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DOI: 10.1016/j.jhydrol.2015.01.060

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Document Version Peer reviewed version

Citation for published version (Harvard):

Lavers, DA, Hannah, DM & Bradley, C 2015, 'Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England, Journal of Hydrology, vol. 523, pp. 179-189. https://doi.org/10.1016/j.jhydrol.2015.01.060

Link to publication on Research at Birmingham portal

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.060

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Accepted Manuscript

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PII:	S0022-1694(15)00077-3
DOI:	http://dx.doi.org/10.1016/j.jhydrol.2015.01.060
Reference:	HYDROL 20217
To appear in:	Journal of Hydrology
Received Date:	25 July 2014
Revised Date:	12 December 2014
Accepted Date:	23 January 2015



Please cite this article as: Lavers, D.A., Hannah, D.M., Bradley, C., Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England, *Journal of Hydrology* (2015), doi: http://dx.doi.org/10.1016/j.jhydrol.2015.01.060

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1	Connecting large-scale atmospheric circulation, river flow and
2	groundwater levels in a chalk catchment in southern England
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10	Revised manuscript submitted to
11	Journal of Hydrology
12	
13	12th December 2014
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17	Abstract
18	Groundwater is an important water resource and globally it represents the largest distributed
19	store of freshwater. In southern England, groundwater is a major source for public water
20	supply, and many aquifers have recently experienced both extreme low and high groundwater
21	levels. In this paper, we use observations of precipitation, river discharge and groundwater
22	levels (1964 to 2010) and an atmospheric reanalysis to explore the large-scale climate

23 patterns preceding the nine highest and lowest March river discharge and groundwater levels 24 in the chalk catchment of the River Lambourn (Berkshire Downs, southern England). Peak 25 monthly precipitation is shown to occur from October to January, while the highest river 26 discharge and groundwater levels are found from February to April. For high discharge / 27 groundwater levels, composite anomaly patterns of the mean sea level pressure show a 28 stronger than average pressure gradient across the North Atlantic Ocean, with enhanced water 29 vapour transport across southern England. For the lowest discharge / groundwater levels, a 30 blocking high pressure system is found across the British Isles deflecting storms and 31 precipitation to the north. Significantly, the intra-composite variability suggests that different 32 sequences of atmospheric states may lead to high and low discharge / groundwater events. MA

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34 1. Introduction

35 Groundwater is an increasingly important water resource: globally groundwater 36 represents the largest distributed store of freshwater (Taylor et al., 2013). Groundwater 37 discharge sustains river base flow (Winter et al., 1998) and supports characteristic 38 groundwater-dependent ecosystems (Boulton, 2005; Boulton & Hancock, 2006). In the 39 context of changes in the frequency and magnitude of hydrological extremes, groundwater 40 abstraction has helped sustain human water security during periods of rapid population 41 increase and provided potable water close to population centres and reliable water for irrigated agriculture (Gleeson et al., 2012). These resources are potentially vulnerable to 42 43 drought events, and particularly rainfall during those periods that account for the majority of 44 groundwater recharge (Marsh et al., 2007; Bloomfield & Marchant, 2013). Conversely in 45 some river catchments, seasonal increases in groundwater levels may lead to prolonged 46 inundation of low-lying land, and groundwater flooding following high recharge (Hughes et 47 al., 2011; Négrel & Petelet-Giraud, 2005) as experienced in southern England during the winter of 2013/14. 48

Hence, for multiple practical reasons, it is important that groundwater resources are 49 50 utilised sustainably and in an integrated manner. This requires long-term rates of groundwater 51 abstraction to be, at least, sustained by current recharge (Gleeson et al., 2012), so as to 52 minimise impact on associated groundwater-dependent ecosystems. However, attribution of 53 'cause and effect' in understanding the behaviour of many groundwater systems is 54 problematic. Notably, there are difficulties disaggregating anthropogenic impacts on 55 groundwater bodies (i.e. abstraction), from 'natural' variability due to climate drivers (Green 56 et al., 2011). These problems are compounded by the likelihood that anthropogenic effects 57 will induce changes in a groundwater body of a similar magnitude to those that could be 58 anticipated by climate variability. Accordingly, more work is required urgently in catchments

that are relatively unaffected by groundwater abstraction, to improve our understanding of the atmospheric controls on groundwater storage (and flux rates), and to provide analogues to benchmark the 'natural' response in systems where human impacts are significant.

62 One of the key difficulties when seeking to quantify climate – riverflow – groundwater 63 relationships is accurate estimation of groundwater recharge. Woldeamlak et al. (2007) 64 highlight the sensitivity of groundwater levels in a catchment in North Belgium to recharge, 65 and the implications for increased flood risk. However, recent studies indicate considerable uncertainty in projected estimates for groundwater recharge. Herrera-Pantoja & Hiscock 66 67 (2008) suggest the likelihood of lower groundwater recharge in England and Scotland, whilst Jackson et al. (2011) project significant variability in future groundwater recharge in 68 69 southern England (ranging very widely between -26% to +31% of current levels). The 70 significance of this is spatially variable, depending upon the characteristics of individual 71 catchments, as demonstrated by work on the chalk catchment of the River Pang in southern 72 England (Peters et al., 2006; Tallaksen et al., 2009). This research has demonstrated the 73 degree to which drought events can be attenuated and delayed in permeable catchments, and 74 emphasises the importance of catchment properties in determining the variability in drought 75 severity across a catchment.

These uncertainties in estimating UK groundwater recharge are matched elsewhere (e.g. Africa: Kingston & Taylor, 2010; Australia: Crosbie et al., 2011; N. America: Kurylyk & MacQuarrie, 2013) reflecting problems that include the difficulty in quantifying any changes in the seasonality of precipitation, and more particularly in the composition (e.g., duration, intensity, and precipitation type; rain or snow) of individual rain events. In this respect, the simulation of groundwater recharge associated with extreme precipitation is critical; Green et al. (2011) suggest that global climate models currently predict too many days with (1) weak

precipitation, and (2) too little precipitation and they conclude that more research quantifying the links between groundwater resources and atmospheric moisture transport is required. For groundwater, the uncertainty of projections is complicated and propagated by translation of the climate signal through the river basin- aquifer system to groundwater levels.

87 Despite the importance of groundwater, relatively few studies have investigated the 88 linkage between groundwater systems and the large-scale atmospheric circulation (e.g. Anderson & Emanuel, 2008). Commonly river baseflow has been used as a groundwater 89 90 proxy, although in some catchments fluctuations in groundwater levels have been 91 successfully correlated with low frequency climate patterns (Holman et al., 2011; El Janyani et al., 2012). For example, Holman et al. (2011) employed wavelet analysis to show 92 93 statistically significant wavelet coherence on multi-annual to decadal time scales between 94 monthly groundwater-level time series (in three boreholes along a northeast to southwest 95 transect across England) and the North Atlantic Oscillation (NAO), East Atlantic Pattern and 96 the Scandinavian Pattern. Periods of high and low climate-groundwater coherence were found to be related to variations in the NAO index (Holman et al., 2011). These studies have 97 98 used coarse large-scale climate indices, such as the NAO, to investigate climate-groundwater 99 connections. However, studies of European precipitation and river flow have shown climate 100 diagnostics with fixed centres-of-actions are unable to capture important, dynamic and 101 informative subtleties in atmospheric controls driving hydrological response (e.g. Kingston et 102 al., 2006; Lavers et al., 2010, 2013).

In this study, we advance this area of research by considering variables that are of more direct relevance to groundwater levels, specifically atmospheric water vapour transport, upper tropospheric winds and pressure fields. Our aim is to investigate links between periods of high and low groundwater level and the large-scale atmospheric circulation, focussing on a

107	permeable catchment	(the River Lambou	rn, Berkshire, UK) that is unaffected	by abstraction.
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108 To meet this aim, the following objectives are addressed to:

109	•	Determine the seasonal cycle in rainfall, groundwater levels and river flow in the
110		Lambourn catchment;
111	•	Investigate the climatic 'states' that contribute to periods of high and low river flows

- 112 and groundwater levels. Use composite analyses to reveal the large-scale atmospheric 113 conditions that yield extreme groundwater levels and peak river discharges;
- 114 Improve process understanding of the groundwater response to hydroclimatological MAN 115 drivers.

116

2. Data and Methods 117

118 2.1 Atmospheric data

119 Atmospheric reanalyses provide one of the best, and most consistent estimates of the historical state of the Earth's atmosphere; they are produced by assimilating 120 121 meteorological/oceanic observations into the short-range forecasts of a fixed version of a 122 Numerical Weather Prediction model. In this study, the mean sea level pressure (MSLP), 123 specific humidity q (in kg / kg), and the zonal and meridional (u and v) wind fields (in ms^{-1}) 124 on pressure levels at a monthly resolution for 1964 to 2010 were retrieved from the Twentieth 125 Century Reanalysis (20CR) at a $2.0^{\circ} \times 2.0^{\circ}$ resolution (Compo et al., 2011). The MSLP is a 126 useful indicator of where low pressure and extratropical storm activity occurs, while the 127 upper tropospheric wind field at 250 hPa highlights the location of the jet stream and storm 128 track (a region in which extratropical cyclones tend to develop). It is within these storms that 129 atmospheric moisture transport predominantly occurs in mid-latitude regions, a quantity that 130 is essential for precipitation generation and resultant groundwater recharge and river flow. To

show areas of moisture transport, we calculate the vertically-integrated horizontal water
vapour transport (hereafter, integrated vapour transport IVT) as follows:

$$IVT = \sqrt{\left(-\frac{1}{g}\int_{1000}^{300} qu\,dp\right)^2 + \left(-\frac{1}{g}\int_{1000}^{300} qv\,dp\right)^2} \tag{1}$$

where q, u and v are the layer-averaged variables, g is the acceleration due to gravity, and dp is the depth of each layer.

In this study we note that temperature is not explicitly analysed. While temperature is an important variable for evapotranspiration and resultant river recharge, herein we assume that temperature is considered to be partially included in the IVT, as high IVT values are often associated with relatively warm air from the southwest and west of the British Isles.

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141 **2.2 River Lambourn catchment description**

We focus on the catchment of the River Lambourn, which covers ~234 km² of the West 142 143 Berkshire Downs in southern England. The catchment is largely rural (pasture) with rolling 144 hills that are dissected by a dendritic dry valley network. Mean annual precipitation is 736mm, with surface elevations ranging from 250 m asl in the northwest to 70 m asl in the 145 146 southeast (Figure 1). The catchment is entirely underlain by the Chalk formation, which dips 147 at a shallow angle to the southeast. The Chalk is characterised by an upper zone of active 148 groundwater movement, for example, through solution enlarged fractures, which overlies a 149 deeper zone of regional groundwater movement (Bradford, 2002). It is groundwater 150 discharge from the upper zone that largely sustains the flow of the River Lambourn and its 151 tributary stream. The Lambourn is relatively unaffected by groundwater abstraction and as 152 such is listed as a benchmark catchment by the UK National River Flow Archive (NRFA).

153 The catchment was also studied intensively during two research campaigns: (1) the Thames

154 Groundwater Scheme (1967–1976) and (2) the UK Lowland Catchment Research (LOCAR)

155 programme (2000–2006) (Grapes et al., 2005; Griffiths et al., 2006; Butler et al., 2012).

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157

2.3 River Lambourn catchment data

A surrogate index of monthly mean groundwater (hereafter, GW) levels was generated 158 159 for the period from September 1964 to August 2010 as the mean of GW levels observed 160 manually at 4 boreholes (locations given in Figure 1). Our approach recognises the 161 observation by Peters et al. (2006) of the difficulty in characterising an aquifer using data 162 from one key borehole. The methodology used to derive the mean catchment GW series is 163 summarised in the supplementary material as there were occasional periods when concurrent 164 data were not available for all 4 boreholes. In most years, GW levels exhibit a strong seasonal 165 cycle reflecting the timing and magnitude of GW recharge. Monthly basin-averaged precipitation and daily river flows were retrieved from the NRFA from 1 September 1964 to 166 30 August 2010 (46 years); the river flows were averaged to yield a monthly river flow 167 series. Herein, we regard the start of the water year as September because Bower et al. 168 169 (2004) identified this to be the month of minimum river flow across the UK. Furthermore, as 170 significant precipitation in September can eradicate soil moisture deficits that develop during 171 the summer, we feel it is appropriate that the start of the autumn climate season is used as the 172 start of the water year.

As extreme events have greatest socio-economic impact, our focus here is on those periods with the highest and lowest river discharge and GW levels. The bottom and top nine years for each month, in terms of river discharge and GW levels, were selected which relate approximately to the 20th and 80th percentiles (an approach taken also by Kingston et al.,

177 2007). The monthly atmospheric fields corresponding to these high and low years (for each 178 month) were then used in a composite analysis. Composite analysis has the benefit of 179 considering non-linear associations, as well as being easy to interpret (Kingston et al., 2006). An anomaly composite analysis was computed, which involved subtracting the long-term 180 181 mean (1965 to 2010) from each of the nine atmospheric fields, and then finally averaging the 182 anomaly fields. These anomalies highlight the average departures from the climatological 183 mean that led to the extreme events. 190

184

185 3. Results and discussion

3.1. Monthly precipitation, discharge and GW level variability (1965–2010) 186

187 Boxplots of monthly precipitation, discharge and GW level are shown in Figure 2a, b and 188 c, respectively. Typically precipitation peaks in autumn and winter (October to January), 189 which is followed generally by the highest discharge and GW level between February and April. It is evident from Figure 2 that the highest percentiles (> 75th percentile) of river 190 191 discharge and GW level distributions occur from February to April. As the upper quartile of 192 the March distributions are marginally larger, and mean river flow peaks in this month (Figure 2b), it was decided that the analysis would focus on the large-scale circulation 193 194 preceding discharge and GW level in March.

195 As expected, there is a strong association between monthly discharge and GW level, 196 quantified by a Spearman Rank correlation ρ of 0.88 over 1965–2010. In March, the 197 correlation p between discharge and GW level is 0.83 (Figure 2d). The close link between 198 GW and discharge is confirmed by the similarity between the top and bottom March events 199 for both. For the highest discharge / GW levels seven out of nine years are the same. For 200 discharge, these are 2001, 1995, 2007, 1994, 1967, 1988, 1975, 2003, 1977; and, for GW

201 levels, these are 2001, 1995, 2003, 1994, 2007, 1975, 1988, 1969, 2008 (years are given in 202 their order of magnitude). For the lowest discharge / GW levels eight out of nine years are the 203 same. For discharge, these are 1976, 1992, 1965, 1997, 2006, 1991, 1989, 2005, 1973; and, for GW levels, these are 1992, 1965, 1976, 1991, 1997, 2006, 1989, 2005, 2010. We note that 204 205 our analysis on the lowest discharge / GW levels only investigates the lower tail of the 206 distribution for the period when GW recharge would be expected, rather than examining the 207 absolute low flows (and GW levels), which normally occur in the late summer and early 208 autumn.

209

3.2. Composite analysis of the highest nine March events (1965–2010)

Figure 3 shows the concurrent and lagged composites of the MSLP and IVT anomalies 211 212 for the nine highest March discharges. (A lagged analysis of 6 months is considered to be 213 appropriate primarily because the GW borehole sites used are situated in the more productive 214 upper zone of active groundwater movement, where the permeability and yield are highest.) For all months, the MSLP anomaly pattern has a larger than average pressure gradient across 215 216 the North Atlantic Ocean (especially from December to February) and lower than normal 217 pressure across the British Isles. The resultant westerly (or zonal) wind pattern would advect 218 moisture into southern England. In Figure 3, the larger than average IVT (red colours) is 219 situated to the south of the low pressure anomaly, but a significant signal is not observed in 220 moisture transport. A 90% confidence interval has been calculated around the composite 221 mean IVT anomaly using a t-distribution with eight degrees of freedom (calculated as 1.86 $\times \frac{\sigma}{\sqrt{n}}$ where σ is the standard deviation, and *n* is the sample size). Although we 222 223 acknowledge that this is a small sample size to make strong assertions on the IVT patterns 224 behind the high March discharges, an anomaly pattern significantly different from zero at the

90% confidence level is not found over southern England. This suggests that a large variation exists in the atmospheric patterns that constitute the composite implying that variable monthly-averaged climate states are responsible for high flow periods in the Lambourn catchment.

229 The 250 hPa zonal wind anomalies are used to identify the location of the jet stream 230 across the North Atlantic. The jet stream is a region of strong winds at the top of the 231 troposphere, which exists because of the equator-to-pole temperature gradient. It is within the 232 jet stream that extra-tropical cyclones develop and travel eastwards along storm tracks across 233 the North Atlantic Ocean (Holton, 1992). These storms transport large quantities of water 234 vapour, which can result in extreme precipitation and floods upon landfall in Britain (Lavers 235 et al., 2011). For the Lambourn, a succession of these storm events will progressively saturate 236 the catchment, accounting for significant GW recharge and resulting in high discharge and GW levels (e.g., Lavers et al., 2011). Figure 4 shows the 250 hPa zonal wind anomalies 237 238 before the nine highest discharges and it appears that in each case the jet stream area was 239 located further south than normal, as seen by the significant anomaly signals (red areas) in 240 four months (October, November, February and March). However, it is important to note that 241 there is again high intra-composite variability in the wind patterns, as evidenced by the few 242 areas with statistical significance.

The composites of the MSLP and IVT anomalies for the nine highest March GW levels are shown in Figure 5. There are two significant points of note. First, it is striking that the IVT fields are largely not significantly different from zero at the 90% confidence level. This, as for the river flow, suggests that a variety of atmospheric patterns contribute to the highest GW levels, and thus there is no single cause that results in extreme GW levels. Second, although the March discharge and GW levels have the same fields for seven out of nine years, the composite anomalies are quite different. The pressure gradient across the North

Atlantic is weaker for GW than discharge, and a stronger signal of moisture transport is found in January (cf. Figures 3 & 5). The fact that only two different years (or fields) give such different results highlights the varying patterns that constitute the mean composite anomaly.

253

3.3. Composite analysis of the lowest nine March events (1965–2010)

255 For the lowest nine March discharges, a strong positive MSLP anomaly exists (especially 256 from November to February) to the west of the British Isles (Figure 6). This 'blocking high'-257 like pressure anomaly (with MSLP anomalies of 7 hPa in January; Figure 6c) precludes extra-258 tropical cyclones from affecting southern England, and their associated water vapour 259 transport and precipitation is shifted to the north (e.g., Figure 6c). In turn, lower than average IVT anomalies (blue colours in Figure 6) occur over southern England tending to cause 260 261 reduced precipitation receipt and lower discharge. The 250 hPa zonal wind anomalies in 262 Figure 7 highlight how the jet stream region of anomalously strong upper-level winds, and 263 thus the storm track, is located to the north of Britain (especially in December and January; 264 Figure 7 c–d).

The composite anomaly patterns for the lowest nine March GW levels are shown in Figure 8. As with the lowest discharge events, a positive MSLP anomaly is located over (and to the west of) the British Isles, which deflects the storms, moisture transport and precipitation to the north. By comparing Figures 6 and 8, it is evident that the climate patterns are broadly similar between low March discharge and GW levels owing to the fact that eight of the nine events are the same.

271

272 **4.** Conclusions

273 The aims of this paper were (1) to determine the seasonal cycle of hydrological variables, 274 (2) assess the large-scale climatic circulation that occurred during the months preceding the 275 highest and lowest discharges / GW levels in the river Lambourn, southern England, and thus 276 (3) improve hydrometeorological process understanding. The analyses presented here link 277 river discharge and GW levels for the Lambourn catchment with large-scale atmospheric 278 reanalysis data.

279 Our findings show that the highest monthly precipitation typically occurs from October to 280 January, the highest river discharge generally occurs from February to March, while the 281 highest GW levels are on average found later from March to April. Given that the upper 282 quartiles of the March discharge / GW level distributions were found to be marginally larger 283 than February or April, March was used as the target month in our analyses. There was large 284 similarity between the years with the highest March discharge / GW level, with seven of the 285 nine years being the same; for the lowest March discharge / GW level it was eight of the nine 286 years. As the GW boreholes were predominantly in the

287 For highest March river discharge / GW levels a stronger than normal pressure gradient 288 was in place across the North Atlantic resulting in extra-tropical storms and higher than average water vapour transport affecting the Lambourn catchment. Using the small sample herein, a significant water vapour transport signal was not revealed, which suggests a large variation in the atmospheric patterns that constitute the composite anomalies. From the results we conclude that different sequences of atmospheric patterns and water vapour transport (and thus precipitation receipt) lead to high discharge and GW levels. It is known that a series of extra-tropical cyclones are required to produce extreme river flows in the 295 Lambourn (Lavers et al., 2011), but the results in this study suggest that their order or spacing 296 in time is variable. Typically, the lowest March discharge/ GW levels have stronger than 297 normal pressure situated over the British Isles, which is also known as a blocking high

298 pressure system. This atmospheric set up acts to deflect storms, their moisture transport and 299 precipitation to the north of the British Isles. By comparing the atmospheric patterns between 300 the highest and lowest events (discharge and GW), an important result to highlight is how the 301 composite anomaly patterns are not the opposite of each other, which suggests that the 302 system studied is behaving in a non-linear manner. 303 The analysis undertaken raises important questions for future research. Firstly, do similar 304 non-linear patterns between high and low river flow / GW levels occur in other months where 305 GW recharge is expected, such as, January, February, and April. Secondly, what types of 306 patterns exist in catchments of differing geology (e.g., sandstone), where the response of GW 307 and river flow may be more attenuated. Thirdly, to what extent do the results that we present 308 here advance the goal of forward modelling conditions of both extreme high and low GW and 309 river flow conditions. If successful, the latter could enable improved conjunctive 310 management of GW and surface-water resources in permeable catchments with respect to 311 both GW flooding, and drought. Fourthly, if models of hydroclimatological connections can 312 be developed for GW / river flow in catchments unaffected by abstraction, they can be used 313 to assess 'natural' system variability and thus (a) quantify the potential effects of abstraction 314 in impacted catchments and (b) provide a basis for defining environmental flows. 315 316 317 318

319

320 Acknowledgements

- 321 David Lavers acknowledges support from the UK Natural Environment Research Council
- under the Changing Water Cycle programme, HyDef project (NE/I00677X/1). We thank the
- 323 UK National River Flow Archive, based at the Centre for Ecology and Hydrology in
- 324 Wallingford UK, for kindly providing the daily river flow data, and the British Geological
- 325 Survey for provision of the groundwater level data. We are very grateful for the helpful and
- 326 constructive comments of Dr. John Bloomfield and an anonymous reviewer on this paper.
- 327
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410 **Figures** 411



Figure 1: A map of the River Lambourn basin (after Grapes et al., 2005). 413

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Figure 2: Boxplots of monthly (a) rainfall, (b) river flow, (c) groundwater (GW) levels, and (d) time series of March discharge (solid line) and groundwater levels (dashed line) for the river Lambourn basin (over the period 1965–2010). For panels a–c the line in each box is the median, the dot in each box is the mean, the box represents the 25th and 75th percentiles, and the whiskers are the 5th and 95th percentiles. The crosses in panels (a)–(c) represent the minimum and maximum values.

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- Figure 3: Composite monthly mean anomaly fields of the IVT (in kg m⁻¹ s⁻¹) and MSLP 435
- 436 (contours; in hPa) before the top nine March river flows. Coloured regions identify areas
- 437 where the IVT composite mean is different from zero at the 10% confidence level. Acception
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- Figure 4: Composite monthly mean anomaly fields of the zonal wind at 250 hPa (in ms⁻¹) 440
- 441 before the top nine March river flows. Coloured regions identify areas where the composite
- 442 mean is different from zero at the 10% confidence level. Acception
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- Figure 5: Composite monthly mean anomaly fields of the IVT (in kg m⁻¹ s⁻¹) and MSLP 446
- 447 (contours; in hPa) before the top nine March GW levels. Coloured regions identify areas
- 448 where the IVT composite mean is different from zero at the 10% confidence level. Acception
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- Figure 6: Composite monthly mean anomaly fields of the IVT (in kg m⁻¹ s⁻¹) and MSLP 452
- 453 (contours; in hPa) before the lowest nine March river flows. Coloured regions identify areas
- 454 where the IVT composite mean is different from zero at the 10% confidence level. Accterition
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- Figure 7: Composite monthly mean anomaly fields of the zonal wind at 250 hPa (in ms⁻¹) 458
- 459 before the lowest nine March river flows. Coloured regions identify areas where the
- 460 composite mean is different from zero at the 10% confidence level. Acception
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- Figure 8: Composite monthly mean anomaly fields of the IVT (in kg m⁻¹ s⁻¹) and MSLP 464 465 (contours; in hPa) before the lowest nine March GW levels. Coloured regions identify areas
- 466 where the IVT composite mean is different from zero at the 10% confidence level. Acctentic
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470	Linking variations in groundwater level in southern England to
471	large-scale atmospheric circulation
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479	HIGHLIGHTS
480	1). Strong pressure gradient is over North Atlantic Ocean during high groundwater events.
481	2). A blocking high pressure system is found across Britain during low groundwater events.
482	3). Varying sequences of atmospheric patterns cause high and low groundwater levels.
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