditional probability can be expressed as

$$\Pr\left(W_t = i | W_{t-1} = j, \sum_{T=t-k-1}^{t-2} I_{W_T}(i) \geq u\right), i, j = 1, \dots, 30, \quad (1)$$

where $I_{W_t}(x)$ is the indicator function defined as

$$I_{W_t}(x) := \begin{cases} 1 & \text{if } x = W_t, \\ 0 & \text{otherwise.} \end{cases}$$

That is, Equation (1) calculates the probability of a WP i occurring given a different WP j on the previous day and u occurrences of WP i in the k days prior to the final transition. For notational simplicity we re-write Equation (1) as

$$\Pr(W_t = i \mid W_{t-1} = j, W^{(k,u)} = i). \quad (2)$$

The phrase “ k -day period” will always refer to the time period prior to the final transition, $t - k - 1, \dots, t - 2$. Equation (2) reveals whether the occurrence of a particular WP in a given window is likely to be followed by a repeat of this WP, despite other WPs occurring during the k -day period and between the k -day period and the final W_t . Furthermore, we can compare these probabilities with the equivalent first-order transition probabilities in $\mathbf{P}$:

$$D_{i,j}^{(k,u)} = \Pr(W_t = i \mid W_{t-1} = j) - \Pr(W_t = i \mid W_{t-1} = j, W^{(k,u)} = i).$$

Negative $D_{i,j}^{(k,u)}$ occur when $\Pr(W_t = i \mid W_{t-1} = j, W^{(k,u)} = i) > \Pr(W_t = i \mid W_{t-1} = j)$ i.e. when WP i has already occurred at least u times in the k -day window, and the resulting probability of $W_{t-1} = j$ transitioning to $W_t = i$ is greater than if the sequence was considered independently. These transitions interest us as they indicate persistence. This Markov method will be referred to as MM. The choices of k and u used for MM are shown in Table 1. We choose higher values of k to investigate whether there is long-range dependence in time, and the range of values chosen for u are to assess the differences between relaxed and strict persistence rules for each k .

Comparing with a benchmark ensemble of synthetic WP series

To test whether a time-inhomogeneous first-order Markov model can reproduce observed persistence in the MO-30 data, we conduct a simulation study. Inhomogeneity in time is a necessary imposition, as ignoring the seasonality in MO-30 would result in the under-estimation of persistence. For example, as summer is dominated by WP1 through WP11,

using a non-seasonal transition matrix would result in higher numbers of the other WPs and therefore fewer summer WPs, and hence a decreased likelihood of persistence. We simulate an ensemble of 1000 WP series using the following procedure:

1. Calculate the 12 monthly transition matrices, $\mathbf{P}^m$, $m = 1, \dots, 12$, of MO-30:

$$p_{i,j}^m = \Pr(W_t = i \mid W_{t-1} = j), \text{ for } i, j = 1, \dots, 30.$$

2. Generate an initial W_1 according to its frequency of occurrence and set time $t = 1$.

3. Generate a random number p^* from the standard uniform distribution $U(0,1)$.

4. Find the index q such that:

$$\sum_{j=1}^{q-1} p_{i,j}^m < p^* < \sum_{j=1}^q p_{i,j}^m \text{ where } i = W_t.$$

5. Set $W_{t+1} = q$ and $t = t + 1$.

6. Repeat steps 3 to 5 until $t = T$, the length of the series to be generated.

The benchmark ensemble has reasonable skill at replicating the observed WP frequencies of occurrence (Figure S1). For most WPs and months, the observed frequencies fall within 90% of the simulated series. There are some significant exceptions. In particular, the simulation methodology underrepresents the occurrences of the two easterly WPs, WP27 and WP28, between January and March. Winter appears to be the least-well simulated season, with WP4, WP8, WP10, WP22, WP23, WP25, WP29 and WP30 all featuring at least one month over- or under-simulated, implying that the first-order transition probabilities are least suited to modelling this season. The simulated series also fail to capture the observed maximum persistence of individual WPs, with 90% of the ensemble underestimating this statistic for 22 WPs (Figure 3).

3. Results

272 *EC results*

273 Despite the transient nature of individual WPs, we can identify multi-month periods where
274 small numbers of WPs dominate. Furthermore, within these periods, the persistence of
275 individual WPs tends to be above average. EC30 identifies 67 persistence periods from 54 sets
276 with a median persistence of 31 days (Figure 5a), equivalent to roughly one persistence
277 period every 2.5 years. The longest persistence period was 48 days over winter 1962/63,
278 which was characterised by anticyclonic, often easterly, flow over the UK, as can be seen
279 from the high frequencies of WP25, WP27 and WP28 (Figure 6a). Another example is for 30
280 days over winter 1990, with WPs in this period suggesting very windy and often stormy
281 conditions, culminating in a 10-day sequence of WP30, which is the longest amount of time
282 this WP has persisted over the whole 167 years (Figure 6b). EC60 identifies 79 persistence
283 periods from 58 sets, with almost half lasting for at least nine weeks (Figure 5b). The two
284 longest examples are almost a full season in length, over summer 1968 and, again, in winter
285 1962/63 (Figure 6c and d). The former features a near month-long stretch of anticyclonic
286 WPs (WP6, WP9, WP17 and WP25) between 16th July and 10th August. The latter shows
287 how the inclusion of three WPs in S_f can extend a persistence period by almost a month
288 (Figures 6a and d). However, the key aspect of this persistence period is the dominance of
289 easterly WPs between 26th December and 9th February, which is completely captured by the
290 shorter persistence period with $S_f = \emptyset$ (Figure 6a). All cases in Figure 6 highlight how,
291 within each period, individual WP persistence is greater than average, with many cases of
292 persistence greater than two days (the highest average persistence for any WP). This was
293 particularly stark during the winter of 1995/96 (Figure 6e), with nine-, 11- and 12-day
294 stretches of WP17, WP28 and WP27, respectively. That the behaviour of these daily,
295 typically ephemeral WPs is sometimes reduced down to small sets occurring over such long
296 time-scales is remarkable and suggests that the WPs, and possibly atmospheric circulation in

general, can be more predictable than usual for months at a time. A dominant easterly flow might be the most likely circumstance under which WP predictability is enhanced, as WP27 and WP28 feature strongly in EC30 and (less so) EC60 persistence periods (Figures 5c and 5d). However, any enhanced predictability during such periods is expected, as there are just two easterly WPs but many more featuring westerly flow (over the UK). Further discussion of the consequences of the small number of easterly WPs is presented later.

EC30 persistence periods are most numerous in winter (December through February; 43 out of 67), while those identified by EC60 are more common in summer (June through August; 37 out of 79), with winter also well-represented (25 out of 79); refer to Table 2. The reason that there are many summer persistence periods of at least 60 days in length, but fewer that are of at least 30 days is due to the percentage of days allowed to be WPs not in S or S_f (10% for EC30 and 20% for EC60). Although the ratio of this percentage and the minimum persistence period length is the same for both EC30 and EC60, the latter allows for longer sequences of WPs outside S or S_f (six consecutive days compared to three days for EC30). Therefore we may conclude that summer persistence periods identified by EC60 have stretches of WPs not in S or S_f of length greater than three days, whereas those identified by EC30 do not. The other key feature highlighted by the seasonal distribution of persistence periods is how the number of winter events decreases for EC60 compared to EC30. This is due to the different numbers of WPs associated with each season. In winter, there are more WPs that tend to occur, and so it is less likely there will be persistence of sufficient length to satisfy the conditions of EC60. This is even more the case for the spring and autumn. In these seasons the WP behaviour is transitioning between winter and summer and the frequencies of occurrence are more evenly spread between all 30 WPs.

Overall, persistence periods are associated with drier conditions for western and northern regions than for eastern and southern regions. These persistence periods sometimes coincide

with notable meteorological events. Given the WPs that occurred during EC30 persistence periods, the majority of precipitation simulations are below average in NI, NWE, NS and SS and average for the other regions (Figure 7a). This east-west divide is probably due to the predominance of easterly WPs WP27 and WP28 in EC30 periods (Figure 5c), resulting in wetter conditions for eastern UK. Precipitation for individual persistence periods, on the other hand, is likely to be determined largely by the flow direction. Expected and observed anomalies have very similar distributions for both EC30 and EC60, with the main difference being greater 95th percentile anomalies for observed EC30 anomalies (Figure 7). Including the three driest WPs in S_f for EC60 does not change the median and lower-tail distribution statistics by very much, with the main effect being a reduction in the upper-tail anomalies, particularly in the observations (Figure 7d). The eastern regions remain wetter than those in the west, again likely due to WP27 and WP28 being amongst the most common WPs in EC60 persistence periods and also to the higher precipitation variability associated with WP25 in eastern regions (Richardson *et al.*, 2018). Examples of easterly-flow persistence are winter 1962/63 (Figures 6a and d) and winter 1995/96 (Figure 6e), with observed and expected precipitation greater for eastern regions. These correspond to notable meteorological events, with the former known to be a particularly cold and dry winter (Prior and Kendon, 2011) and the latter part of the 1995/96 Yorkshire drought (Fowler and Kilsby, 2002). Another example coincident with drought conditions was towards the end of the 2010-12 drought (Figure 6f), which was particularly severe for central, southern and eastern England in meteorological, hydrological and agricultural contexts (Kendon *et al.*, 2013). The persistence period occurred over February and March of 2012, with that March being the driest on record since 1953 (Kendon *et al.*, 2013). EC30 also yielded a particularly notable storm: an extremely wet January 1990 (Figure 6b), which culminated in the Burns' Day Storm (McCallum, 1990) over southern Scotland on the 25th and 26th January. However, our

results imply that it is difficult to say anything about precipitation based on WP persistence alone. While there does appear to be a geographical difference (drier conditions in western regions), this may be an artefact caused by the lack of variety of easterly WPs in MO-30; we will discuss this more later.

Markov model results

For some WPs, their probability of occurrence is increased if they have occurred previously, including situations in which other WPs occur in-between. This holds for different lengths of the k -day window for up to almost three weeks. Over all WPs, the more often a WP occurs in this window, the higher probability it has of reoccurring after the final transition. We show results for MM with $k = 5$, with stricter persistence rules (i.e. higher u) yielding more probability in the lower tail of the $D_{ij}^{(5,u)}$ distributions (Figure 8a to d). This is also true for other k (not shown). This suggests that when a particular pattern of atmospheric circulation has been dominating over recent days, it is more likely to persist into the future (dependent on the actual synoptic situation represented by the WPs). To identify the WP transitions that are influenced by this type of persistence, we count how often each WP transition is below the 20th percentile of the $D_{ij}^{(k,u)}$ distributions (for all 23 combinations of k and u). Persistence of anticyclonic WPs appear to influence each other, for example WP6 shows higher probabilities of reoccurring if the previous WP is WP6, WP17, WP18 or WP25. Similarly, some cyclonic WPs are more likely to persist if the penultimate WP is also cyclonic, such as WP7 preceded by WP7, WP8, WP11, WP22, WP24 or WP28 (Figure 9). We collate these results to identify the most persistent WPs by considering the transitions independent of the penultimate WP, equivalent to summing the counts given by the rows of Figure 9. It appears as though the summer WPs are more persistent than the winter WPs, with WP1 and WP7 the two most persistent (Figure 10a). However, this seasonal divide is also present in the simulated series. When taking the difference between the observed and simulated medians,

this contrast is less stark (Figure 10b). Accounting for seasonality, the most persistent WPs are WP28, WP16, WP7, WP23, WP18 and WP25. Apart from WP7, these occur more often in winter than summer, although the following three most persistent WPs are all associated with summer (WP2, WP4 and WP6). We do not find a link between WP persistence and the corresponding WP's MSLP definition, with high persistence from WPs that differ by their MSLP anomalies (e.g. cyclonic WP7 and WP28 versus anticyclonic WP18 and WP25) and direction of flow over the UK (e.g. westerly or south-westerly WP7, WP18, WP23; southerly WP16 and south-easterly WP28).

The persistence characteristics outlined previously are not replicated by the first-order transition probabilities. Those WP transitions that are more likely when conditioned on persistence (i.e. when $D_{i,j}^{(k,u)} < 0$) are more numerous and have higher magnitude transition probabilities for the observations than for the benchmark ensemble. This is shown by the differences between the lower tails of the observed and simulated $D_{i,j}^{(k,u)}$ ECDFs (Figure 8). An exception is how, for higher k and u , there is more probability in the lowest part of the distribution for the benchmark, not observed, WP series. This can be likened to 'repelling' behaviour: for longer k -day windows with stricter persistence rules, the occurrence of certain WPs in the prior window reduces the chance of these WPs persisting. However, this is likely due to these strict transitions occurring infrequently; we have a much smaller sample size in the observed series than over the 1000 simulated series. Two examples of this behaviour are for $D_{i,j}^{10,6}$ and $D_{i,j}^{15,10}$ (Figures 8e and f). The simulated ensemble also does not capture the variation in persistence amongst WPs, with the only differences attributable to seasonality: summer WPs are more persistent than winter WPs (boxplots in Figure 10a), whereas the reality is more complex (circles in Figure 10a). For computational reasons we did not run EC for the synthetic series. However, upper-tail statistics of uninterrupted persistence are, for the majority of individual WPs, not reproduced in the ensemble (Figure 3). As discussed earlier,

persistence periods are characterised by above-average persistence of individual WPs and therefore we may infer that the first-order Markov principle is insufficient to replicate persistence periods.

WPs with an easterly flow

The only two WPs with a distinct easterly flow over the UK, WP27 and WP28, stand out throughout this study for several reasons. They are the WPs with the two longest uninterrupted sequences over the entire record and have the highest or joint-highest mean and median persistence (Figure 3). They are also the most common WPs in EC30 persistence periods (Figure 5c) and are amongst the most common for those identified by EC60 (Figure 5d). Furthermore, the first-order Markov assumption is least suited to these two WPs, as they show the greatest difference between observed and simulated maximum persistence (Figure 3), and their monthly frequencies are particularly under-simulated in winter (Figure S1). As there are just two easterly WPs, we might expect most daily MSLP fields with an easterly flow to be assigned to them and hence for these WPs to have high within-WP variability. To check this, we calculated the spatial correlation between the WPs and their underlying (concurrent) MSLP fields. These results show that, in fact, WP27 and WP28 have amongst the lowest within-WP variability (Figure S2). As such, the fact that these WPs stand out cannot be attributed to an unsatisfactory assignment process and instead suggests that long periods of atmospheric persistence in the European-North Atlantic domain are characterised by easterly flow patterns closely resembling WP27 and WP28.

4. Conclusions

We have investigated the persistence properties of a time series of 30 WPs defined by MSLP over the North Atlantic Ocean and Europe. By developing an empirical counting method that accounts for more relaxed persistence rules than currently in the literature, we have shown

that there are multi-month periods when normally transient WP behaviour can be reduced down to many occurrences of small sets of WPs. These periods generally result in drier than average conditions for western UK regions and have coincided with notable meteorological events, including droughts. This geographical divide is a result of the predominance of easterly WPs in the identified persistence periods. We also analysed persistence properties using a novel Markov model, which quantified the difference between first-order WP transition probabilities and those conditioned on prior occurrences, without the need for estimating the large numbers of parameters usually required by high-order Markov chains. Some WPs are more likely to reoccur than others, although we could not find a link between their persistence and the MSLP definition.

WP frequencies of occurrence are likely modulated by lower-frequency (slowly varying) physical processes, such as large-scale atmospheric teleconnection patterns and land-atmosphere interactions. For example, studies have associated variations in the North Atlantic Oscillation (NAO) with changes and trends in the frequencies of WPs from a range of classifications (e.g. Stefanicki *et al.*, 1998; Casado *et al.*, 2009; Kučerová *et al.*, 2017). In particular, during the 1990s the NAO entered a more positive phase (Ostermeier and Wallace, 2003), which means an increased pressure gradient between the teleconnection's high and low pressure centres near the Azores and Iceland, respectively, resulting in a strengthening of the prevailing westerly flow. Coinciding with this, Kučerová *et al.* (2017) show that WPs featuring zonal (meridional) flow became more (less) frequent over northern and central Europe. Similarly, more frequent northerly WPs over the central and eastern Mediterranean corresponded to an eastward shift of the NAO pressure centres during the same decade (Jung *et al.*, 2003; Beranová and Huth, 2008). To our knowledge, there are no studies formally linking changes in WP persistence to changes in large-scale atmospheric circulation (or other physical mechanisms), offering an opportunity for further research. WP persistence, explored

as both mean persistence over time (see references in Section 1) and longer-term persistence (as analysed in this study) could be linked to variations in atmospheric and oceanic processes thought to influence MSLP in the relevant domains. As highlighted by Kučerová *et al.* (2017), these kind of climatological studies should be done using multiple, and indeed as many as possible, WP classifications in order to avoid the over-interpretation of results arising from use of a single classification. This merits investigation, as previous research suggest that there are certain conditions that foster atmospheric persistence. The monthly persistence of low-frequency atmospheric circulation patterns, such as the NAO and other teleconnections, is well known (van den Dool and Livezey, 1984; Barnston and Livezey, 1987; Perlwitz and Graf, 2001). It is thought that this persistence is partly modulated by stratospheric processes, as anomalies in the stratosphere tend to propagate into the troposphere at lead-times of one to two weeks (Baldwin and Dunkerton, 1998; Thompson *et al.*, 2002). Of particular interest for Europe is how stratospheric anomalies in the northern hemisphere have a similar surface signature to some teleconnection patterns, including the NAO (Baldwin and Dunkerton, 2001).

Land-atmosphere feedbacks may also contribute to modifying WP frequencies of occurrence and persistence. For example, the importance of soil moisture in contributing to heatwaves has been well documented, with major European events, such as that over western Russia in 2010, being preceded by anomalously dry soils (Fischer *et al.*, 2007; Vautard *et al.*, 2007; García-Herrera *et al.*, 2010; Mueller and Seneviratne, 2012; Quesada *et al.*, 2012; Miralles *et al.*, 2014; Hauser *et al.*, 2016). Relatedly, several studies have linked changes in the mean persistence of WPs from the Grosswetterlagen classification (Hess and Brezowsky, 1952) between 1988 and 1997 to severe central European heatwaves in the 1990s (Kysely, 2002; Kysely and Domonkos, 2006; Kysely, 2007). Interestingly, these studies show that the persistence of all WPs increase during this period, not just those we might typically associate

with heatwaves (i.e. anticyclonic WPs), although as Kysely and Domonkos (2006) note, persistent atmospheric anomalies can support climate anomalies in both directions. However, Cahynová and Huth (2009) questioned the credibility of changes in WP persistence of this classification in the 1980s, as they were not reflected in analyses of other data sets. This again reinforces the point made by Kučerová *et al.* (2017) that studies of this nature should utilise multiple classifications.

This study may be useful for further research in several ways. For example, the methods used to identify and quantify persistence are applicable to any WP classification, making them useful for any region in the world that has such a classification. Furthermore, we have demonstrated the potential to build a statistical forecast model for WP occurrences by showing that their transition probabilities change when conditioned on persistence. While physically-based WP forecast models are in use operationally (Neal *et al.*, 2016), to our knowledge there is no data-driven approach to this problem, except by Fayos and Fayos (2007). Harnessing the persistence shown here may be a viable option for building this model, which may be of value as a way of benchmarking the dynamical systems.

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691

692 Figure captions

693 Figure 1: Weather patterns in MO-30. Shading indicates mean sea level pressure (MSLP)
694 anomalies. The black contours are isobars showing the absolute MSLP values associated with
695 each weather pattern, with the centres of high and low pressure also indicated.

696 Figure 2: HadUKP daily precipitation regions.

697 Figure 3: Box plots show the distribution of consecutive occurrences of each WP. Black
698 circles represent the 90th percentile of the distribution of maximum consecutive occurrences
699 from the 1000 simulated series. A simulated value less than the observed maximum indicates
700 that 90% of the simulated series fail to capture the persistence of the observed series.

701 Figure 4: First-order transition probabilities for MO-30 WPs.

702 Figure 5: a) and b) show box plots and the underlying data for the number of days in each
703 persistence period for EC30 and EC60. Whiskers are 1.5 times the interquartile range beyond
704 the 25th and 75th percentiles. c) and d) are counts of how often each WP appears in the
705 persistence period sets.

706 Figure 6: WP time series (top), with expected precipitation anomalies derived from WPs and
707 observed precipitation anomalies (bottom). Plotted for two EC30 persistence periods during
708 a) winter 1962/63 and b) winter 1990 and four EC60 persistence periods during c) summer
709 1968, d) winter 1962/63, e) winter 1995/96 and f) winter/early spring 2012.

710 Figure 7: Boxplots of a) and b) expected, and c) and d) observed precipitation anomalies
711 during persistence periods for a) and c) EC30, and b) and d) EC60. Expected anomalies are
712 sampled from the distributions of precipitation anomalies for WPs occurring in each
713 persistence period. Whiskers represent the 5th and 95th percentiles.

714 Figure 8: ECDFs for $D_{ij}^{5,u}$ with a) $u = 1$, b) $u = 2$, c) $u = 3$, d) $u = 4$, and for e) $D_{ij}^{(10,6)}$ and f)
 715 $D_{ij}^{(15,10)}$ for observed (solid line) and simulated (dashed line) series.

716 Figure 9: Counts of how often each individual value (i.e. WP transition) in the $D_{ij}^{(k,u)}$
 717 distribution is below the 20th percentile, over all k and u .

718 Figure 10: a) Independent of the penultimate WP_j , how often each value (i.e. WP transition)
 719 in the $D_{ij}^{(k,u)}$ distribution is below the 20th percentile, over all k and u . Observed series
 720 represented by the black circles and 1000 simulated series by the boxplots. Whiskers are the
 721 5th and 95th percentiles. b) Observed counts minus median of the simulated counts.

722 Table 1: Choices of window length, k , and strictness of persistence, u , for MM.

723 Table 2: Number of persistence periods beginning in each month.

724 Supporting Information

725 Figure S1: Frequencies of MO-30 WPs by month for the observed series (grey circles) and
 726 1000 simulated series (boxplots). Whiskers are the 5th and 95th percentiles.

727 Figure S2: Boxplots showing correlation between each WP and the concurrent underlying
 728 SLP anomaly fields 1850-2016. Whiskers are the 5th and 95th percentiles.

Figure 1

258x282mm (300 x 300 DPI)

Figure 2

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Figure 3

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Figure 4

195x167mm (300 x 300 DPI)

Figure 5

101x50mm (300 x 300 DPI)

Figure 6

58x88mm (300 x 300 DPI)

Figure 7

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Figure 8

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Figure 9

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Figure 10

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<i>k</i>	<i>u</i>
5	1, 2, 3, 4
10	2, 3, 4, 5, 6, 7
15	3, 5, 7, 9, 10, 11, 12
20	3, 5, 7, 10, 12, 15

Table 1: Choices of window length, *k*, and strictness of persistence, *u*, for MM.

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Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EC30	25	14	4	2	3	3	9	3	0	0	0	4
EC60	9	0	9	0	1	22	14	1	0	3	4	16

Table 2: Number of persistence periods beginning in each month.

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Graphical Abstract

Title: Weekly to multi-month persistence in sets of daily weather patterns over Europe and the North Atlantic Ocean

Authors: Douglas Richardson*, Christopher G. Kilsby, Hayley J. Fowler, András Bárdossy

Persistence in time series of daily weather pattern classifications can provide useful information such as on the memory of broad-scale atmospheric circulation. We develop two novel methods for identifying persistence in a 167-year time series of weather patterns defined over the North Atlantic-European domain, showing that there were multi-month periods when small sets of WPs dominated. Some of these periods coincided with notable meteorological events, such as the Burn's Day Storm over southern Scotland in 1990 (see image).

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Graphical Abstract

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