

The 2013 hot, dry summer in Western Europe

Article

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THE 2013 HOT, DRY SUMMER IN WESTERN EUROPE

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7 *Summary*

8 Anthropogenic forcing played a substantial part in Western Europe's hot, dry summer
9 in 2013. North Atlantic sea surface temperatures were likely a factor in the large contrast with
10 summer 2012.

11 *Observations*

12 Western Europe experienced sweltering high temperatures in summer 2013. On 22
13 July 2013, the United Kingdom recorded its hottest day since July 2006, with 33.5°C
14 recorded at Heathrow and Northolt in west London (Met Office 2014). Averaged over
15 Western Europe (Fig 1c), the seasonal mean (June–August) anomaly in surface air
16 temperature (SAT) was 1.33°C above the mean over the period of 1964–93, which is 3.2
17 standard deviations of the interannual variability. [HadCRUT4 data (Morice et al. 2012)
18 shows a similar warming of 1.28°C.] This magnitude of warming is slightly less but
19 comparable with the previous hot summers in Western Europe, such as 2003 (e.g., Schaer et
20 al. 2004) and 2010 (e.g., Barriopedro et al. 2011) for which summer mean SAT anomalies
21 were 1.46°C and 1.86°C respectively, corresponding to 3.5 and 4.5 standard deviations.

22 The atmospheric circulation in summer 2013 was characterized by anomalously high
23 sea level pressure (SLP) extending from the United Kingdom into northern Europe and
24 anomalously low SLP over the Arctic (Fig. 1a). This pattern projects strongly onto the
25 positive phase of the summer North Atlantic Oscillation (SNAO; Folland et al. 2009). The
26 anomalous SNAO index of 2.7 hPa in 2013 was +1.0 standard deviation of the interannual
27 variability, in stark contrast with the previous summer of 2012 for which the index was -2.7
28 standard deviations (Supplementary Fig. S1b). The circulation pattern in 2013 was associated
29 with a northward shift of summer North Atlantic storm track (Fig. 1e and f). The climatology
30 of cyclone track density (Dong et al. 2013a and Fig. 1e) shows a split into two preferred
31 cyclone paths at the North Atlantic jet exit region (5°W–5°E): one passing near Iceland at

32 ~71°N and into the Nordic Seas and the other passing across the British Isles at ~56°N and
33 into Western Europe. In summer 2013, more storms than usual passed over Iceland and fewer
34 over the United Kingdom and into Western Europe (Fig. 1f). This led to dry conditions in the
35 United Kingdom and most of Western Europe. The area-averaged precipitation anomaly was
36 $-0.35 \text{ mm day}^{-1}$, which is -2.2 standard deviations of the interannual variability
37 (Supplementary Fig. S1c). The low rainfall was also in stark contrast to the summer of 2012,
38 which was a record wet summer in the United Kingdom and was last in a series of wet UK
39 summers since 2007, each of which was associated with a negative SNAO index (Allan and
40 Folland 2012; Dong et al. 2013b). [Note that the inhomogeneity of the data in E-OBS
41 precipitation is a potential source of bias (Zolina et al. 2014), but negative precipitation
42 anomalies in Western Europe are consistent with the northward shifted storm track.]

43 Global SST anomalies for summer 2013 are illustrated in Fig. 1d. Warm SSTs
44 (relative to 1964–93) were present in many regions, with a prominent warm anomaly ($>$
45 1.0°C) along the Gulf Stream extension in the North Atlantic. Associated with this feature
46 were an enhanced meridional SST gradient to the north and a reduced gradient to the south
47 (Supplementary Fig. S2c). These anomalous SST gradients may have played a role in the
48 observed northward shift of the North Atlantic storm track (e.g., Sampe et al. 2010; Ogawa et
49 al. 2012) and influenced the related anomalies in the SNAO and Western European climate
50 (Folland et al. 2009; Sutton and Dong 2012; Dong et al. 2013a). Warm anomalies were also
51 observed in the Arctic, consistent with the continuing low sea ice extent (SIE); these SIE
52 anomalies might also have had an influence on the atmospheric circulation (Balmaseda et al.
53 2010; Petrie et al. 2014).

54 Relative to the climatological period of 1964–93, by 2012 there were significant
55 increases in anthropogenic greenhouse gas (GHG) concentrations (e.g., WMO 2013) and
56 significant changes in anthropogenic aerosols. European and North American sulphur dioxide

57 emissions had declined while Asian emissions had increased (e.g., Lamarque et al. 2010). In
58 this study, we investigate the roles of changes in SST, SIE, and radiative forcing in shaping
59 the European summer of 2013, as well as possible reasons for the striking contrast between
60 summer 2013 and summer 2012. Our focus is on seasonal mean conditions rather than on
61 shorter-lived events that occurred within the season.

62 *Climate model experiments*

63 Climate model experiments have been carried out to identify the roles of changes in:
64 (a) SST/SIE and (b) anthropogenic GHG and aerosol forcing in the European summer climate
65 anomalies of 2013. In this study, we do not address the anthropogenic contribution to the
66 SST/SIE changes, but rather consider these changes as an independent forcing factor. We use
67 the atmosphere configuration of the Met Office Hadley Centre Global Environment Model
68 version 3 (HadGEM3-A; Hewitt et al. 2011), with a resolution of 1.875° longitude by 1.25°
69 latitude and 85 levels in the vertical. Dong et al. (2013b) used the same model to study the
70 2012 summer in Europe. A series of experiments was performed, the details of which are
71 summarized in Table 1. We use the same control experiment (CONTROL) for the period
72 1964–93 as Dong et al. (2013b) and perform two other experiments: ALL2013 and SST2013.
73 Both of these experiments use 2013 SST and SIE boundary conditions but they differ in the
74 specification of anthropogenic GHG and aerosol forcing: ALL2013 uses anthropogenic
75 forcing appropriate for 2013 while SST2013 uses the same anthropogenic forcing as for the
76 CONTROL experiment, appropriate for 1964–93. The last 25 years of each experiment are
77 used for analysis. The CONTROL experiment reproduces realistic climatological SLP and
78 precipitation patterns for summer (Supplemental Fig. S10.2 of Dong et al. 2013b).

79 The model simulates a significant warming over Europe in summer 2013 in response
80 to changes in SST, SIE, and anthropogenic forcing (i.e., ALL2013-CONTROL, Fig. 2a) with
81 an area averaged SAT change of 1.11°C over Western Europe. The observed anomaly of

82 1.33°C is within the ± 1 standard deviation range of the interannual variability of the model
83 response (Supplementary Fig. S1a). Changes in SST and SIE explain 63% ($\pm 26\%$) of the
84 area-averaged Western European warming response in HadGEM3 (Fig. 2d), with the
85 remaining 37% ($\pm 29\%$) explained by the direct impact (without forcing-induced SST and sea
86 ice feedbacks) of changes in radiative forcings from GHG and aerosols (Fig. 2g and
87 Supplementary Fig. S1a).

88 The atmospheric circulation anomalies simulated by the model (Fig. 2b) show notable
89 similarities to the observed pattern over the North Atlantic and Europe (Fig. 1a), including
90 low SLP anomalies over Greenland and an anomalous anticyclone over the United Kingdom.
91 The wave train pattern of SLP anomalies suggests that changes in convection over the
92 Caribbean Sea might be an important factor (e.g., Douville et al. 2011). However, in the
93 model simulation the anomalous anticyclone does not extend as far eastward into central
94 Europe as in the observations. The circulation anomalies correspond to a positive anomaly
95 (mean = 1.2 hPa, which is only 0.5 standard deviations) in the SNAO index relative to the
96 CONTROL, which is smaller than the observed anomaly (2.7 hPa; Supplementary Fig. S1b).
97 The pattern of simulated Western European precipitation anomalies (Fig. 2c) is consistent
98 with the positive phase of the SNAO and is similar to the observations, with anomalously low
99 rainfall over most of Western Europe (Fig. 1b). As for the circulation anomaly, the magnitude
100 of the mean precipitation anomaly is smaller than observed (Supplementary Fig S1c),
101 although there is substantial interannual variability in the model results.

102 The additional SST2013 experiment suggests that *both* SST/SIE changes and the
103 direct impact of changes in anthropogenic radiative forcing contributed to the anomalous
104 circulation (Figs. 2e and h, Fig. S1b) and reduced rainfall over Western Europe in summer
105 2013 (Figs. 2f and i; Supplementary Fig. S1c). The SST change has the most impact on the
106 low SLP anomalies simulated over Greenland, but GHG and aerosol forcing causes a

107 substantial anticyclonic anomaly over, and north of, the United Kingdom. This anticyclonic
108 circulation anomaly is similar to the summer mean circulation response to an increase in
109 GHG forcing (Blade et al. 2012) and is presumably due to an increase in the frequency of the
110 positive SNAO-like circulation regimes over the Atlantic sector (Boe et al. 2009).

111 Changes in GHG and aerosol forcing are unlikely to be a major factor in explaining
112 the striking contrast in circulation and precipitation between the European summers of 2012
113 and 2013 (Supplementary Fig. S2a), as the changes in these forcings between these two years
114 were small. However, the model experiments suggest that changes in SST and SIE in the
115 North Atlantic were a significant factor (Supplementary Fig. S2e). In particular, the
116 anomalous meridional SST gradient to the north of the Gulf Stream in 2013, relative to 2012
117 (Supplementary Fig. S2c), may have favored a positive phase of the SNAO and a northward
118 shift of North Atlantic summer storm track (e.g., Folland et al. 2009; Dong et al. 2013a), as
119 was observed (Supplementary Figs. S2d and f). The model experiments show some evidence
120 of capturing this shift, although the mean signal (Supplementary Fig. S2e) is again much
121 weaker than was observed (Supplementary Fig. S2a).

122 The model results show an encouraging degree of consistency with observations, but
123 it is difficult to assess precisely what level of consistency should be expected in view of the
124 high level of internal variability and uncertainty about the true magnitude of forced signals in
125 the real world. It is clear from Supplementary Fig. S1 that the signal-to-noise ratio for the
126 changes in SAT is large, which permits more confident conclusions, whereas that for changes
127 in circulation and precipitation is much lower (though it is interesting to note that the model
128 suggests a stronger forced signal in Western European summer precipitation than in the
129 SNAO). One limitation of the current experiments, which may well influence the signal-to-
130 noise ratio, is the use of a prescribed SST boundary condition. Active ocean–atmosphere
131 coupling may modify the response to forcings and is an important area of future work (Sutton

132 and Mathieu 2002; Dong et al. 2013a). Another extension not addressed here is the
133 anthropogenic contribution to the SST/SIE changes.

134 *Conclusions*

135 The European summer of 2013 was marked by hot and dry conditions in Western
136 Europe associated with a northward shifted Atlantic storm track and a positive phase of the
137 SNAO. Model results suggest that, relative to a 1964–93 reference period, changes in
138 SST/SIE explain 63% ($\pm 26\%$) of the area-averaged warming signal over Western Europe,
139 with the remaining 37% ($\pm 29\%$) explained by the direct impact of changes in anthropogenic
140 radiative forcings from GHG and aerosols. The results further suggest that the anomalous
141 atmospheric circulation, and associated low rainfall, were also influenced both by changes in
142 SST/SIE and by the direct impact of changes in radiative forcings; however, the magnitude of
143 the forced signals in these variables is much less, relative to internal variability, than for
144 surface air temperature. Further evidence suggests that changes in North Atlantic SST were
145 likely an important factor in explaining the striking contrast between the European summers
146 of 2013 and that of 2012. A major area for further work is to understand more completely the
147 mechanisms that explain these influences.

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224 12-00134.1)

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226 **Table 1.** Summary of numerical experiments.

Experiments	Boundary conditions	Length of run
CONTROL	Forced with monthly mean climatological sea surface temperature (SST) and sea ice extent (SIE) averaged over the period of 1964 to 1993 using HadISST data (Rayner et al. 2003) and with anthropogenic greenhouse gases (GHG) concentrations averaged over the same period and anthropogenic aerosols emissions averaged over the period of 1970 to 1993.	32 years
ALL2013	Forced with monthly mean SST and SIE from December 2012 to November 2013 using HadISST data, with anthropogenic GHG concentration in 2012 (WMO 2013) and anthropogenic aerosol emissions for 2010 (Lamarque et al. 2010), which is the most recent year for which emissions data were available.	27 years
SST2013	As ALL2013, but with anthropogenic GHG concentrations and anthropogenic aerosol emissions the same as in CONTROL.	27 years

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229 Figure legends

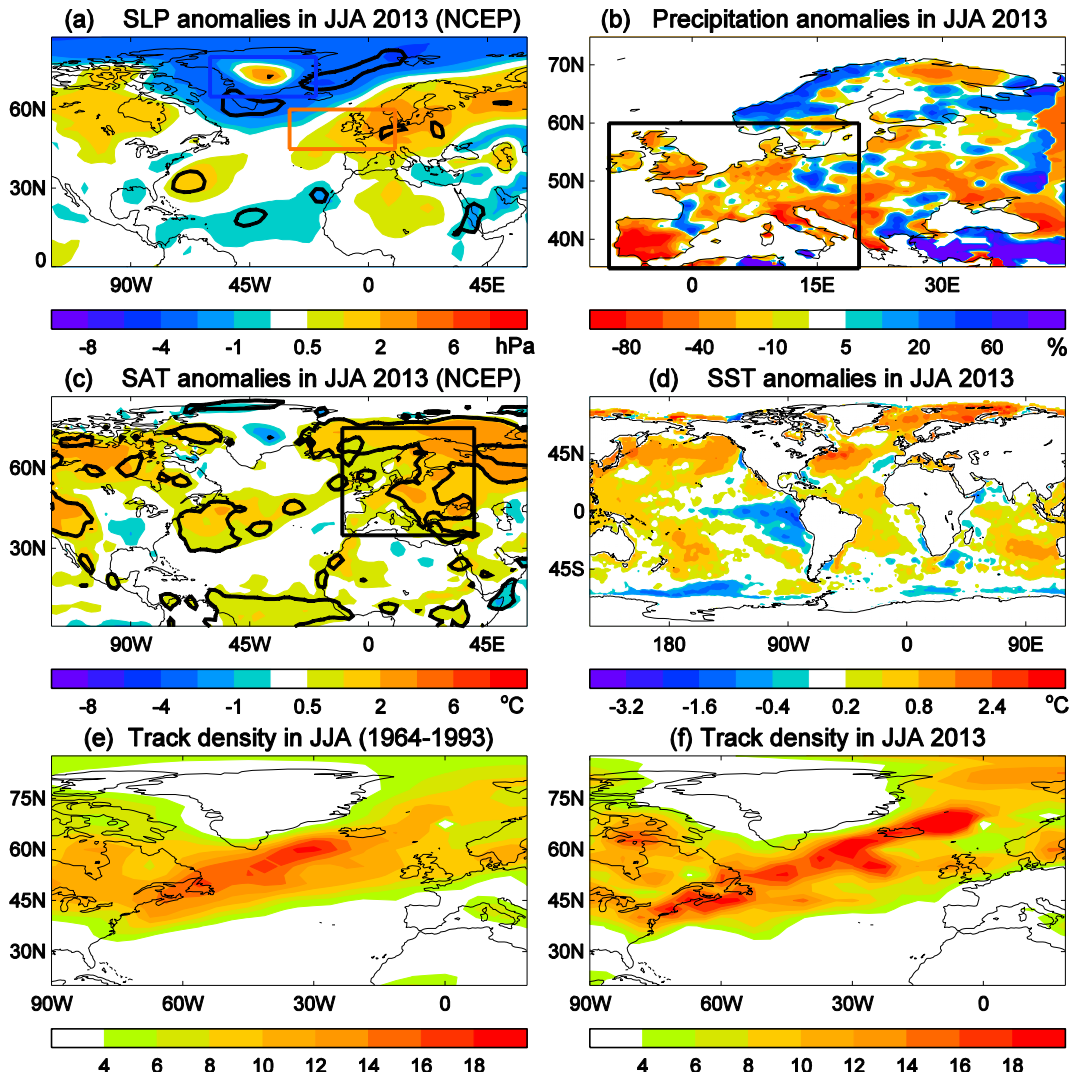
230 **FIGURE. 1.** Anomalies for JJA 2013 from the climatological period 1964-1993 for (a) SLP
231 (hPa) and (c) SAT (°C) from NCEP reanalysis (Kalnay et al. 1996), (b) percentage
232 precipitation change (%) from the daily gridded E-OBS precipitation (version 9.0) over
233 Europe (Haylock et al. 2008) and (d) SSTs (°C) from HadISST (Rayner et al. 2003). (e) and
234 (h) for the climatological period and 2013 cyclone track density as in Hoskins and Hodges
235 (2002) based on NCEP reanalysis. Track density is in unit of numbers per month per unit
236 area, where the unit area is equivalent to a 5° spherical cap (about 10⁶ km²). Note that this
237 climatological period is dominated by cold AMO conditions and is the period used for the
238 climatological model simulations. Thick lines in (a) and (c) highlight regions where the
239 differences are statistically significant at the 90% confidence level using a two-tailed Student
240 t-test.

241 **FIGURE. 2.** SAT (°C) (left column), SLP (hPa) (middle column) and precipitation changes
242 (right column) (%) in the model simulations forced by different configurations of forcings in
243 2013 relative to the control simulation. (a), (b) and (c) forced by changes in SST and SIE,
244 GHG concentrations, and aerosols emissions (ALL2013-CONTROL). (d), (e) and (f) forced
245 by changes in SST and SIE (SST2013-CONTROL). (g), h) and (i) forced by changes in GHG
246 and aerosols emissions (ALL2013-SST2013). Only changes that are statistically significant at
247 the 90% confidence level using a two-tailed Student t-test are plotted in (a), (d) and (g) while
248 thick lines in other panels highlight regions where the differences are statistically significant
249 at the 90% confidence level.

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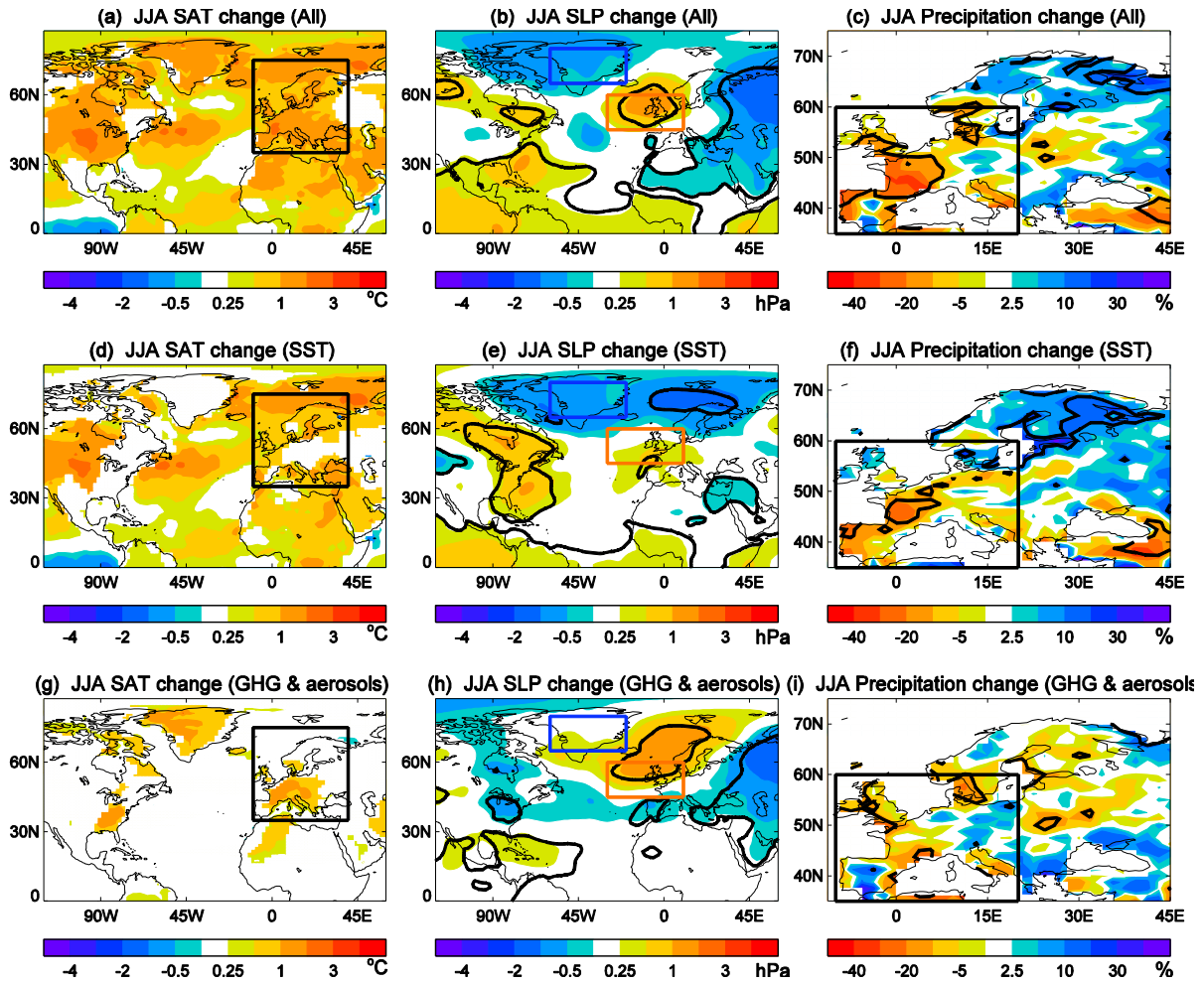
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254 **FIGURE 1.** Anomalies for JJA 2013 from the climatological period 1964-1993 for (a) SLP
 255 (hPa) and (c) SAT (°C) from NCEP reanalysis (Kalnay et al. 1996), (b) percentage
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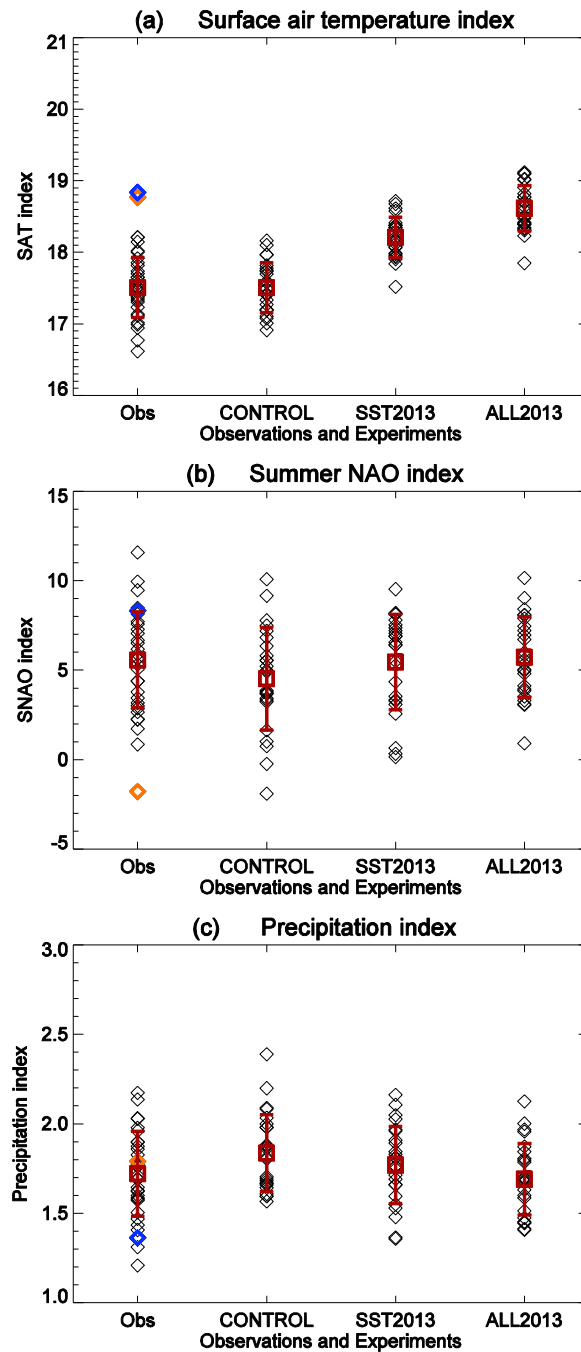
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FIGURE 2. SAT ($^{\circ}\text{C}$) (left column), SLP (hPa) (middle column) and precipitation changes (%) in the model simulations forced by different configurations of forcings in 2013 relative to the control simulation. (a), (b) and (c) forced by changes in SST and SIE, GHG concentrations, and aerosols emissions (ALL2013-CONTROL). (d), (e) and (f) forced by changes in SST and SIE (SST2013-CONTROL). (g), (h) and (i) forced by changes in GHG and aerosols emissions (ALL2013-SST2013). Only changes that are statistically significant at the 90% confidence level using a two-tailed Student t-test are plotted in (a), (d) and (g) while thick lines in other panels highlight regions where the differences are statistically significant at the 90% confidence level.

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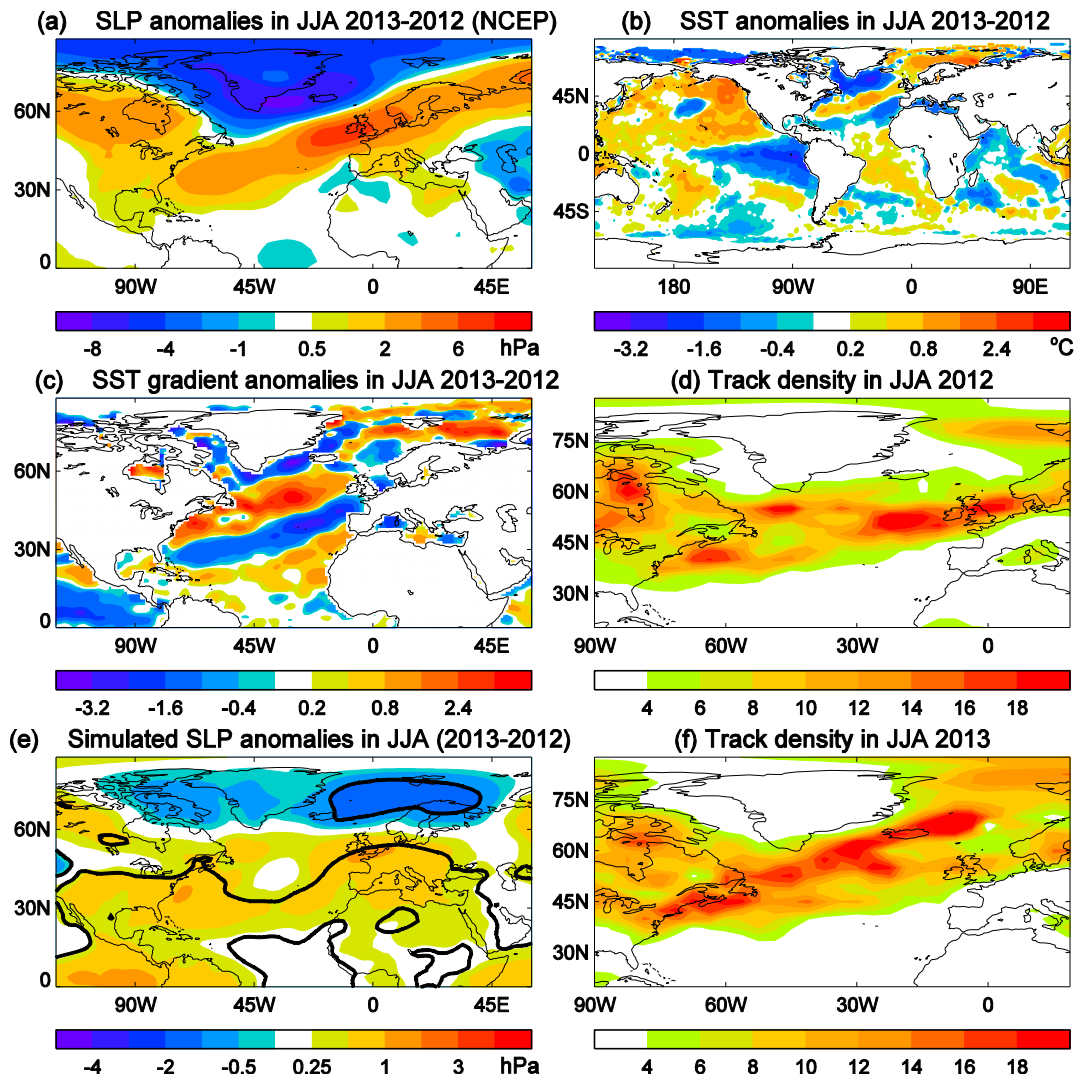
SUPPLEMENTAL MATERIALS: THE 2013 HOT, DRY SUMMER IN WESTERN EUROPE

BUWEN DONG, ROWAN SUTTON AND LEN SHAFFREY



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Figure S1: (a) SAT ($^{\circ}\text{C}$), (b) summer NAO (hPa), and (c) precipitation (mm day^{-1}) indices for observations and model experiments. SAT index is area averaged SAT over region (35°N - 75°N , 10°W - 40°E , land only) (black box in Fig.1c). The SNAO index is defined as the difference of the area mean SLP between two regions around the British Isles (45°N - 60°N , 30°W - 10°E) and over Greenland (65°N - 80°N , 60°W - 20°W) (red and blue boxes in Fig. 1a). Precipitation index is area averaged precipitation over region (35°N - 60°N , 10°W - 20°E , land only) (black box in Fig.1b). All black diamonds in observations are for years from 1964 to 1993 with red diamonds for 2012 and blue diamonds for 2013. Red squares and lines are the mean and mean \pm sigma ranges where sigma is the corresponding standard deviation.



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295 Figure S2. Anomalies in JJA between 2013 and 2012. (a) SLP (hPa), (b) SST ($^{\circ}\text{C}$), and (c)
 296 SST gradient ($^{\circ}\text{C}$ per 1000 km) in observations. (e) Simulated SLP difference between 2013
 297 and 2012 from the changes in SST and SIE. The experiment of 2012 was documented in
 298 Dong et al. (2013b). (d) and (f) are 2012 and 2013 cyclone track density. Track density is in
 299 unit of numbers per month per unit area, where the unit area is equivalent to a 5° spherical
 300 cap (about 10^6 km^2). Note that this climatological period is dominated by cold AMO
 301 conditions and is the period used for the climatological model simulations. Thick lines in (e)
 302 highlight regions where the differences are statistically significant at the 90% confidence
 303 level using a two-tailed Student t-test.

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