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1 **The drying up of Britain? A national estimate of changes**
2 **in seasonal river flows from 11 Regional Climate Model**
3 **simulations**

4
5 **Short title:** A national estimate of changes in seasonal river flows from 11 RCMs

6

7 To be submitted to Hydrological Processes Today as scientific briefing

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17

18 **Abstract**

19 As climate change may modify the hydrological cycle significantly, understanding the
20 impact on river flow is important because it affects long term water resources

21 planning. Here we describe a high-resolution British assessment of changes in river

22 flows in the 2050s under eleven different realisations of HadRM3. In winter, river
23 flows may either increase or decrease, with a wide range of possible decreases in
24 summer flow. These results should encourage adaptation that copes with a broad
25 range of future hydrological conditions.

26

27 (80 words)

28

29 **Keywords**

30 hydrological impact assessment, river flows, climate change, adaptation, change
31 factor method, 2050s.

32 **Word count:** 1869

33

34 **Introduction**

35 Adapting to changes in the terrestrial hydrological cycle is an increasingly pressing
36 problem (Bates et al., 2008; Milly et al., 2008; Stern, 2007) as rivers provide water
37 supply and contribute to ecosystem services (Costanza et al., 1997). As changes to
38 water infrastructure and governance take tens of years to implement and have an
39 expected lifespan from decades (eg legislation) to a century or more (eg reservoirs),
40 water planning and policy must consider changes in river flows over at least the next
41 25 years (Watts, 2010).

42 Methods for calculating the impact of climate change on river flows are well
43 established (Fowler et al., 2007) and have been implemented at the catchment scale
44 to explore climate model uncertainty (eg Lopez et al., 2009) and model parameter
45 uncertainty (eg Wilby, 2005). Results from specific catchments are valuable but
46 difficult to generalise and do not on their own provide a sound basis for water policy.
47 River flow studies at the river basin to country scale usually consider a few climate
48 scenarios (Environment Agency, 2008a; Kay and Jones, 2010) or use a spatial or
49 temporal resolution not readily applied to water policy questions (eg Arnell, 2003)
50 and only provide a limited range of possible changes. The latest UK climate
51 projections, UKCP09, explicitly consider climate model parameter uncertainty
52 (Murphy et al, 2007; Jenkins et al., 2009; Murphy et al, 2009), and are likely to form
53 the basis for future climate impact assessment and adaptation planning in the UK.
54 This paper provides, for the first time, a national assessment of seasonal changes in
55 river flows for the 2050s from the eleven climate scenarios that underpin UKCP09.

56 **Data and methods**

57 Changes for Britain were estimated following the change factors method (Hay et al.,
58 2000) where mean seasonal flow simulated by the semi-distributed hydrological
59 model CERF (Young 2006; Environment Agency, 2008b) for a 30-year baseline
60 (1961-1990) and future (2040-2069) were compared. The CERF rainfall run-off
61 model has regionalised parameters that have been related to catchment
62 characteristics by simultaneous parameter optimisation at 260 undisturbed
63 catchments across the UK. This allows CERF to be applied consistently without the
64 need for site-specific calibration, making it a powerful tool for evaluating changes in
65 hydrological response across the UK. Gridded daily precipitation P (Environment
66 Agency, 2008c), temperature T (Perry et al., 2009) and monthly potential
67 evapotranspiration PE (Thompson et al., 1982) time series derived from
68 observations were used to calculate baseline catchment averages as input to CERF.
69 For PE, monthly totals were equally distributed within each month. CERF was run
70 with a daily timestep from 1961 to 1990 to provide the baseline flows.

71 Climate change factors of P and PE, spatially coherent over the UK at a 25 km
72 resolution, were derived from the UK Met Office Regional Climate Model perturbed
73 physics ensemble HadRM3-PPE, which, in the development of UKCP09, was nested
74 within a perturbed physics ensemble of the HadCM3 coupled atmosphere-ocean
75 global climate model (see Murphy et al. 2007 for more details). The ensemble of
76 RCMs contains 11 physically plausible simulations of detailed climate variability and
77 change run under the A1B SRES emission scenario (IPCC, 2000), referred to as the
78 “medium” emissions scenario in UKCP09 (Jenkins et al., 2009). For P, the monthly
79 change factors were derived from time series bias-corrected using a gamma function
80 (Piani et al., 2010), using 1961-90 as the baseline for bias correction. PE estimates

81 follow the FAO56 method (Allen et al., 1998); investigation showed that this energy
82 balance Penman-Monteith method (Monteith 1965) was the most effective way to
83 close the water balance in the baseline period (this will be the subject of a future
84 paper). The PE estimates use HadRM3-PPE time series for radiation, vapour
85 pressure and wind speed. Temperature was bias-corrected and spatially
86 disaggregated at 5 km using a linear (Lenderink et al., 2007) method, using 1961-05
87 as a baseline. Ideally, other components of the energy balance would also be bias-
88 corrected, but this is limited by the paucity of appropriate observed data. However, it
89 should be noted that the separate bias correction of temperature and rainfall may
90 lead to rainfall and PE series that are not physically coherent, though this is less
91 likely to be a problem where change factor approaches are used to represent future
92 climate, as in this work. Bias correction will be the subject of a future paper. The
93 monthly change factors for P and PE were applied to the 1961-90 data to make
94 series representing the 2050s; these were used in the CERF model and the resulting
95 flows were compared to the baseline series to calculate changes in seasonal flow.
96 This approach means that any changes in flow are a direct response to the climate
97 signal from the 11 RCMs.

98 **Results**

99 The percentage changes in mean flow between the baseline and 2050s are shown in
100 Figure 1 for four seasons for each of the 11 RCMs. Increases in flow are indicated
101 with shades of blue, decreases with shades of yellow/red whilst no change (-5% to
102 +5%) is shown in beige. The overall pattern for the different RCM scenarios is varied.
103 In winter (December, January, February) there is a mixed pattern in England and
104 Wales with drier, similar or wetter signals, within - 20% to +40% change (one
105 scenario with up to 60% in a small region). In contrast, flows in Scotland show a

106 small increase or decrease, although this is still mainly within $\pm 20\%$ with changes in
107 the west reaching up to 40%. In spring (March, April, May) more of the RCM
108 scenarios are drier for most of the UK, with decreases of up to 40%. However, for 3
109 scenarios central England has increased flows (up to 60%). In summer (June, July,
110 August) scenarios predominantly show decreases in runoff through the UK, but
111 range from +20% to -80%. The largest percentage decreases are mainly in the north
112 and west of the UK although the range in these areas between scenarios can be
113 large (0 to -80%). In autumn (September, October, November) there is a mixed
114 pattern with a full range of percentage changes (+60 to -80%) across the UK. Most
115 scenarios indicate decreases in flows, especially in the south and east (up to -80%)
116 whilst in the west and north changes can be small. One scenario shows no change
117 or an increase in runoff across the UK.

118 In summary, the results indicate marked variations between the RCM scenarios.
119 While mixed patterns exist, for autumn and winter especially, all scenarios indicate a
120 decrease in flow in the summer almost everywhere. Some of the summer flow
121 decreases are large even compared to natural variability. For example, in the River
122 Thames Teddington flow series that starts in 1883, only four summers (1976, 1934,
123 1921 and 1944) had flows that were more than 80% below the 1961-90 average.
124 However, the differences between the scenarios at any location can be large.

125 **Discussion**

126 Using HadRM3-PPE climate data in a national hydrological model results in eleven
127 spatially coherent scenarios of river flow that help to explain how climate model
128 uncertainty and climatic variability are manifested as a hydrological response.
129 Considered together, the scenarios present a more complex picture of possible
130 change than that from the earlier UK climate projections UKCIP02 (Hulme et al.,

131 2002). Almost all scenarios suggest lower summer (JJA) flows across Britain, though
132 the magnitude of the change is variable. In winter, spring and autumn there is much
133 more variability both between scenarios and between different parts of Britain.

134 As this study uses the change factor method that scales historic weather sequences
135 to represent the future climate, the resulting flows may not capture the full range of
136 change. This may be a lesser issue for long-term average change assessments.

137 Note also that no change in the catchment behaviour (e.g. due to vegetation change)
138 was considered, and that these results show hydrological response to only one
139 climate model ensemble; other models would give different results. Despite these
140 assumptions, the range of results demonstrates that “predict and provide”
141 approaches to adaptation are unlikely to be successful, as climate change
142 adaptation measures and actions are more effective if they are robust to a range of
143 possible futures.

144 Future work will consider other time horizons and exploit fully the transient HadRM3-
145 PPE time series to create transient flow scenarios, so that rates of change of river
146 flow can be explored, answering important questions about when different
147 management actions should be taken.

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152 The views expressed are those of the authors and not of the funding organisations.

153 Two anonymous reviewers improved the clarity of the paper considerably. UKCP09
154 probabilistic sample and gridded temperature observed dataset were obtained from

155 the UK Climate Impacts Programme (<http://ukcip.org.uk/>) and HadRM3-PPE time
156 series from the British Atmospheric Data Centre (www.badc.nerc.ac.uk). Other data
157 were obtained from the National River Flow Archive
158 (<http://www.ceh.ac.uk/data/nrfa/>).

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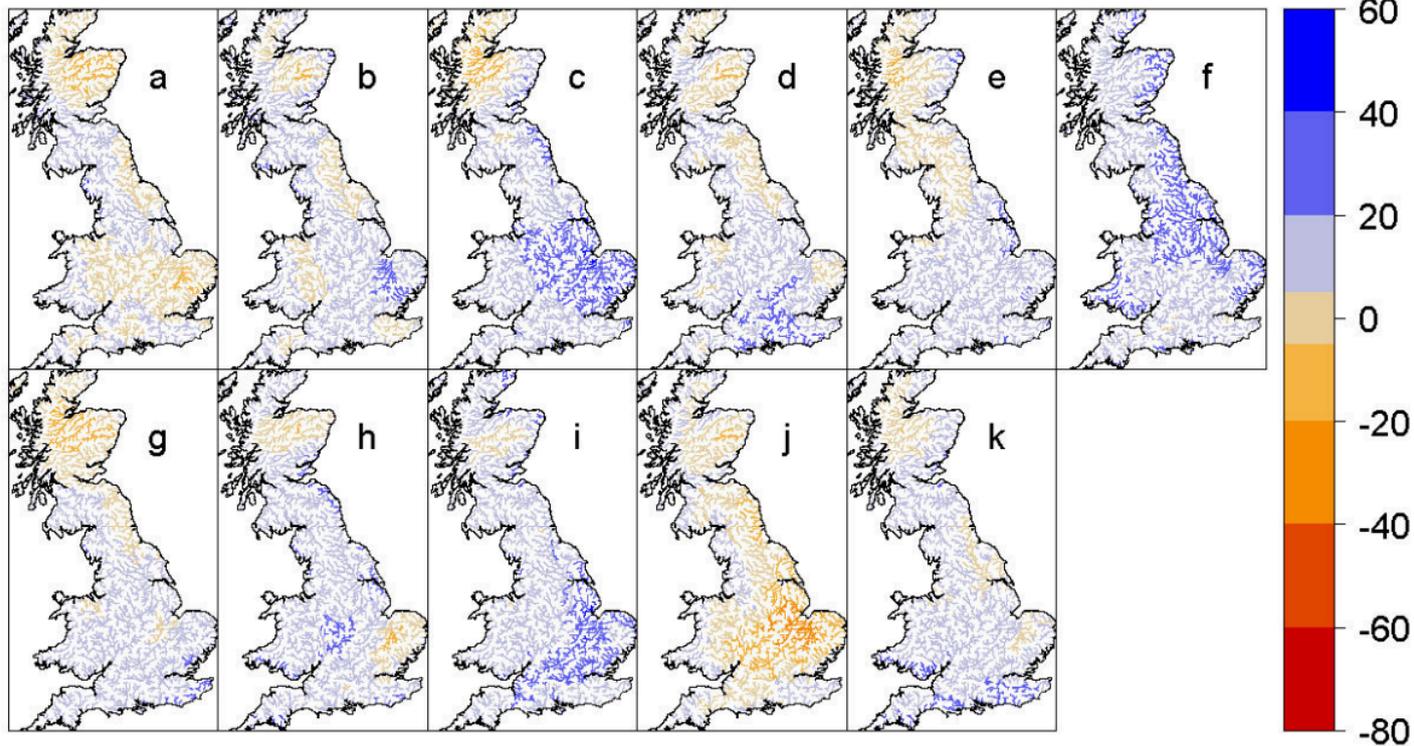
242

243 **Figure caption:**

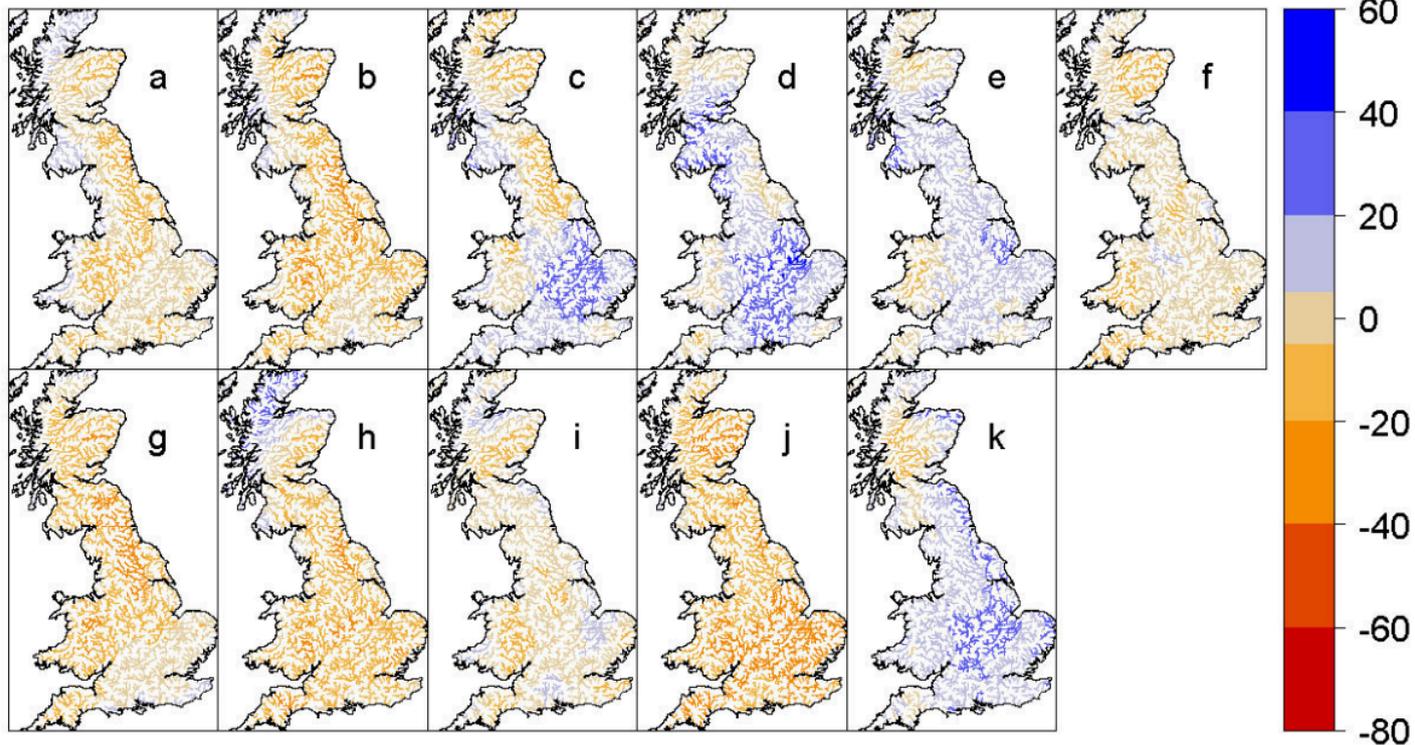
244 Figure 1: Percentage change in seasonal mean flow for the 2050s as simulated by
245 CERF with each of the HadRM3-PPE members. a HadRM3Q0 (unperturbed, run
246 afgcx); b HadRM3Q3 (run afixa); c HadRM3Q4 (run afixc); d HadRM3Q6 (run afixh);
247 e HadRM3Q9 (run afixi); f HadRM3Q8 (run afixj); g HadRM3Q10 (run afixk); h
248 HadRM3Q14 (run afixl); i HadRM3Q11 (run afixm); j HadRM3Q13 (run afixo); k
249 HadRM3Q16 (run afixq)

250

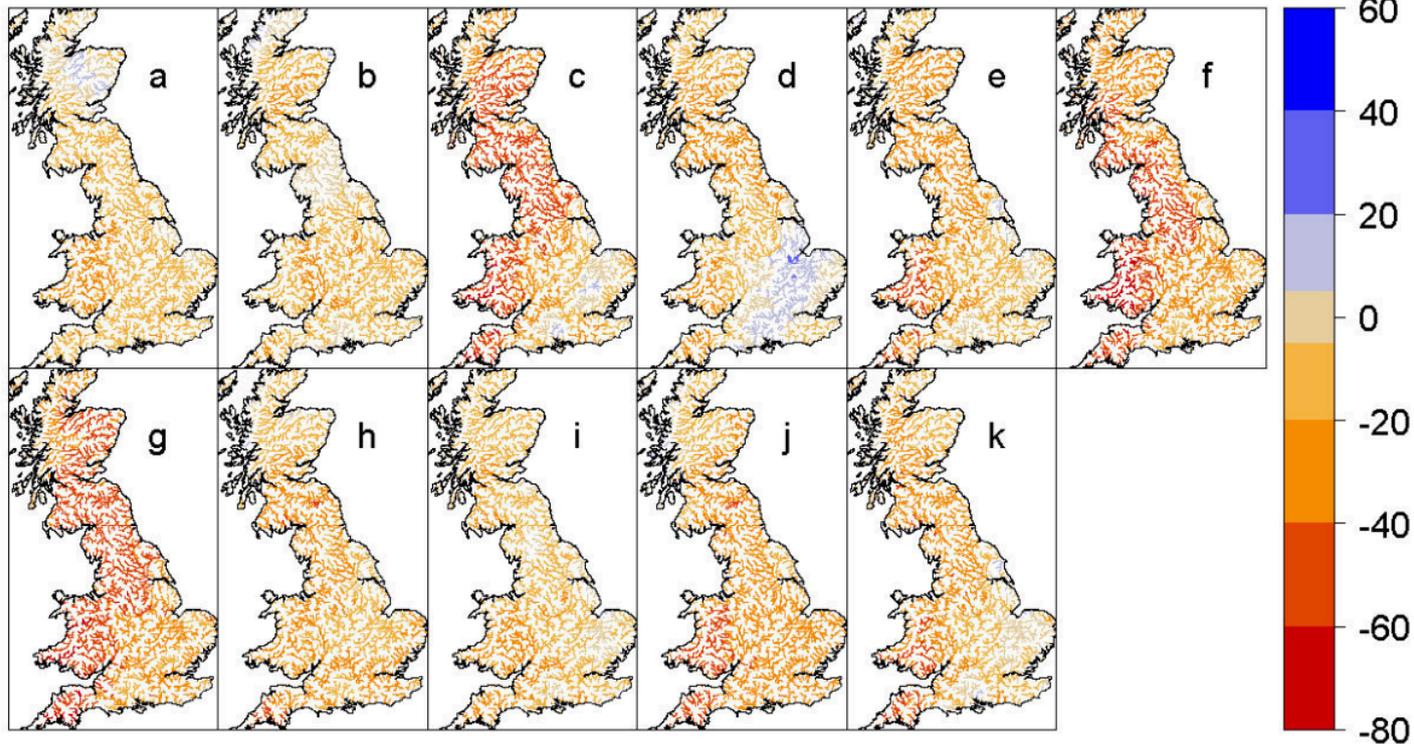
Winter (DJF)



Spring (MAM)



Summer (JJA)



Autumn (SON)

