



LJMU Research Online

Matthews, TR, Murphy, C, Wilby, R and Harrigan, S

A cyclone climatology of the British-Irish Isles 1871–2012

<http://researchonline.ljmu.ac.uk/id/eprint/3102/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Matthews, TR, Murphy, C, Wilby, R and Harrigan, S (2016) A cyclone climatology of the British-Irish Isles 1871–2012. *International Journal of Climatology*, 36 (3). pp. 1299-1312. ISSN 1097-0088

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

<http://researchonline.ljmu.ac.uk/>

A cyclone climatology of the British-Irish Isles 1871-2012

Matthews¹ T, Murphy² C, Wilby³ RL, Harrigan² S

¹ School of Natural Sciences and Psychology, Liverpool John Moores University, UK

² ICARUS, Department of Geography, National University of Ireland Maynooth, Republic of Ireland

³Department of Geography, Loughborough University, UK

Abstract

The British-Irish Isles (BI) lie beneath the North Atlantic storm track year-round and thus are impacted by the passage of extra-tropical cyclones. Given recent extreme storminess and projections of enhanced winter cyclone activity for this region, there is much interest in assessing the extent to which the cyclone climate of the region may be changing. We address this by assessing a 142-year (1871-2012) record of cyclone frequency, intensity and ‘storminess’ derived from the 20CR dataset. We also use this long-term record to examine associations between cyclone activity and regional hydroclimate. Our results confirm the importance of cyclone frequency in driving seasonal precipitation totals which we find to be greatest during summer months. Cyclone *frequency* and *storminess* are characterised by pronounced inter-annual and multi-decadal variability which are strongly coupled to atmospheric blocking in the Euro-Atlantic region, but we detect no evidence of an increasing trend. We observe an upward trend in cyclone *intensity* for the BI region, which is strongest in winter and consistent with model projections, but promote caution interpreting this given the changing data quality in the 20CR over time. Nonetheless, we assert that long-term reconstruction is helpful for contextualising recent storminess and for identifying emerging changes in regional hydroclimate linked to cyclones.

Key words: cyclone; storm; 20th Century Reanalysis; North Atlantic storm track; North Atlantic Oscillation; British-Irish Isles precipitation

Corresponding author:

Tom Matthews, School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, UK.

E-mail: t.r.matthews@ljmu.ac.uk

30 **1. Introduction**

31 Extra-tropical cyclones are of tremendous physical and societal importance due to their role
32 in redistributing heat, moisture and momentum between latitudes and the extreme surface
33 weather events associated with their passing. The climatological significance of cyclones (or
34 ‘storms’) is particularly apparent for the British-Irish Isles (BI) as the North Atlantic storm
35 track crosses these densely-populated islands year-round (Woolings, 2010). Producing long-
36 term cyclone climatologies for this region has, therefore, attracted attention from the research
37 community (e.g. Sweeney, 2000; Hickey, 2003, 2011; Hanna et al., 2008; Allan et al., 2009;
38 Cornes and Jones, 2011), not least because this area of the North Atlantic is projected to
39 experience enhanced winter cyclone activity as the climate warms (Woolings et al., 2012;
40 Collins et al., 2013; Feser et al., 2014 and references therein). Long-series of observed
41 cyclonicity provide a means to contextualize apparently ‘extreme’ seasonal storminess (e.g.
42 Blackburn et al., 2008; Dong et al., 2013a; Matthews et al., 2014) as well as to benchmark
43 emerging trends.

44 Some long-term cyclone climatologies for Europe and/or the BI have used extreme wind
45 speeds as a proxy for storminess, derived from direct surface observations (e.g. Sweeney,
46 2000; Hickey 2003, 2011) or geostrophic principles applied to air pressure records
47 (Alexandersson et al., 1998, 2000; Matulla et al., 2008; Wang et al., 2009; Cornes and Jones,
48 2011). Others have scrutinized high-frequency air pressure variability (Hanna et al., 2008;
49 Allan et al., 2009), or have used tide gauge data (Woodworth and Blackman, 2002; Vilibic
50 and Sepic, 2010; Esteves et al., 2011) to assess historic storminess. Thus, existing work has
51 relied largely upon in-situ measurements from long-running weather/oceanographic stations
52 to serve as a proxy for cyclone frequency and intensity. Feature identification/tracking
53 algorithms which detect cyclones from gridded pressure fields offer scope for identifying and
54 characterising cyclones explicitly. Such techniques have yielded cyclone climatologies of the
55 North Atlantic and beyond (Simmonds and Keay, 2000; Wang et al., 2006; Raible et al.,
56 2008), but have rarely been used to gain insight into the cyclone climatology of the BI in
57 particular. Historically, this is explained by the brevity of reanalysis products (~50 years)
58 compared with station data.

59 However, the advent of the 20th Century Reanalysis V2 dataset (hereafter 20CR: Compo et
60 al., 2011), permits storm reconstruction back to the 1870s. For example, Wang et al. (2013)
61 used the 20CR to identify cyclones over the extra-tropics in both hemispheres, whilst Jones et

62 al. (2013) used this dataset to produce an objective catalogue of Lamb Weather Types (LWTs)
63 for the BI. In addition, Wang et al. (2014) presented a ‘Cyclone Activity Index’ (defined in
64 Section 4), and a time series of extreme wind speeds for the North Sea region. Despite the
65 potential that 20CR offers for providing insights into long-term cyclone characteristics
66 (Cornes, 2014) it has not yet been used to construct a cyclone climatology for the BI. We
67 address this gap and seek to complement and extend long-running storminess metrics
68 provided by station-based methods.

69 **2. Aims and Objectives**

70 Our main aim is to derive a long-term cyclone record for the BI based on 20CR. Our
71 objectives are to 1) establish the seasonal climatology of cyclones over the region, including
72 their influence on precipitation totals; and 2) explore interannual variations in cyclone
73 activity for the study area linked to large-scale atmospheric circulation.

74 We pursue objective 1 because despite the recognised role of cyclones as an important feature
75 of the BI climate, and of precipitation and flood frequency in particular (Allan et al., 2009;
76 Pattison and Lane, 2012; Wilby and Quinn, 2013), relatively little attention has been directed
77 toward their seasonal characteristics, or influence on surface climate. In constructing the
78 longest direct record of BI cyclonicity to-date, our study is well placed to make a contribution
79 in this regard. Objective 2 is addressed because changes in cyclone activity over the region
80 and their drivers are of the utmost societal concern. Our study allows emergent cyclone
81 properties to be viewed in the context of a 142-year period, facilitating assessment of low-
82 frequency variations in cyclone activity and the role of wider-scale atmospheric processes in
83 driving cyclone activity.

84 The following sections provide details of the data (Section 3) and methods (Section 4) used in
85 our study, before proceeding to the results in Section 5. There we outline the role of cyclones
86 within the regional hydroclimate (5.1) and interpret the temporal variability in cyclone
87 activity, including coupling to larger-scale atmospheric processes (5.2). These results are then
88 discussed in Section 6 and conclusions are drawn in Section 7.

89 **3. Data**

90 **3.1 The Twentieth Century Reanalysis V2**

91 The 20CR project is described in detail by Compo et al. (2011). Briefly, the product provides
92 a comprehensive tropospheric reanalysis spanning the period 1871-2012 at $2^\circ \times 2^\circ$ spatial

93 resolution, based on a 56-member ensemble using only observations of surface air pressure,
94 sea surface temperatures, and sea ice extent. Uncertainty in the reanalysis is quantified by the
95 spread among ensemble members. Here 20CR data were extracted for each ensemble
96 member at six-hourly resolution (1871-2012: provided by NOAA/OAR/ESRL PSD available
97 at <http://www.esrl.noaa.gov/psd/>) for the BI domain (50°N to 60°N, 16°W to 6°E) used by
98 Matthews et al. (2014).

99 Whilst the accuracy of 20CR is described as equivalent to contemporary three-day numerical
100 weather predictions, quality in the earlier part of the record has been questioned in
101 assessments of storminess, particularly for data-sparse periods and regions (Wang et al., 2013;
102 Krueger et al., 2014). In particular, variations in the number of observations assimilated into
103 the 20CR through time challenges the identification of trends in storm activity (Section 4.2),
104 as detected changes may be a spurious consequence of changing data quality (Wang et al.,
105 2013). However, previous research suggests that the 20CR is most likely of good quality and
106 homogeneous throughout the BI region (Wang et al., 2014; Matthews et al., 2014). Figure 1
107 shows that data quality over the BI and Western Europe is less uncertain and quality degrades
108 relatively little earlier in the record, compared with the mid/high latitude Northern
109 Hemisphere as a whole. Thus, our domain is amongst the most stable regions and, therefore,
110 amenable to producing a robust, long-term cyclone climatology from the 20CR.

111 **3.2. Lamb Weather Types and Precipitation**

112 To corroborate our 20CR cyclone climatology we compared cyclone counts with the number
113 of pure and hybrid cyclonic Lamb Weather types (LWTs) classified objectively by Jones et al.
114 (2013) centred on the BI using the 20CR for the period 1871-1947, and the National Centers
115 for Environmental Prediction/National Centre for Atmospheric Research Reanalysis
116 (NCEP/NCAR: Kalnay et al., 1996) for the period 1948-present. The cyclonic LWTs are a
117 useful comparison for our counts because the former have a long legacy in regional
118 climatology (Lamb, 1972) and the Jones et al. (2013) version of the catalogue employed here
119 has already demonstrated wider utility in hydrological assessment for the BI back to the 19th
120 Century (e.g. Wilby and Quinn, 2013). We refer to pure and hybrid cyclonic LWTs following
121 the terminology of Lamb (1972), whereby hybrids are those which are a mix of pure synoptic
122 (in this case cyclonic) and directional circulations (e.g. northwest). Objective rules for
123 determining the LWTs are based on geostrophic flow strength/direction and relative vorticity;
124 a description of this scheme can be found in Jones et al (1993, 2013).

125 In exploring seasonal cyclone climatologies we assessed the correlation between cyclone
126 metrics and rainfall totals in the gridded CRU TS3.21 dataset (Harris et al., 2014) which
127 covers the period 1901-2012 at $0.5^\circ \times 0.5^\circ$ spatial resolution. We also use the long-running
128 England and Wales Precipitation (EWP) record (Alexander et al., 2001) to assess any
129 association between years of extreme cyclone activity and precipitation.

130 To determine links between large-scale atmospheric processes and interannual variability in
131 cyclonicity, we used three indices to describe atmospheric flow in the North Atlantic region:
132 the North Atlantic Oscillation Index (NAOI: Hurrell, 1995), Greenland Blocking Index (GBI:
133 Fang, 2004), and the Blocking Index of Tibaldi and Molteni (1990), extended to two
134 dimensions (Scherrer et al., 2006), and hereafter referred to as BITM. This index identifies
135 blocks by a meridional reversal of the normal poleward geopotential height gradient at the
136 500 hPa level. The GBI and BITM were thus calculated using the height field of the 500 hPa
137 surface extracted from the 20CR at monthly and daily resolution, respectively. Two versions
138 of the NAOI were used: a principal component (PC) series, derived from the monthly mean
139 20CR sea-level pressure fields, and the station-based index (data provided by the Climate
140 Analysis Section, NCAR available at: [https://climatedataguide.ucar.edu/climate-data/hurrell-](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based)
141 [north-atlantic-oscillation-nao-index-station-based](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based)).

142 4. Methods

143 4.1 Cyclone Identification and Metrics

144 Following Matthews et al. (2014) cyclones were identified using an objective algorithm: an
145 implementation of the Serreze et al. (2008) scheme for a regular latitude/longitude grid. The
146 technique classifies cyclones based on the local Laplacian of sea-level pressure. As in
147 Matthews et al. (2014) we apply a threshold criterion that a sea-level pressure gradient of at
148 least $1 \text{ hPa } 250 \text{ km}^{-1}$ must be present between a low centre and surrounding cells to qualify as
149 a cyclone.

150 The algorithm was applied by scanning each six-hourly grid from the 56 ensemble members
151 separately. When a cyclone is identified, the location (lat/lon) of the cyclone centre and local
152 Laplacian (intensity: L) are stored. Three cyclone metrics for the BI domain were tallied at
153 seasonal resolution: cyclone counts ($C_{i,j}$), which are simply the number of cyclone centres
154 observed in all grids during year i and season j (note that this measure is equivalent to the
155 “cyclone centre count” as defined in Neu et al., 2013); mean cyclone intensity ($\bar{L}_{i,j}$);
156 calculated as the arithmetic mean of the local Laplacians for the $C_{i,j}$ cyclones; and the

157 Cyclone Activity Index (*CAI*; Wang et al., 2006), given by $CAI_{i,j} = C_{i,j} \bar{L}_{i,j}$. The *CAI* thus
158 weights total counts by mean cyclone intensity. Note that the Laplacian is equivalent to the
159 geostrophic relative vorticity around the cyclone centre and is, therefore, an indicator of low-
160 level convergence. We follow the terminology of Matthews et al. (2014) and refer to the *CAI*
161 as ‘storminess’ hereafter. Metrics were calculated for each of the 56 ensemble members then
162 averaged to produce an ensemble-mean series. Seasons were defined as successive three-
163 month blocks with winter as December (from previous calendar year) to February.

164 **4.2 Interannual variability in cyclonicity**

165 To assess interannual variability in BI cyclonicity we calculated trends in cyclone metrics
166 over the 142-year (1871-2012) period and examined periods of enhanced storminess cyclone
167 activity in detail. Trends were defined using the non-parametric Theil-Sen slope estimation
168 method (Theil, 1950; Sen, 1968). This metric gives a robust estimate of linear trend in the
169 presence of outliers by using the median slope from an ensemble of trends calculated between
170 every pair of x - y data coordinates. Trend significance (two-tailed) was assessed using the
171 non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975). Although we report
172 significance for all statistical tests at the 5% level, these values should be interpreted with
173 caution. There is growing recognition that statistical significance is challenging to establish
174 due to the difficulty of defining a valid null hypothesis in poorly understood physical systems
175 (see Cohn and Lins, 2005), as well as dependency of trend significance on choice of start and
176 end dates (e.g. Murphy et al., 2013).

177 We also recommend that trends should be viewed critically. Although reanalysis projects
178 employ a physically-consistent and temporally-fixed framework for assimilating data, the
179 spatial density of climate observations is not constant through time, which means that archives
180 cannot be considered homogeneous (Chang and Fu, 2002; Smits et al., 2005; Hanna et al.,
181 2008). This problem is apparent for reanalysis datasets in general, and can result in spurious
182 variability and trends (Dee et al., 2014). Whilst attempts have been made to correct for
183 inhomogeneities in the 20CR itself (Wang et al., 2013), these corrections are not without a
184 degree of subjectivity, as statistically-identified change points used to correct data may reflect
185 legitimate climatic variations. Faced with these complexities we, therefore, select the simplest
186 and most transparent solution of reporting trends based on raw 20CR data and use the
187 significance as a relative indicator of trend strength. The trend analysis is thus included for
188 completeness and comparison with previous studies. Note that the 20CR has been used in the

189 same unadjusted format for the relatively high-quality data of the BI region by Jones et al.
190 (2013), Donat et al. (2011) and Brönnimann et al., (2012), with the latter two studies also
191 conducting trend analyses on these unadjusted data.

192 Individual seasons and spells of enhanced cyclone activity were identified by ranking years
193 and decades according to each cyclone metric. Years characterised as extreme were used to
194 explore the role of wider-scale atmospheric processes in driving enhanced cyclone frequency
195 and intensity. This was achieved by compositing standardized 500 hPa height anomalies for
196 those seasons in the top 5% when ranked by the respective cyclone metric (cyclone frequency
197 or intensity). The 500 hPa surface was chosen for analysis as this provides information about
198 atmospheric flow in the mid- and upper-troposphere, permitting insight into the dynamical
199 process generating and steering storms over the North Atlantic.

200 Linear associations between BI cyclone frequency and intensity with wider-scale circulation
201 were explored by calculating Pearson product-moment correlation coefficients between these
202 variables and the NAOI, GBI and BITM. The NAOI was calculated as the monthly time
203 series of the leading empirical orthogonal function of sea-level pressure over the region 20-
204 80°N, 40-90°W (e.g. Blessing et al., 2005; Hanna et al., 2014), whilst the GBI was computed
205 as the geopotential monthly height anomaly for the 500 hPa surface over the region 60-80°N,
206 20-80°W (Fang, 2004; Hanna et al., 2013). BITM was calculated for the Atlantic sector (34-
207 76°N, 84°W-44°E) following the method outlined in Scherrer et al. (2006). Unless otherwise
208 stated, all correlations cited below are regarded significant when $p \leq 0.05$.

209 **5. Results**

210 **5.1 Cyclone metrics, Lamb Weather Types and rainfall**

211 Correlations between our (20CR) cyclone counts and total pure and hybrid cyclonic LWTs
212 (Figure 2) are all statistically significant. Correlation strength is generally greater between
213 20CR and hybrid cyclonic weather types and in winter. 20CR total cyclone counts are higher
214 (lower) than the number of pure (hybrid) cyclonic LWTs, consistent with the findings of
215 Matthews et al. (2014) for their winter-only assessment. The overestimation compared to
216 counts of pure cyclonic LWTs may be because we sample the pressure field more frequently
217 (six-hourly here *versus* 24-hourly in the LWT analysis), meaning that short-lived lows are
218 more likely to be detected. The fact that the number of hybrid cyclonic LWTs exceeds our
219 cyclone counts could be due to the more stringent definition of a cyclone employed here,

220 which includes an intensity threshold. This may also explain why correlation between LWT
221 counts and our cyclone metrics are weaker outside of winter. Mean cyclone intensity is lower
222 in warmer months and, in the presence of weaker lows, there is evidently a greater chance of
223 disagreement in the detection of a cyclone according to these classification schemes (see
224 below for details of the seasonal cycle in cyclone intensity).

225 Correlation surfaces for interannual seasonal rainfall variability and cyclone metrics are
226 shown in Figure 3. Correlations between our metrics and rainfall are significant not just for
227 the BI, but for large parts of northwest Europe. Maps of counts and storminess appear similar
228 because interannual variations in storminess are mainly driven by cyclone counts. This metric
229 has a higher standard deviation than intensity when expressed as a percentage of the mean (C_v
230 of 18.7% *versus* 6.0%: see Table 1 and Section 5.3) and storminess is calculated with a
231 multiplicative formula (Section 4.1). For conciseness, we focus on the correlation for cyclone
232 counts.

233 In winter, an area of significant positive correlations with cyclone frequency extends over
234 much of northwest Europe, with the exception of western Scandinavia which registers
235 significant negative correlations. In summer, the area exhibiting significant correlations
236 between the cyclone metrics and precipitation contracts and the strength of the correlations
237 throughout northern Europe is also generally lower, particularly for western Scandinavia.
238 However, average correlation strength is greatest across the BI during summer and there is a
239 weak spatial gradient in correlation across the domain. This is unlike winter where there is a
240 noteworthy decrease in the strength of the correlation between cyclone count and
241 precipitation with increasing latitude, becoming non-significant for northwest Scotland. In
242 this region, cyclone intensity is significantly correlated with precipitation.

243 The seasonal regime of cyclone metrics is illustrated in Figure 4. Mean cyclone intensity
244 progresses from a maximum during winter to minimum in summer. The seasonal change in
245 counts is more complex. The probability of cyclone presence over the BI is greatest in late
246 summer (August), with secondary peaks in late spring (May) and late autumn (November).
247 Minimum cyclone frequency occurs in winter. Further insight into this aspect of cyclonicity
248 of the region is provided by Figure 5, where counts are aggregated into three-month seasons
249 for consecutive 30-year periods (except the abridged period 1991-2012). The summer peak in
250 cyclone frequency is evident again, but interestingly the seasonal maxima is absent from
251 1961-1990. According to Figure 4, the stormiest period for the BI generally occurs in late

252 autumn, as the secondary peak in cyclone frequency combines with the symmetrical cycle in
253 intensity which ascends from the summer minima.

254 **5.3 Interannual variability in BI cyclonicity**

255 Annual and seasonal series of cyclone metrics are shown in Figure 6; coefficients of variation
256 and linear trends are presented in Table 1. Cyclone counts exhibit greatest year-to-year
257 variability. Seasonally, both cyclone frequency and intensity are most variable in winter, with
258 the standard deviation exceeding 40% of the mean for the former. Regarding trends, counts in
259 all seasons have decreased over the period analysed, but the decline is weak and non-
260 statistically significant. Stronger trends are observed for mean cyclone intensity which has
261 increased in all seasons, with the strongest and weakest trends in winter and summer,
262 respectively. The counteracting effects of decreasing cyclone counts with increased mean
263 intensity, results in no net change in storminess throughout the period of study: trends for this
264 metric are increasing for all seasons except spring, but all are very weak and statistically
265 insignificant.

266 The top seven years (corresponding to ~5% of the record) by cyclone frequency, intensity
267 and storminess are shown in Table 2, while inter-decadal variation in cyclonicity is ranked
268 and illustrated in Figure 7. The stormiest year was 1872 due to high cyclone frequency in
269 winter and autumn. More recently, the years 2000 and 2009 feature as extreme and summer
270 2012 also registers as exceptional. This extreme seasonal storminess joins the winter of
271 2013/2014, which Matthews et al. (2014) determined as unprecedented since 1871/72 by
272 updating the winter 20CR BI cyclone series to 2013/2014 using the NCEP reanalysis. The
273 stormiest decade was the 1910s, mainly due to frequent cyclones in winter and spring. The
274 second and third stormiest decades were the 1920s and 1980s respectively, with the 1920s
275 peak driven by frequent cyclones in spring, summer and autumn, which were also intense in
276 the latter two seasons. The storminess of the 1980s is due to very high cyclone intensity: this
277 decade experienced the most intense cyclones in every season except winter, where it ranked
278 second according to this metric. The quietest decade for storminess was the 1970s on account
279 of the relatively low number of cyclones in spring and summer. The decades of lowest
280 cyclone intensity are mainly found in the earlier part of the record in all seasons, with the
281 1870s, 1880s and 1890s ranked 14th, 13th and 12th, respectively. This is consistent with the
282 strongly increasing trends found for this metric (Table 1).

283 **5.4 BI cyclonicity and atmospheric circulation**

284 To explore how the frequency and intensity of cyclones relate to larger-scale atmospheric
285 circulation, we used the years listed in Table 2 to produce composite plots of anomalies at the
286 500 hPa level (Figure 8). The most coherent anomalies are observed for winter when high
287 cyclone frequency is associated with a low height anomaly over a broad region of the
288 northeast Atlantic, approximately centred over the BI. The downstream anomaly is
289 reminiscent of a Rossby wave train with alternating high/low height anomalies, whilst
290 upstream there is a suggestion of higher geopotential heights in the vicinity of Greenland. A
291 clear geopotential height anomaly signal also emerges in winter when cyclone intensity is
292 considered. Seasons with more intense cyclones are characterised by a height field with
293 positive (negative) anomalies in the low (high) latitudes of the North Atlantic. Outside of
294 winter, coherence in the anomaly field for years of extreme cyclonicity is less evident for
295 both cyclone counts and intensity. In all seasons more frequent cyclones act to lower
296 geopotential heights in the vicinity of the BI.

297 To further investigate the link between cyclonicity and larger scale atmospheric circulation
298 we also determined associations between cyclone metrics and indices of atmospheric
299 circulation in the North Atlantic region. As the BITM is a two-dimensional index, we explore
300 associations between blocking frequency at each grid point and cyclone frequency/intensity
301 (Figure 9). For all seasons an increase in cyclone frequency for the BI is associated with a
302 decrease in blocking over the region and an increase in blocking at higher latitudes over the
303 Atlantic. In winter the area of significant positive correlations between high-latitude blocking
304 and BI cyclone frequency is relatively extensive, with significant correlations found to the
305 west and east of Greenland. In other seasons, positive correlations only persist to the east. In
306 spring, summer, and autumn, cyclone intensity generally exhibits weaker correlations (than
307 frequency) with blocking. During the winter months, cyclones over the BI tend to be more
308 intense when blocking is increased (decreased) to the south (north) of the islands.

309 Correlations between the cyclone metrics and the NAOI and GBI are provided in Table 3. For
310 comparison, and on the basis of Figure 9, we also report correlations between blocking
311 frequency for the BI domain (50-60°N, 16°W-6°E; hereafter ‘BIBF’ - BI Blocking Frequency)
312 and cyclone frequency/intensity. BIBF is defined as the daily probability of at least one grid
313 cell being blocked within the BI domain. The strongest correlations for cyclone counts are
314 observed for BIBF, but significant correlations are similarly apparent between frequency and
315 both the NAOI and GBI. These indices are also significantly correlated with average cyclone
316 intensity. The results indicate that periods of positive (negative) NAO (GBI) conditions are

317 associated with fewer, but more intense cyclones over the BI. This relationship breaks down
318 somewhat in summer (no significant correlation with cyclone intensity) and autumn (no
319 significant correlation with cyclone frequency), but is otherwise persistent. This is
320 characteristic of the fact that, with the exception of the association between BIBF and counts,
321 correlations between cyclone metrics and circulation indices are generally strongest in the
322 winter.

323 **6. Discussion**

324 **6.1 BI cyclonicity and regional hydroclimate**

325 The 142-year record yields new insights into the cyclone climate of the BI. Strong and
326 statistically significant correlations between seasonal precipitation and cyclone frequency
327 confirm the regional hydroclimatic importance of cyclones. The stormiest periods have also
328 been recognised as extreme in other hydroclimatic indicators: e.g. the top-ranking winter
329 (1915) and autumn (2000) are the wettest in the long-running EWP series for the overlapping
330 period (1871/72-2012), whilst the stormiest spring (1983) and summer (2012) also rank
331 highly (4th and 3rd, respectively). Extensive seasonal flooding has additionally been
332 documented during periods recognized as extremely stormy: e.g. autumn 2000 (Marsh and
333 Dale, 2002; Jones et al., 2006), and summer 2012 (Parry et al., 2012; Dong et al., 2013a).
334 Moreover, the stormiest year (1872) is wettest in the EWP series and has been noted as a
335 particularly flood-rich period (Jones et al., 2006; Wilby and Quinn, 2013). The most subdued
336 decade in terms of storminess (the 1970s) was a period of exceptional drought in the BI
337 (Jones et al., 2006; Marsh et al., 2007; Rodda and Marsh, 2011; Murphy et al., 2013).
338 Correspondence with independent hydroclimatic indicators highlights the importance of
339 cyclones for the regional hydroclimate, and simultaneously corroborates the 20CR cyclone
340 reconstruction.

341 Correlation between precipitation and cyclone counts was highest during summer. This
342 differs from Lavers et al. (2013), who found the relationship between mean sea-level pressure
343 (MSLP) and precipitation across northwest Europe (including the BI) was weaker in summer
344 than in winter. One explanation for this discrepancy is that the storm track is known to be
345 more spatially restricted in summer than winter over the northeast Atlantic (Mesquita et al.
346 2008). Thus, where cyclone frequency is an important driver of precipitation totals, it is
347 reasonable to expect that regions of significant correlations between rainfall totals and MSLP
348 (which bare the imprint of depression passage) should be similarly constrained. The different

349 period (1957-2002) and spatial resolution ($2.5^\circ \times 2.5^\circ$) of the reanalysis dataset used by
350 Lavers et al. (2013) could be another factor. In highlighting the importance of cyclones in
351 driving high precipitation amounts over the BI throughout the year, our results agree with
352 Murphy and Washington (2001), who, in all seasons, observed a cyclonic pattern in the
353 correlation field centred on the BI when assessing the association between mean sea-level
354 pressure and the leading Empirical Orthogonal Function of BI rainfall.

355 Correlations between summer precipitation and summer cyclone counts are more spatially-
356 consistent over BI relative to other seasons. During winter, correlations between cyclone
357 counts/storminess, and precipitation are insignificant for the northwest of our domain where
358 we observed stronger correlations between cyclone intensity and precipitation. Periods of
359 enhanced cyclone intensity for the BI have been associated with positive phases of the NAO
360 (Allan et al., 2009, and see Section 6.2). This correspondence is strongly hinted at in Figure 3
361 as the correlation between BI cyclone intensity and precipitation mirrors the association
362 between the NAOI and European winter precipitation (Wilby et al., 1997; Trigo et al., 2002),
363 reflecting the more northerly (southerly) position of the storm track during NAO positive
364 (negative) conditions. When cyclones take a more northerly route over the northeast Atlantic,
365 they will not be counted in our BI domain but may still enhance seasonal precipitation in the
366 northwest BI through the passage of trailing fronts. During positive NAO conditions, the
367 stronger westerly flow is also understood to increase orographic rainfall for the British
368 uplands (Burt and Holden, 2013). These mechanisms explain the lack of correlation between
369 cyclone counts and precipitation in the northwest in winter: precipitation can be enhanced in
370 the northwest BI by the passage of “local” cyclones (which will register in our counts)
371 through low-level convergence and frontal lifting, but also by “remote” cyclones north of our
372 domain, as both trailing fronts and enhanced orographic uplift associated with a more
373 northerly storm track are important rainfall generating mechanisms. We suggest that in winter
374 the latter are more important, due to the stronger westerly flow, but that in summer the former
375 emerges as dominant when the westerly flow weakens (cf. Wilby et al., 2002). This would
376 also account for the more spatially homogenous summer correlation field in Figure 3.
377 Regardless of the physical processes driving correlations, cyclone frequency has already been
378 linked to spatially-extensive flooding episodes (Wilby and Quinn, 2013) due to high rainfall
379 amounts across the BI associated with cyclone passage (Burt et al., 2014). We emphasise that
380 these conclusions are perhaps *most* appropriate for summer based on the evidence presented
381 here.

382 **6.2 Atmospheric circulation and temporal variability in BI cyclonicity**

383 Days with cyclonic circulation over the BI are most frequent in summer. This finding is
384 consistent with Mesquita et al. (2008) who showed that the northeast North Atlantic is among
385 the few regions in the Northern Hemisphere to experience a summer cyclone maximum. The
386 assessment of cyclonicity (Section 5.4) provides some insight to physical processes driving
387 the seasonal cycle in cyclone frequency. Cyclone counts were found to correlate most
388 strongly with the BIBF, such that increased regional blocking translates into fewer cyclonic
389 circulation days. This fits with the summer-only investigation of Dong et al. (2013b) and
390 agrees with the negative correlation between cyclonic and anticyclonic LWTs noted by Burt
391 et al. (2014). Figure 10 (left) demonstrates that this relationship generally holds when the
392 seasonal climatological cycle is assessed: the blocking minimum in summer, characteristic of
393 conditions across the north-eastern margin of Europe (Figure 10 - right), coincides with the
394 summer cyclone maxima. The relationship between interannual blocking and cyclone
395 frequency is further highlighted by anomalous conditions during the 1961-1990 climate
396 normal period (cf. Section 6.1 and Figure 5), during which the summer cyclone maximum was
397 not observed. This was also a 30-year period characterised by frequent summer blocking
398 (Table 4). It is interesting to note that a 30-year period (1961-1990) widely used to define
399 climate normals was actually highly unusual from the perspective of summer atmospheric
400 circulation for the BI.

401 To assess the role of larger-scale atmospheric processes modulating BI cyclonicity climate,
402 we correlated cyclone metrics with climate indices. The GBI and NAOI exhibited correlation
403 coefficients that were opposite in sign, which is unsurprising given the association between
404 Greenland blocking and the NAO (Woolings et al., 2008). As correlations were stronger for
405 the NAOI, we focus on this index here. Interannual variability in cyclone frequency was
406 generally found to be negatively correlated with the NAOI in most seasons, the signal being
407 strongest (highest r values) using the PC-based NAOI, and in winter. The sign of relationship
408 is consistent with analyses using the cyclonic LWT (e.g. Wilby et al., 1997; Burt et al., 2014).
409 Negative correlation may reflect either slower-moving cyclonic systems during NAO
410 negative years (subdued westerly circulation), or the passage of more cyclonic weather
411 systems, as both processes could contribute to a higher number of cyclone days for our
412 domain.

413 Cyclone intensity was positively correlated with the NAOI in most seasons, with strongest
414 associations in winter, which concurs with Allan et al. (2009) and Wang et al. (2009, 2011).
415 The relationship between the NAO and cold-season cyclone intensity is also consistent with
416 the intense winter storminess identified during the 1990s (exceptionally positive NAO - see
417 Hanna et al., 2014)) in this study (Section 5.4) and in previous investigations (Jones et al.,
418 1999; Allan et al., 2009; Wang et al., 2009, 2011; Cornes and Jones, 2011; Donat et al., 2011).
419 Whilst the NAOI exhibits statistically significant correlations with our cyclone metrics, we
420 note that even during winter when these associations are strongest, the NAO only accounts
421 for ~16 and 31% of the variance in cyclone frequency and intensity, respectively. Thus, the
422 utility of the NAO for interpreting BI cyclonicity is perhaps limited (cf. Burningham and
423 French, 2013).

424 Our results suggest an increase in cyclone intensity for all seasons over the BI that is
425 strongest in winter. Detailed comparison with other research is confounded by differences in
426 the choice of metrics, domains and sampling resolutions. However, increased BI cyclone
427 intensity is broadly supported by investigations of trends in extreme wind speeds using the
428 20CR (Brönnimann et al., 2012; Donat et al., 2012) and by Wang et al. (2013) who found
429 increasing mean Laplacian from the 20CR for the high-latitude North Atlantic (in which our
430 domain is mostly situated). These results stand in contrast with studies using in-situ pressure
431 observations to determine changes in BI cyclone intensity (e.g. Hanna et al., 2008; Wang et
432 al., 2009, 2011). Although such contradictions regarding the 20CR has been raised before
433 (Krueger et al., 2014; Wang et al., 2014) the cause remains unclear. Improved understanding
434 of this disagreement is needed as enhanced cold-season cyclone intensity has been projected
435 for the BI region (Collins et al., 2013; Zappa et al. 2013; Feser et al., 2014). Robust long-term
436 cyclone climatologies are required if emerging trends are to be differentiated from natural
437 variability.

438 Cyclone frequency and storminess were more closely related to interannual variation in BI
439 precipitation. Recent years have seen three of the stormiest seasons on record, with autumn
440 (2000) and summer (2012) joining the winter of 2013/2014 (see Matthews et al. (2014)) as
441 the most exceptional seasons since the beginning of 20CR. Despite this clustering, we
442 detected no evidence for an upward trend in storminess, reflecting the signal (or lack of) in
443 cyclone frequency compared to the noise of interannual variability. However, pronounced,
444 low-frequency variability in these metrics is evident, which underscores the utility of the
445 long-term cyclone climatology presented here in contextualising recent extremes. For

446 example, the highly-subdued storminess observed during the 1961-1990 climate normal
447 period has perhaps made the return to more typical conditions in recent years seem unusual.
448 Trends with start dates during this quiescent period are likely to be misleading: calculating
449 the Mann Kendall test statistic on the period 1979-2012 (the period of satellite observation
450 that signals the start date of the ERA-Interim Reanalysis dataset: Dee et al. (2011)), yields
451 upward trends in summer cyclone frequency and storminess with p -values of 0.017 and 0.044,
452 respectively. Thus, despite the higher quality of more recent gridded data products for
453 objective assessment of atmospheric circulation, there remains a need for the longer-term
454 perspective afforded by products such as the 20CR is clear.

455 **7. Conclusions**

456 We have constructed a 142-year cyclone climatology for the BI using the 20CR. This product
457 both confirms and clarifies the importance of cyclones to the hydroclimate of this region.
458 Seasonal precipitation totals were found to be strongly correlated with cyclone frequency
459 across large parts of the BI, but this is most apparent during the summer, when these weather
460 types are more frequent. We therefore conclude that any changes in the frequency of “local”
461 cyclones for the region would be particularly important for seasonal precipitation totals
462 during summer. In this context, we detected no trend in cyclone frequency or storminess in
463 any season, but did establish that the 1961-1990 climate normal was extraordinary for the
464 rarity of summer cyclones, which is consistent with the severe droughts reported for the same
465 period. Such low-frequency variability in cyclone frequency was found to be strongly
466 associated with atmospheric blocking – a control which also emerged when the seasonal
467 cycle in this metric was assessed. Thus, we emphasise that to better understand the processes
468 driving variability in the frequency of cyclones for the BI, it is necessary to investigate
469 mechanisms that modulate atmospheric blocking in the Euro-Atlantic sector.

470 Cyclone intensity was observed to be significantly correlated (positive) with the NAOI,
471 particularly in winter, which is generally in agreement with the literature. However, our
472 detection of a strong upward trend in cyclone intensity highlights a discrepancy between
473 long-term reanalysis reconstructions and assessments of cyclone intensity based on station
474 data. Given expectations of enhanced cyclone activity for the BI in a warmer climate, we
475 emphasise that resolving this matter should be a high priority for future research.

476 **References**

- 477 Alexander LV and Jones PD. 2001. Updated precipitation series for the UK and discussion of
478 recent extremes. *Atmos. Sci. Lett.* **1**: 142-150.
- 479 Alexandersson H, Schmith T, Iden K. and Tuomenvirta H. 1998. Long-term variations of the
480 storm climate over NW Europe. *The Global Atmosphere and Ocean System* **6**: 97-120.
- 481 Alexandersson H, Tuomenvirta H, Schmith T and Iden K. 2000. Trends of storms in NW
482 Europe derived from an updated pressure data set. *Clim. Res.* **14**: 71-73.
- 483 Allan R, Tett S and Alexander L. 2009. Fluctuations in autumn–winter severe storms over the
484 British Isles: 1920 to present. *Int. J. Climatol.* **29**: 357–371.
- 485 Blackburn M, Methven J and Roberts N. 2008. Large-scale context for the UK floods in
486 summer 2007. *Weather* **63**: 280-288.
- 487 Blessing S, Fraedrich K, Junge M, Kunz T, Lunkeit F. 2005. Daily North-Atlantic Oscillation
488 (NAO) index: Statistics and its stratospheric polar vortex dependence. *Meteorol. Z.* **14**: 763–
489 769.
- 490 Brönnimann S, Martius O, Von Waldow H, Welker C, Luterbacher J, Compo GP,
491 Sardeshmukh PD, and Usbeck T. 2012. Extreme winds at northern mid-latitudes since
492 1871. *Meteorol. Z.* **21**: 13-27.
- 493 Burningham H and French J. 2013. Is the NAO winter index a reliable proxy for wind
494 climate and storminess in northwest Europe?. *Int. J. Climatol.*, **33**: 2036-2049.
- 495 Burt TP and Howden NJK. 2013. North Atlantic Oscillation amplifies orographic
496 precipitation and river flow in upland Britain. *Water Resour. Res.* **49**: 3504–3515.
- 497 Burt TP, Jones PD and Howden NJK. 2014. An analysis of rainfall across the British Isles in
498 the 1870s. *Int. J. Climatol.* DOI: 10.1002/joc.4184
- 499 Chang EKM and Fu Y. 2002. Interdecadal variations in Northern Hemisphere winter storm
500 track intensity. *J. Climate* **15**: 642–658.
- 501 Cohn TA and Lins HF. 2005. Nature’s style: Naturally trendy. *Geophys. Res. Lett* **32**: L23402.

- 502 Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, Gao X,
503 Gutowski WJ, Johns T, Krinner G, Shongwe M, Tebaldi C, Weaver AJ and Wehner M.
504 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate
505 Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth
506 Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D,
507 Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM
508 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 509 Compo G P, Whitaker JS, Sardeshmukh P D, Matsui N, Allan RJ, Yin X, Gleason BE, Vose
510 RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN,
511 Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli
512 Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD and Worley SJ. 2011. The Twentieth
513 Century Reanalysis Project. *Q.J.R. Meteorol. Soc.* **137**: 1–28.
- 514 Cornes RC and Jones PD. 2011. An examination of storm activity in the northeast Atlantic
515 region over the 1851–2003 period using the EMULATE gridded MSLP data series. *J.*
516 *Geophys. Res.* **116**: D16110.
- 517 Cornes RC. 2014. Historic storms of the northeast Atlantic since circa 1700: a brief review of
518 recent research. *Weather* **69**: 121–125.
- 519 Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda
520 MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, Van de Berg L, Bidlot J, Bormann N,
521 Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV,
522 Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-sanz BM, Morcrette J,
523 Park B, Peubey C, de Rosnay P, Tavolato C, Thépaut J and Vitart F. 2011. The ERA-Interim
524 reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol.*
525 *Soc* **137**: 553-597.
- 526 Dee D, Fasullo J, Shea D, Walsh John and National Center for Atmospheric Research Staff
527 (Eds). *The Climate Data Guide: Atmospheric Reanalysis: Overview & Comparison*
528 *Tables*. Retrieved from [https://climatedataguide.ucar.edu/climate-data/atmospheric-](https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables)
529 [reanalysis-overview-comparison-tables](https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables). Last modified 05 Nov 2014.

- 530 Donat MG, Renggli D, Wild S, Alexander LV, Leckebusch GC, Ulbrich U. 2011. Reanalysis
531 suggests long-term upward trends in European storminess since 1871. *Geophys. Res. Lett.* **38**:
532 L14703.
- 533 Dong B, Sutton R and Woolings T. 2013a. The extreme European Summer 2012 [in
534 “Explaining Extreme Events of 2012 from a Climate Perspective]. *Bull. Amer. Meteor. Soc* **9**:
535 s28-s32.
- 536 Dong B, Sutton RT, Woollings T and Hodges K. 2013b. Variability of the North Atlantic
537 summer storm track: mechanisms and impacts on European climate. *Environ. Res. Lett.* **8**:
538 034037.
- 539 Esteves LS, Williams JJ and Brown JM. 2011. Looking for evidence of climate change
540 impacts in the eastern Irish Sea. *Nat. Hazard. Earth Sys.* **11**: 1641-1656.
- 541 Fang ZF. 2004. Statistical relationship between the northern hemisphere sea ice and
542 atmospheric circulation during wintertime. In *Observation, Theory and Modeling of*
543 *Atmospheric Variability. World Scientific Series on Meteorology of East Asia*, Zhu X (ed).
544 World Scientific Publishing Company: Singapore; 131–141
- 545 Feser F, Barcikowska M, Krueger O, Schenk F, Weisse R and Xia L. 2014. Storminess over
546 the North Atlantic and northwestern Europe—A review. *Q. J. Roy. Meteor. Soc.* DOI:
547 10.1002/qj.2364
- 548 Hanna E, Cappelen J, Allan R, Jónsson T, Le Blancq F, Lillington T and Hickey K. 2008.
549 New insights into North European and North Atlantic surface pressure variability, storminess,
550 and related climatic change since 1830. *Int. J. Climatol.* **21**: 6739-6766.
- 551 Hanna E, Jones JM, Cappelen J, Mernild SH, Wood L, Steffen K and Huybrechts P. 2013.
552 The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010
553 Greenland summer climate and ice melt/runoff. *Int. J. Climatol.* **33**: 862–880.
- 554 Hanna E, Cropper TE, Jones PD, Scaife AA and Allan R. 2014, Recent seasonal asymmetric
555 changes in the NAO (a marked summer decline and increased winter variability) and
556 associated changes in the AO and Greenland Blocking Index. *Int. J. Climatol.* DOI:
557 10.1002/joc.4157

- 558 Harris I, Jones PD, Osborn TJ and Lister DH. 2014. Updated high-resolution grids of
559 monthly climatic observations – the CRU TS3.10 Dataset. *Int. J. Climatol.* **34**: 623–642.
- 560 Hickey KR. 2003. The Storminess Record from Armagh Observatory 1796-1999. *Weather* **58**:
561 28-35.
- 562 Hickey KR. 2011. The hourly gale record from Valentia Observatory, SW Ireland 1874-2008
563 and some observations on extreme wave heights in the NE Atlantic, *Climatic Change* **106**:
564 483-506.
- 565 Hurrell J W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures
566 and precipitation. *Science* **269**: 676-679.
- 567 Jones, P. D., Hulme, M., & Briffa, K. R. 1993. A comparison of Lamb circulation types with
568 an objective classification scheme. *Int. J. Climatol.* **13**: 655-663.
- 569 Jones PD, Horton EB, Folland CK, Hulme M, Parker DE and Basnett TA. 1999. The use of
570 indices to identify changes in climatic extremes. *Climatic Change* **42**: 131-149.
- 571 Jones PD, Lister DH, Wilby RL and Kostopoulou E. 2006. Extended river flow
572 reconstructions for England and Wales, 1865-2002. *Int. J. Climatol.*, **26**: 219–231.
- 573 Jones PD, Harpham C and Briffa KR. 2013. Lamb weather types derived from reanalysis
574 products. *Int. J. Climatol.*, **33**: 1129–1139.
- 575 Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S,
576 White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins
577 W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R and Joseph D. 1996: The
578 NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.* **77**: 437–471.
- 579 Kendall MG. 1975. *Rank correlation methods*. Charles Griffin: London
- 580 Krueger O, Feser F, Bärring L, Kaas E, Schmith T, Tuomenvirta H and von Storch H. 2014.
581 Comment on Trends and low frequency variability of extra-tropical cyclone activity in the
582 ensemble of twentieth century reanalysis by Xiaolan L. Wang, Y. Feng, GP Compo, VR
583 Swail, FW Zwiers, RJ Allan, and PD Sardeshmukh, Climate Dynamics, 2012. *Clim.*
584 *Dynam.* **42**:1127-1128.

- 585 Lavers D, Prudhomme C and Hannah DM. 2013. European precipitation connections with
586 large-scale mean sea-level pressure (MSLP) fields. *Hydrolog. Sci. J* **58**: 310-327.
- 587 Lamb HH. 1972. British Isles weather types and a register of daily sequence of circulation
588 patterns, 1861-1971: Geophysical Memoir **116** HMSO, London.
- 589 Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**: 245–259.
- 590 Marsh TJ and Dale M. 2002. The UK Floods of 2000–2001: A Hydrometeorological
591 Appraisal. *Water Environ. J.* **16**: 180–188.
- 592 Marsh T, Cole G and Wilby RL. 2007. Major droughts in England and Wales, 1800-2006.
593 *Weather*, **62**: 87–93.
- 594 Matthews T, Murphy C, Wilby RL and Harrigan S. 2014. Stormiest winter on record for
595 Ireland and UK. *Nature Clim. Change* **4**: 738-740.
- 596 Matulla C, Schöner W, Alexandersson H, Von Storch H and Wang XL. 2008. European
597 storminess: late nineteenth century to present. *Clim. Dynam.* **31**: 125-130.
- 598 Mesquita MDS, Gunnar Kvamstø N, Sorteberg A and Atkinson DE. 2008. Climatological
599 properties of summertime extra-tropical storm tracks in the Northern Hemisphere. *Tellus A*,
600 **60**: 557–569.
- 601 Murphy C, Harrigan S, Hall J and Wilby RL. 2013. Climate-driven trends in mean and high
602 flows from a network of reference stations in Ireland. *Hydrolog. Sci. J.* **58**: 755-772.
- 603 Murphy SJ and Washington R. 2001. United Kingdom and Ireland precipitation variability
604 and the North Atlantic sea-level pressure field. *Int. J. Climatol.* **21**: 939–959.
- 605 Neu U, Akperov MG, Bellenbaum N, Benestad R, Blender R, Caballero R, Coccozza A, Dacre
606 HF, Feng Y, Fraedrich K, Grieger J, Gulev S, Hanley J, Hewson T, Inatsu M, Keay K, Kew
607 SF, Kindem I, Leckebusch GC, Liberato MLR, Lionello P, Mokhov II, Pinto JG, Raible CC,
608 Reale M, Rudeva I, Schuster M, Simmonds I, Sinclair M, Sprenger M, Tilinina ND, Trigo IF,
609 Ulbrich S, Ulbrich U, Wang XL, and Wernli H. 2013. Imilast: a community effort to
610 intercompare extratropical cyclone detection and tracking algorithms. *Bull. Amer. Meteor.*
611 *Soc.* **94**: 529–547.

- 612 Parry S, Marsh T and Kendon M. 2013. 2012: from drought to floods in England and Wales.
613 *Weather* **68**: 268–274.
- 614 Pattison I and Lane SN. 2012. The relationship between Lamb weather types and long-term
615 changes in flood frequency, River Eden, UK. *Int. J. Climatol.* **32**: 1971-1989.
- 616 Raible CC, Della-Marta PM, Schwierz C, Wernli H and Blender R. 2008. Northern
617 Hemisphere extratropical cyclones: A comparison of detection and tracking methods and
618 different reanalyses. *Mon. Weather Rev.* **136**: 880-897.
- 619 Rodda JC and Marsh TJ. 2011. The 1975-76 Drought - a contemporary and retrospective
620 review. *National Hydrological Monitoring Programme series*. NERC/Centre for Ecology and
621 Hydrology: Wallingford, UK.
- 622 Scherrer SC, Croci-Maspoli M, Schwierz C and Appenzeller C. 2006. Two-dimensional
623 indices of atmospheric blocking and their statistical relationship with winter climate patterns
624 in the Euro-Atlantic region. *Int. J. Climatol.* **26**: 233–249.
- 625 Sen P K. 1968. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat.*
626 *Assoc.* **63**: 1379–1389
- 627 Serreze MC and Barrett AP. 2008. The summer cyclone maximum over the central Arctic
628 Ocean. *J. Climatol.* **21**: 1048-1065.
- 629 Simmonds I and Keay K. 2000. Mean Southern Hemisphere extratropical cyclone behavior in
630 the 40-year NCEP-NCAR reanalysis. *J. Climatol.* **13**: 873-885.
- 631 Smits A, Klein Tank AMG and Können GP. 2005. Trends in storminess over the Netherlands,
632 1962–2002. *Int. J. Climatol.* **25**: 1331–1344.
- 633 Sweeney J. 2000. A three-century storm climatology for Dublin 1715–2000. *Irish*
634 *Geography* **33**: 1-14.
- 635 Theil H. 1950. A Rank-invariant Method of Linear and Polynomial Regression Analysis I.
636 *Nederlands Akad. Wetensch. Proc.* **53**: 386–392.

- 637 Tibaldi S and Molteni F. 1990: On the operational predictability of blocking.
638 *Tellus* **42A**:343-365.
- 639 Trigo RM, Osborn TJ and Corte-Real JM. 2002. The North Atlantic Oscillation influence on
640 Europe: climate impacts and associated physical mechanisms. *Clim. Res.* **20**: 9-17.
- 641 Vilibić I and Šepić J. 2010. Long-term variability and trends of sea-level storminess and
642 extremes in European Seas. *Global and Planet. Change* **71**: 1-12.
- 643 Wang XL, Swail VR and Zwiers FW. 2006. Climatology and changes of extratropical
644 cyclone activity: Comparison of ERA-40 with NCEP-NCAR reanalysis for 1958-2001. *J*
645 *Climatol* **19**: 3145-3166.
- 646 Wang XL, Zwiers FW, Swail VR and Feng Y. 2009. Trends and variability of storminess in
647 the Northeast Atlantic region, 1874–2007. *Clim. Dynam.* **33**: 1179-1195.
- 648 Wang XL, Wan H, Zwiers FW, Swail VR, Compo GP, Allan, Vose RS, Jourdain S and Yin
649 X. 2011. Trends and low-frequency variability of storminess over western Europe, 1878–
650 2007. *Clim. Dynam.* **37**: 2355-2371.
- 651 Wang XL, Feng Y, Compo GP, Swail VR, Zwiers FW, Allan RJ and Sardeshmukh PD. 2013.
652 Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of
653 twentieth century reanalysis. *Clim. Dynam.* **40**: 2775-2800.
- 654 Wang XL, Feng Y, Compo GP, Zwiers FW, Allan RJ, Swail VR and Sardeshmukh PD. 2014.
655 Is the storminess in the Twentieth Century Reanalysis really inconsistent with observations?
656 A reply to the comment by Krueger et al. (2013b). *Clim. Dynam* **42**:1113-1125.
- 657 Wilby RL, O'Hare G. and Barnsley N. 1997. The North Atlantic Oscillation and British Isles
658 climate variability, 1865–1996. *Weather* **52**: 266–276.
- 659 Wilby RL, Conway D and Jones PD. 2002. Prospects for downscaling seasonal precipitation
660 variability using conditioned weather generator parameters. *Hydrol. Process.* **16**: 1215–1234.
- 661 Wilby RL and Quinn NW. 2013. Reconstructing multi-decadal variations in fluvial flood risk
662 using atmospheric circulation patterns. *J. Hydrol.* **487**: 109-121.

- 663 Woodworth PL and Blackman DL. 2002. Changes in extreme high waters at Liverpool since
664 1768. *Int. J. Climatol.* **22**: 697–714.
- 665 Woollings T, Hoskins B, Blackburn M and Berrisford P. 2008: A new Rossby wave-breaking
666 interpretation of the North Atlantic Oscillation. *J. Atmos. Sci.* **65**: 609–626.
- 667 Woollings T. 2010. Dynamical influences on European climate: an uncertain future. *Philos.T*
668 *Roy. Soc. A* **368**: 3733-3756.
- 669 Woollings T, Gregory J M, Pinto JG, Reyers M and Brayshaw DJ. 2012. Response of the
670 North Atlantic storm track to climate change shaped by ocean-atmosphere coupling. *Nat.*
671 *Geosci.***5**: 313-317.
- 672 Zappa G, Shaffrey LC, Hodges KI, Sansom PG and Stephenson DB. 2013: A Multimodel
673 Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in
674 the CMIP5 Climate Models. *J. Climate* **26**: 5846–5862, doi:10.1175/JCLI-D-12-00573.1.

675 **Tables**

676 **Table 1.** Changes in cyclone metrics time series. Trends (β) are given as change per decade in % of the mean over the whole
 677 period. Trend significance (in brackets as a percentage) for the corresponding Mann-Kendall statistic (not shown).
 678 Coefficients of variation (C_v : mean/standard deviation) are expressed as a percentage.

	Count (C)		Intensity (\bar{L})		Storminess (CAI)	
	β	C_v	β	C_v	β	C_v
DJF	-0.25 (26.8)	41.7	1.23 (100.0)	13.1	0.67 (55.4)	40.8
MAM	-0.86 (74.7)	33.2	0.67 (99.4)	10.5	-0.19 (22.8)	36.5
JJA	-0.41 (42.4)	33.1	0.42 (92.6)	10.3	0.07 (18.4)	36.5
SON	-0.36 (38.0)	36.6	0.83 (99.9)	11.1	0.35 (34.0)	38.2
Full year	-0.51 (79.8)	18.7	0.75 (100.0)	6.0	0.27 (47.4)	18.9

679

680 **Table 2.** Top seven ranked years (i.e. ~5% of the dataset) for each cyclone metric by season. Note that Matthews et al.
 681 (2014) found that winter of 2013/14 was the stormiest since 1871/72, based on NCEP reanalysis for years outside the
 682 1871/72-2012 period of 20CR.

Rank	1	2	3	4	5	6	7
	<i>Counts</i>						
DJF	1915	1936	1960	1919	1951	1872	1977
MAM	1983	1981	1920	1909	1979	1888	1882
JJA	1927	1879	2012	1888	1912	1917	1882
SON	2000	1872	1935	1976	1960	1896	1974
Full year	1872	1927	1882	1916	1951	2000	1930
	<i>Intensity</i>						
DJF	2012	1989	1990	1995	1993	1952	2000
MAM	1943	1982	2011	2007	2002	1963	1919
JJA	1986	1923	1948	1949	1956	1959	1962
SON	1986	1996	1991	1989	1954	1950	1945
Full year	1989	1986	1974	1984	1959	1990	2002
	<i>Storminess</i>						
DJF	1915	1984	1936	1960	1910	1919	1900
MAM	1983	1981	1920	1908	1919	1922	1909
JJA	2012	1879	1927	1888	1986	1917	1956
SON	2000	1935	1872	1976	1916	1974	1896
Full year	1872	1927	1916	1930	1951	2000	2009

683

684 **Table 3.** Correlation between BI cyclone metrics and atmospheric circulation indices. BIBF denotes the blocking frequency
 685 in the BI domain (50-60°N, 16°W-6°E); 20CR PC and station-based NAO indices are subscripted with *pc* and *station*,
 686 respectively. Correlations in **bold** are significantly different from zero at $p < 0.05$, according to a two-tailed *t*-test.

Season	Cyclone metric	NAO _{pc}	NAO _{station}	GBI	BIBF
DJF	Counts	-0.40	-0.20	0.33	-0.53
	Intensity	0.56	0.48	-0.48	<i>0.05</i>
MAM	Counts	-0.27	<i>-0.11</i>	0.25	-0.65
	Intensity	0.26	0.19	-0.26	<i>0.05</i>
JJA	Counts	-0.33	<i>-0.09</i>	0.21	-0.65
	Intensity	<i>0.01</i>	<i>0.00</i>	<i>-0.08</i>	<i>0.02</i>
SON	Counts	<i>0.01</i>	<i>0.12</i>	<i>0.13</i>	-0.68
	Intensity	0.29	0.23	-0.23	-0.18

687

688 **Table 4.** Relative cyclone and blocking frequency for the BI domain in summer for 30-year normal periods (except 1991-
 689 2012). Here blocking frequency is calculated according to the definition of the BIBF with percentages derived relative to the
 690 long-term (1871– 2012) summer mean.

Period	Relative Cyclone Frequency (%)	Relative Blocking Frequency (%)
1871-1900	101.8	86.6
1901-1930	105.5	99.8
1931-1960	106.7	100.6
1961-1990	80.9	123.0
1991-2012	105.1	90.1

691

692

693

694

695 **Figure captions**

696 **Figure 1.** Panels **a** and **b** indicate the decadal mean standard deviation of daily-mean sea-level pressure amongst the 56
 697 20CR ensemble members for the respective decades. To produce these fields, the standard deviation of the daily mean sea-
 698 level-pressure was calculated across the 56 ensemble members at each grid cell. Time averages for these fields were then
 699 calculated for each grid cell and respective decade. Panel **c** shows the data in the middle panel as a fraction of that plotted in
 700 **a**. The larger the fraction, the less uncertainty has changed with time implying greater homogeneity in those regions.

701 **Figure 2.** Relationship between 20CR cyclone counts and total pure (left) and hybrid (right) cyclonic LWTs. Seasonal
 702 correlation coefficients (multiplied by 100) between series are also shown. Solid black lines denote the 1:1 relationship.
 703 ‘Cyclone days’ is defined as the number of cyclones identified in the six-hourly grids, divided by 4 (to be consistent with the
 704 once-daily LWT classification).

705 **Figure 3.** Correlation between gridded CRU TS3.21 precipitation and seasonal cyclone metrics. White areas over land
 706 denote where correlations are insignificant ($p > 0.05$). Upper and lower correlation coefficients (r) given in each panel are the
 707 mean correlations for the whole domain (36.25°N to 69.75°N, 11.75°W to 19.75°E) and BI only, respectively.

708 **Figure 4.** Seasonal variations in cyclone metrics for the BI. All 56 ensemble members’ six-hourly time series of cyclone
 709 counts and intensity were convolved with a 31-day window (with weights equal to the reciprocal of window length). This
 710 converts counts to a probability of at least one cyclone being present in the BI domain for the respective time of the year.
 711 Storminess was calculated from these smoothed series, expressed as units of probability-weighted intensity; cyclone
 712 intensity is in units of Laplacians of sea-level pressure. Smoothed series were averaged over all ensemble members and 142
 713 years (i.e. 1871-2012) to generate the seasonal profiles. Shaded areas denote \pm one standard error of the mean; tick marks
 714 indicate the beginning of a month.

715 **Figure 5.** Mean cyclone counts by season. Bars denote \pm one standard error in the ensemble mean for 30-year blocks (except
 716 1991-2012).

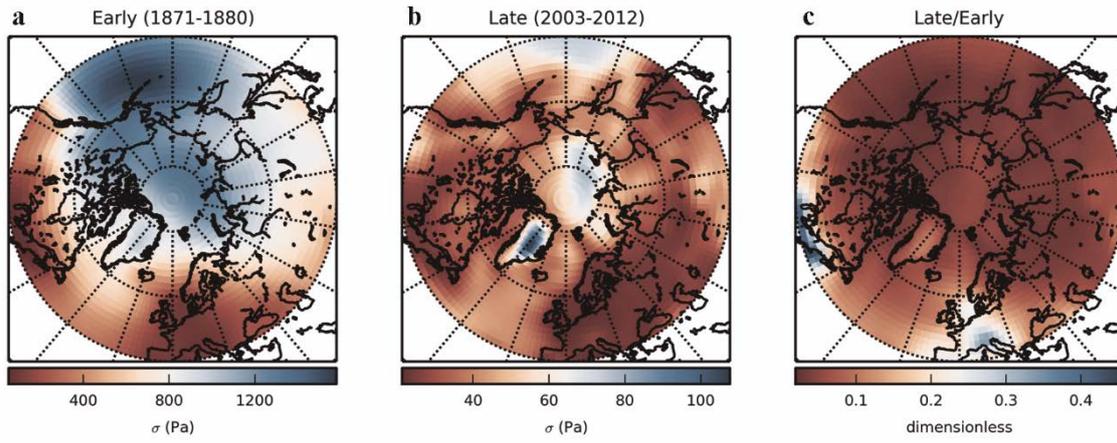
717 **Figure 6.** Annual cyclone metrics by season and full year. Solid lines show the ensemble mean and shaded regions span the
 718 range of the 56 ensemble members. Dotted lines are the 11-year moving average. Units of count are simply the number of
 719 centres detected in the six-hourly grids, whilst intensity and storminess have units of Laplacians of mean sea-level pressure.

720 **Figure 7.** Decadal mean cyclone statistics by season expressed as a z-score averaged over all 56 20CR ensemble members.
 721 Error bars indicate \pm one standard deviation of the 56 decadal means. Numbers above/below the bars give the rank of the
 722 decade for the respective metric and season.

723 **Figure 8.** Composite standardized anomalies (z-scores) in the 500 hPa geopotential height field for the years of exceptional
 724 cyclone frequency (left) and intensity (right) (see Table 2). Grid cells with absolute z-scores less than 1 are white.

725 **Figure 9.** Correlation between blocking frequency (BITM) at each grid point and cyclone frequency (left) and intensity
 726 (right) over the BI. Regions where the correlation is significantly different from zero at $p < 0.05$ (according to a two-tailed t -
 727 test) are coloured.

728 **Figure 10.** Left: Seasonal cycle of cyclone probability and blocking probability for the BI domain. The cyclone probability
 729 curve is taken from Figure 4. The blocking curve is calculated via the same convolution procedure described in Figure 4
 730 caption, and represents the probability of at least one grid cell being blocked in the BI domain. Right: Summer minus winter
 731 blocking frequency (%) across the North Atlantic region, averaged over the full length of the 20CR.



732

733

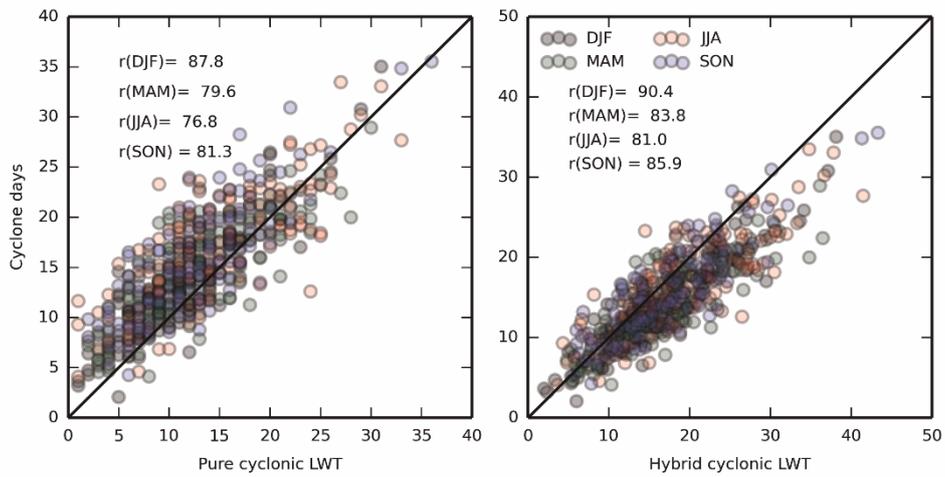
734

735

736

737

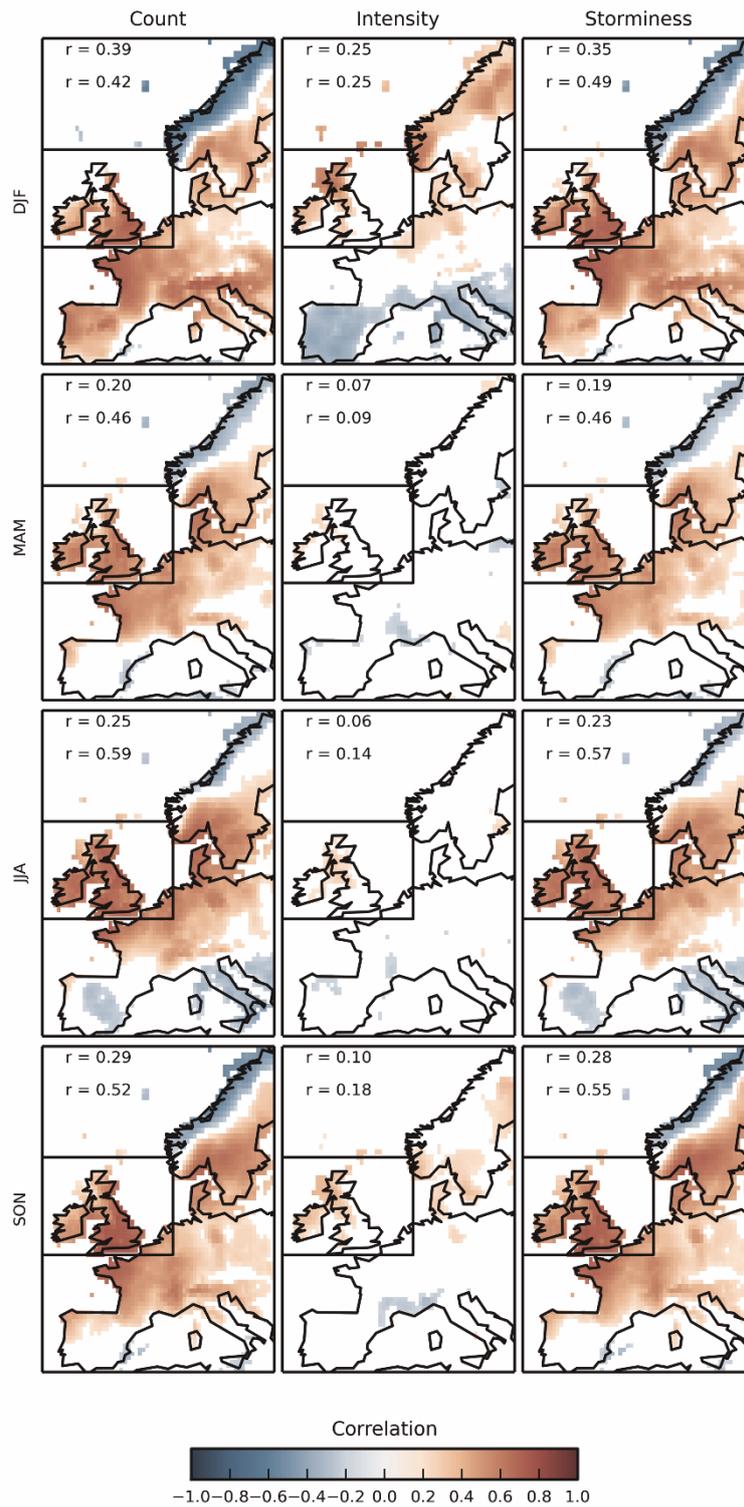
Figure 4.



738

739

Figure 5.



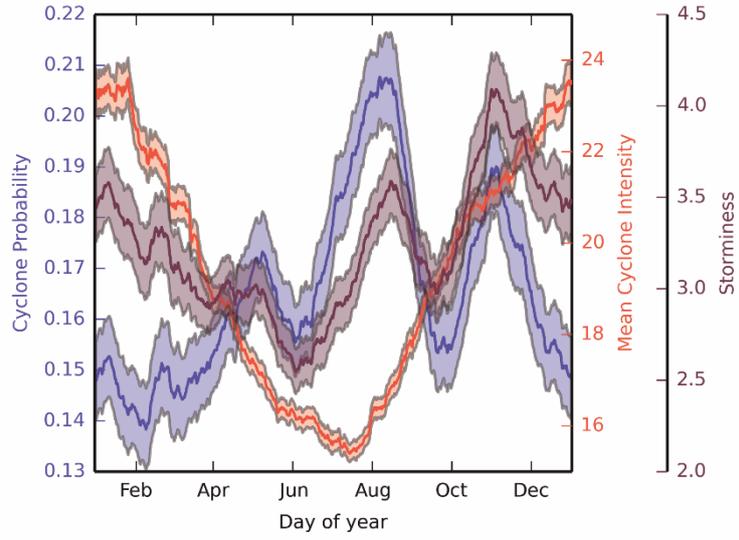
740

741

742

Figure 6.

British-Irish Isles cyclone climatology



743

744

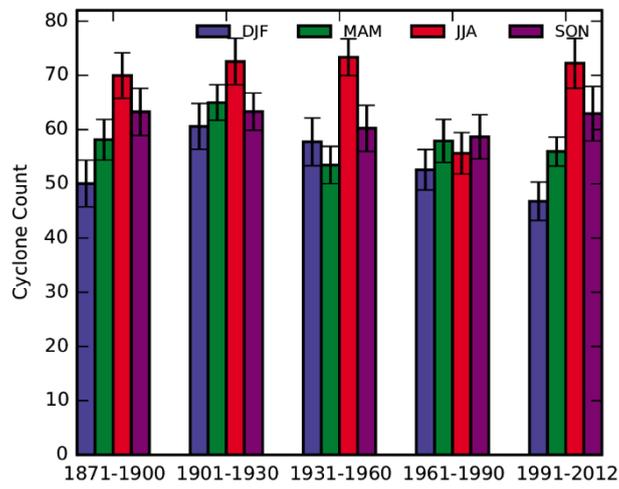
Figure 4.

745

746

747

748



749

750

Figure 5.

751

British-Irish Isles cyclone climatology

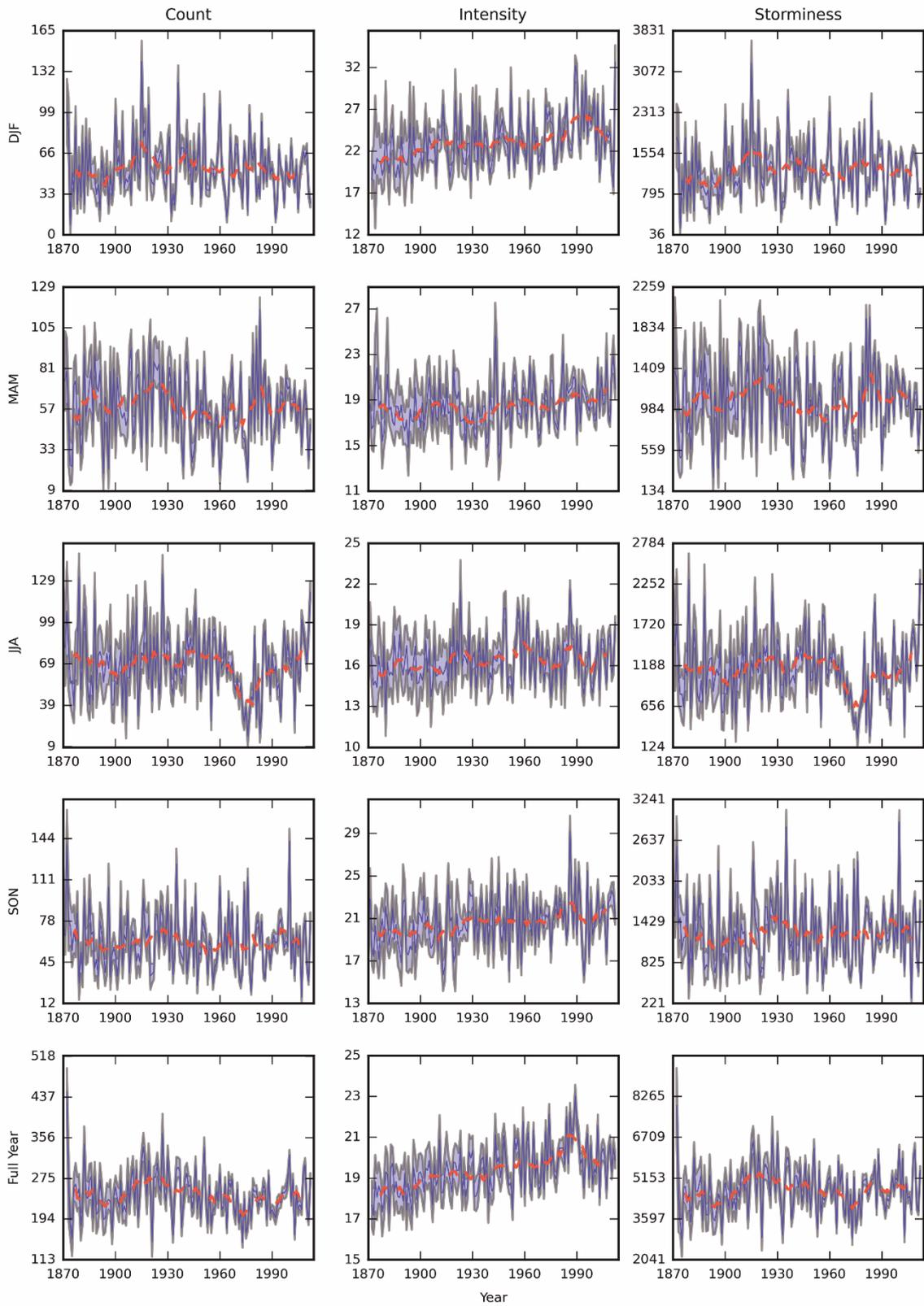


Figure 6.

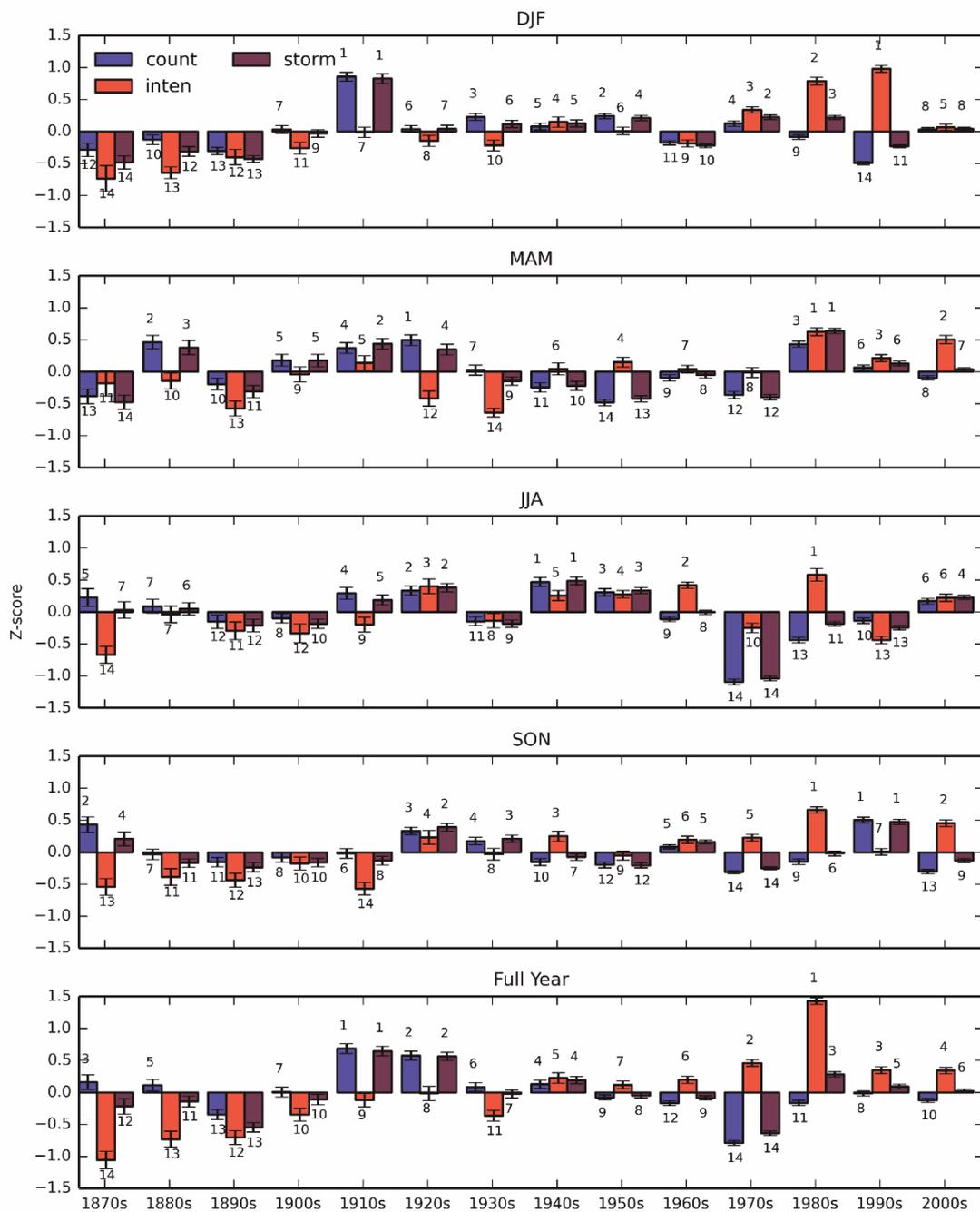
752

753

754

755

British-Irish Isles cyclone climatology



756

757

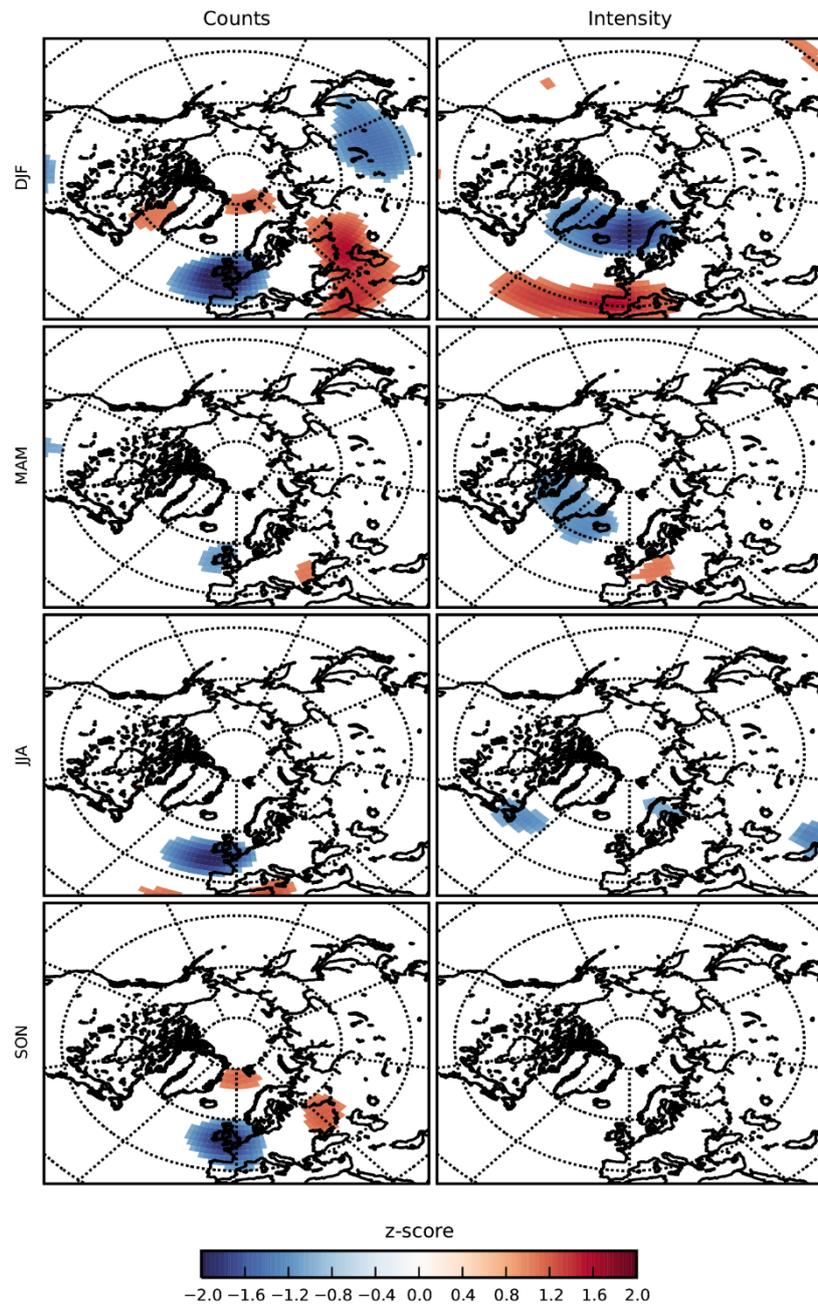
758

759

760

761

Figure 7.



762

763

764

765

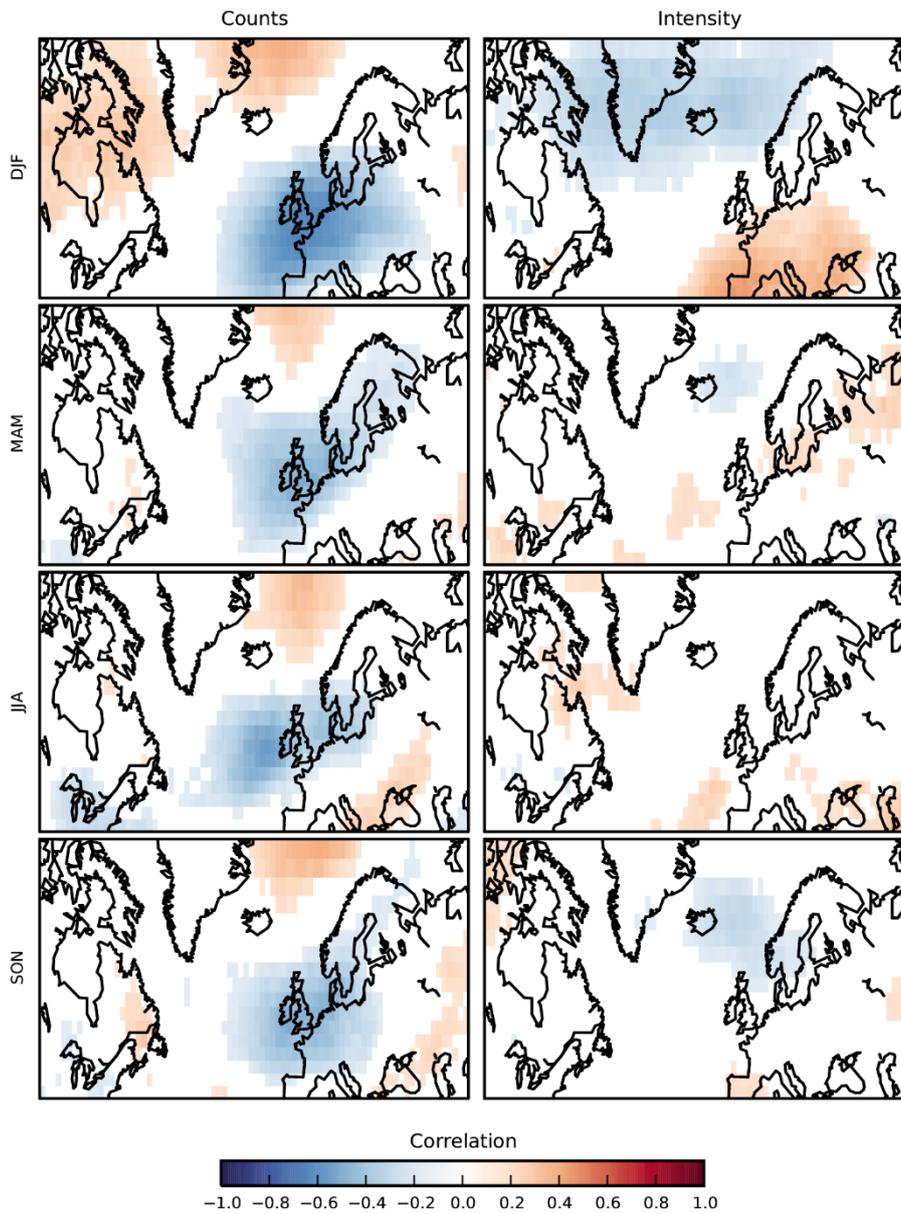
766

767

768

769

Figure 8.



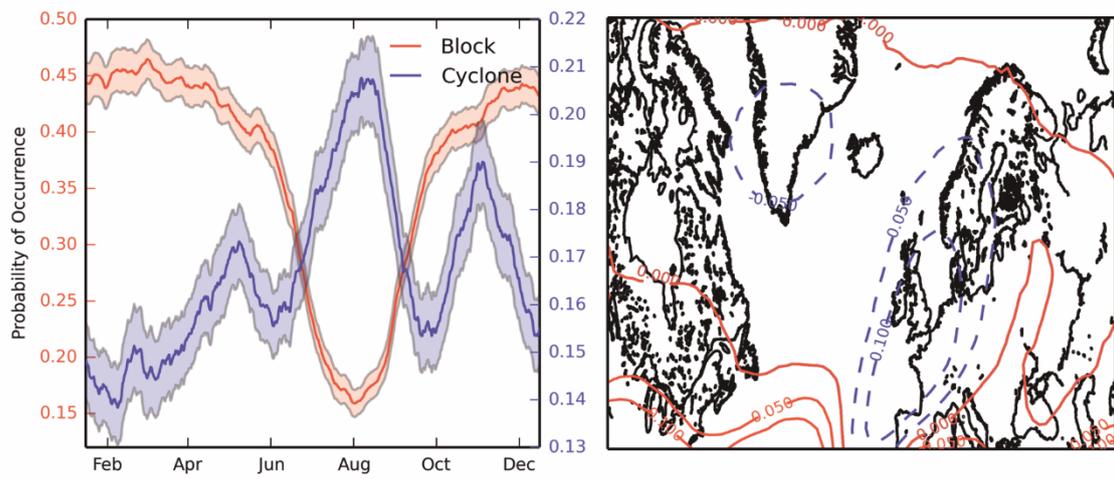
770

771

772

773

Figure 9.



774

775

Figure 10.