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1 **Heat extremes in Western Europe increasing faster than simulated** 2 **due to atmospheric circulation trends**

3

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23 **Abstract**

24 **Over the last 70 years, extreme heat has been increasing at a disproportionate rate in**
25 **Western Europe, compared to climate model simulations. This mismatch is not well**
26 **understood. Here, we show that a substantial fraction (0.8°C [0.2°-1.4°C] of 3.4°C per**
27 **global warming degree) of the heat extremes trend is induced by atmospheric circulation**
28 **changes, through more frequent southerly flows over Western Europe. In the 170**
29 **available simulations from 32 different models that we analyzed, including 3 large model**
30 **ensembles, none have a circulation-induced heat trend as large as observed. This can be**

31 due to underestimated circulation response to external forcing, or to a systematic
32 underestimation of low-frequency variability, or both. The former implies that future
33 projections are too conservative, the latter that we are left with deep uncertainty
34 regarding the pace of future summer heat in Europe. This calls for caution when
35 interpreting climate projections of heat extremes over Western Europe, in view of
36 adaptation to heat waves.

37

38 Introduction

39

40 Extreme heat has been increasing at global scale [1,2], with a rapid rate in several regions. In
41 Western Europe [3], summer temperatures and heat extremes have warmed much faster than
42 elsewhere in the mid-latitudes over the last two decades [3,4]. As a consequence, several
43 unprecedented heatwaves took place in the last 20 years. In 2003, the full summer season mean
44 temperature was unprecedented in Europe [5]. Northwestern Europe was hit by record
45 temperatures in 2018 [6,7]. In 2019, two short (3-day) but intense heat waves saw all-time
46 temperature records broken in many places, associated with a rapid northward advection of
47 Saharan air [6]. All-time records were broken again in 2022, with temperatures above 40°C
48 reaching far north (eg. Brittany, U.K.) [8]. Unprecedented, and even record-shattering extremes
49 are plausible in climate projections [9], but the pace of their increasing magnitude in Western
50 Europe is generally not predicted by these climate models, as well as trends in mean summer
51 temperatures [4, 10-13].

52

53 Here we focus on summer (JJA) maximum and mean of daily maximal temperatures (resp.
54 denoted hereafter TXx and TXm for simplicity), and the regional amplification of their trends
55 relative to the global temperature trend. Trends in TXx and TXm are calculated over the 73-
56 year 1950-2022 period using a linear regression with the Global mean Surface Air Temperature
57 (GSAT, see methods section) from ERA5, and are expressed in °C per global warming degree
58 (GWD). As shown in Figure 1 and Supplementary Fig. 1, both ERA5 reanalyses [14] and E-
59 OBS interpolated observations [15] exhibit trends reaching more than 5°C/GWD for TXx in
60 northern France and Benelux. Over the limited area spanning 5W-15E; 45N-55N (blue box,
61 called hereafter “Western Europe”), the land area-average TXx trend is 3.4°C/GWD for ERA5
62 and E-OBS [2.4 - 4.3°C/GWD]. It exceeds the more moderate TXm trends by about 40% for
63 ERA5 (2.4°C/GWD [1.7 - 3.0°C/GWD] and 30% for E-OBS (2.6°C/GWD [1.9 -
64 3.3°C/GWD]). These rapid warming trends are exceptional on a global scale: The 20°x10°

65 Western Europe region has the highest TXx (all year round) trend of all regions of the same
66 size around the globe between 75°S and 75°N shifted by steps of 5° (including sea points).

67

68 A variety of processes have been proposed for explaining these overproportional warming
69 trends with respect to global temperature change. For mean summer temperatures, changes in
70 mean atmospheric circulation [16,17], changes in aerosol [18] and changes in early summer
71 soil moisture [19] and related feedbacks were considered for explaining (part of) the trends.
72 For extreme heat, the increase in the frequency and persistence of split midlatitude jet states
73 over the last 40 years, possibly associated with the reported weakening of the mean summer
74 zonal circulation [20], can explain about a third of the amplified trend in heatwave intensity
75 [3]. Changes in atmospheric circulations around Europe that favor heat were also emphasized
76 [21,22], in particular a positive trend in a dipole structure with a low pressure over the Eastern
77 Atlantic [23,24] and a high pressure over the Mediterranean extended towards central Europe
78 [25]. Yet, no increasing trend was found in blocking over Scandinavia that has led to the 2018
79 heat wave [6,26]. Moreover, reported changes in Rossby waves are not robust and are sensitive
80 to their exact definition [27]. In addition, variability of summer temperatures has been shown
81 to be large in Central Europe [28]. Thus, while several studies have hinted at a potential role
82 of dynamical changes in amplifying European heat waves, a systematic analysis is lacking,
83 including also how models simulate these changes.

84

85 **Results and discussion**

86

87 **Role of dynamical changes in the temperature trends**

88 We used a method based on circulation analogues to assess the role of dynamical changes in
89 the TXx and TXm trends (see the methods section for a full description). Regional atmospheric
90 circulation patterns are characterized by their 500 hPa streamfunction over the domain shown
91 in Fig. 1a (black box). We identify circulation analogues for a given day by searching for other
92 summer dates (JJA months) with similar anomaly structures, measured by the spatial anomaly
93 correlation coefficient (ACC). A set of dates with circulation analogues allows us to calculate
94 statistics conditionally to a given circulation [29-32], or to assess the role of dynamical changes
95 in circulation-conditioned variables [33,34].

96

97 In order to estimate the contribution of dynamical changes to TXx and TXm trends (called
98 hereafter the “dynamical TXx and TXm trends”), we replace each daily temperature field by

99 the temperature field from a different day that had the best analogue circulation. In the absence
100 of long-term trends in circulation, this is equivalent to shuffling the temperature time series
101 while keeping the dynamics, thereby creating a trend-free “analogue temperature time series”.
102 In the presence of long-term circulation trends, the trend in the analogue temperature time
103 series comes from the changes in circulations (e.g. an increase in circulations favorable to heat,
104 or vice versa). Replacement by analogues should in principle remove thermodynamical effects
105 from global warming. As global warming is not homogeneous across the time period, and to
106 ensure analogue regional temperatures represent a given global warming level, we further apply
107 a correction by scaling all analogue temperatures to a reference year for global warming (2022)
108 (see Methods). We verified that results were similar in both cases (with and without scaling).

109
110 The dynamical TXx trend (Fig 1b) is generally positive over Western Europe and reaches about
111 $1.5^{\circ}\text{C}/\text{GWD}$ in several areas. The dynamical TXm trend is found to exceed $1^{\circ}\text{C}/\text{GWD}$ over
112 Southwestern Europe (Fig 1d). Over Western Europe, the average TXm and TXx dynamical
113 trends are respectively $0.74^{\circ}\text{C}/\text{GWD}$ [$0.26\text{-}1.21^{\circ}\text{C}/\text{GWD}$] and $0.79^{\circ}\text{C}/\text{GWD}$ [0.24-
114 $1.35^{\circ}\text{C}/\text{GWD}$]. For E-OBS the dynamical trends are $0.78^{\circ}\text{C}/\text{GWD}$ [$0.27\text{-}1.29^{\circ}\text{C}/\text{GWD}$] and
115 $0.86^{\circ}\text{C}/\text{GWD}$ [$0.29\text{-}1.43^{\circ}\text{C}/\text{GWD}$] for TXm and TXx respectively.

116
117 We verify these findings on the dynamical contributions to extreme temperatures trends with a
118 second method, called “dynamical adjustment” [35]: The method uses a spatial circulation field
119 (here: z500 for consistency with previous studies) as a proxy in order to estimate the
120 contribution of circulation to temperature variability. Here, we use ridge regression, a linear
121 regression technique that regularizes the coefficients of the high-dimensional circulation
122 predictors [36], and we subsequently evaluate the dynamical contribution of z500 to the
123 Western Europe TXx trends and averaged results over Western Europe (see method details in
124 the Methods section). Results are consistent with the analogue approach (Supplementary
125 Figure 2), although with a slightly weaker dynamical TXx trend of $0.56^{\circ}\text{C}/\text{GWD}$.

126
127 To test the sensitivity of our results to the analogue domain, we performed sensitivity
128 experiments by extending and reducing the domain by 10° longitude and 5° latitude (leaving
129 about $\frac{2}{3}$ or more of the domain common with the reference one). The dynamical trend is
130 significant and within $0.5^{\circ}\text{C}/\text{GWD}$ and $0.9^{\circ}\text{C}/\text{GWD}$, except when reducing the domain towards
131 the North-Eastern part ($20\text{W}\text{-}20\text{E}; 35\text{N}\text{-}60\text{N}$), (dynamical tendency reduced to $0.38^{\circ}\text{C}/\text{GWD}$) a
132 probable consequence of the key role of the upstream part of the pattern.

133

134 Further, we investigate the specific streamfunction patterns associated with summer maximum
135 extreme temperatures over central France [1.5E;46.5N] – i.e., a region where the TXx
136 dynamical trend is large (see Fig. 1). We select the reference date (29/06/2019) for which the
137 streamfunction pattern (Fig. 2a) has a maximal average ACC (0.59) with other streamfunction
138 patterns occurring each year when maximal temperature (TXx) is reached at this grid point, so
139 it is most representative of those “TXx days”. We find that about 15% of the summer days in
140 total have an ACC larger than 0.5 with the 29/06/2019 pattern, and that 53 out of 72 other TXx
141 patterns also correlate by more than 0.5. For the sake of simplification, we will refer this class
142 of patterns as the “Southerly Flow” patterns (SF), since almost all of the patterns bear a positive
143 west-east streamfunction gradient (eg. 99% of patterns when considering the gradient between
144 15°W and 5°E at 50°N), inducing southerly flows over the Western margin of Europe. This
145 pattern also includes a strong anticyclonic component over Central Europe, which induces
146 increased radiation and potential land-atmosphere feedbacks if persistent. As another example,
147 the outstanding temperatures in London on 19/07/2022 were also obtained with a similar
148 circulation pattern (ACC=0.81 with 29/06/2019). To assess sensitivity to the reference pattern
149 we also repeat all calculations with the 10 most representative TXx patterns (Supplementary
150 Figure 3) in the above sense. In these other cases, the frequency of associated correlated flows
151 is within the 10-20% range.

152

153 To check how the SF days contribute to the dynamical trend, we recalculated the dynamical
154 trend excluding the SF days: we removed SF days from the time series, calculated the analogue
155 temperatures of remaining days, the resulting yearly TXx, and recalculated the dynamical
156 trend. We also did the opposite operation by keeping only SF days in the time series. On
157 average over Western Europe (Figure 2b), the dynamical TXx trend without SF patterns
158 becomes insignificant over Western Europe (0.08°C/GWD on average over Western Europe),
159 while the SF-only TXx dynamical trend is both high and statistically significant (1.3°C/GWD).
160 Similar results are found when using a different reference date among the 10 most
161 representative patterns. Dynamical TXx trends over Western Europe can therefore largely be
162 explained by changes in the characteristics of SF patterns. First, their frequency has increased
163 by 43% [10%;76%] per GWD (52% with time between 1950 and 2022) (see Supplementary
164 Table 1). Second, the number of “events” (one event is defined here as a set of consecutive
165 days) per year and their mean persistence have increased (see Supplementary Figure 4). The
166 persistence of SF patterns has increased by about 24% along the period [-1%, +50%] as a

167 function of GWD. Such changes all give more chance, within a season, to reach the high end
168 of the conditional temperature distribution. Other characteristics may also have changed (eg.
169 amplitude) but were not investigated here. Significant frequency increases are also found for
170 at least the 10 most representative patterns of Supplementary Figure 3, with rates in the range
171 of 35% to 55%.

172

173 Note that SF is not the only flow pattern changing, and not all patterns associated with TXx
174 days have an increasing frequency or persistence. For instance, the 23/07/2021 pattern,
175 corresponding with summer TXx in central France for 2021, shows no particular evolution
176 (Supplementary Fig. 4). Our results are also consistent with the increase in occurrence and
177 persistence of the specific class of double jet circulations explaining a large fraction of
178 European heat extremes [3], and about half (i.e., much more than the mean probability, 15%)
179 of double-jet days are found within the SF days.

180

181 **Simulated temperature trends and their dynamical contributions**

182

183 The representation of summer TXx and TXm trends has also been analyzed for a large number
184 of CMIP6 model simulations (273 simulations in total for 36 models) (see Methods section for
185 data processing). Over Western Europe, almost all CMIP6 simulations fail to simulate the
186 observed strong TXx trends, as seen in Figure 3a, plotting the percentage of simulations with
187 larger trends than observed, for each grid point. These differences are less pronounced for TXm
188 (Fig. 3b) but the number of runs reaching the ERA5 trend remains small here too (10-20% in
189 large parts of South-Western Europe). There are also other land areas outside Western Europe
190 where the CMIP6 simulations are mostly above the observed warming TXx trend (i.e. Sahara,
191 Northern Scandinavia, Southern Balkans). This suggests that there is no general
192 underestimation of extreme heat trends over all regions (or land regions). However,
193 understanding these regional discrepancies across the globe is beyond the scope of this article.

194

195 When averaging TXx trends over the Western Europe region above defined, only 4 of the 273
196 individual runs analyzed (members of 3 models out of 36, ACCESS-ESM1, NorESM2-LM and
197 KIOST-ESM) have a larger trend than the observations. The strong TXx trends observed
198 correspond to the ~98-99th percentile of the overall CMIP6 distribution and could, from a
199 statistical standpoint, be interpreted as consistent with Western Europe witnessing a very
200 unlikely phase of low-frequency internal variability. However, in the five large model

201 ensembles that were at our disposal (eg. ACCESS-ESM1-5, CanESM5, IPSL-CM6-LR,
202 MIROC6, MPI-ESM1-2-LR), only ACCESS-ESM1-5 has a few members for which TXx
203 warms as rapidly as observed (Figure 3c), but this ensemble strongly overestimates the TXm
204 trend (Figure 3d). Hence, this ensemble does not correctly estimate the daily maximum
205 temperature distribution as observed in ERA5.

206

207 Our results are qualitatively robust to the way trends are calculated. We estimated trends
208 relative to time instead of GWD, and to each model initial-condition ensemble mean GWD
209 instead of individual member GWD. In the first (resp. second) case, 9 (resp. 5) simulations
210 (from 4 different models) slightly exceed the ERA5 TXx trend. Trends relative to time allowed
211 in particular two members of CanESM5 to reach observations thanks to the strong global
212 warming (about 1.7°C since 1950), while the regional response to global warming (the regional
213 trend as a function of GWD is about twice weaker than in ERA5.

214

215 We also implemented a multiple testing procedure, the False Discovery Rate [37-39], to test
216 the significance of the result in Western Europe. Under the hypothesis that "models are
217 indistinguishable from reality", the rank of the observed TXx and TXm trends in the
218 distribution of members is uniform and there can be regions over which the observation falls
219 outside the model range only by chance. Supplementary Figure 5 shows that even taking into
220 account the multiple nature of the test, Western Europe is among the regions where the
221 mismatch between observed and simulated TXx trends is significant at the 95% confidence
222 level in the sense of the FDR procedure, while no significant mismatch is found in this region
223 for TXm trends.

224

225 Climate simulations do not capture the dynamical changes underlying these temperature
226 extreme changes. We applied the analogue analysis to all available realizations for each model
227 for which 500 hPa wind fields were available (170 simulations in total). This set was found to
228 be rather representative to the overall simulation distributions, albeit with more weight on
229 faster-warming simulations (see Figure 3a-b histograms) regarding TXx trends. None of their
230 dynamical TXx trends reach the amplitude of the observed one over Western Europe (Figure
231 4a). This shows that there is less than 1% chance that the observed trend estimate is drawn from
232 the same population as simulation estimates, accounting for all uncertainties. Remarkably, all
233 members of the three available large ensembles (ACCESS-ESM1-5 [40 members], IPSL-
234 CM6A-LR [31 members] and MPI-ESM1-LR [30 members]) exhibit values lower than

235 observed, despite a few members exceeding the overall TXx trend. Also, on average over
236 Western Europe, for TXm, a handful of models do have dynamical trends comparable to or
237 larger than observations, but all others exhibit lower trends (Supplementary Figure 6).

238

239 We also calculated the thermodynamical trend obtained as a residual by subtracting the
240 dynamical trend from the total trend and reported the result in Figure 4b. This shows that
241 climate models exhibit thermodynamical contributions that are broadly consistent with ERA5,
242 but there is a tendency for an underestimation of TXx thermodynamical trends, and a general
243 agreement for TXm trends (see Supplementary Figure 6). This analysis clearly shows that
244 dynamical changes are largely responsible for the mismatch between modeled and observed
245 TXx trends.

246

247 All 170 climate simulations realistically simulate the climatological mean frequency of the SF
248 patterns (range from 12.5% to 18%). However, the rapid observed increase in frequency of this
249 flow field (+43%/GWD [10%-76%]) is only roughly captured by one among the 170
250 simulations (NorESM2-LM, and weaker in the others (Supplementary Table 1)).

251

252 **Discussion and conclusion**

253

254 Overall, our results show that, except for a very few of them, CMIP6 simulations do not capture
255 the rapid observed warming of extreme heat over Western Europe. The analysis of atmospheric
256 circulation changes shows that there is a large dynamical contribution to this observed trend,
257 which is underestimated in all the 170 climate simulations analyzed, explaining a large part of
258 the discrepancy in trend between models and observations. By contrast, models and
259 observational trends are broadly consistent in terms of the thermodynamic contribution to the
260 trend in mean temperatures. Although it cannot be completely ruled out, the systematic
261 mismatch between dynamical trends of 170 simulations and the observations, suggest that it is
262 unlikely due to pure chance under the assumption of perfect models. We cannot either rule out
263 other sources of systematic uncertainties such as lack of homogeneity of reanalyses, in
264 particular for circulation patterns, or inaccuracies in the aerosol and land use forcing changes
265 that would translate in systematic model/observation trend mismatches.

266

267 Determining the cause of model-observations dynamical trends mismatch is critical to assess
268 whether the large observed warming TXx trend is likely or unlikely to continue. If due to a

269 wrong forced dynamical regional response – models underestimate the forced response to
270 greenhouse gases – then this mismatch is expected to remain and even strengthen in the future,
271 as global warming increases. If related to unforced internal variability [40,41] – internal
272 variability simulated by models is too small [42] – then the mismatch is expected to decrease
273 in the future, but the term of this decrease is unknown and could be years or decades, leaving
274 the fate of Western Europe heatwaves in large uncertainty.

275

276 Here we have shown that the observed extreme temperature trends for Western Europe are
277 weaker in CMIP6 simulations than in observations, largely due to model dynamical trends
278 systematically weaker than the observed ones. Similar conclusions were found for wintertime
279 weather over Europe [43]. Note that there are also other regions on Earth where model TXx
280 trends have large excursions from ERA5, but our study focused on Western Europe. Further
281 research is needed to determine the causes of the mismatch between simulated and observed
282 heat trends, whether this is due to uncaptured internal variability or missing (dynamical)
283 forcing/processes. Either way, our results call for caution when using climate model projections
284 for adaptation and resilience plans.

285

286

287 **Methods**

288 **Calculation of dynamical contributions to mean and extreme summer temperature**
289 **trends:** The method used to estimate dynamical contribution to the change in one variable
290 follows the conceptual framework developed in Vautard et al. (2016), with a different
291 implementation here. It is based on the estimation of the change in the variable solely due to
292 the changes in regional upper-air circulations. For instance, even without extra heating from
293 radiative and diabatic processes, an increase in the frequency of southerly flows in Western
294 Europe would induce a mean regional warming. An increase in anticyclonic conditions would
295 similarly lead to increased radiation and thus temperature. This can also lead to a cooling if
296 increasingly frequent circulations are linked to cooler temperatures (eg. in Northerly winds).
297 To estimate this dynamical effect of changing circulations on temperatures, we need to
298 carefully remove any thermodynamical effect of climate change.

299

300 We assume that daily temperature T (which can be mean, minimum or maximum daily
301 temperature, and in the current article will be maximum temperature) has a distribution at a
302 given location or grid point which depends on the atmospheric circulation and on other
303 processes, including global warming. We then assume a decomposition into:

304

$$305 \quad T = \langle T|X \rangle_{GWD} + T' \quad (1)$$

306

307 where X is the 500 hPa streamfunction anomaly, characterizing the atmospheric circulation
308 (simultaneous to the temperature), GWD stands for the global warming degree, $\langle T|X \rangle_{GWD}$ is
309 the average daily maximum temperature conditioned to the circulation, assumed to be
310 dependent on GWD , and T' is a fluctuation. This circulation-conditioned temperature includes
311 not only advection effects (i.e. from cooler/warmer regions), but also all processes linked to
312 the circulation (subsidence in anticyclone, increased radiation, surface-atmosphere feedbacks,
313 ...), so the overall dynamical trend includes all underlying processes tied to the dynamical
314 conditions. In order to remove thermodynamical effects due to climate change, we scale all
315 temperatures to a reference warming level. For this, we assume that the circulation-conditioned
316 mean temperature depends linearly on the global warming level, so the decomposition can be
317 written:

318

$$319 \quad T = \langle T|X \rangle_{ref} + b(X) \cdot (GWD - GWD_{ref}) + T' \quad (2)$$

320

321 where *ref* refers to a reference global warming level, taken here as that of 2022, so all changes
322 are expressed relative to 2022. The coefficient $b(X)$ represents the mean warming rate
323 conditioned to the circulation X , which includes thermodynamical effects of the climate change
324 response – it is therefore assumed that the amount of warming depends on the circulation type.
325 Assuming one can calculate $b(X)$ and GWD , all daily temperatures are then scaled to the
326 reference level with the following thermodynamical correction:

327

$$328 \quad T_s = T - b(X) \cdot (GWD - GWD_{ref}) \quad (3)$$

329

330 The dynamical contribution to any temperature trend constructed from daily temperatures (eg.
331 here TXm, TXx) can then be calculated from the T_s time series, because changes with GWD
332 are only through the changes in the frequency of occurrences of X for given GWD s. Trends
333 should also not depend on the particular time T_s values are drawn as long as they occur
334 simultaneously to a streamfunction anomaly which is similar to that encountered in the same
335 sequence order as that of the series. Hence to increase statistical robustness and remove any
336 residual link to the specific order of temperatures, we replace T_s temperatures by those
337 occurring in circulations X along the time series. This has the advantage of “randomizing” the
338 timing of analogues and providing multiple realizations to calculate dynamical trends. A new
339 temperature analogue series is created by replacing each daily with that of the best circulation
340 analogue, then another new series is made with the second best analogue, etc... (see below for
341 practical analogue calculation). From each of these analogue time series, TXm and TXx are
342 recalculated for each year, then averaged across analogues, and a regression with GWD is
343 calculated at each grid point, together with its confidence interval, (plus or minus twice the
344 standard error of the regression coefficient). To keep analogue quality high, we limit the
345 number of time series to 3. To calculate time series of averages over Western Europe land, we
346 apply the $0.5^\circ \times 0.5^\circ$ land mask of E-OBS and average over the grid points included in [-5W -
347 15E ; 45N - 55N]

348

349 **Estimation of yearly GWD** : In practice, GWD is calculated as a moving centered 5-year
350 average of the global temperature with available data, for reanalyses and models, accounting
351 for series ends in ERA5 (i.e. for 1950, taking into account an average only over 1950 to 1952,

352 and for 2022 an average over 2020 and 2021). The 2022 value is then subtracted to all values,
353 so GWD is 0 in 2022, and generally negative before.

354

355 **Selection of circulation analogues :** In practice, circulations are characterized by the 500 hPa
356 streamfunction over the [-30 +20°E ; 30 60°N] domain. Analogs of a given circulation are
357 characterized by anomaly correlation coefficient (ACC) between streamfunction fields. For
358 each summer day, we collect the best analogues (highest ACCs), and impose that they remain
359 spaced by 6 days or more within a season, and self-analogues are not considered. This is done
360 by successively testing fields in descending order of the ACC, and skipping days not respecting
361 the separation with previously selected fields.

362

363 **Calculation of the circulation-conditioned thermodynamical trend $b(X)$:** To calculate
364 $b(X)$, we also use analogue circulations, in a different way than above: For each summer day d
365 of the 1950-2022 period, we estimate $b(X(d))$ using a regression of each raw temperature $T(d)$
366 (before thermodynamical correction) associated with a large set of best analogue circulations
367 of $X(d)$ found between 1950 and 2022 with the GWD values of their respective year. We use
368 the best 1% summer analogues (67 days) with the same spacing of at least 6 days. 99% of the
369 worst of these 67 analogues across all summer days have $ACC > 0.5$, 65% have $ACC > 0.7$.
370 Imposing a quality criterion on analogues such as $ACC > 0.7$ or more would leave days with an
371 insufficient number of analogues for regression.

372

373 **Dynamical adjustment:** Dynamical adjustment is used as a second, alternative technique to
374 estimate the influence of circulation-induced temperature trends. This method relies on the idea
375 that temperature variability can be decomposed into a component that is driven by circulation-
376 induced variability, and a residual, thermodynamical component. The “thermodynamical”
377 component is expect to contain a forced signal as well as any other unexplained variability or
378 feedbacks [44]. Most applications of this technique characterize circulation-induced
379 temperature variability using a proxy variable such as geopotential height [35,36,45,46].
380 Dynamical adjustment techniques typically rely on linear methods such as variants of linear
381 regression or circulation analogue techniques.

382

383 Here, we use the spatial pattern of $z500$ in a relatively large circulation domain over Europe
384 and the North Atlantic (-30 to 20°E, 30 to 60°N, similar to Fig. 1), following the method
385 outlined in [47]. However, we introduce some modifications and additional details. We use a

386 regularized regression technique, called “ridge regression”, which is well-suited to deal with
387 the large number of circulation predictor grid cells and a relatively short observed record. For
388 TXx, we train our ridge regression model on the 15 warmest days in each summer during 1950-
389 2021 at each grid cell in the ERA5 reanalysis, resulting in a total of 1080 observations (72
390 summers and 15 days per summer). Since the z500 field contains information about the lower
391 troposphere, and is affected by temperature change via thermal expansion, we detrend the
392 spatial z500 field by subtracting the global average z500 at each time step and over each grid
393 cell in the circulation domain. Hence, the analysis is based only on relative changes within the
394 z500 field. To obtain regional estimates of the circulation-induced component of TXx, we
395 performed an area-weighted average across the grid cells within the study domain.

396

397

398 **Data availability**

399

400 All analyzes have been conducted using 3 main data sets. The ERA5 reanalysis and the E-OBS
401 data sets (processed from the <https://climate.copernicus.eu>) has been downloaded, and are
402 available from the Climate Explorer <https://climexp.knmi.nl>. CMIP6 model simulations are
403 available from the IPSL ESGF node <https://esgf-node.ipsl.upmc.fr/>.

404

405 **Code availability**

406

407 Codes used in this article develop classical statistical algorithms, and are available upon
408 request. Application codes are provided in the archive: <https://zenodo.org/record/8310140>

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414 **References**

415 [1] Seneviratne, S.I., et al. [Masson-Delmotte, et al. (eds.)]. Cambridge University Press,
416 Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766 (2021).

417

418 [2] Robinson, A. et al. Increasing heat and rainfall extremes now far outside the historical
419 climate. *npj Clim Atmos Sci* 4, 45 (2021).

420

421 [3] Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. Accelerated
422 western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature*
423 *communications*, 13(1), 1-11 (2022).

424

425 [4] van Oldenborgh, et al. Western Europe is warming much faster than expected, *Clim. Past*,
426 5, 1–12, <https://doi.org/10.5194/cp-5-1-2009> (2009).

427

428 [5] García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., & Fischer, E. M. A review of the
429 European summer heat wave of 2003. *Critical Reviews in Environmental Science and*
430 *Technology*, 40(4), 267-306 (2010).

431

432 [6] Yiou, P., et al. Analyses of the Northern European summer heatwave of 2018. *Bulletin of*
433 *the American Meteorological Society*, 101(1), S35-S40 (2020).

434

435 [7] McCarthy, M., Christidis, N., Dunstone, N., Fereday, D., Kay, G., Klein-Tank, A., ... &
436 Stott, P. Drivers of the UK summer heatwave of 2018. *Weather*, 74(11), 390-396 (2019).

437

438 [8] [https://www.worldweatherattribution.org/without-human-caused-climate-change-](https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/)
439 [temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/](https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/) , 2022

440

441 [9] Fischer, E.M., Sippel, S. & Knutti, R. Increasing probability of record-shattering climate
442 extremes. *Nat. Clim. Chang.* 11, 689–695 (2021).

443

444 [10] van Oldenborgh, et al. Attributing and projecting heatwaves is hard: we can do better.
445 *Earth's Future*, 10(6), e2021EF002271 (2022).

446

- 447 [11] Vautard, R., et al. Human contribution to the record-breaking June and July 2019
448 heatwaves in Western Europe. *Environmental Research Letters*, 15(9), 094077 (2020).
449
- 450 [12] Ribes, A., et al. An updated assessment of past and future warming over France based on
451 a regional observational constraint. *Earth System Dynamics Discussions*, 1-29 (2022).
452
- 453 [13] Lorenz, R., Stalhandske, Z., & Fischer, E. M. Detection of a climate change signal in
454 extreme heat, heat stress, and cold in Europe from observations. *Geophysical Research Letters*,
455 46(14), 8363-8374 (2019).
456
- 457 [14] Hersbach, H., et al. The ERA5 global reanalysis. *Quarterly Journal of the Royal*
458 *Meteorological Society*, 146(730), 1999-2049 (2020).
459
- 460 [15] Cornes, R. C., van der Schrier, G., van den Besselaar, E. J., & Jones, P. D. An ensemble
461 version of the E-OBS temperature and precipitation data sets. *Journal of Geophysical Research:*
462 *Atmospheres*, 123(17), 9391-9409 (2018).
463
- 464 [16] Boé, J., et al. Past long-term summer warming over western Europe in new generation
465 climate models: role of large-scale atmospheric circulation. *Environmental Research Letters*,
466 15(8), 084038 (2020).
467
- 468 [17] Hoogeveen, J., & Hoogeveen, H. Winds are changing: An explanation for the warming of
469 the Netherlands. *International Journal of Climatology* (2022).
470
- 471 [18] Nabat, P., Somot, S., Mallet, M., Sanchez-Lorenzo, A., & Wild, M. Contribution of
472 anthropogenic sulfate aerosols to the changing Euro-Mediterranean climate since 1980.
473 *Geophysical Research Letters*, 41(15), 5605-5611 (2014).
474
- 475 [19] Stegehuis, A. I., et al. Early summer soil moisture contribution to Western European
476 summer warming. *Journal of Geophysical Research: Atmospheres*, 126(17), e2021JD034646
477 (2021).
478
- 479 [20] Coumou, D., Lehmann, J., & Beckmann, J. The weakening summer circulation in the
480 Northern Hemisphere mid-latitudes. *Science*, 348(6232), 324-327 (2015).

481
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499
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513

[21] Patterson, M. (2023). North-West Europe hottest days are warming twice as fast as mean summer days. *Geophysical Research Letters*, 50, e2023GL102757. <https://doi.org/10.1029/2023GL102757>

[22] Terray, L. A dynamical adjustment perspective on extreme event attribution. *Weather and Climate Dynamics*, 2(4), 971-989 (2021).

[23] Horton, D. E., et al. Contribution of changes in atmospheric circulation patterns to extreme temperature trends. *Nature*, 522(7557), 465-469 (2015).

[24] Faranda, D., Messori, G., Jézéquel, A., Vrac, M., Yiou, P.. Atmospheric circulation compounds anthropogenic warming and extreme climate impacts in Europe. *PNAS*, 2023

[25] Fery, L., Dubrulle, B., Podvin, B., Pons, F., & Faranda, D. Learning a weather dictionary of atmospheric patterns using Latent Dirichlet Allocation. *Geophysical Research Letters*, 49(9), e2021GL096184 (2022).

[26] Davini, P., & d'Andrea, F. From CMIP3 to CMIP6: Northern Hemisphere atmospheric blocking simulation in present and future climate. *Journal of Climate*, 33(23), 10021-10038 (2020).

[27] Kornhuber, K., et al. Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern. *Environmental Research Letters*, 14(5), 054002 (2019).

[28] Suarez-Gutierrez, L., Li, C., Müller, W. A., & Marotzke, J. Internal variability in European summer temperatures at 1.5 C and 2 C of global warming. *Environmental Research Letters*, 13(6), 064026 (2018).

[29] Yiou, P., Vautard, R., Naveau, P., & Cassou, C. Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe. *Geophysical Research Letters*, 34(21) (2007).

514 [30] Cattiaux, J., et al. Winter 2010 in Europe: A cold extreme in a warming climate.
515 Geophysical Research Letters, 37(20) (2010).
516

517 [31] Jézéquel, A., Yiou, P., & Radanovics, S. Role of circulation in European heatwaves using
518 flow analogues. *Climate dynamics*, 50(3), 1145-1159 (2018).
519

520 [32] Faranda, et al. A climate-change attribution retrospective of some impactful weather
521 extremes of 2021, *Weather Clim. Dyn.*, 3, 1311–1340, [https://doi.org/10.5194/wcd-3-1311-](https://doi.org/10.5194/wcd-3-1311-2022)
522 2022 (2022).
523

524 [33] Vautard, R., & Yiou, P. Control of recent European surface climate change by atmospheric
525 flow. *Geophysical Research Letters*, 36(22) (2009).
526

527 [34] Vautard, R., et al. Attribution of human-induced dynamical and thermodynamical
528 contributions in extreme weather events. *Environmental Research Letters*, 11(11), 114009
529 (2016).
530

531 [35] Deser, C., A. Phillips, M. A. Alexander, and B. V. Smoliak. Projecting North American
532 climate over the next 50 years: Uncertainty due to internal variability. *J. Climate*, 27, 2271–
533 2296 (2014).
534

535 [36] Sippel, S., et al. Uncovering the forced climate response from a single ensemble member
536 using statistical learning. *Journal of Climate*, 32(17), 5677-5699 (2019).
537

538 [37] Wilks, D. S. (2006). On “field significance” and the false discovery rate. *Journal of*
539 *applied meteorology and climatology*, 45(9), 1181-1189.
540

541 [38] Wilks, D. (2016). “The stippling shows statistically significant grid points”: How
542 research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin*
543 *of the American Meteorological Society*, 97(12), 2263-2273
544

545 [39] Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical
546 and powerful approach to multiple testing. *Journal of the Royal statistical society: series B*
547 *(Methodological)*, 57(1), 289-300.

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580

[40] Qasmi, S., Cassou, C., & Boé, J. Teleconnection between Atlantic multidecadal variability and European temperature: Diversity and evaluation of the Coupled Model Intercomparison Project phase 5 models. *Geophysical Research Letters*, 44(21), 11-140 (2017).

[41] McKinnon, K. A., & Deser, C. Internal variability and regional climate trends in an observational large ensemble. *Journal of Climate*, 31(17), 6783-6802 (2018).

[42] O'Reilly, C.H., Befort, D.J., Weisheimer, A. et al. Projections of northern hemisphere extratropical climate underestimate internal variability and associated uncertainty. *Commun Earth Environ* 2, 194 (2021). <https://doi.org/10.1038/s43247-021-00268-7>

[43] Blackport, R., & Fyfe, J. C. Climate models fail to capture strengthening wintertime North Atlantic jet and impacts on Europe. *Science Advances*, 8(45), eabn3112 (2022).

[44] Merrifield, A., F. Lehner, S.-P. Xie, and Deser, C. Removing circulation effects to assess central US land-atmosphere interactions in the CESM large ensemble. *Geophys. Res. Lett.*, 44, 9938–9946 (2017).

[45] Smoliak, B. V., J. M. Wallace, P. Lin, and Fu, Q. Dynamical adjustment of the Northern Hemisphere surface air temperature field: Methodology and application to observations. *J. Climate*, 28, 1613–1629 (2015).

[46] Saffioti, C., E. M. Fischer, and Knutti, R. Improved consistency of climate projections over Europe after accounting for atmospheric circulation variability. *J. Climate*, 30, 7271–7291 (2017).

[47] Sippel, S., Meinshausen, N., Fischer, E. M., Székely, E., & Knutti, R. Climate change now detectable from any single day of weather at global scale. *Nature climate change*, 10(1), 35-41 (2020).

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582

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587 Nasser and the ESPRI IPSL data and computing service for their support in handling the large
588 ensemble of climate simulations. The GMT v6.3 software is used for figure maps.

589

590 **Authors contributions**

591

592 R. V., J. C. and J. S. carried out the statistical analysis. T. H. provided the streamfunction fields
593 for ERA5 and the calculation method. R. B., C. C., D. C., F. D., D. F., E. F., A. R., S. S. and
594 P.Y. contributed to the design of the study and the interpretation of results. All authors
595 contributed to the writing of the article.

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597 **Competing interests**

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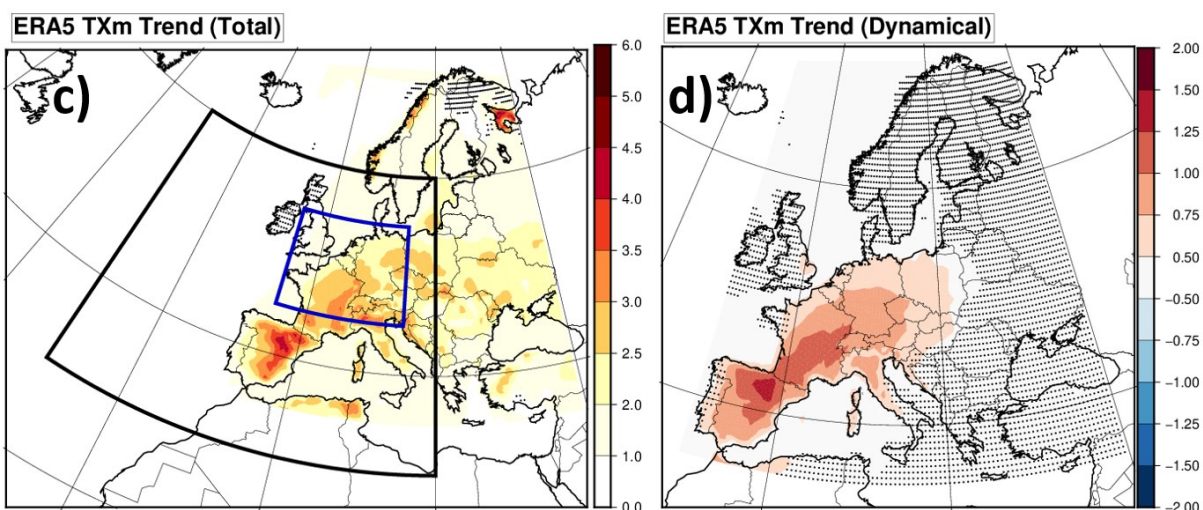
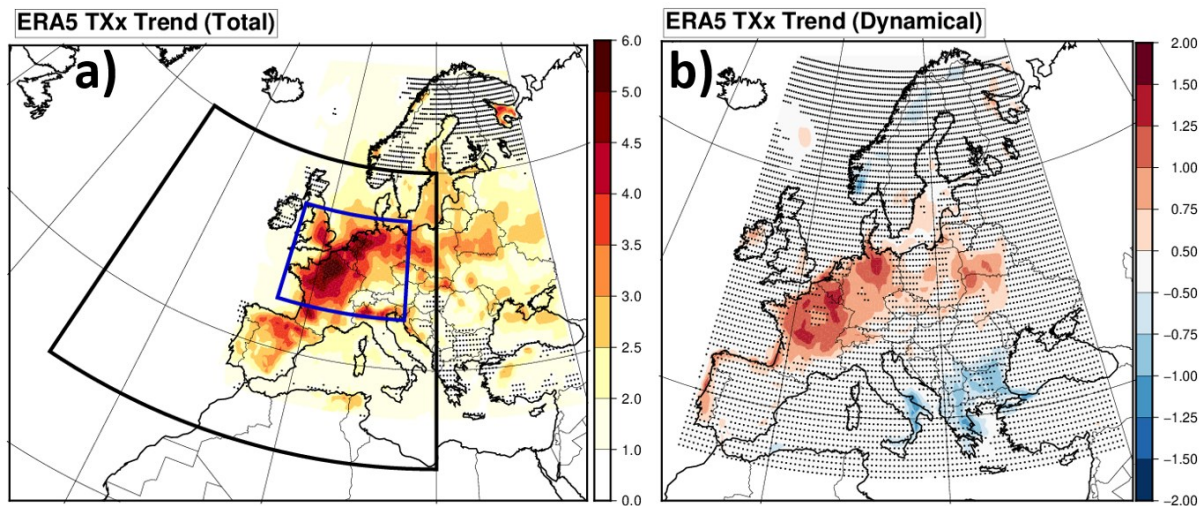
599 The authors declare no competing interest.

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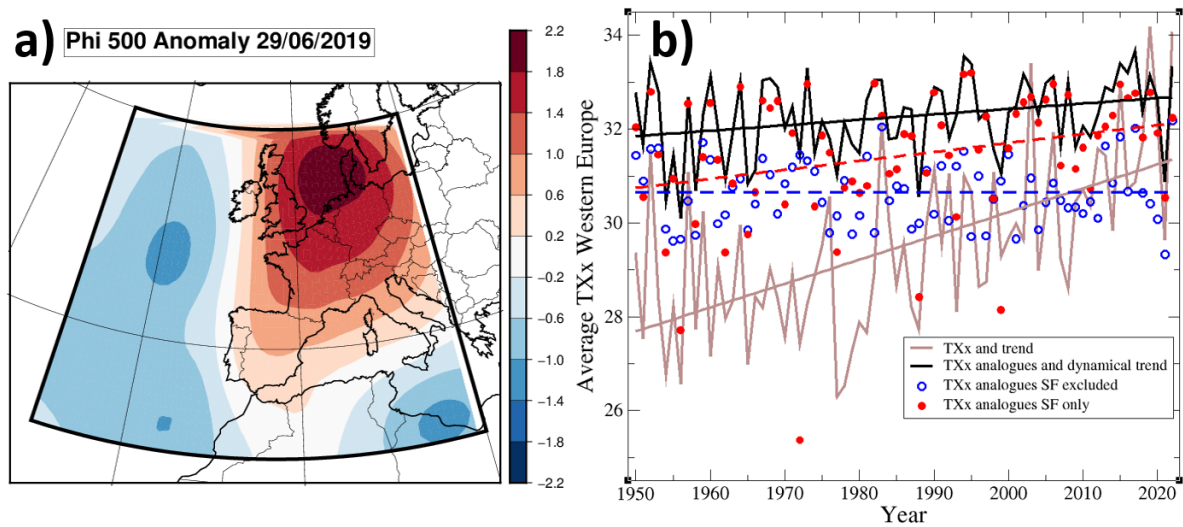
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609 **Figure 1: Total and dynamical contributions to extreme and mean TX trends**

610 ERA5 reanalysis temperature trends relative to the global warming level ($^{\circ}\text{C}/\text{GWD}$), for
 611 summer Maximum of maximal daily temperature (TXx) (a) and b)) and summer Mean of
 612 maximal daily temperature (TXm, c) and d)). The raw trend (a) and c)) is compared to the
 613 estimated dynamical contribution to these trends (b) and d)), obtained by replacing daily
 614 temperatures by those of best circulation analogues with a thermodynamic correction (see
 615 Methods). The areas highlighted are: (black box) the area used to calculate the anomaly
 616 correlation of 500 hPa streamfunction for the definition of analogues; the Western Europe focus
 617 area (blue box), where maximal daily temperature trends are averaged in this study. Dotted
 618 points show areas where statistical significance of trends is less than 95% (two sided). The

619 statistical test uses a 2-sigma rule for the regression coefficient, accounting for the total number
620 of well-separated analogues (see Methods).
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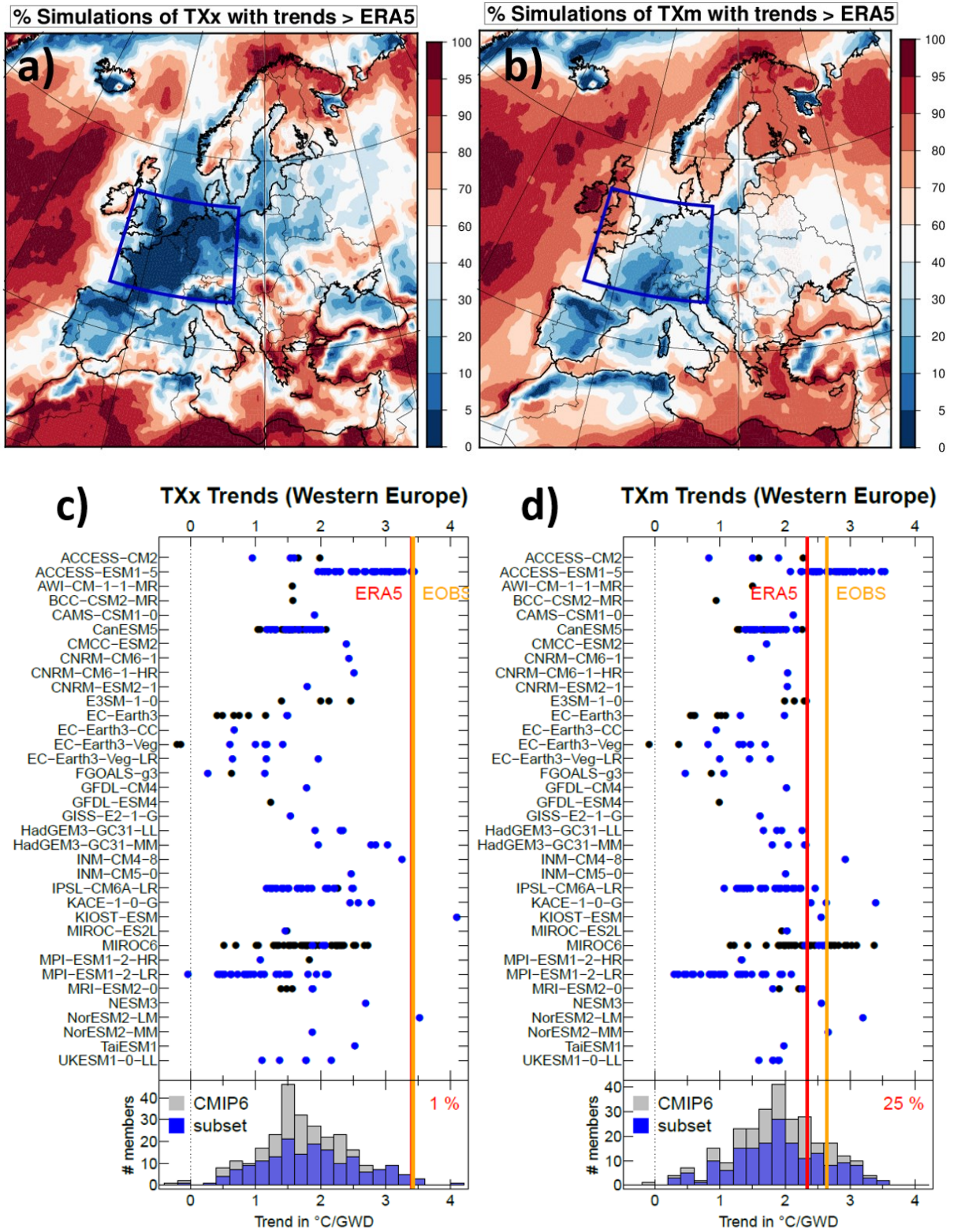


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625 **Figure 2: Southerly flow anomalies and their contributions to summer temperature**
626 **maxima**

627 a) 500 hPa Streamfunction anomaly (Phi 500) of the 29/06/2019; b) yearly time series of
628 the Western Europe average of Summer maximal temperature TXx (brown), the TXx
629 of the analogue time series, averaged over Western Europe and using the 3 best
630 analogues (black curve) (see Methods), and the corresponding time series obtained by
631 excluding (resp. including only) Southerly Flow (SF) pattern dates before calculating
632 the analogue TXx values (blue circles, resp. red circles). The sets of dates (SF dates or
633 SF excluded dates) within a year over which the yearly maximum is sought are therefore
634 complementary. In each case, analogues are calculated using the full set of patterns (i.e.
635 for SF excluded dates, analogues may contain SF patterns). Linear trends for all series
636 are also shown, with the same color as the series. The dashed trends are for SF-only or
637 SF-excluded cases.

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642 **Figure 3: Simulated vs. observed TX trends in Western Europe**

643 Comparison between the ECMWF reanalysis ERA5 and 273 CMIP6 simulations of trends in

644 Summer maximum summer of daily maximum temperature, TX, (TXx, panels a) and c)) and

645 summer mean summer TX (TXm, panels b) and d)) in °C/GWD represented in different ways;

646 top panels: percentage of simulations with a trend larger than ERA5 at each grid point; bottom
647 panels: representation of trends for model ensembles (dots) and observations (red and orange
648 lines) after averaging over Western Europe (5°W to 15°E ; 45°N-55°N); blue dots represent
649 the 170 simulations that were analyzed with the analogue approach. Histograms at the bottom
650 of the figure summarize the overall distribution of the TXx (left) and TXm (right) trends across
651 the 273 simulations considered, together with the (blue) part analyzed with the analogue
652 approach. Percentages of simulations with a trend larger than ERA5 are indicated in top right
653 corners.

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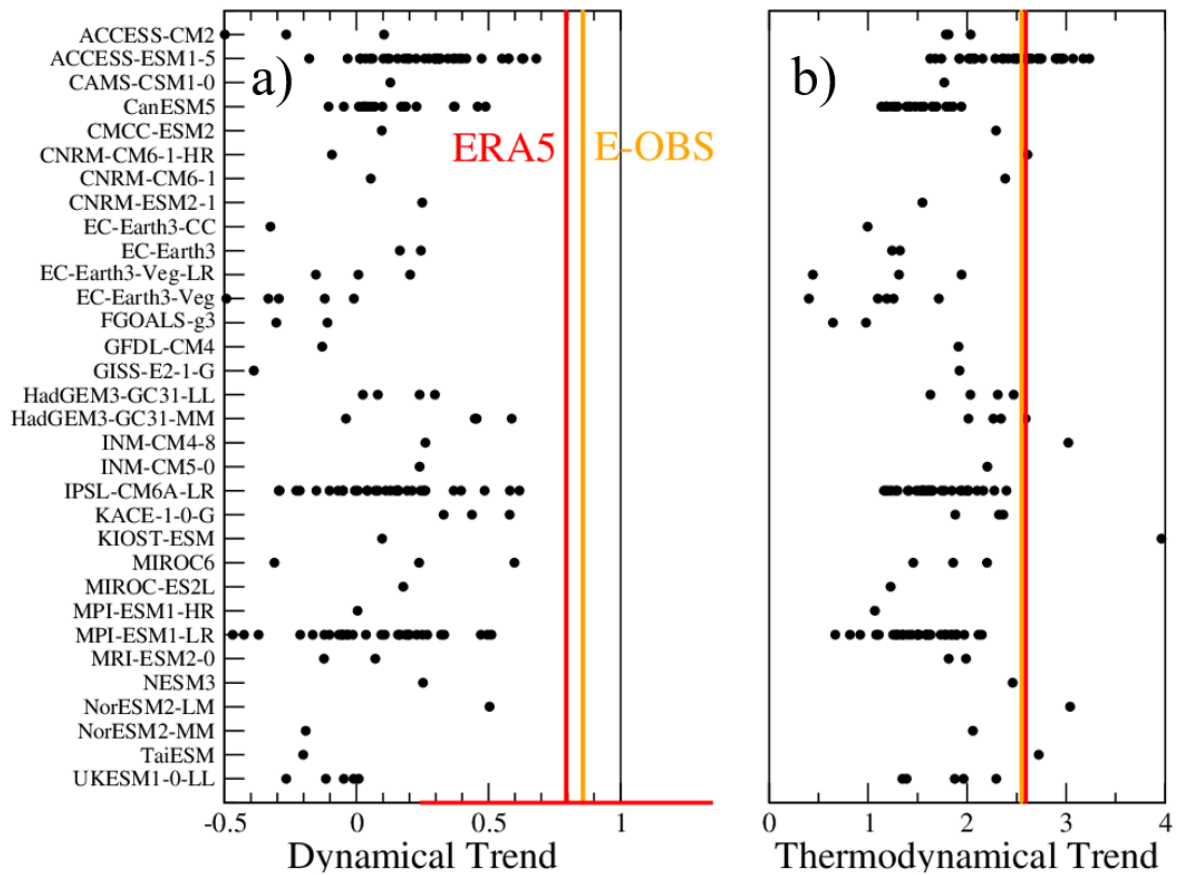
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666 **Figure 4: Observed and dynamical and thermodynamical temperature trends**

667 Dynamical (a) and thermodynamical (b) contributions to the summer TXx (summer maximum
668 of maximal daily temperature) trends from ERA5 ECMWF Reanalysis (red line), E-OBS
669 observation (orange line), and the 170 CMIP6 model simulations (names in ordinate) that were
670 available (black dots) averaged over Western Europe. The thermodynamical contributions are
671 simply calculated as residual by subtracting the dynamical trend from the total trend (Figure
672 3). For reference, the red bar at the bottom of Figure 4a stands for the 95% confidence interval
673 of the estimate of the ERA5 TXx dynamical trend, estimated with a Gaussian assumption, i. e.
674 the interval is calculated as plus or minus 2* the standard deviation (STD) of the error estimate
675 on the trend coefficient. This confidence range describes the uncertainty related to the internal
676 variability. This shows that this confidence range, calculated with the single realization of the
677 observation, is consistent with the uncertainty range calculated from simulation members
678 (respective standard deviations for observed trend and simulated trends of 0.28 and 0.25).

679
680

681 **Supplementary Information**

682 **Heat extremes in Western Europe increasing faster than simulated** 683 **due to atmospheric circulation trends**

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685 Bonnet[1], Christophe Cassou[5], Dim Coumou[3,1,6], Fabio D’Andrea[7], Davide
686 Faranda[8], Erich Fischer[4], Aurélien Ribes[2], Sebastian Sippel [4], Pascal Yiou[8]

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701

702 **Observation and model data**

703

704 We used ERA5 reanalysis of daily maximum temperatures and streamfunction fields.
705 Streamfunction is calculated from u- and v- wind fields at 500 hPa on a T127 Gaussian grid,
706 and then interpolated on a 1x1 regular grid, following:

707 $u = -\frac{\partial\psi}{\partial y}$, and $v = \frac{\partial\psi}{\partial x}$, where ψ is the streamfunction, u is the zonal- and v the meridional
708 component of the wind fields.

709

710 Surface daily maximum temperatures from ERA5 are interpolated to a 0.5x0.5 grid. We also
711 used observations from the E-OBS dataset v24e [20] for daily maximum temperature (TX). E-

712 OBS was initially taken from a 0.25 x 0.25 grid and projected onto the 0.5x0.5 grid. When
713 considering averages over the selected Western Europe area [5W-15E;45N-60N], data are
714 masked using the E-OBS land/sea mask (see below).

715

716 Daily maximum temperatures and streamfunction are also calculated from model simulations
717 including all first members of each CMIP6 model ensemble. In order to increase as much as
718 possible the estimation of capacity of models to simulate TXx and TXm trends, we used all
719 possible CMIP6 simulations made available through the ESGF infrastructure. When
720 considering only TXx and TXm calculations for Figure 3, we used 273 simulations made with
721 36 different models (see Figure 3). For Figure 4 and the analogue analysis for models, we keep
722 only 32 models and 1 realization for which we have simultaneous 500 hPa wind fields and
723 daily maximum temperatures.

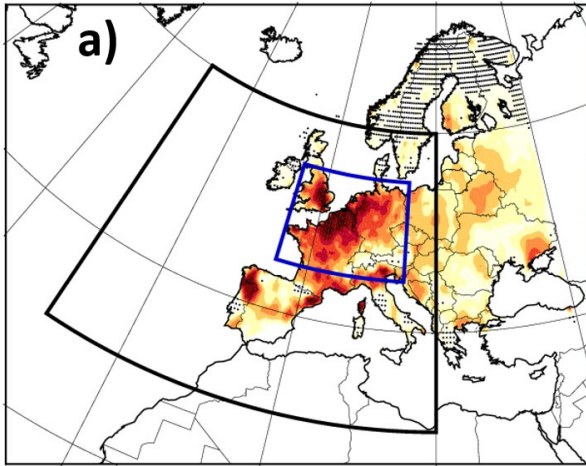
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725 To have an historical time series to be compared with reanalysis or observations, we
726 concatenate historical and SSP5-8.5 scenarios available (from 2015 to 2022). Initial tests made
727 with SSP2-4.5 showed that results presented here are insensitive to this choice.

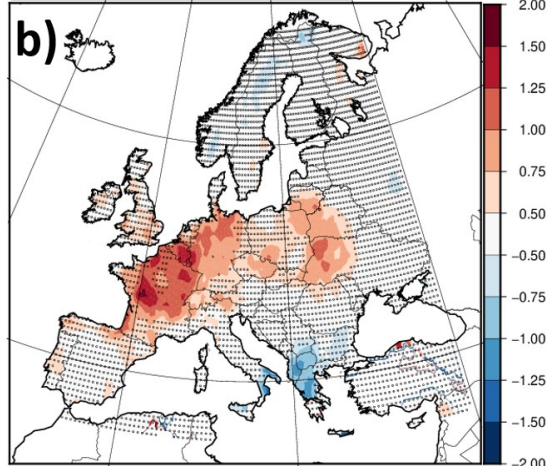
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E-OBS TXx Trend (Total)

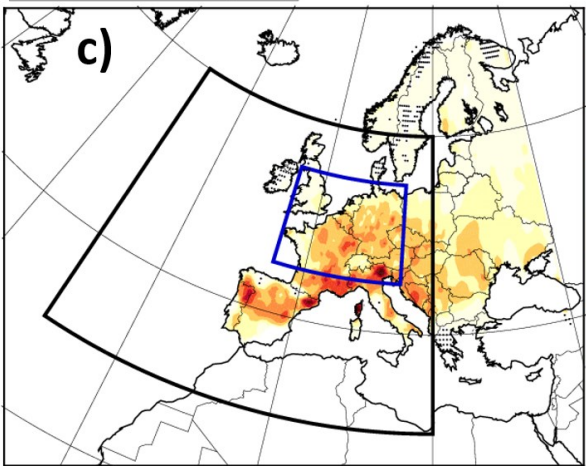


E-OBS TXx Trend (Dynamical)

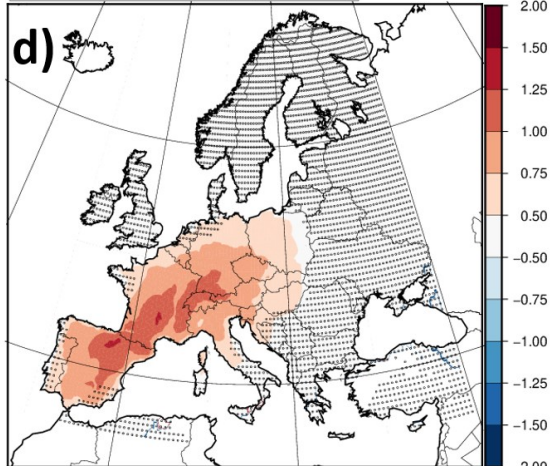


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E-OBS TXm Trend (Total)



E-OBS TXm Trend (Dynamical)



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732 **Supplementary Figure 1: TXx trends from the E-OBS observations**

733 Same as Figure 1 but for E-OBS maximum daily temperatures: a)

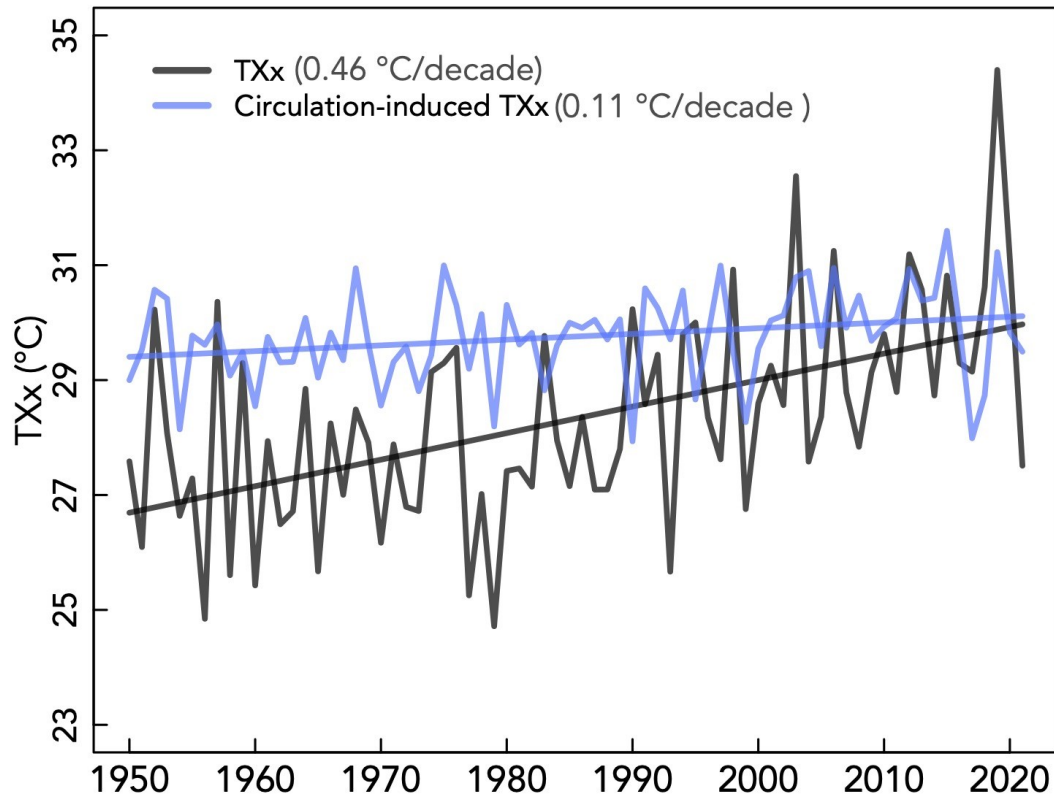
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741 **Supplementary Figure 2: Dynamical contribution to forced TXx trend in Western Europe**

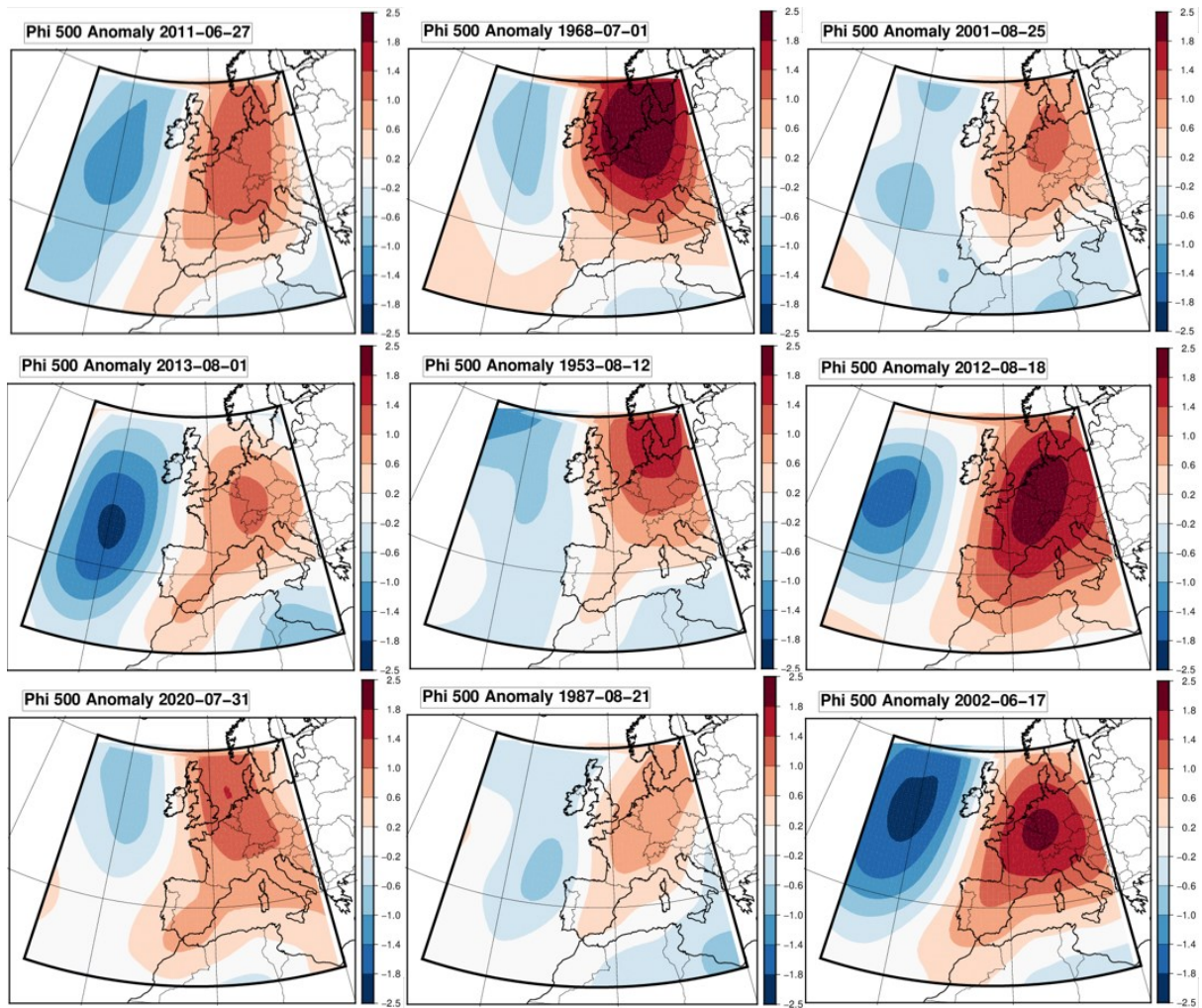
742 Black and blue lines present the area-averaged Summer maximum temperature TXx and

743 circulation-induced TXx over western Europe (5-15E, 45-55N), respectively. The values in

744 parenthesis indicate the trend in the corresponding TXx time series. The trends are estimated

745 based on Sen's slope estimator.

746



747

748 **Supplementary Figure 3: Most representative hot anomaly patterns**

749 500 hPa streamfunction anomalies (Phi 500) of the 9 most representative circulations, beyond
 750 29/06/2019, when TXx is reached over Central France [1.5E-46.5N], by decreasing order of
 751 representativeness.

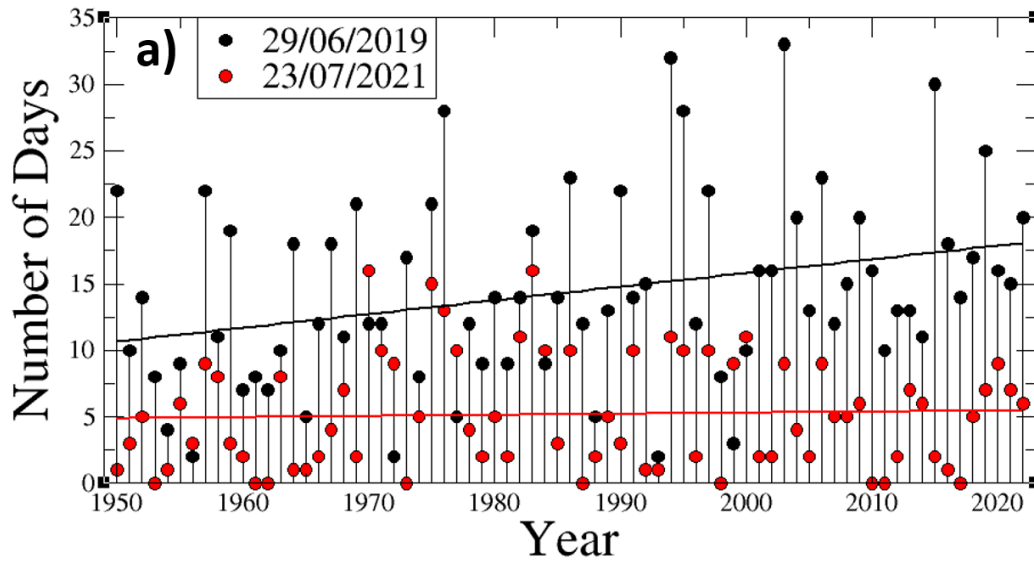
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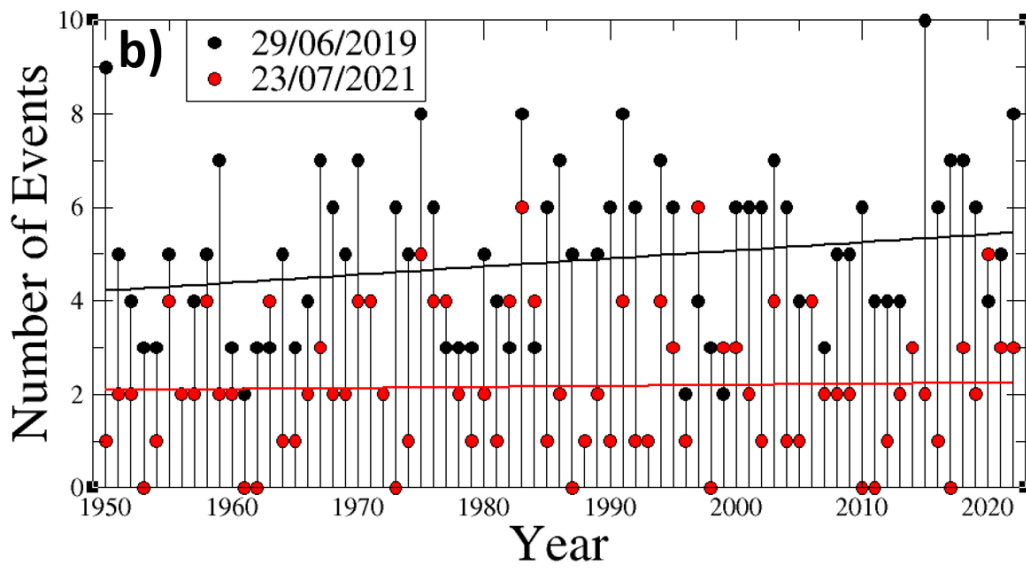
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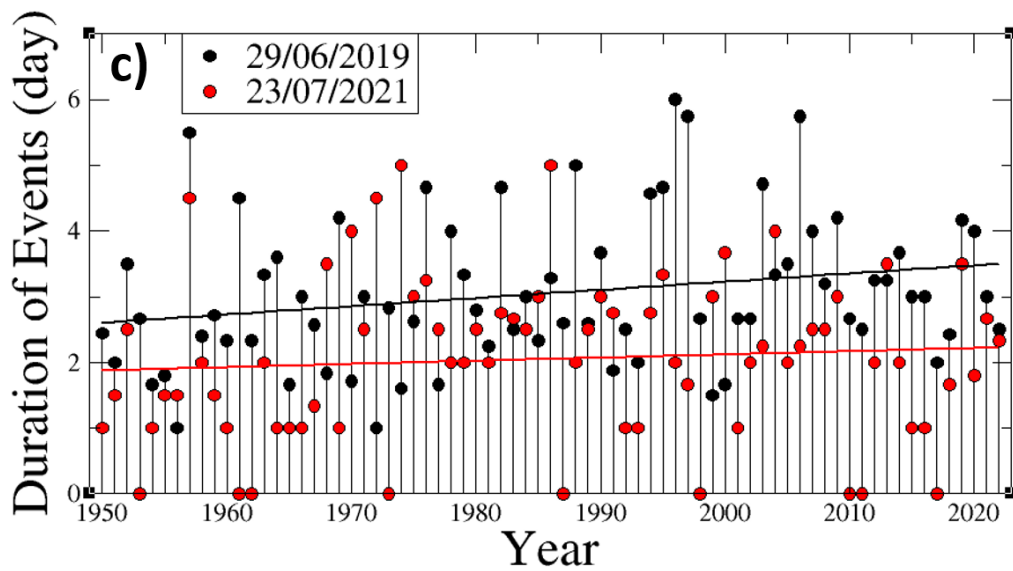
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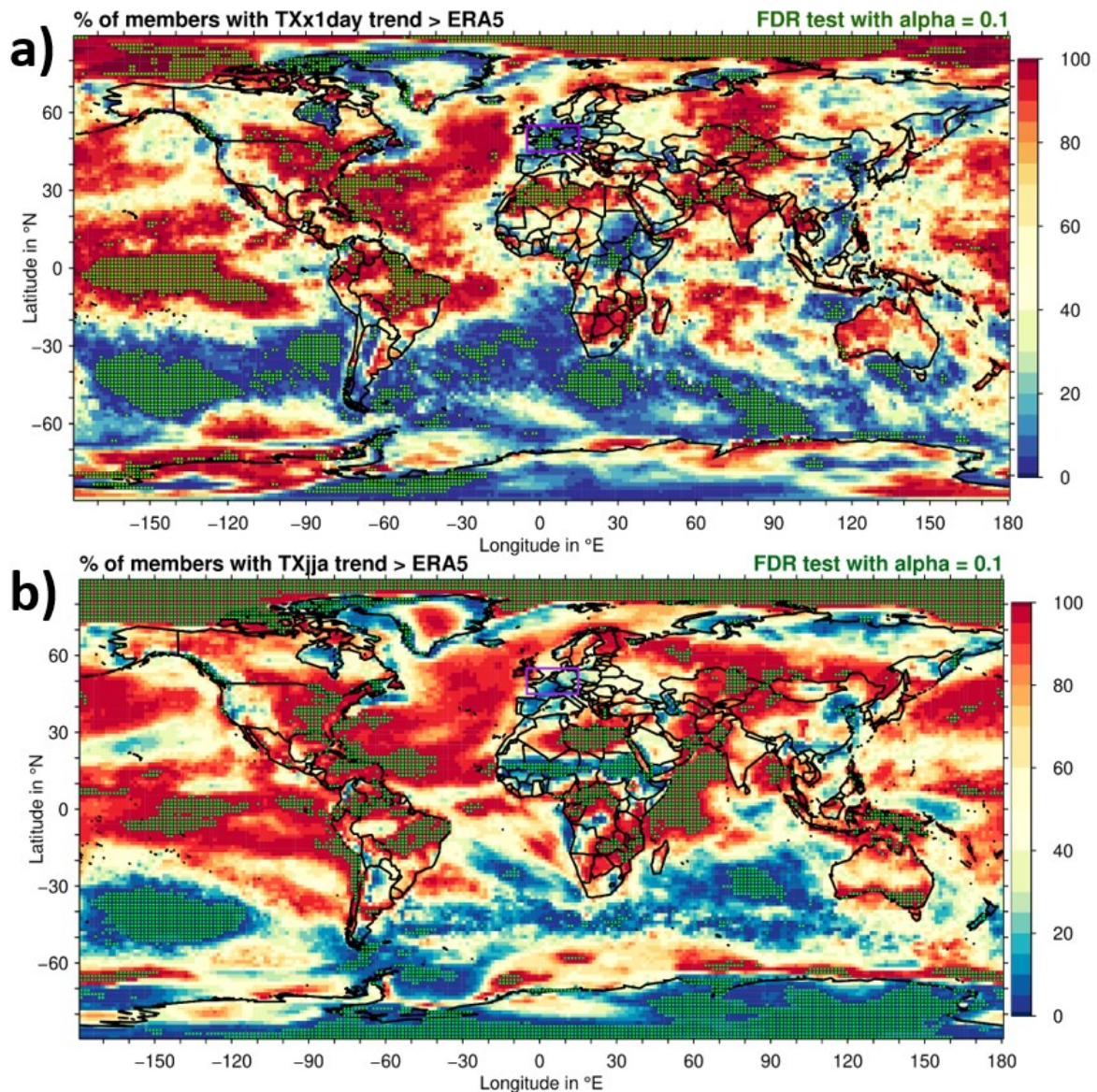


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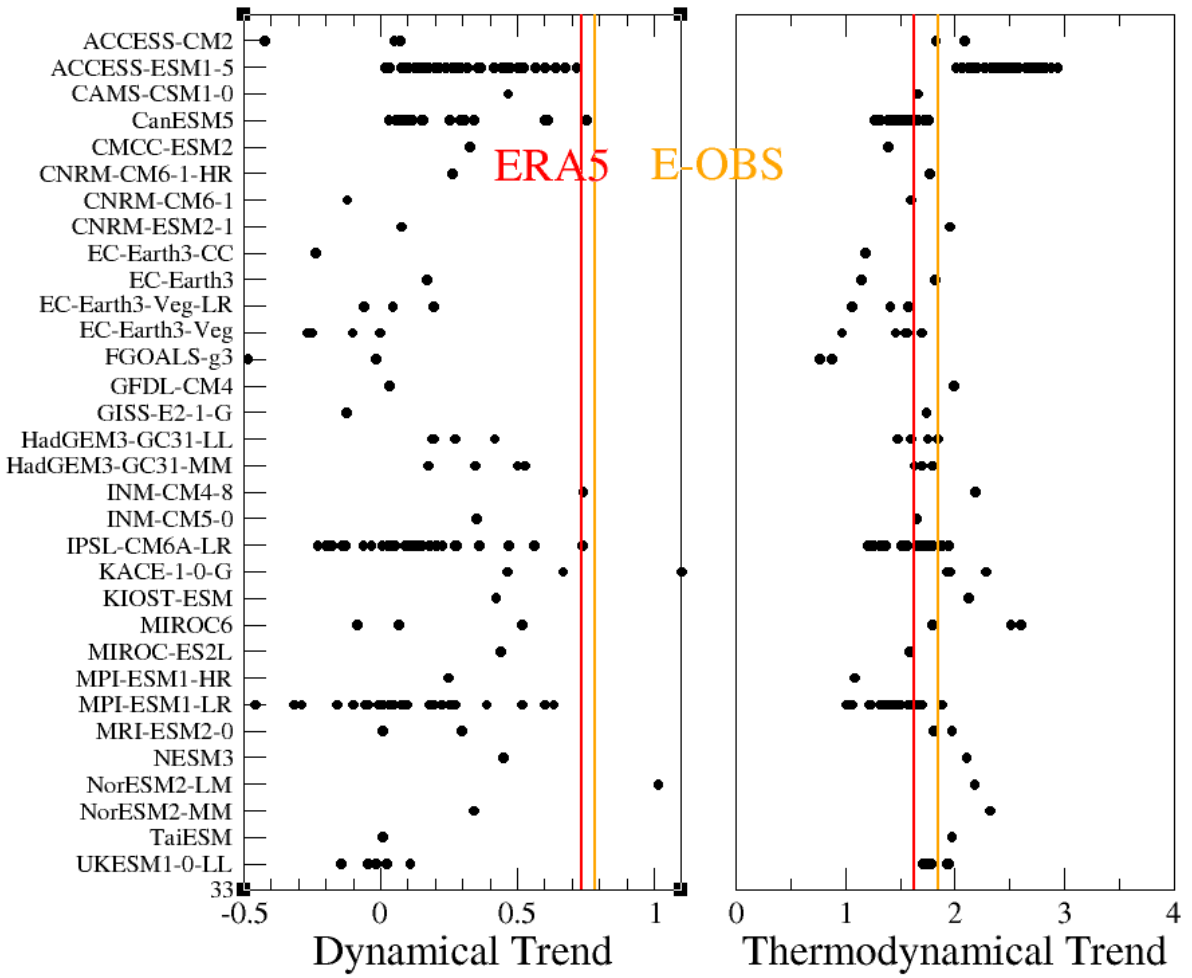
Supplementary Figure 4: Evolution of Southerly flow patterns

761 Evolution of the yearly number of days (a), number of events (b) and mean duration of events
 762 (c) (0 when no event found) for Southerly Flow patterns (black) (streamfunction anomalies
 763 with an ACC with the 29/06/2019 anomaly greater than 0.5). For comparison, the figure also
 764 shows (in red) the same statistics but for another pattern, that of the anomaly of the 23/07/2021,
 765 which corresponds to the date of TXx for 2021 in central France.
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 769 **Supplementary Figure 5: Generalization of Figure 3 at global scale**
 770 Percentage of simulations with a trend larger than ERA5 at each grid point for (a) the annual
 771 maximum of TX (TXx) and (b) the JJA mean of TX (TXm). Green stippling indicates grid
 772 points where the mismatch between observed and simulated trends is significant at the 95%
 773 confidence level in the sense of the False Discovery Rate procedure (i.e. a two-sided multiple

774 test with $\alpha=0.1$). The Western Europe box is highlighted in magenta. For the top panel,
 775 the annual (rather than JJA in Figure 3) maximum of TX is used here to capture summer heat
 776 extremes in both hemispheres; in Western Europe annual or JJA maximum are equivalent.
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Supplementary Figure 6: Dynamical and thermo-dynamical TXm trends

Same as Figure 4 but for TXm instead of TXx.

Model_realization	SF frequency trends	TXx dynamical trend	Model_realization	SF frequency trends	TXx dynamical trend
ERA5 E-OBS	42.9%	0.79 0.86		42.9%	
ACCESS-CM2_r1i1p1f1	-16.4	-0.27	HadGEM3-GC31-MM_r2i1p1f3	8.8	-0.04
ACCESS-CM2_r4i1p1f1	9.3	0.10	HadGEM3-GC31-MM_r3i1p1f3	4.8	0.59
ACCESS-CM2_r5i1p1f1	-29.4	-0.50	HadGEM3-GC31-MM_r4i1p1f3	2.4	0.46
ACCESS-ESM1-5_r10i1p1f1	25.5	0.05	INM-CM4-8_r1i1p1f1	16.4	0.26
ACCESS-ESM1-5_r11i1p1f1	11.9	0.40	INM-CM5-0_r1i1p1f1	0.7	0.24
ACCESS-ESM1-5_r2i1p1f1	7.0	0.02	IPSL-CM6A-LR_r10i1p1f1	-5.3	-0.15
ACCESS-ESM1-5_r34i1p1f1	8.9	0.35	IPSL-CM6A-LR_r11i1p1f1	-9.5	0.15
ACCESS-ESM1-5_r3i1p1f1	17.5	0.68	IPSL-CM6A-LR_r12i1p1f1	-20.4	-0.07
ACCESS-ESM1-5_r4i1p1f1	12.6	0.12	IPSL-CM6A-LR_r13i1p1f1	14.7	0.11
ACCESS-ESM1-5_r5i1p1f1	10.0	0.36	IPSL-CM6A-LR_r14i1p1f1	21.5	0.01
ACCESS-ESM1-5_r9i1p1f1	28.2	0.19	IPSL-CM6A-LR_r15i1p1f1	-8.8	0.04
ACCESS-ESM1-5_r11i1p1f1	10.8	0.31	IPSL-CM6A-LR_r16i1p1f1	9.2	0.21
ACCESS-ESM1-5_r12i1p1f1	26.7	-0.03	IPSL-CM6A-LR_r17i1p1f1	6.8	0.58
ACCESS-ESM1-5_r13i1p1f1	15.8	0.12	IPSL-CM6A-LR_r18i1p1f1	12.1	-0.23
ACCESS-ESM1-5_r14i1p1f1	25.6	0.15	IPSL-CM6A-LR_r19i1p1f1	34.8	0.37
ACCESS-ESM1-5_r15i1p1f1	18.3	0.01	IPSL-CM6A-LR_r1i1p1f1	-1.8	0.26
ACCESS-ESM1-5_r16i1p1f1	15.3	0.31	IPSL-CM6A-LR_r20i1p1f1	-15.3	-0.29
ACCESS-ESM1-5_r17i1p1f1	32.9	0.39	IPSL-CM6A-LR_r21i1p1f1	7.5	0.16
ACCESS-ESM1-5_r18i1p1f1	37.6	0.63	IPSL-CM6A-LR_r22i1p1f1	16.2	0.26
ACCESS-ESM1-5_r19i1p1f1	-2.5	0.06	IPSL-CM6A-LR_r23i1p1f1	0.9	-0.05
ACCESS-ESM1-5_r20i1p1f1	21.2	0.31	IPSL-CM6A-LR_r24i1p1f1	-2.1	0.24
ACCESS-ESM1-5_r21i1p1f1	22.9	0.63	IPSL-CM6A-LR_r25i1p1f1	-5.3	-0.10
ACCESS-ESM1-5_r22i1p1f1	-7.3	0.23	IPSL-CM6A-LR_r26i1p1f1	-3.7	0.19
ACCESS-ESM1-5_r23i1p1f1	28.7	0.30	IPSL-CM6A-LR_r27i1p1f1	-18.1	-0.21
ACCESS-ESM1-5_r24i1p1f1	9.3	0.03	IPSL-CM6A-LR_r28i1p1f1	0.7	0.08
ACCESS-ESM1-5_r25i1p1f1	9.0	0.20	IPSL-CM6A-LR_r29i1p1f1	0.5	0.04
ACCESS-ESM1-5_r26i1p1f1	3.8	0.30	IPSL-CM6A-LR_r30i1p1f1	-2.2	-0.05
ACCESS-ESM1-5_r27i1p1f1	24.7	0.38	IPSL-CM6A-LR_r31i1p1f1	15.9	0.40
ACCESS-ESM1-5_r28i1p1f1	38.8	0.42	IPSL-CM6A-LR_r32i1p1f1	-21.5	0.07
ACCESS-ESM1-5_r29i1p1f1	25.3	0.58	IPSL-CM6A-LR_r3i1p1f1	1.4	0.15
ACCESS-ESM1-5_r30i1p1f1	32.5	0.58	IPSL-CM6A-LR_r4i1p1f1	1.7	0.13
ACCESS-ESM1-5_r31i1p1f1	27.0	0.27	IPSL-CM6A-LR_r5i1p1f1	12.4	-0.29
ACCESS-ESM1-5_r32i1p1f1	6.4	0.30	IPSL-CM6A-LR_r6i1p1f1	20.9	0.48
ACCESS-ESM1-5_r33i1p1f1	22.4	0.47	IPSL-CM6A-LR_r7i1p1f1	19.8	0.62
ACCESS-ESM1-5_r35i1p1f1	31.4	0.32	IPSL-CM6A-LR_r8i1p1f1	-1.1	0.16
ACCESS-ESM1-5_r36i1p1f1	20.0	0.26	IPSL-CM6A-LR_r9i1p1f1	-11.2	-0.01
ACCESS-ESM1-5_r37i1p1f1	15.5	-0.18	KACE-1-0-G_r1i1p1f1	17.0	0.33
ACCESS-ESM1-5_r38i1p1f1	17.2	0.10	KACE-1-0-G_r2i1p1f1	23.4	0.58
ACCESS-ESM1-5_r39i1p1f1	-13.2	0.18	KACE-1-0-G_r3i1p1f1	39.5	0.44
ACCESS-ESM1-5_r40i1p1f1	27.3	0.55	KIOSK-ESM_r1i1p1f1	8.4	0.10
CAMS-CSM1-0_r2i1p1f1	-1.0	0.13	MIROC6_r1i1p1f1	20.1	0.24
CanESM5_r10i1p1f1	-4.9	-0.11	MIROC6_r2i1p1f1	-23.4	-0.31
CanESM5_r10i1p2f1	-2.0	0.17	MIROC6_r3i1p1f1	26.6	0.60
CanESM5_r1i1p1f1	10.6	0.23	MIROC-ES2L_r1i1p1f2	13.6	0.18
CanESM5_r1i1p2f1	11.7	0.01	MPI-ESM1-2-HR_r1i1p1f1	8.0	0.00
CanESM5_r2i1p1f1	9.5	0.07	MPI-ESM1-2-LR_r10i1p1f1	-0.8	-0.04
CanESM5_r2i1p2f1	-9.1	0.05	MPI-ESM1-2-LR_r1i1p1f1	2.6	0.33
CanESM5_r3i1p1f1	-7.9	-0.05	MPI-ESM1-2-LR_r2i1p1f1	23.6	0.27
CanESM5_r3i1p2f1	1.3	0.02	MPI-ESM1-2-LR_r3i1p1f1	35.6	0.20
CanESM5_r4i1p1f1	-1.8	0.03	MPI-ESM1-2-LR_r4i1p1f1	36.1	0.25
CanESM5_r4i1p2f1	2.8	0.04	MPI-ESM1-2-LR_r5i1p1f1	-23.3	-0.37
CanESM5_r5i1p1f1	4.8	0.03	MPI-ESM1-2-LR_r6i1p1f1	-6.3	0.04
CanESM5_r5i1p2f1	1.3	0.10	MPI-ESM1-2-LR_r7i1p1f1	-26.6	-0.12
CanESM5_r6i1p1f1	25.7	0.37	MPI-ESM1-2-LR_r8i1p1f1	-21.1	-0.06
CanESM5_r6i1p2f1	16.0	0.46	MPI-ESM1-2-LR_r9i1p1f1	-19.2	-0.21
CanESM5_r7i1p1f1	19.4	0.06	MPI-ESM1-2-LR_r11i1p1f1	9.2	0.32
CanESM5_r7i1p2f1	4.7	0.18	MPI-ESM1-2-LR_r12i1p1f1	1.4	-0.07
CanESM5_r8i1p1f1	-4.2	0.03	MPI-ESM1-2-LR_r13i1p1f1	-17.3	0.11
CanESM5_r8i1p2f1	-5.0	0.19	MPI-ESM1-2-LR_r14i1p1f1	1.3	-0.43
CanESM5_r9i1p1f1	25.8	0.37	MPI-ESM1-2-LR_r15i1p1f1	34.5	0.20
CanESM5_r9i1p2f1	5.9	0.49	MPI-ESM1-2-LR_r16i1p1f1	-39.3	-0.10
CMCC-ESM2_r1i1p1f1	2.6	0.10	MPI-ESM1-2-LR_r17i1p1f1	2.1	0.09
CNRM-CM6-1-HR_r1i1p1f2	23.2	-0.09	MPI-ESM1-2-LR_r18i1p1f1	-16.0	-0.01
CNRM-CM6-1_r1i1p1f2	-10.6	0.05	MPI-ESM1-2-LR_r19i1p1f1	7.9	0.47
CNRM-ESM2-1_r1i1p1f2	6.0	0.25	MPI-ESM1-2-LR_r30i1p1f1	0.4	-0.03

Model_realization	SF frequency trends	TXx dynamical trend	Model_realization	SF frequency trends	TXx dynamical trend
EC-Earth3-CC_r1i1p1f1	-14.4	-0.33	MPI-ESM1-2-LR_r21i1p1f1	0.4	0.17
EC-Earth3_r1i1p1f1	14.2	0.16	MPI-ESM1-2-LR_r22i1p1f1	21.9	-0.05
EC-Earth3_r4i1p1f1	3.4	0.24	MPI-ESM1-2-LR_r23i1p1f1	-31.7	-0.47
EC-Earth3-Veg-LR_r1i1p1f1	-9.3	0.20	MPI-ESM1-2-LR_r24i1p1f1	-19.1	0.16
EC-Earth3-Veg-LR_r2i1p1f1	9.2	0.01	MPI-ESM1-2-LR_r25i1p1f1	-4.1	-0.17
EC-Earth3-Veg-LR_r3i1p1f1	-15.3	-0.15	MPI-ESM1-2-LR_r26i1p1f1	26.2	0.50
EC-Earth3-Veg_r1i1p1f1	-5.3	-0.12	MPI-ESM1-2-LR_r27i1p1f1	29.7	0.51
EC-Earth3-Veg_r2i1p1f1	-16.9	-0.01	MPI-ESM1-2-LR_r28i1p1f1	-4.0	0.18
EC-Earth3-Veg_r3i1p1f1	-14.6	-0.33	MPI-ESM1-2-LR_r29i1p1f1	8.7	0.23
EC-Earth3-Veg_r4i1p1f1	5.0	-0.29	MRI-ESM2-0_r1i1p1f1	10.7	-0.12
EC-Earth3-Veg_r6i1p1f1	-14.4	-0.49	MRI-ESM2-0_r5i1p1f1	16.6	0.07
FGOALS-g3_r1i1p1f1	-53.1	-0.30	NESM3_r1i1p1f1	17.8	0.25
FGOALS-g3_r4i1p1f1	-10.3	-0.11	NorESM2-LM_r1i1p1f1	42.7	0.50
GFDL-CM4_r1i1p1f1	-1.7	-0.13	NorESM2-MM_r1i1p1f1	-8.7	-0.19
GISS-E2-1-G_r1i1p1f2	-16.3	-0.39	TaiESM1_r1i1p1f1	-4.2	-0.20
HadGEM3-GC31-LL_r1i1p1f3	15.9	0.30	UKESM1-0-LL_r1i1p1f2	-13.1	0.01
HadGEM3-GC31-LL_r2i1p1f3	21.3	0.24	UKESM1-0-LL_r2i1p1f2	-21.8	-0.05
HadGEM3-GC31-LL_r3i1p1f3	3.0	0.08	UKESM1-0-LL_r3i1p1f2	-3.5	-0.12
HadGEM3-GC31-LL_r4i1p1f3	5.1	0.02	UKESM1-0-LL_r4i1p1f2	-10.5	-0.01
HadGEM3-GC31-MM_r1i1p1f3	13.6	0.45	UKESM1-0-LL_r8i1p1f2	-3.6	-0.27

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Supplementary Table 1: Southerly Flow (SF) frequency trend and summer TXx dynamical trends for ERA5, E-OBS, and 170 simulations for which the daily 500 hPa wind and the maximum surface temperature fields were available for both historical and SSP5-8.5 scenarios. TXx Trends are expressed in °C/GWD and frequency trends in %/GWD.

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