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► **To cite this version:**

M Carmen Alvarez-Castro, Davide Faranda, Pascal Yiou. Atmospheric dynamics leading to West European summer hot temperatures since 1851. *Complexity*, 2018, 2018, pp.2494509. 10.1155/2018/2494509 . hal-01370975v3

HAL Id: hal-01370975

<https://hal.science/hal-01370975v3>

Submitted on 23 Nov 2017

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1 Atmospheric dynamics leading to West European 2 summer hot temperatures since 1851

3 M. Carmen Alvarez-Castro, Davide Faranda, Pascal Yiou

4 Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212

5 CEA-CNRS-UVSQ, IPSL, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

6 E-mail: carmen.alvarez-castro@lsce.ipsl.fr

7 November 2017

8 **Abstract.** Summer hot temperatures have many impacts on health, economy
9 (agriculture, energy, transports) and ecosystems. In western Europe, the recent
10 summers of 2003 and 2015 were exceptionally warm. Many studies have shown that
11 the genesis of the major heat events of the last decades was linked to anticyclonic
12 atmospheric circulation and to spring precipitation deficit in southern Europe. Such
13 results were obtained for the second part of the 20th century and projections into
14 the 21st century. In this paper, we challenge this vision by investigating the earlier
15 part of the 20th century from an ensemble of 20CR reanalyses. We propose an
16 innovative description of Western-European heat events applying the dynamical system
17 theory. We argue that the atmospheric circulation patterns leading to the most
18 intense heat events have changed during the last century. We also show that the
19 increasing temperature trend during major heatwaves is encountered during episodes
20 of Scandinavian blocking, while other circulation patterns do not yield temperature

21 trends during extremes.

22 *Keywords:* Weather Regimes, Climate Dynamics, Heat Events

23 **1. Introduction:**

24 In western Europe, recent hot summers were characterized by anomalous meteorological
25 conditions. In those situations, such as 2003, the heat was prolonged and intense, and the
26 consequences were disastrous for society and ecosystems (Schär & Jendritzky 2004, Ciais
27 et al. 2005, Poumadere et al. 2005, Robine et al. 2008, Wreford & Adger 2010).

28 European surface temperature variations are influenced by processes that combine
29 radiative forcing, the large-scale atmospheric circulation and local phenomena. Over
30 the last five decades, most of the intense European heat events have been connected
31 to prolonged spells of anticyclonic circulation (Scandinavian blocking) and dry spring
32 conditions in Southern Europe (Schär et al. 1999, Fischer et al. 2007, Vautard
33 et al. 2007, Zampieri et al. 2009, Mueller & Seneviratne 2012, Quesada et al. 2012).

34 However, the Summer 2011 was cool and preceded by a dry spring; the Summer 2013
35 was warm and preceded by a wet spring; and the Summer 2015 was warm with persisting
36 southerly atmospheric flows and no lasting blocking episodes (Jézéquel et al. 2017).

37 The goal of this paper is to assess the robustness of the link between heat events and
38 atmospheric circulation. We perform a statistical and dynamical analysis on a long
39 period that covers 1851–2014. Since anticyclones extend to a radius of few hundreds
40 kilometers, such a connection must be investigated on a regional scale (Della-Marta

41 et al. 2007, Stefanon et al. 2012). Hence, we restrict our analysis to Western Europe
42 in the region covering France and the Iberian Peninsula, whose weather conditions are
43 strongly influenced by the atmospheric circulation over the North Atlantic. This analysis
44 also puts some of the results of Horton et al. (2015) on this link into a broader time
45 perspective.

46 **2. Data and Methods:**

47 We base our analysis on the sea-level pressure (SLP) and the surface temperature fields
48 during summers (June-July-August: JJA) in 20th Century Reanalysis data version 2c
49 (20CRv2c: 1851–2014, (Compo et al. 2011)) with 2° of resolution and bias correction
50 applied in the sea ice distribution by assimilating new SST and sea-ice cover (SIC)
51 data (Hirahara et al. 2014). To ensure the robustness of the results, we used the
52 ensemble mean (EM) and the 56 members of the ensemble. The analysis is completed
53 with other reanalysis products: NCEP (1948–2016) (Kalnay et al. 1996) and ERA20C
54 reanalysis (1900–2000) (Poli et al. 2013) (see supplementary material). In order to
55 describe the variability of the atmospheric circulation, we decompose the summer SLP
56 anomalies field (obtained by removing the seasonal cycle) into four weather regimes
57 following the approach of Yiou et al. (2008) and study their connection with heat events
58 at seasonal(i) and sub-seasonal(ii) timescales in Western-Europe [10°W – 7.5°E; 35 –
59 50°N]. i) Seasonal: the 24 summers with high mean temperature anomalies (with respect
60 to the climatology) of the period 1851–2014, and ii) Subseasonal: heatwaves defined as

61 periods with high temperatures anomalies for at least five consecutive days. In both
62 analyses temperatures are detrended by removing a linear trend calculated from the
63 time series of summer seasonal means. The goal of the detrending is to remove the
64 effect of the well-documented European temperature increase, which does not depend
65 on the weather pattern.

66 *2.1. Weather Regimes:*

67 Weather regimes are recurring states of the atmospheric circulation and provide a useful
68 description of the atmospheric variability (Michelangeli et al. 1995, Corti et al. 1999).
69 Following the methods of Michelangeli et al. (1995) and Yiou et al. (2008) we compute
70 four weather regimes ($k = 4$) over the North Atlantic region [$80^{\circ}\text{W} - 50^{\circ}\text{E}$; $20 -$
71 70°N] (Fig. 1a-d) on daily NCEP SLP anomalies (reference period: 1970–2010) over
72 the summers (June–July–August: JJA). We take the first ten Empirical Orthogonal
73 Functions (EOFs) of SLP anomalies (with weights that are proportional to the cosine
74 of latitude) and the corresponding Principal Components (PCs). Then we perform
75 a classification, with a k-means algorithm (Michelangeli et al. 1995), and a choice of
76 four weather regimes. This classification is iterated several times with random initial
77 conditions following the procedure of Yiou et al. (2008) in order to obtain weather
78 regimes that are stable. The choice of four weather regimes is to be consistent with the
79 seminal paper of (Cassou et al. 2005). For comparison, we classify different reanalysis
80 datasets with the NCEP weather regimes. All the reanalysis data are interpolated

81 onto the NCEP grid ($2.5^\circ \times 2.5^\circ$). The SLP data classifications of all reanalyses are
82 obtained by determining the minimum of the Euclidean distances to the four NCEP
83 summer weather regime centroids. This is achieved without further EOF truncation.
84 The NCEP summer weather regimes are shown in Fig. 1a-d, with the same nomenclature
85 as in Cassou et al. (2005): a) the negative phase of North Atlantic Oscillation (NAO−)
86 showing a dipole between Greenland and Northern Europe, b) the Atlantic Ridge (AR),
87 with a high pressure over the center of the North Atlantic and some common features
88 with the positive phase of NAO, c) Scandinavian Blocking (BLO), with a high pressure
89 center over Scandinavia, d) Atlantic Low (AL), with a low pressure center covering the
90 central North Atlantic.

91

92 To ensure that there are no inhomogeneities in the method, we have verified
93 that the root mean square error (RMSE) between the reference period and the other
94 periods/datasets is small (Fig. S1 and Table S1).

95 *2.2. Projection onto weather regimes for a dynamical representation:*

96 In order to visualize the dependence between the daily SLP fields and the four weather
97 regimes, we represent the *trajectory* of each summer in the space of correlations (Fig.
98 3a-h) using an approach based on dynamical systems theory (Katok & Hasselblatt 1997)
99 . In this framework, the motion of a particle is represented in the space defined by its
100 position and speed (the so-called phase space). In our set-up, the particle is replaced

101 by a SLP field and the directions in phase space correspond to the projections on the
102 four weather regimes. Trajectories provide additional information with respect to the
103 monthly average statistical quantities, on the time dependence and the coherence of
104 the dynamical projection with respect to weather regime bases. If a trajectory jumps
105 every day to a different region of the phase space, then a dominant weather regime is
106 not representative of the dynamical behavior of events lasting several days. If instead
107 the trajectory occupies a restricted region of the phase space with smooth transitions of
108 the projection among weather regimes, then the dynamical representation is informative
109 and the base of weather regimes is appropriate.

110 This is equivalent to assuming the existence of a low-dimensional attractor. The
111 caveat is that the weather regime description is a first order simplification of the
112 atmospheric circulation that captures large scale features. Although this phase-space
113 method has been debated since Lorenz (1991), there is theoretical (Chekroun et al. 2011)
114 and experimental (Casdagli et al. 1991) evidence that such a procedure is effective when
115 the dynamics can be projected on a low dimensional phase space with a stochastic
116 perturbation.

117 **3. Results and Discussion:**

118 The link between the North Atlantic atmospheric circulation and heat events over France
119 and the Iberian Peninsula is investigated at short and long timescales. Both timescales
120 carry a physical and societal relevance.

121 *3.1. Seasonal scale: weather regimes during the warmest summers*

122 We carried out a statistical analysis of the hottest summers of the period 1851–2014
123 using 56 members and the Ensemble Mean (EM) of the 20CRv2c. In Western-Europe
124 [$10^{\circ}\text{W} - 7.5^{\circ}\text{E}$; $35 - 50^{\circ}\text{N}$], the 24 warmest summers (Fig. 1e-f) are defined in each
125 dataset as the ones having the highest average temperature anomalies with respect to
126 the climatology. Figure 1e shows the probability to have a dominant weather regime,
127 which is the one with highest anomalous frequency, in each summer detected. From the
128 selection of the 24 warmest summers for each member we detect 52 different summers.
129 In order to show the agreement between the members, we calculate the probability to
130 have a summer dominated by each weather regime (Fig. 1e). We divide the number of
131 members that detects a weather regime dominating that summer by the total number
132 of members that has detected that summer as a warm summer. For instance, we find
133 that for 30 members, the summer of 1887 is one of the 24 warmest summers. For 21
134 of those 30 members NAO– is the dominant weather regime and BLO for the other 9
135 members. However, we find a total agreement within 51 members detecting 2003 as a
136 warmer summer with AL as the unique weather regime dominating the summer. Hence,
137 as figure 1e shows, there is a higher probability to find a total agreement within the
138 members after 1950, being mainly BLO the dominant regime of warmest summers during
139 the second half of the 20th century and also briefly during the end of the 19th century.
140 NAO– and AR are the most dominant regimes during the first half of the 20th century.
141 This is also evident when we study the EM (Fig. 1f-j). Figure 1f shows the dominant

142 weather regime (colors) for the warmest summers (circle size) of the EM(20CRv2c, see
143 Figure S2i of supplementary material for NCEP, ERA20C and 20CR and Figure S3 for
144 some examples of warmest summers). We have divided the warmest summers detected
145 (vertical bars and figure 1g-j) in 4 groups, in order to study the variability during short
146 periods of 30 years. Boxplots in Figures 1g-j indicate the daily frequency of weather
147 regimes by group. In groups G1 (fig. 1g), G3 (fig.1j) and G4 (fig. 1j) BLO is the most
148 frequent regime during warmest summers, while in group G2 NAO– and AR are the
149 most representatives ones. Most of the warmest summers (largest circles in Fig. 1f)
150 occur during the second part of the 20th century. As observed by Stott et al. (2004)
151 and Meehl & Tebaldi (2004), they also increase in frequency over time.

152 Figure 2a-e) (Figure S2a-d for NCEP and figure S2e-h for ERA20C) shows the
153 anomalous summer frequency of weather regimes in EM of 20CRv2c with respect to
154 the NCEP reference period. In this figure we see that NAO– is the unique regime
155 decreasing in frequency with the time, and BLO is the one increasing in frequency with
156 the time (see also Figures S4 and S5).

157 To understand such trends we decompose the average information found with the
158 statistical analysis via the dynamical representation of the warmest summers (Fig 3 and
159 Fig. S6), defined in section 2.2. We project the daily SLP anomaly fields (grey lines)
160 onto the 4 weather regimes (NAO– and AR regimes in Fig. 3a,c,e,g and BLO and AL
161 regimes in Fig. 3b,d,f,h). This analysis synthesizes the trajectory of the atmospheric
162 circulation during heat events (colors) in a space represented by the weather regimes.

163 Circles in the axes represents the average correlations of warmest summers.

164 Consistently with the previous analysis, we find that the atmospheric dynamics
165 has evolved from patterns that are positively correlated with NAO– during the late
166 19th century and the beginning of the 20th century (Groups G1 and G2, Fig. 3 a,c),
167 to negative correlations during the rest of the record (Fig. 3 e,g). Similar projections
168 on BLO and AL regimes show: that BLO has the opposite change of NAO– (mainly
169 in groups G2 and G3), being negative during the early period of 20th century (Fig.
170 3d) and positive during the middle and late 20th century (Fig. 3f-h). AR and AL
171 regimes do not show significant differences between the periods. Those correlations add
172 a daily temporal information and highlight a change of atmospheric behavior. Thus
173 the dominant weather regime is a valid concept as the trajectories of heatwaves persist
174 at sub-seasonal scales around the same region of the phase space. These changes are
175 consistent within the 20CRv2c ensemble, as the analysis of the 56 members (Fig. 4a)
176 shows consistent results with the EM. In Figure 4 we represent the average correlations
177 of warmest summers as for figure 3 (circles in the axes) but for all the 56 members
178 and the EM. As for the EM, the 56 members have a positive or negative correlation
179 to NAO– and BLO depending of the period (groups in colors) being clearly separated
180 in the cloud of points the first to groups (G1 and G2, hereinafter P1) to the two last
181 groups (G3 and G4, hereinafter P2) that happens around 1930. Therefore, if we study
182 now the daily frequency of weather regimes classifying the warmest summers by only
183 two periods; before (P1) and after (P2) 1930, we find similar results as in figure 3 and

184 4a, opposite frequencies between NAO– and BLO. Higher frequencies of NAO– are
185 detected in P1 for 56 members (Fig. 4c) and the EM (Fig. 4e), and higher frequencies
186 of BLO are detected in P2 for 56 members (Fig. 4d) and the EM (Fig. 4f).

187 To complement this weather regimes analysis, we compute the difference of the
188 mean SLP for EM between these two periods during the warmest summers, $\Delta_{SLP} =$
189 $\mu_{SLP(P2)} - \mu_{SLP(P1)}$. We obtain a BLO regime pattern (Fig. 4g) using the EM or 56
190 members (not shown here). This means that it is the most representative pattern for
191 the period P2, being the period P1 similar to the NAO–.

192 Therefore, our analysis shows significant changes in the dominating weather regimes
193 associated with warmest summers. If BLO is dominant from the second part of 20th
194 century, scarce occurrences of this weather regime are found before 1930, with the
195 exception of a small period at late 19th century, even within the ensemble members
196 of 20CRv2c. These results reflect a change in the regime frequencies and dominance
197 conducting to warm extremes in a multidecadal scale due to, most likely, an internal
198 variability. BLO and AL regimes are conducive to warm extremes and NAO– and AR
199 are the opposite (Cassou et al. 2005). We found that, after 1930, it is more frequent to
200 find hottest summers linked to what we know as warm regimes. BLO (the most frequent
201 one after 1930) leads to stagnant air and potential land-surface feedbacks, whereas AL
202 relies on advection from lower latitudes. In the other hand, NAO– is the dominant
203 weather regime during warmest summers up to 1930. This weather regime contributes
204 to a weakening of the westerly flow from the Atlantic into Western Europe. AR regime

205 is more stable in time.

206 *3.2. Subseasonal scale: weather regimes during heatwave events*

207 To understand whether those results hold also for short time events (at least
208 5 consecutive days), independently from the fact that they have been observed
209 during hot summers, we compute the average temperature during heatwaves striking
210 Western-Europe.

211 Heatwave events are defined when the summer temperature exceeds a threshold
212 based on percentiles (P90, P95) for more than 5 consecutive days. Figure 5 shows
213 heatwave events above the P95 threshold, computed on the area temperature anomalies
214 (mean of France and the Iberian Peninsula) for the 56 members (Fig 5a-d) and for the
215 EM (Fig. 5e) (See Figure S7 of supplementary material). Temperatures in figure 5
216 are average values during each heatwave event. Heatwaves events are grouped by the
217 dominating weather regime. We find that 11% of total events are dominated by NAO–
218 (Fig. 5a), 49%, by BLO (Fig. 5c). Heatwaves that are associated by AR (Fig. 5b)
219 and AL (Fig. 5d) weather regimes have a frequency of 16% and 24%, respectively. The
220 multidecadal variability in terms of frequency of weather regimes associated to warmest
221 summers is also evident in the study of summer heatwave events. The summer average
222 temperatures for Western Europe (Figure S5, supplementary material) shows higher
223 temperatures in the early and late time span. Those temperature anomalies are more
224 evident once we apply a high criteria to define heatwaves. There is a decrease in the

225 occurrence of heatwave events during the first half of the 20th century being 1930-1950
226 the only period with some heatwave events that are more frequently associated with
227 BLO regime. Although the late 19th century is dominated by BLO regime, each weather
228 regime might induce a heatwave event. However, during the late 20th century and the
229 beginning of 21st century, the NAO- regime is scarcely present during heatwave events,
230 which are dominated by AL and, mainly, BLO. We also find that the longest events are
231 associated to BLO regime (Fig. 5c,e).

232 To shed more light on the circulation changes, we compute composites of SLP and
233 surface temperature anomalies (Fig. 6) during all the days of heatwave events detected
234 in figure 5 divided by periods (table 1). Consistently with Figure 5, most of the heatwave
235 events are concentrated in periods G1 (Fig. 6a) and G4 6d) being NAO- and BLO the
236 mean pressure patterns, respectively, during those periods. There is a change also in
237 the temperature patterns mainly in Northern and Eastern Europe but also in the East
238 coast of North America and the Atlantic Ocean. Similar to G1, G2 (Fig. 6b) has
239 a NAO- as the mean pressure pattern of the period of heatwave events. Although it
240 is the period with scarce occurrence of heatwave events, G3 (Fig. 6c) is dominated
241 by a strong low pressure over the Atlantic ocean (with some influence of BLO over
242 Europe) leading to an increase in temperature anomalies in both East coast of North
243 America and West coast of Europe. Same exercise is repeated but taking into account
244 the occurrence of heatwave events pre-1930 (P1, Fig.6e) and post-1930 (P2, Fig.6f). The
245 temperature pattern changes in pre and post 1930 maps mainly in Greenland and the

246 East coast of North America and Europe (North and East). Pressure patterns for all the
247 heatwave events pre and post-1930 reproduce well NAO– and BLO-AL (respectively)
248 albeit weaker for the BLO regime which has a strong influence of AL regime (Figure S8,
249 supplementary material). So, even if there is a change for NAO–, BLO is the one with
250 a stronger change for short-term events, because it is the most representative pattern
251 in heatwave events from 1930.

252 **4. Conclusions:**

253 These results confirm that most heat events (either warmest summers and heatwaves in
254 Western Europe) of the second half of the 20th century occurred when the Scandinavian
255 Blocking weather regime dominated the North Atlantic region, causing increasing
256 temperatures and more frequent and longer heatwaves events (figure 5 and figure S9).
257 Our results also show that NAO– is more favorable to drive warm summers before
258 1930. This early period corresponds to the most frequent co-occurrence of this regime
259 and heatwave events. Although the increasing temperature trends observed during
260 blocking heatwave episodes could be attributed to secular climate change (Coumou
261 et al. 2014), the change in the dominating weather regimes may also be linked to the
262 decadal variability of the atmospheric dynamics. Those findings are consistent with the
263 results of Horton et al. (2015), although we consider heatwaves on a finer spatial scale
264 (Western-Europe). The analysis of Hoffmann (2017) is also complementary to ours,
265 albeit on another region (Postdam, Germany), whose temperature does not respond to

266 the same atmospheric patterns. However, he found (Figure 11) an increment of two
267 new dominant wave-like patterns with more meridional oscillation, as we have seen for
268 Western Europe at seasonal (Fig. 1, Fig. S2 and Fig. S4) and subseasonal scales (Fig.
269 5).

270 The robustness of our results is demonstrated by the use of 20CRv2c 56 ensemble
271 members and other reanalysis datasets (see supplementary material) where we have
272 found similar results. The dynamical analysis also suggests that there is an increase of
273 negative correlations between warmest summers and the NAO– regime.

274 Although the information extracted in warmest summers and heatwaves is a priori
275 different, our analysis shows similar results at different timescales. In terms of warmest
276 summers, and although there are some evidence of a multidecadal variability of the
277 atmospheric dynamic, NAO– was the most representative pattern up to 1930 and
278 from 1930 on BLO is the most representative one. For short time heat events, the
279 most representative is BLO during the whole period but, as for warmest summers,
280 NAO– events are less frequent after 1930. BLO is associated to the longest and hottest
281 heatwaves and yields an increasing trend, as outlined by Horton et al. (2015).

282 **Acknowledgments:**

283 M.C.A-C. was supported by the Swedish Research Council grant No. C0629701
284 (MILEX). D.F. was supported by the ERC grant No. 338965–A2C2. P.Y.
285 was supported by the European Unions Seventh Framework Programme grant No.

286 607085–EUCLEIA. The authors thank G. Compo, for the help supported with
287 data from members of 20CR reanalysis. 20CR and NCEP Reanalysis data were
288 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and retrieved from
289 <https://climatedataguide.ucar.edu/climate-data/noaa-20th-century-reanalysis-version-2-and-2c>
290 and <http://www.esrl.noaa.gov/psd/>. ERA-20C reanalysis data provided by the
291 ECMWF (European Centre for Medium-Range Weather Forecasts), Reading, UK,
292 from their website at <http://apps.ecmwf.int/datasets/data/era20c-daily/>. The authors
293 declare that there is no conflict of interest regarding the publication of this paper.

294 **Supplementary Material:**

- 295 • Figure S1: Boxplots of Absolute Root Mean Square Error by period and weather
296 regime.
- 297 • Figure S2: Relative long-term summer weather regime frequency over the
298 North-Atlantic region and their dominance in warmest summers in Western-Europe
299 (1871-2015) using three reanalysis products (20CR, ERA20C, NCEP).
- 300 • Figure S3: Temperature anomalies during warmest summers in Western Europe
301 with dominance of each weather regime in three reanalysis products (20CR,
302 ERA20C, NCEP).
- 303 • Figure S4: 31-years running correlation of the Weather Regimes frequency and the
304 mean temperature in western Europe (20CRv2c)
- 305 • Figure S5: Summer average temperatures for Western Europe for three reanalysis

306 products (20CR, ERA20C, NCEP).

307 • Figure S6: Dynamical representation of the warmest summers for ERA20C during
308 1900-2010 in regimes AR-NAO- and BLO-AL.

309 • Figure S7: Dominant weather regimes during Summer Heatwave events in
310 Western-Europe for three reanalysis products (20CR, ERA20C, NCEP).

311 • Figure S8: SLP anomalies in heatwave events (20CRv2c EM) for each period,

312 • Figure S9: Temperature (y-axis) vs numbers of days (x-axis) during each heatwave
313 event for the 20CR Ensemble Mean (1871-2011) weather regimes.

314 • Table S1: Absolute root mean square error by period and weather regime.

315 Correspondence and requests for further materials should be addressed to M.C.A-C

316 (email: carmen.alvarez-castro@lsce.ipsl.fr).

317 **References:**

318 Casdagli, M., Eubank, S., Farmer, J. D. & Gibson, J. (1991). State space reconstruction in the presence
319 of noise, *Physica D.* **51**(1): 52–98.

320 Cassou, C., Terray, L. & Phillips, A. S. (2005). Tropical atlantic influence on European heat waves, *J.*
321 *Climate* **18**(15): 2805–2811.

322 Chekroun, M. D., Simonnet, E. & Ghil, M. (2011). Stochastic climate dynamics: Random attractors
323 and time-dependent invariant measures, *Physica D.* **240**(21): 1685–1700.

324 Ciais, P. et al. (2005). Europe-wide reduction in primary productivity caused by the heat and drought
325 in 2003, *Nature* **437**(7058): 529–533.

326 Compo, G. P. et al. (2011). The twentieth century reanalysis project, *Q. J. Roy. Meteor. Soc.*
327 **137**(654): 1–28.

- 328 Corti, S., Molteni, F. & Palmer, T. (1999). Signature of recent climate change in frequencies of natural
329 atmospheric circulation regimes, *Nature* **398**(6730): 799–802.
- 330 Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S. & Schellnhuber, H. J. (2014). Quasi-resonant
331 circulation regimes and hemispheric synchronization of extreme weather in boreal summer,
332 *Proceedings of the National Academy of Sciences* **111**(34): 12331–12336.
- 333 Della-Marta, P. M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M. & Wanner, H. (2007).
334 Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings
335 and predictability, *Clim. Dynam.* **29**(2-3): 251–275.
- 336 Fischer, E., Seneviratne, S., Lüthi, D. & Schär, C. (2007). Contribution of land-atmosphere coupling
337 to recent European summer heat waves, *Geophys. Res. Lett.* **34**(6).
- 338 Hoffmann, P. (2017). Enhanced seasonal predictability of the summer mean temperature in Central
339 Europe favored by new dominant weather patterns, *Climate Dynamics*. .
340 **URL:** <https://doi.org/10.1007/s00382-017-3772-0>
- 341 Horton, D. E., Johnson, N. C., Singh, D., Swain, D. L., Rajaratnam, B. & Diffenbaugh, N. S. (2015).
342 Contribution of changes in atmospheric circulation patterns to extreme temperature trends,
343 *Nature* **522**(7557): 465–469.
- 344 Jézéquel, A., Yiou, P. & Radanovics, S. (2017). Role of circulation in european heatwaves using flow
345 analogues, *Climate Dynamics*. .
346 **URL:** <https://doi.org/10.1007/s00382-017-3667-0>
- 347 Kalnay, E. et al. (1996). The NCEP/NCAR 40-year reanalysis project, *B. AM. Meteorol. Soc.*
348 **77**(3): 437–471.
- 349 Katok, A. & Hasselblatt, B. (1997). *Introduction to the modern theory of dynamical systems*, Vol. 54,
350 Cambridge University Press.
- 351 Lorenz, E. N. (1991). Dimension of weather and climate attractors, *Nature* **353**(6341): 241–244.
- 352 Meehl, G. A. & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the
353 21st century, *Science* **305**(5686): 994–997.

- 354 Michelangeli, P.-A., Vautard, R. & Legras, B. (1995). Weather regimes: Recurrence and quasi
355 stationarity, *J. Atmos. Sci.* **52**(8): 1237–1256.
- 356 Mueller, B. & Seneviratne, S. I. (2012). Hot days induced by precipitation deficits at the global scale,
357 *Proc. Natl. Acad. Sci.* **109**(31): 12398–12403.
- 358 Poli, P. et al. (2013). The data assimilation system and initial performance evaluation of the ecmwf
359 pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C), *ECMWF*
360 *ERA Rep* **14**: 59.
- 361 Poumadere, M., Mays, C., Le Mer, S. & Blong, R. (2005). The 2003 heat wave in France: dangerous
362 climate change here and now, *Risk Anal.* **25**(6): 1483–1494.
- 363 Quesada, B., Vautard, R., Yiou, P., Hirschi, M. & Seneviratne, S. I. (2012). Asymmetric European
364 summer heat predictability from wet and dry southern winters and springs, *Nature Clim. Change*
365 **2**(10): 736–741.
- 366 Robine, J.-M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P. & Herrmann,
367 F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003, *C. R. Biol.*
368 **331**(2): 171–178.
- 369 Schär, C. & Jendritzky, G. (2004). Climate change: hot news from summer 2003, *Nature*
370 **432**(7017): 559–560.
- 371 Schär, C., Lüthi, D., Beyerle, U. & Heise, E. (1999). The soil-precipitation feedback: A process study
372 with a regional climate model, *J. Climate* **12**(3): 722–741.
- 373 Stefanon, M., D’Andrea, F. & Drobinski, P. (2012). Heatwave classification over Europe and the
374 Mediterranean region, *Environ. Res. Lett.* **7**(1): 014023.
- 375 Stott, P. A., Stone, D. A. & Allen, M. R. (2004). Human contribution to the European heatwave of
376 2003, *Nature* **432**(7017): 610–614.
- 377 Vautard, R., Yiou, P., D’andrea, F., De Noblet, N., Viovy, N., Cassou, C., Polcher, J., Ciais, P.,
378 Kageyama, M. & Fan, Y. (2007). Summertime European heat and drought waves induced by
379 wintertime Mediterranean rainfall deficit, *Geophys. Res. Lett.* **34**(7).

- 380 Wreford, A. & Adger, W. N. (2010). Adaptation in agriculture: historic effects of heat waves and
381 droughts on UK agriculture, *Int. J. Agric. Sustain.* **8**(4): 278–289.
- 382 Yiou, P. et al. (2008). Weather regime dependence of extreme value statistics for summer temperature
383 and precipitation, *Nonlinear Proc. Geoph.* **15**(3): 365–378.
- 384 Zampieri, M., D’Andrea, F., Vautard, R., Ciais, P., de Noblet-Ducoudré, N. & Yiou, P. (2009). Hot
385 European summers and the role of soil moisture in the propagation of mediterranean drought,
386 *J. Climate* **22**(18): 4747–4758.

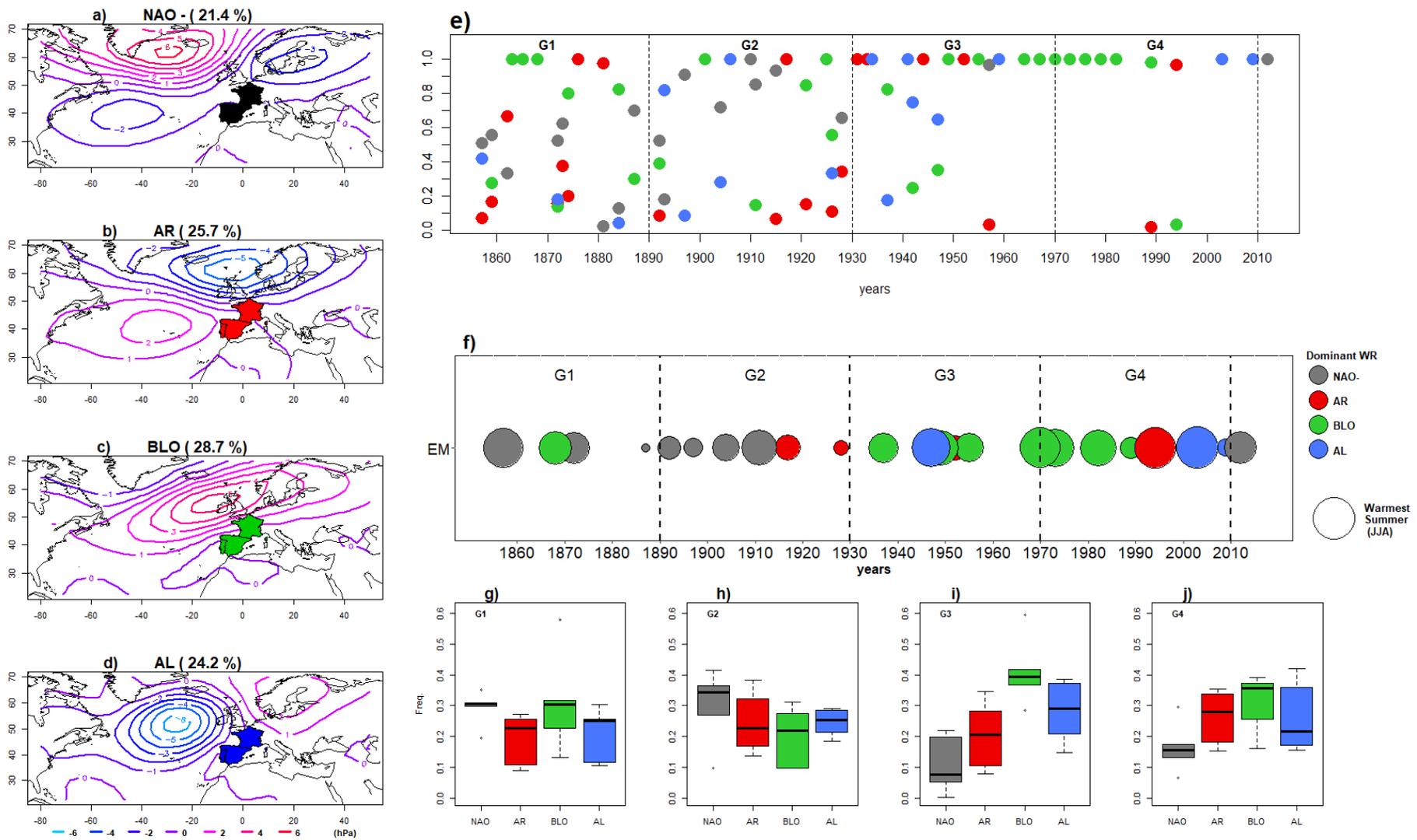


Figure 1. Summer SLP weather regimes over the North-Atlantic region and their dominance in the twenty warmest summers during 1871-2011 in Western-Europe. **a-d**, Summer SLP (hPa anomalies) Weather regimes: **a**, North Atlantic Oscillation in its negative phase (NAO-). **b**, Atlantic Ridge (AR). **c**, Blocking (BLO). **d**, Atlantic Low (AL) weather regime. **e**, Probability to find a dominant weather regime in all the warmest summers (EM and 56 members). **f**, 24 warmest summers in Western-Europe (colored region in **a-d**) with their dominant weather regime (20CRv2c EM). Circle size depends on temperature (anomalies), the largest the warmest. Colors represents the dominant weather regime for each summer based in the highest anomalous frequency. **g-j**, Boxplots of daily weather regimes during the 24 warmest summers of 20CRv2c EM (as in **f**) in Western-Europe separated by groups of 6 summers per 40 years: **g**, shows group G1, **h**, group G2, **i**, group G3, and **j**, group G4 1.

Table 1. Groups and periods used during the analysis of 20CRv2c (EM and 56 members of the ensemble).

Group	Years	Period
G1	1851-1890	P1
G2	1891-1930	
G3	1931-1970	P2
G4	1971-2010	

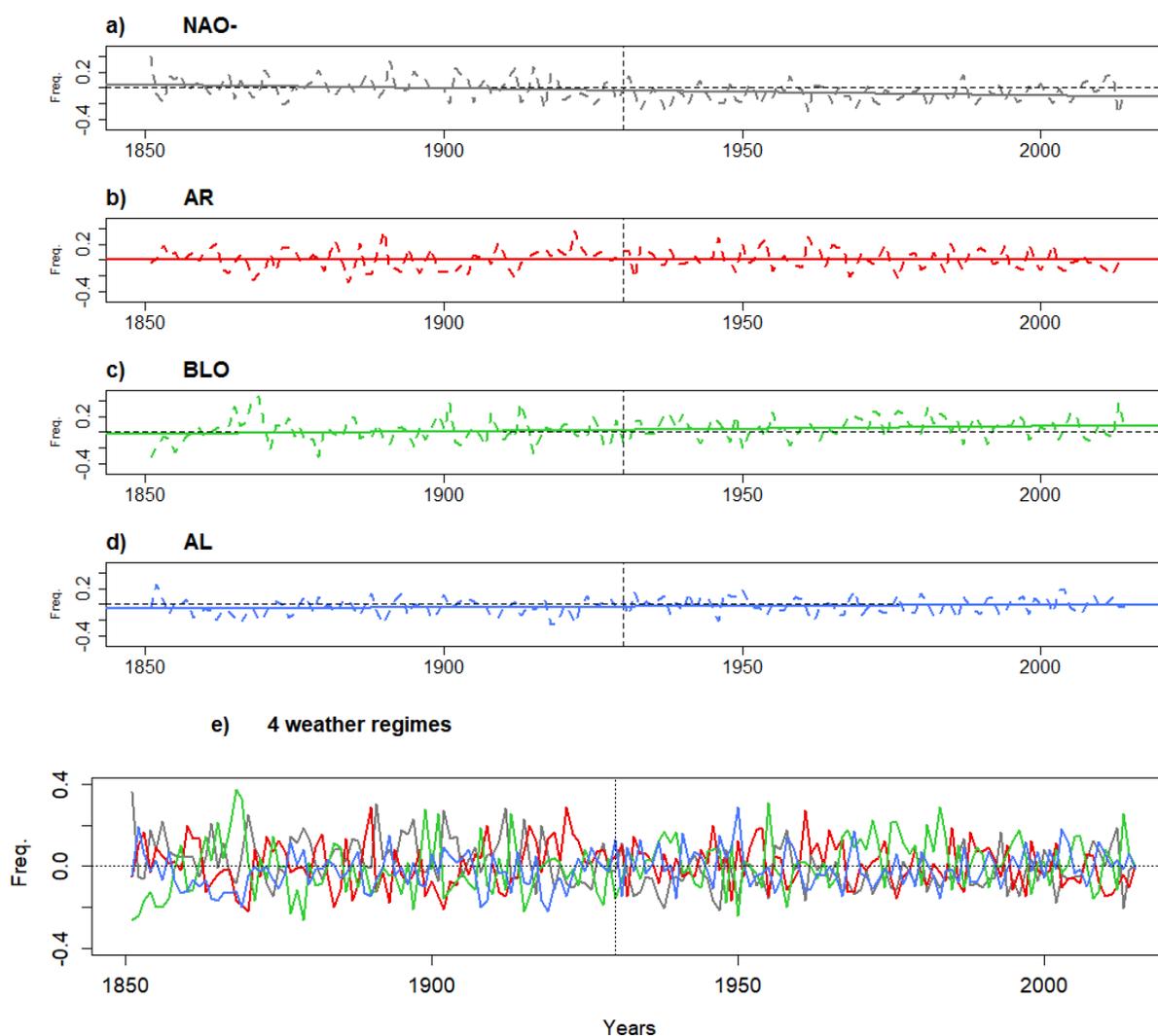


Figure 2. Relative long-term summer weather regime frequency. Relative frequency of summer SLP (hPa) weather regimes over the North-Atlantic region (1851-2014) using 20CRv2c. Here we show SLP anomalies with respect to the reference period 1970-2010 for each (a-d) and all (e) weather regimes, solid lines in a-d) represents the linear trend for each regime. 1930 it is marked with a vertical dashed line.

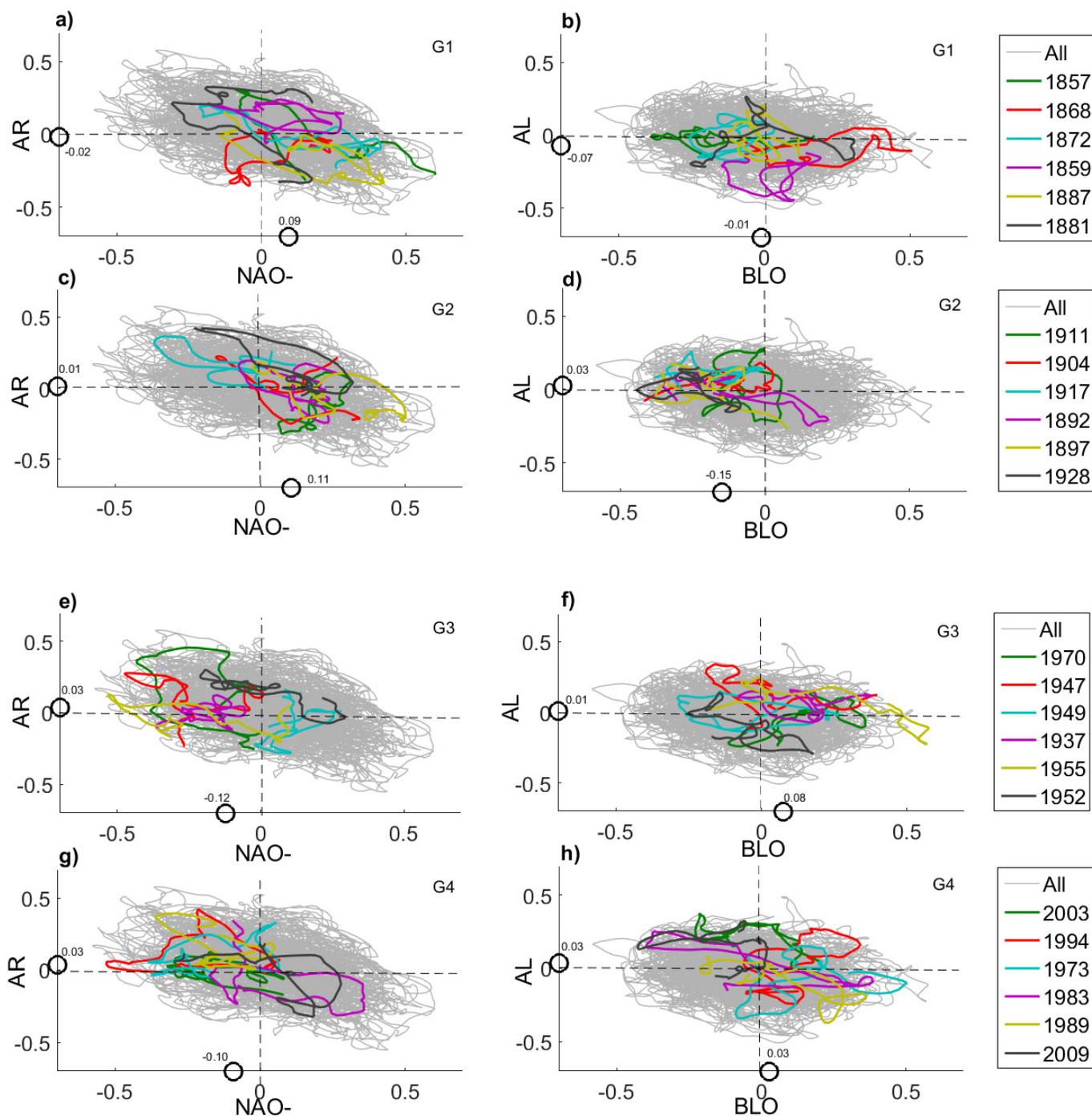


Figure 3. Dynamical representation of the warmest summers. Correlations of daily SLP fields and NAO- (x -axis), AR (y -axis) (top) and AL, BLO (bottom) weather regimes for the 4 groups of summers. Warmest summers are colored as in the legend with, light grey lines represent all data. Average correlations of warmest summers with respect to the NAO- weather regimes (black circle on x -axis). A moving average filter of 30 days window was applied to the warmest summers for better representation.

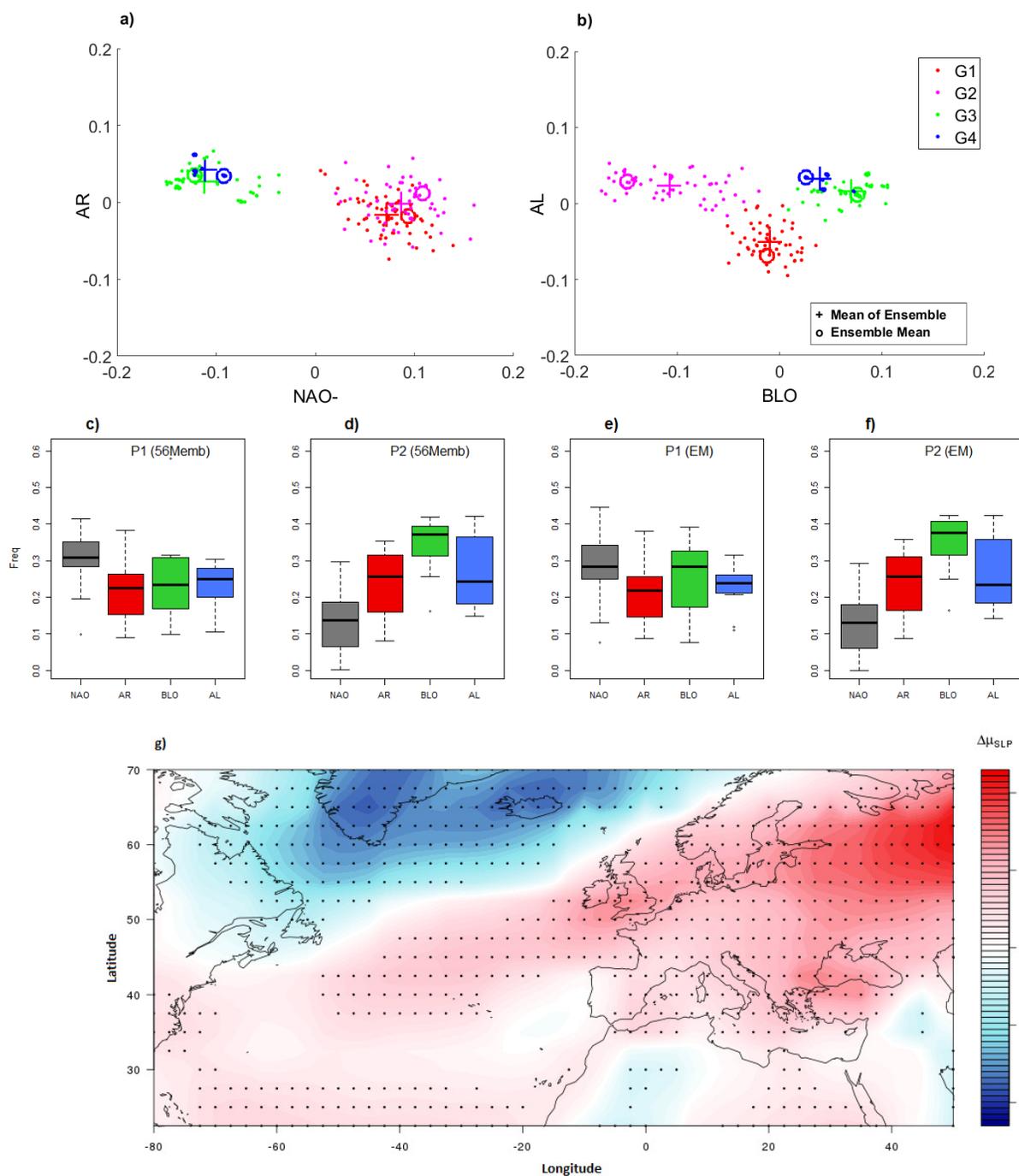


Figure 4. Changes in the dynamical representation of the warmest summers. **a-b**, Average correlations of warmest summers with respect to the 4 weather regimes (black circle on x -axis in Figure 3), points represents each member, crosses represents the mean of all the 56 members and circles represent the EM. Colors represents the 4 groups of summers (G1 red, G2 purple, G3 green, G4 blue). In **c-f** boxplots showing frequencies of the 4 weather regimes classified in two periods: **c,e** for summers before 1930 (groups G1+G2) and **d,f** for summers after 1930 (groups G3+G4), for all the 56 members (**c-d**) and the EM (**e-f**). **g**, shows the difference in the SLP mean between those two periods (after1930- before 1930). Points represents significance at 95 percent after the performance of a Montecarlo test.

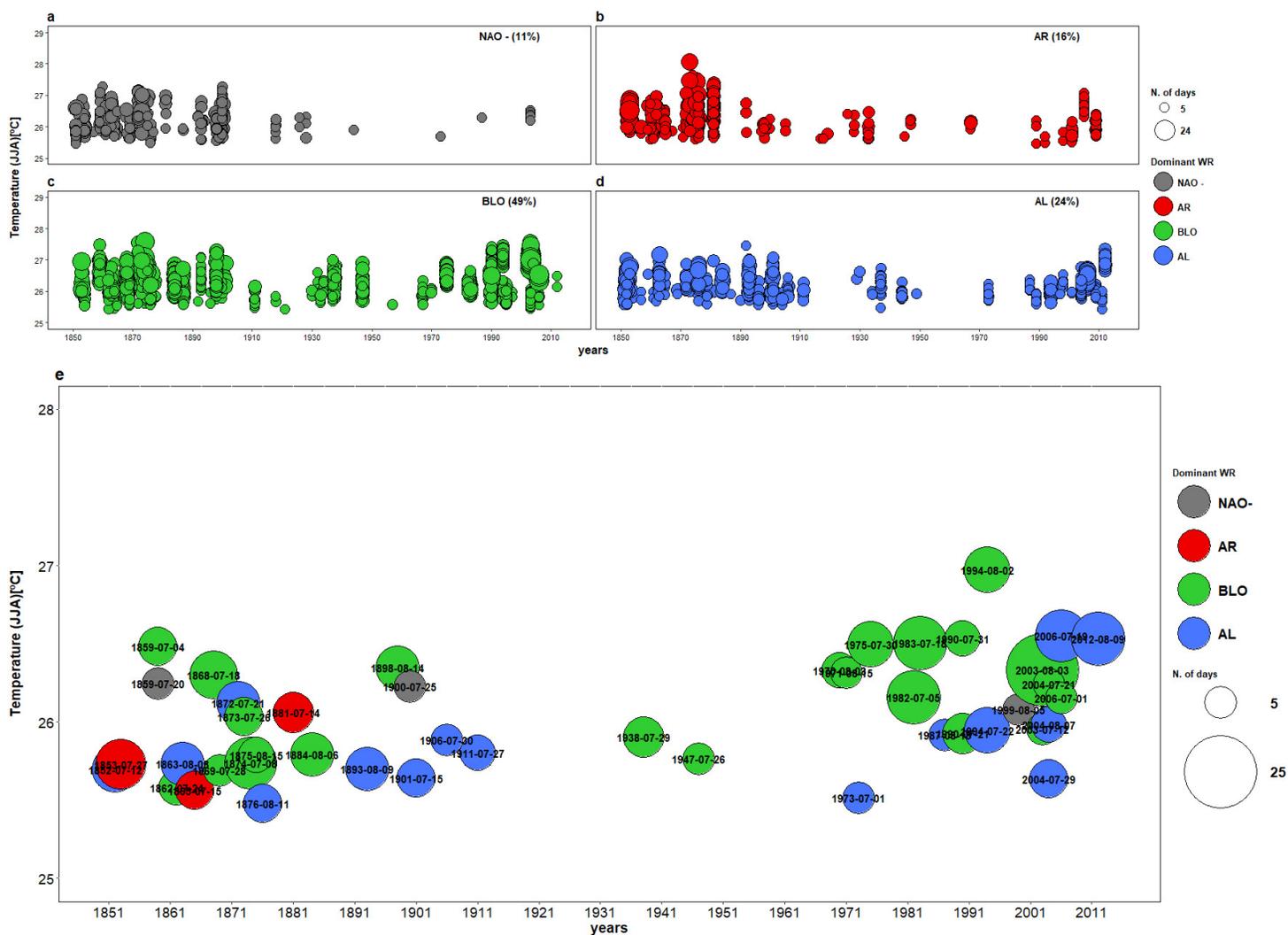


Figure 5. Dominant weather regimes during Summer heatwave events. In a–d, Summer heatwave events (95th Percentile) for all the members and e, EM (circles with stars) of 20CR data, 1851–2014. Colors correspond to the dominant weather regime in each event, temperature (y -axis) and years (x -axis). Circle sizes depend on the event duration by number of days, the larger the longer duration.

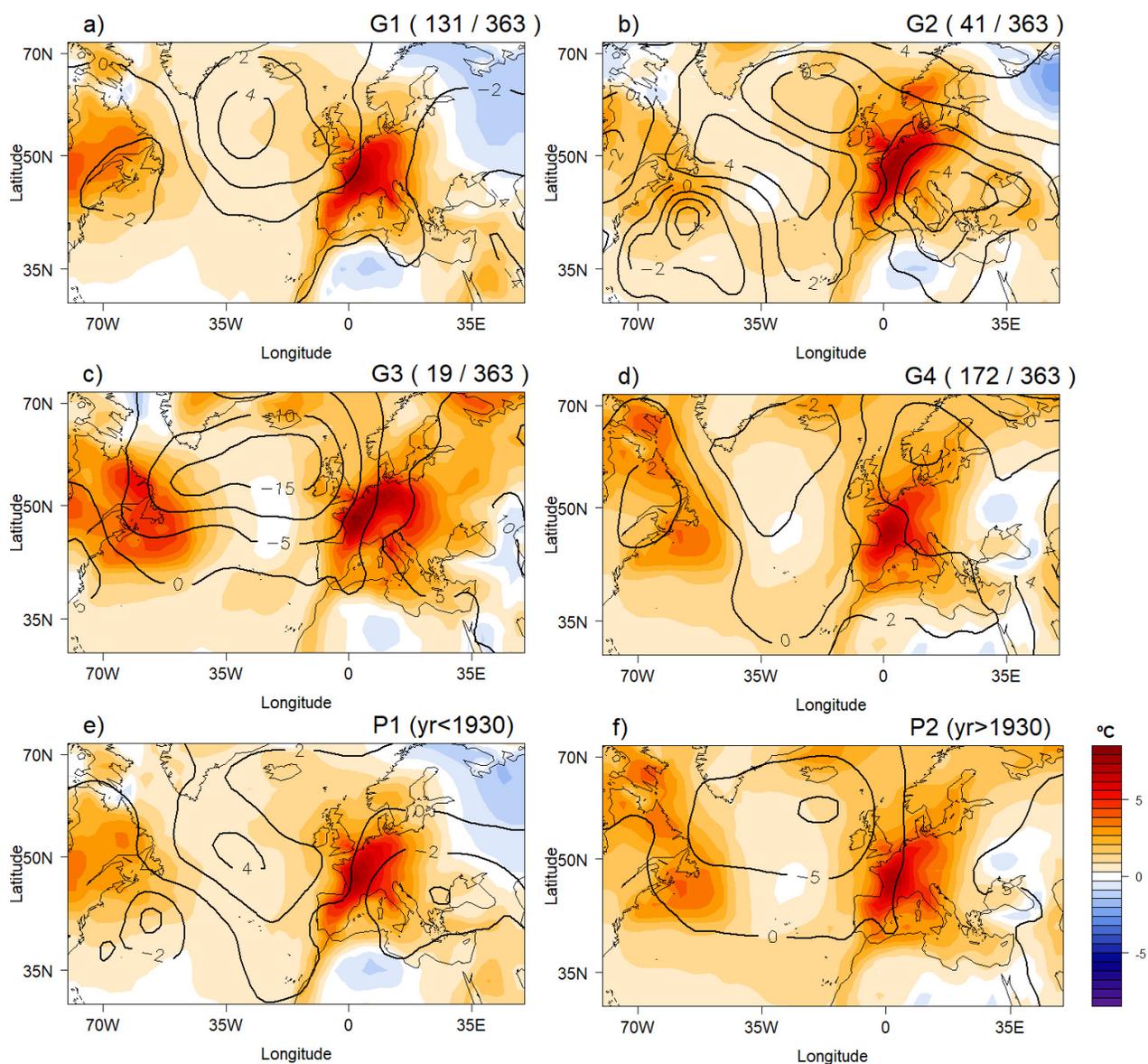


Figure 6. Composites of Sea Level Pressure (SLP) and Surface Temperature anomalies (SAT) during heatwaves events. In a–d, composites SLP (hPa) and SAT (°C) anomalies for all the days during heatwaves events in each period, from G1 to G4, in e, anomalies for all the days during heatwaves events before 1930 and f, after 1930.

Atmospheric dynamics leading to West European summer hot temperatures since 1851

M. Carmen Alvarez-Castro, Davide Faranda, Pascal Yiou

Laboratoire des Sciences du Climat et de l' Environnement, UMR 8212
CEA-CNRS-UVSQ, IPSL, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

E-mail: carmen.alvarez-castro@lsce.ipsl.fr

November 2017

Supplementary Material

- Figure S1: Boxplots of Absolute Root Mean Square Error by period and weather regime.
- Figure S2: Relative long-term summer weather regime frequency over the North-Atlantic region and their dominance in warmest summers in Western-Europe (1871-2015) using three reanalysis products (20CR, ERA20C, NCEP).
- Figure S3: Temperature anomalies during warmest summers (IP-France) with dominance of each weather regime in three reanalysis products (20CR, ERA20C, NCEP).
- Figure S4: 31-years running correlation of the Weather Regimes frequency and the mean temperature in western Europe (20CRv2c)
- Figure S5: Summer average temperatures for Western-Europe for three reanalysis products (20CR, ERA20C, NCEP).
- Figure S6: Dynamical representation of the warmest summers for ERA20C during 1900-2010 in regimes AR-NAO- and BLO-AL.
- Figure S7: Dominants weather regimes during Summer Heatwave events in Western-Europe for three reanalysis products (20CR, ERA20C, NCEP).
- Figure S8: SLP anomalies in heatwave events (20CRv2c EM) for each period,
- Figure S9: Temperature (y-axis) vs numbers of days (x-axis) during each heatwave event for the 20CR Ensemble Mean (1871-2011) weather regimes.
- Table S1: Absolute root mean square error by period and weather regime.

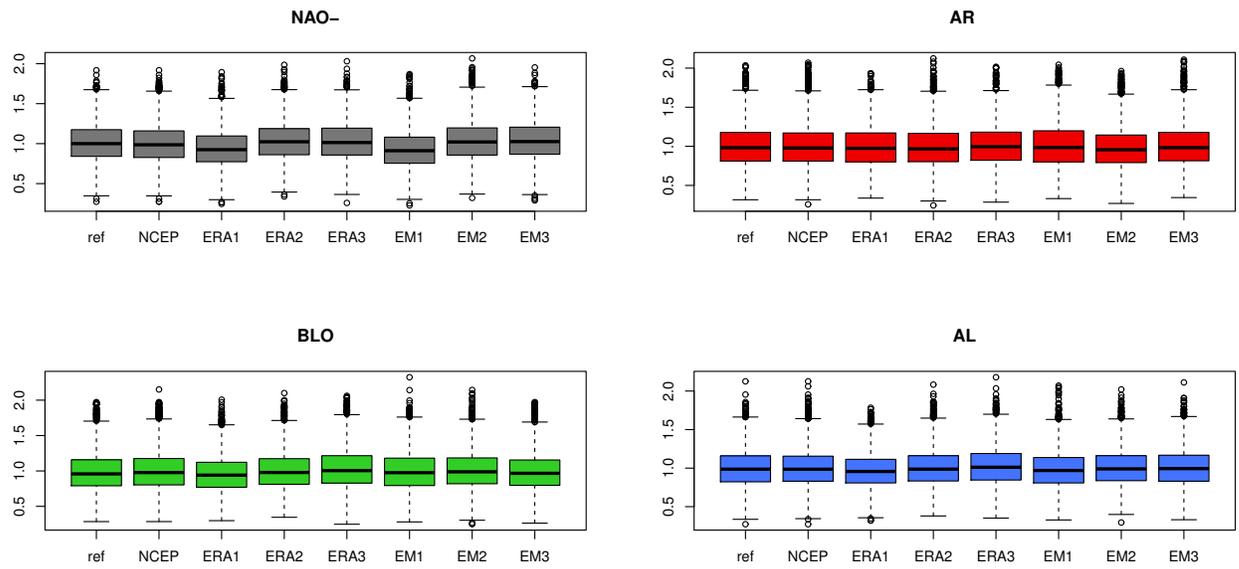


Figure S 1. Boxplots of Absolute Root Mean Square Error by period and weather regime. Colors represent each weather regime. (See also Table S1).

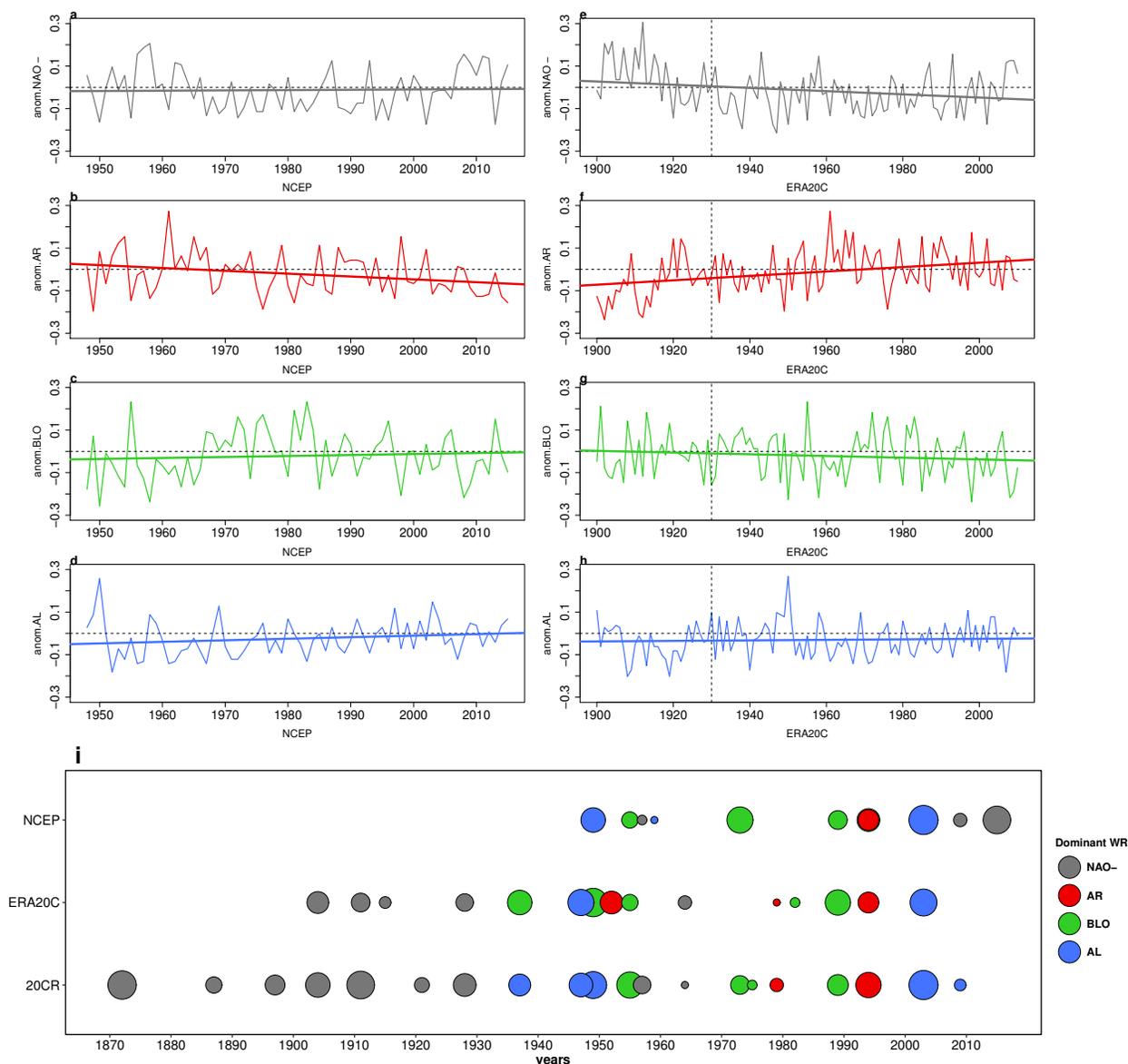


Figure S 2. Relative long-term summer weather regime frequency over the North-Atlantic region and their dominance in warmest summers in Western-Europe (1871-2016) using three reanalysis products (20CR, ERA20C, NCEP). As in figure S1, relative frequency of Summer SLP (hPa anomalies) weather regimes: NAO- (a,e), AR (b,f), BLO (c,g) and AL (d,h), but considering NCEP data (a-d,) and ERA20C (e-h). e, Warmest summers from 1871 to 2015 in Western-Europe with their dominant weather regime. Years are shown in x axis while y axis display each of the reanalysis products (20CR, ERA20C, NCEP). Circle size depends on temperature anomalies, the largest the warmest. Colors (black, red, green, blue) represents the dominant weather regime (NAO-, AR, BLO, AL) for each summer. The number of warmest summers are ponderate with the length of each dataset.

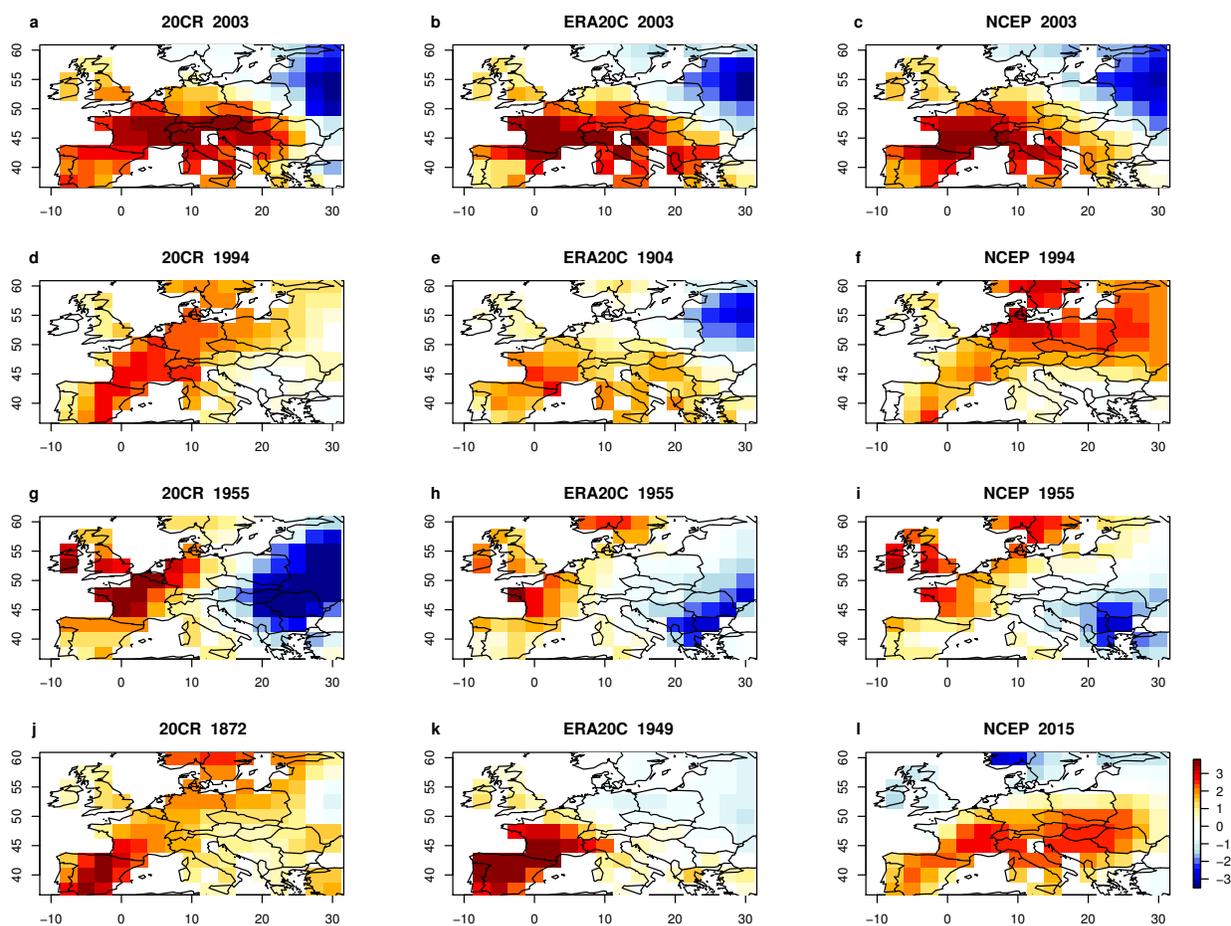


Figure S 3. Temperature anomalies maps for warmest summers in Western-Europe. Each row correspond to a different dominant weather regime for some explanatory summers. Each column is a different reanalysis product. **a-c**, Summer 2003, where AL was the dominant weather regime. **d-f**, Summer of 1994, where AR was the dominant weather regime (Same frequencies of BLO and AR for NCEP during this summer). **g-i**, Summer of 1955, where BLO was the dominant weather regime. **j-l**, Since there is not a common summer for all the reanalysis datasets with NAO- as a dominant weather regime, here we show the most warmest summer (1872, 1904, 2015) where NAO- was the dominant weather regime in each reanalysis dataset (20CR, ERA20C, NCEP).

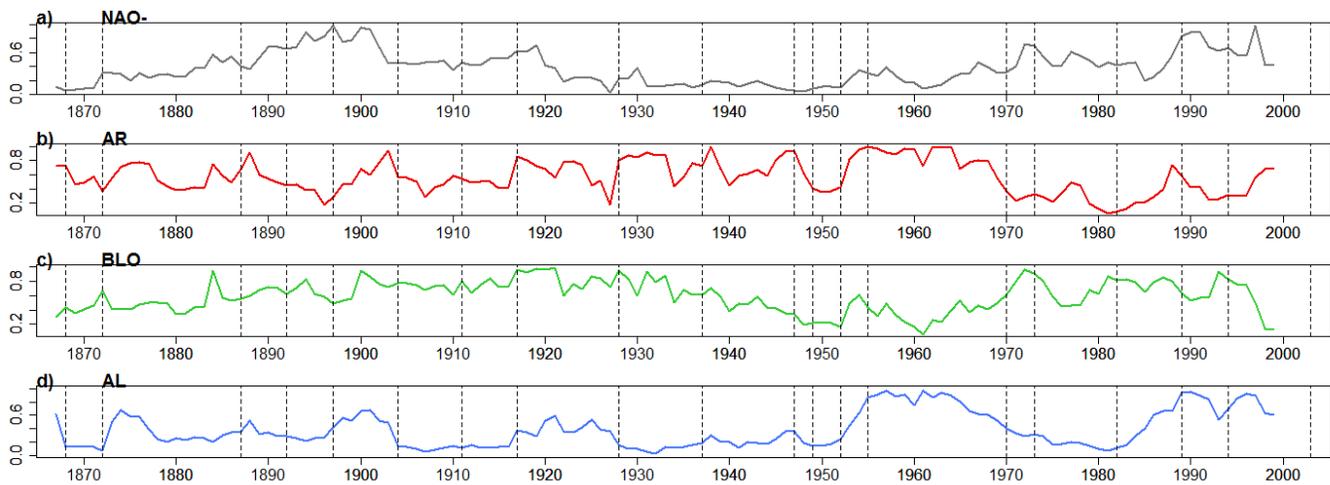


Figure S 4. 30yr-running correlations of summer mean temperatures and weather regime frequency in Western Europe. The data used is the Ensemble Mean of 20CRv2c. Warmest summers are marked with a vertical dashed line. Colors represents the weather regimes

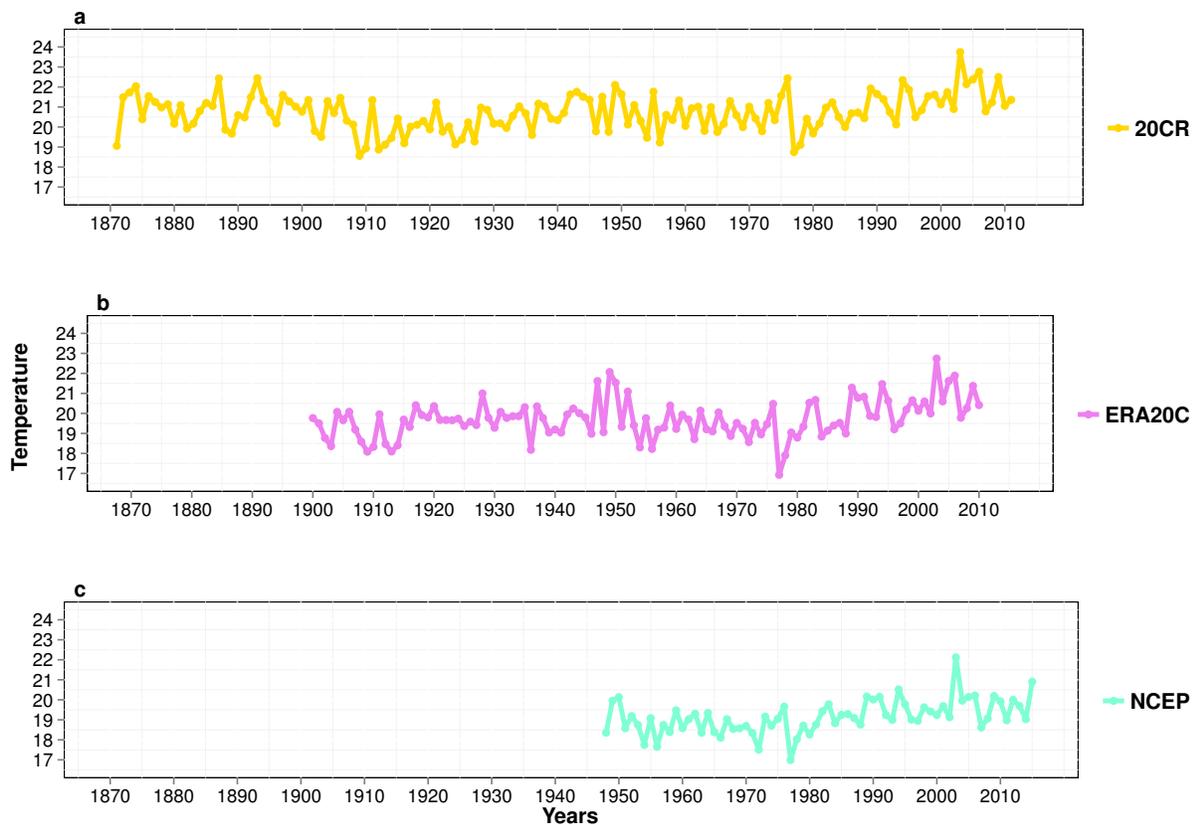


Figure S 5. Summer average temperatures (°C) for Western-Europe. a, 20CR b, ERA20C and c, NCEP).

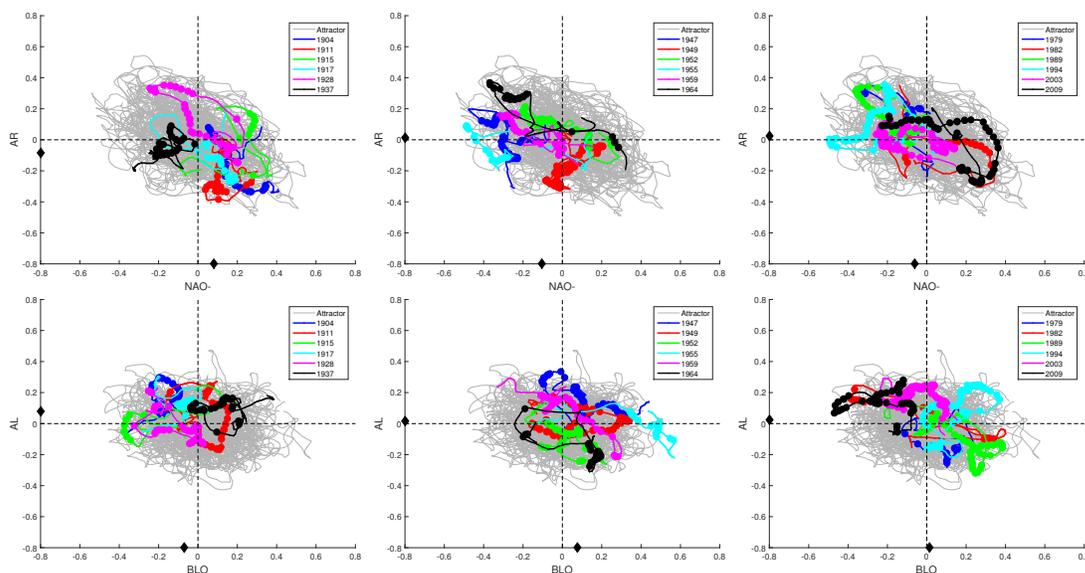


Figure S 6. Dynamical representation of the warmest summers (same as fig.3 in main text) for ERA20C during 1900-2010. Correlations of daily SLP fields and NAO- (x-axis), AR (y-axis) weather regimes in upper panels and correlations of daily SLP fields and BLO (x-axis), AL (y-axis) weather regimes in the bottom panels for three different periods. Warmest summers are colored as in the legend, light grey lines represent all data. Big circles represent days with temperature above 85th percentile. Average correlations of warmest summers with respect to each weather regime (black circle on x-axis). A moving average filter of 30 days window was applied to the warmest summers for better representation.

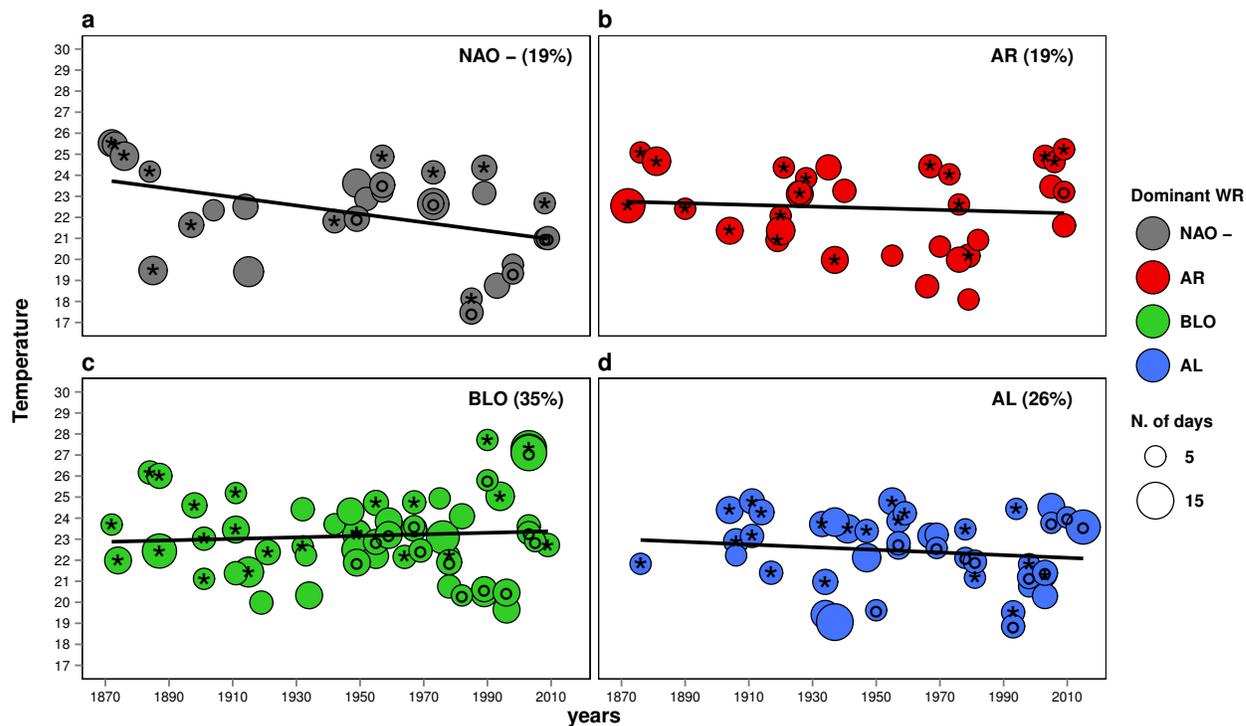


Figure S 7. Dominant weather regimes during Summer Heatwave events in Western-Europe. Summer heatwave events (P90th Percentile) from 1871 to 2015 for different reanalysis products: 20CR (circle with stars), ERA20C (empty circle), and NCEP (circles with inner circle). Colors correspond to the dominant Weather regime (a-d,) in each event, temperature (y-axis) and years (x-axis). Circle sizes depend on the event duration by number of days, the larger the longer duration. Percentages show the frequency of each weather regime. Linear fits are shown in black solid lines.

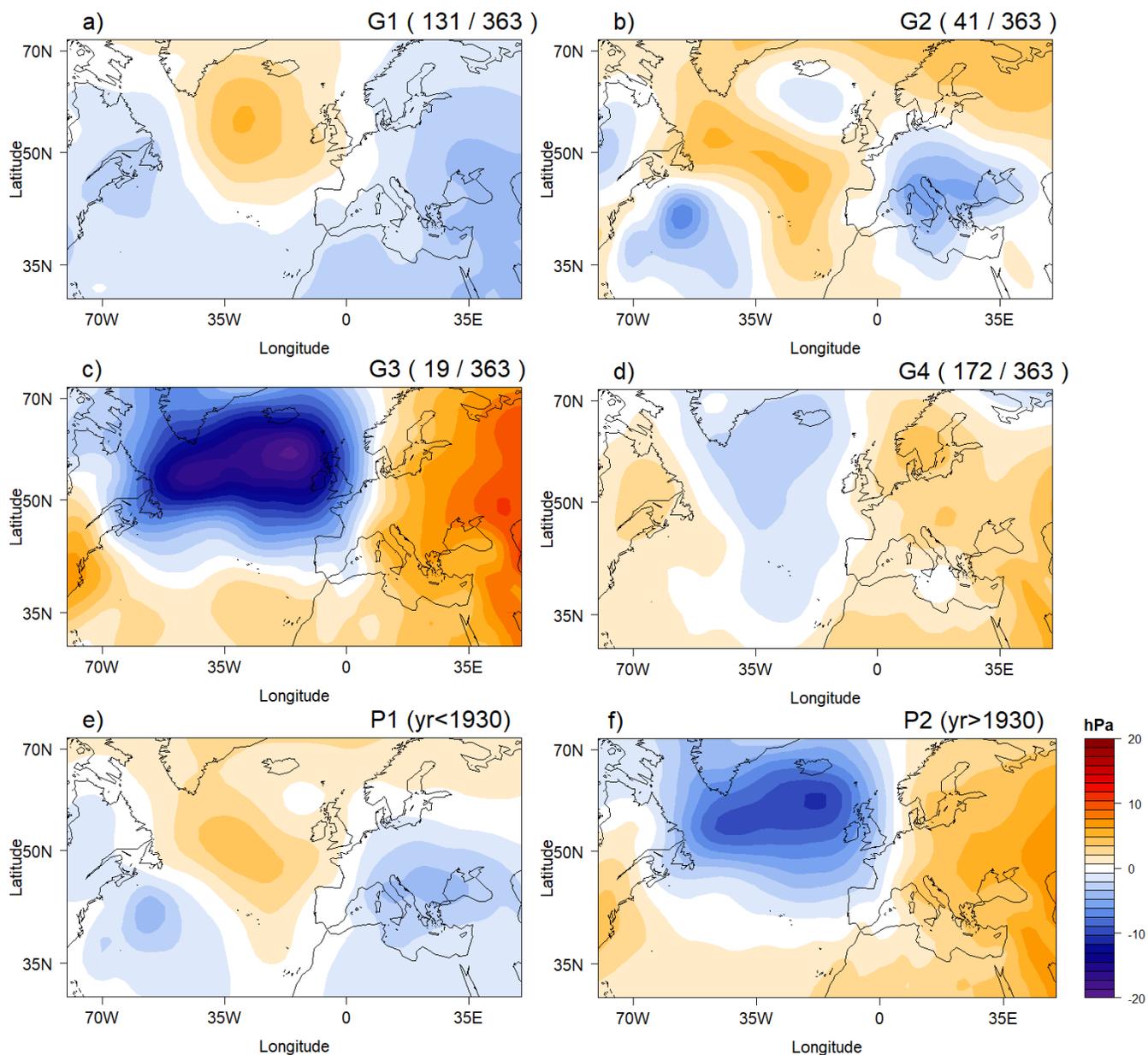


Figure S 8. mean SLP anomalies in heatwave events (20CRv2c EM) for each period. As figure 6, a-d show mean SLP anomalies in heatwaves events for each group of years. Numbers at the top right corner represent the number of heatwave events during that period in comparison with the total number of heatwave events in 20CRv2c EM. Mean SLP anomalies in heatwaves events pre-1930 and post-1930 are represented in e-f, respectively.

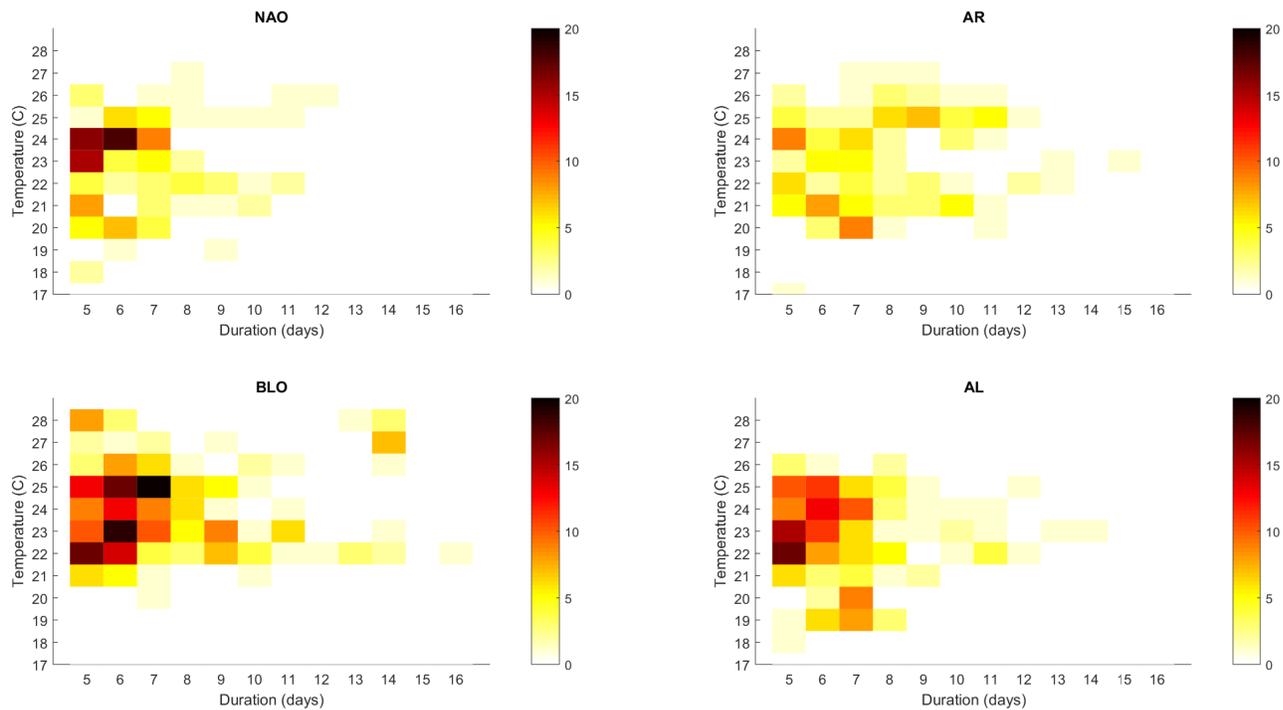


Figure S 9. Density plot of heatwave events. Temperature (y-axis) vs numbers of days (x-axis) during each heatwave event for the 20CR Ensemble Mean (1871-2011) weather regimes. Colors represent the number of hetwaves events.

Abs_{RMSE}	Period	NAO-	AR	BLO	AL
NCEP	(1970-2010)	1.01	1.00	0.98	0.99
	(1948-2015)	1.01	1.0	1.01	1.00
ERA 20C	(1900-1936)	0.95	0.99	0.96	0.97
	(1937-1973)	1.03	0.99	1.01	1.01
	(1974-2010)	1.03	1.01	1.03	1.03
20CR	(1871-1917)	0.94	1.01	1.00	0.99
	(1918-1964)	1.03	0.98	1.02	1.01
	(1965-2011)	1.04	1.01	0.99	1.01

Table S 1. Absolute error of the Root mean square deviation (Abs_{RMSE}) of the truncated EOFs during the training period(NCEP:1970-2010) by Weather Regimes during summer in Western-Europe (see also Figure S1)