Supplementary Material

Past and Projected Weather Pattern Persistence with Associated Multi-Hazards in the British Isles

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1. Supplementary Data and Methods

1.1 CMIP5, reanalyses and Lamb's catalogue

The climate model output used to represent historical, future Representative Concentration Pathway 8.5 (RCP8.5) and RCP4.5 projections of LWTs [1,2] originate from a multi-model sub-ensemble (MME) of 10 Atmosphere-Ocean General Circulation Models (AOGCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [3]. MME output was obtained from the Earth System Grid Federation (https://esgf-node.llnl.gov/search/cmip5/). Per each model the historical, RCP8.5 and RCP4.5 runs of daily (12 UTC) sea-level pressure (SLP) are used to calculate daily LWTs across the BI as described above. The historical period is defined as 1980s (1971-2000). Model runs for the RCPs (2006-2100) are divided into consecutive 30-year periods covering the 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100). Each AOGCM was re-gridded to 5°×10° (latitude × longitude) to match the grid of the objective LWT classification [2,4]. The choice of AOGCMs was constrained by availability of daily SLP for historical, RCP8.5 and RCP4.5 runs. Table 2 lists these models along with some of their characteristics and Figures S1-S5 show results for RCP4.5.

To evaluate CMIP5 MME realism, LWTs were derived from two reanalyses [5] then compared with the 30-year historical (1980s) run of the MME. These were the 20CR [6] and NCEP [7] LWTs datasets [5], available from https://crudata.uea.ac.uk/cru/data/lwt/. In addition to reanalyses, we also compared the historical MME with Lamb's catalogue of subjectively defined LWTs [1,8] which ends in 1997. We evaluate the MME realism using LWTs occurring in four seasons, namely: summer (June-July-August, JJA); autumn (September-October-November, SON); winter (December-January-February, DJF); and spring (March-April-May, MAM). Seasons were assigned to the year with the first month (e.g. summer 2020 includes June 2020, July 2020 and August 2020, whilst winter 2000 includes December 2000, January 2001 and February 2001). Note that for Lamb's catalogue, DJF for the 1980s

has December and January for winter 1996, because the dataset ends in early February 1997. All the complete LWTs datasets used in the analyses are provided in the csv files accompanying this study.

1.2 Statistical methods and analyses

1.2.1 2-day persistence

Two-day persistence of LWTs [1,2] was derived from Markov-chain matrices of transitions between the eight main weather types defined above [9,10]. Persistence was defined as the probability that a given LWT on day(t) is followed by the same LWT on day(t+1). LWTs persistence is calculated for each AOGCM and MME mean (MMEM) for historical 1980s and 2020s, 2050s, 2080s under RCP8.5 and RCP4.5. Uncertainty in persistence estimates for the CMIP5 MME 1980s was calculated by boot-strapping (n=1,000) 30-year simulations to obtain 95% confidence intervals for significance testing. Persistence for the 2020s, 2050s and 2080s was calculated from the transition matrices. Persistence analysis was performed using the functions *markovchainFit* and *createSequenceMatrix*, from the R package 'markovchain' [11], respectively for historical boot-strapping and the three future periods (https://cran.r-project.org/web/packages/markovchain/markovchain.pdf). To evaluate the performance of the CMIP5 MME, the 20CR [6], NCEP [7], and Lamb's subjective classification [1,8] were also used to calculate LWT persistence during the 1980s period. We also computed the CMIP5 MME historical persistence for 1971-1996 (not shown here) to test the slightly shorter period covered by Lamb's subjective catalogue. After performing a Mann-Whitney-Wilcoxon two-tailed test [12] (null hypothesis of no difference in mean persistence), between the MME 1971-1996 and MME 1980s, for A, C, W, and S LWTs within respectively summer (JJA), autumn (SON), winter (DJF) and spring (MAM), we found no statistical significance between the two periods. Therefore, we conclude that Lamb's catalogue is equivalent to the 1980s, despite being 5 years shorter.

The seasonal persistence for each LWT, AOGCM, MMEM, 20CR, NCEP and Lamb's subjective catalogue during the 1980s and (for AOGCMs only) 2020s, 2050s and 2080s under RCP8.5 and RCP4.5 are provided in the spreadsheets accompanying this study.

The statistical significance of changes in persistence for each LWT was assessed by testing: (i) differences in the persistence of the MME between the 1980s and the 2020s, 2050s and 2080s; and ii) differences in the persistence for individual climate models in the MME. In the first case (i) we applied the Mann-Whitney-Wilcoxon two-tailed test [12] under the assumption that data are not normally distributed, with the null hypothesis of no difference in mean persistence (Tables S1-S2). The second test (ii) was performed individually for each model by checking whether persistence in the 2020s, 2050s and 2080s falls outside the boot-strapped 95% confidence intervals of the 1980s (Figures 4 and S2).

1.2.2 Seasonal trends

Trend analysis was performed using annual series of LWT frequencies from 2006-2100 to detect both linear and non-linear changes in LWT frequencies within our CMIP5 [3] MMEM under RCP8.5 and RCP4.5 scenarios. For the sake of brevity, we only show trends for anticyclonic (A, summer JJA), cyclonic (C, autumn SON) and westerly (W, winter DJF) as indicators of impactful weather in the BI and for southerly (S, spring MAM) as this is the LWT showing most significant changes in persistence with the Mann-Whitney-Wilcoxon two-tailed test [12] (Tables S1-S2). A modified Mann-Kendall test [13], which takes into account possible autocorrelation within the time series, was applied to both RCP8.5 and RCP4.5 seasonal MMEM LWTs frequencies.

Results from the trend analysis are presented in Figures 5, S3 and Table S3 in terms of time series and Sen's slope [14] with relative statistical significance (i.e. p-value of modified Mann-Kendall test [13]).

Shaded bands in Figures 5 and S3 represent the 95% confidence interval of the MMEM. Sen's slope gives information about the gradient, with large Sen denoting rapid changes; the sign shows whether the trend is rising (+) or falling (-). Sen's slope values and relative statistical significance are shown in Table S3.

2. Supplementary Figures

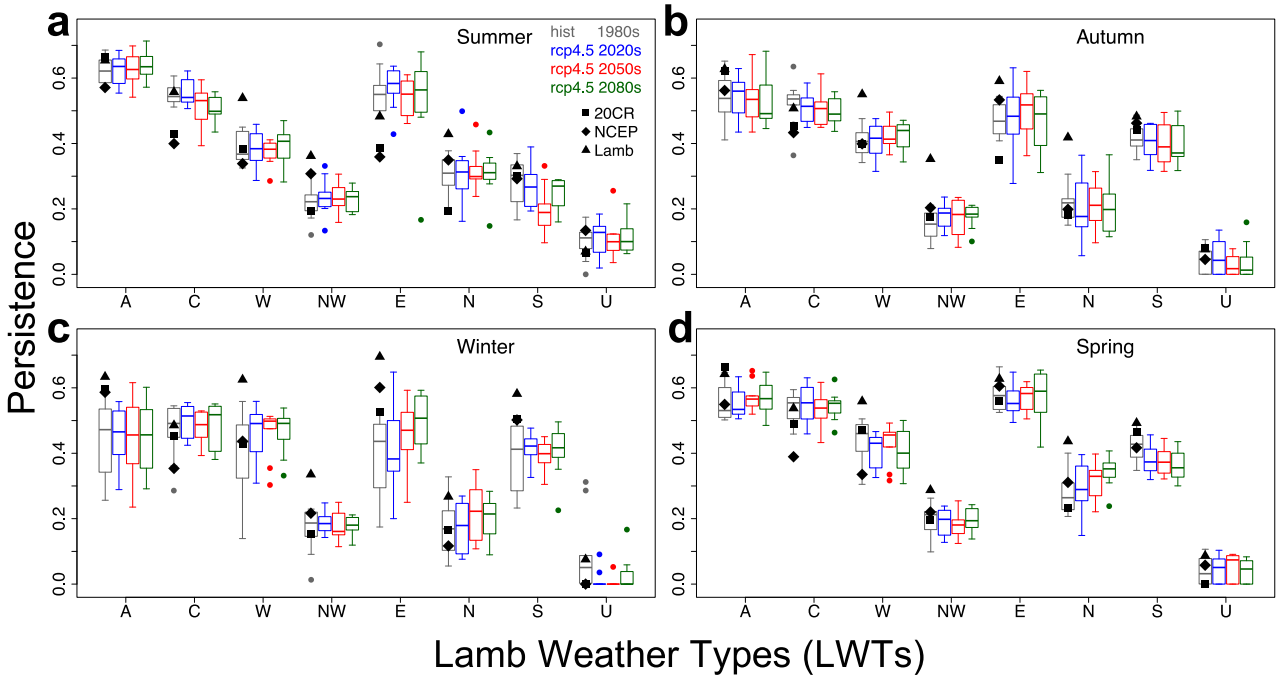


Figure S1. As per Figure 3 but for RCP4.5.

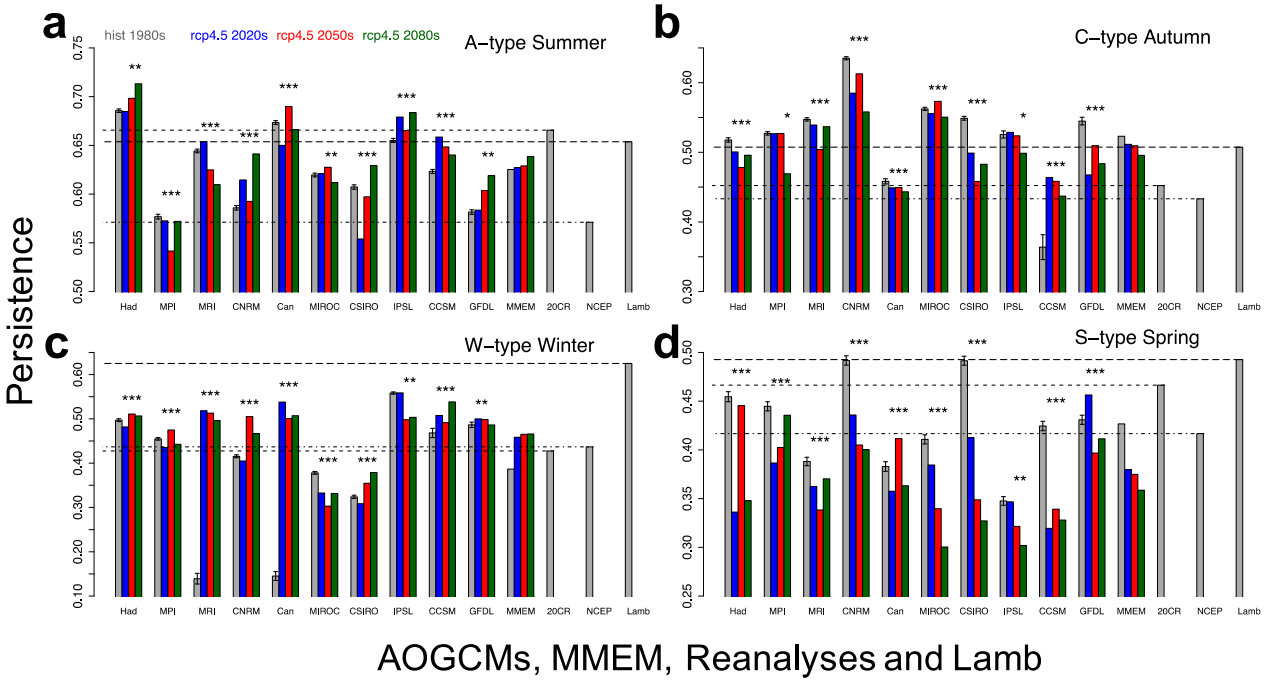
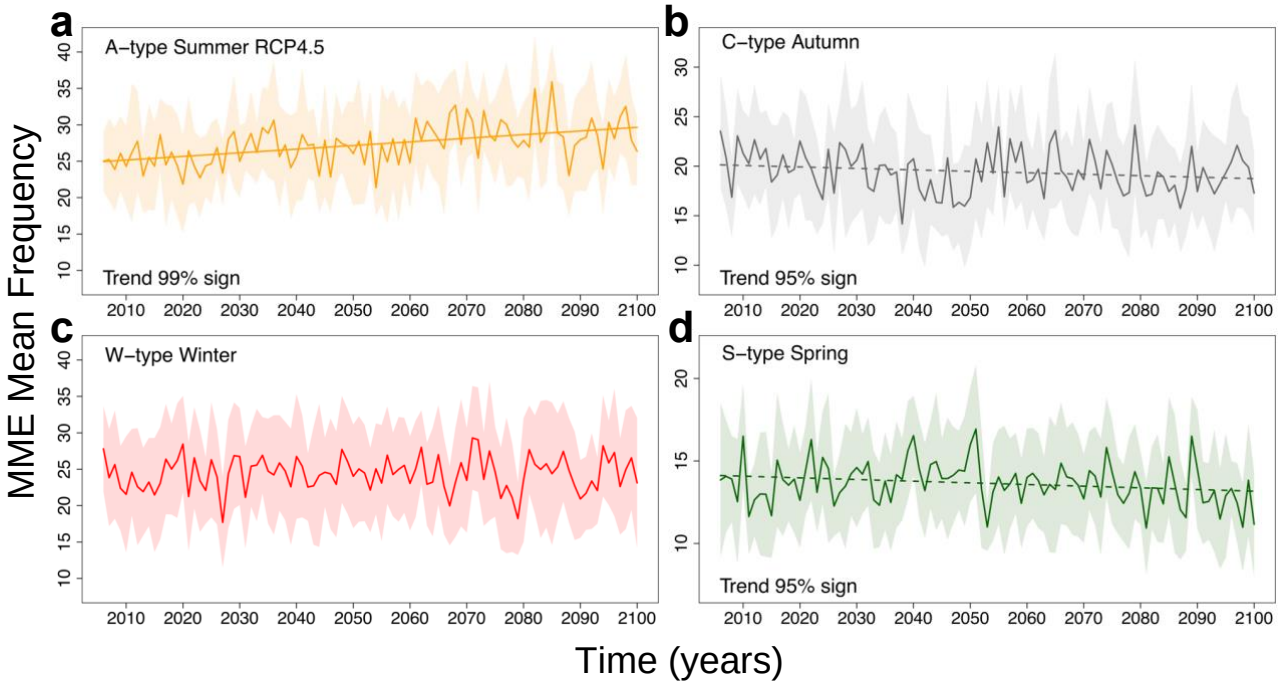


Figure S2. As per Figure 4 but for RCP4.5.



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136 **Figure S3. As per Figure 5 but for RCP4.5.** Trends are statistically significant at the 1% and 5%

137 levels (p-value <0.01 and <0.05, modified Mann-Kendall test).

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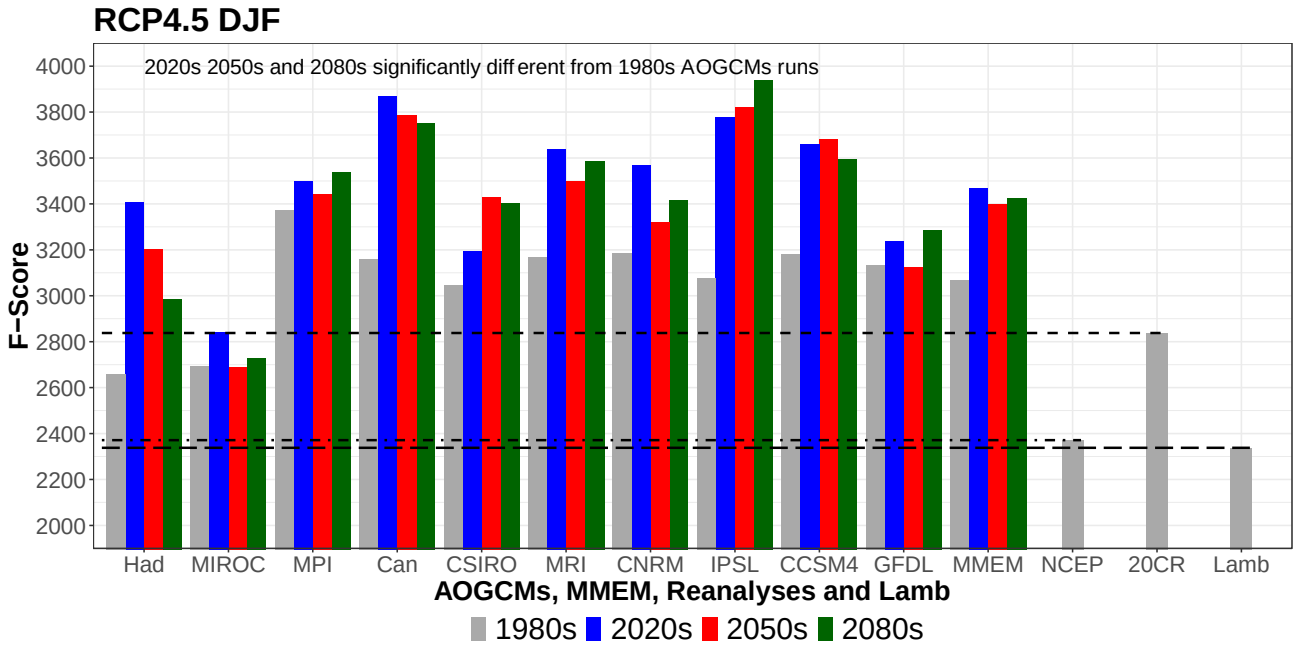

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144 **Figure S4. As per Figure 6 but for RCP4.5.**

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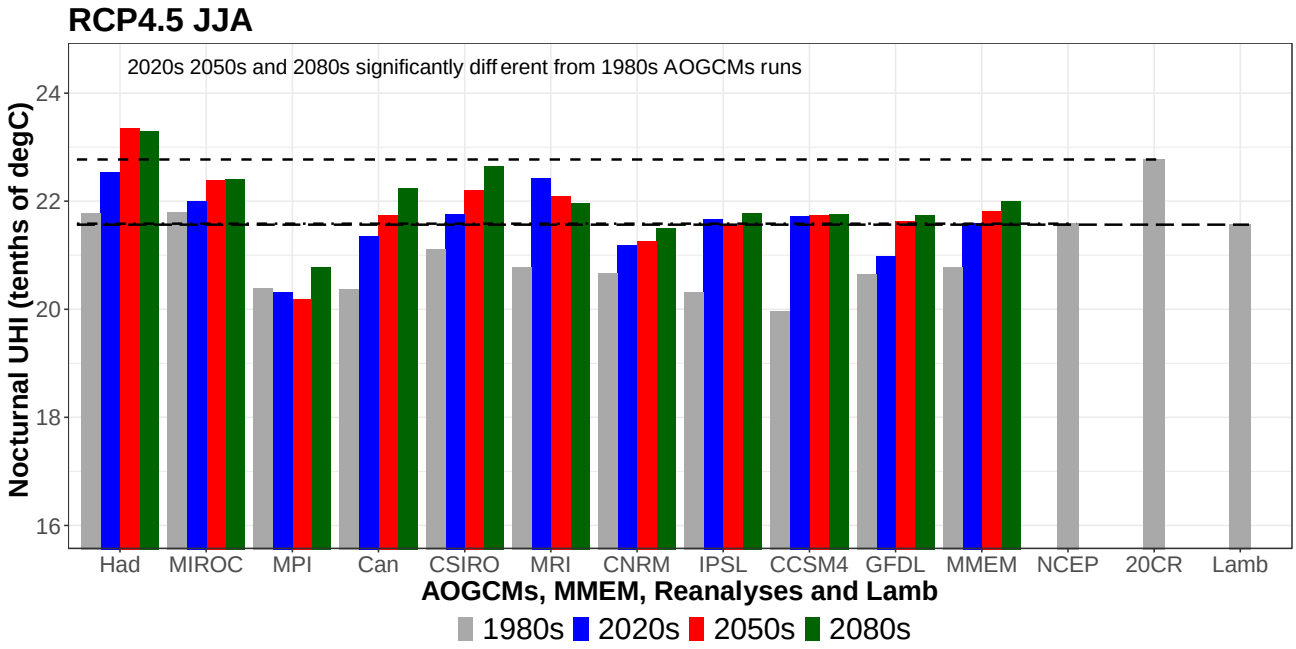

Figure S5. As per Figure 7 but for RCP4.5.

3. Supplementary Tables

RCP8.5	1980s A	1980s C	1980s W	1980s NW	1980s E	1980s N	1980s S	1980s U
JJA 2020s	44	60	38	47	50	38	52	62
JJA 2050s	42	65	40	44	54	44	68	43
JJA 2080s	30	**80**	51	39	**74**	34	**80**	54
SON 2020s	48	60	48	37	53	56	**76**	48
SON 2050s	54	72	39	30	53	54	**75**	42
SON 2080s	55	**74**	33	34	50	52	**78**	42
DJF 2020s	55	38	29	43	**24**	34	40	71
DJF 2050s	51	43	**24**	47	**22**	48	54	72
DJF 2080s	58	52	29	54	43	44	61	**90**
MAM 2020s	36	46	62	55	68	32	57	35
MAM 2050s	39	49	64	47	72	**23**	**86**	40
MAM 2080s	44	66	71	49	60	**19**	**88**	49

Table S1. Statistical significance of LWTs persistence in the MME under RCP8.5. Time periods considered are the 1980s compared to the 2020s, 2050s and 2080s under RCP8.5 during all seasons: summer JJA, autumn SON, winter DJF and spring MAM. Values shown are the W-statistic from the Mann-Whitney-Wilcoxon two-tailed test. Statistically significant values ($p<0.1$) are shown in bold.

RCP4.5	1980s A	1980s C	1980s W	1980s NW	1980s E	1980s N	1980s S	1980s U
JJA 2020s	49	49	46	41	38	54	58	40
JJA 2050s	44	64	51	45	54	47	**82**	52
JJA 2080s	43	**82**	44	47	49	46	69	52
SON 2020s	48	60	48	30	47	58	57	50
SON 2050s	50	64	39	34	36	49	62	64
SON 2080s	60	67	36	32	49	60	65	62
DJF 2020s	53	41	33	47	49	44	47	**80**
DJF 2050s	52	54	**26**	48	36	29	54	**85**
DJF 2080s	50	43	31	52	**22**	34	48	**75**
MAM 2020s	48	44	68	54	63	38	**76**	44
MAM 2050s	36	56	57	64	54	31	**80**	41
MAM 2080s	41	51	62	50	50	**17**	**85**	50

Table S2. The same as Table S1 but for RCP4.5.

		Sen's slopes
Summer JJA	**RCP8.5**	8.04e-02**
(A-type)	**RCP4.5**	4.71e-02**
Autumn SON	**RCP8.5**	-4.17e-02**
(C-type)	**RCP4.5**	-1.71e-02*
Winter DJF	**RCP8.5**	2.32e-02**
(W-type)	**RCP4.5**	4.17e-03
Spring MAM	**RCP8.5**	-1.88e-02**
(S-type)	**RCP4.5**	-9.93e-03*

Table S3. Sen's slopes of MMEM seasonal LWTs frequencies for RCP8.5 and RCP4.5. The slopes are calculated using a modified Mann-Kendall trend test over the 2006-2100 period. Four LWTs are shown: anticyclonic (A) for summer JJA; cyclonic (C) autumn SON; westerly (W) winter DJF and southerly (S) spring MAM. Statistical significance is shown as * p-value <0.05 and ** p-value <0.01.

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