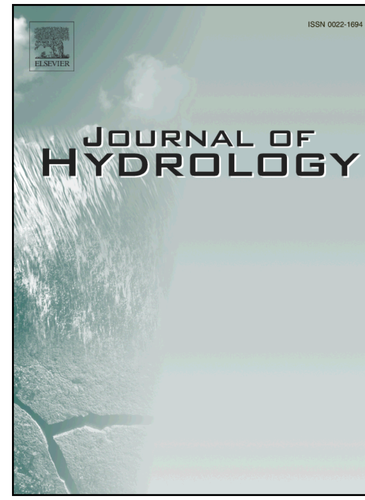
Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England

Lavers, David A.; Hannah, David M.; Bradley, Christopher

DOI:
10.1016/j.jhydrol.2015.01.060

Accepted Manuscript



Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England

David A. Lavers, David M. Hannah, Chris Bradley

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

Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England

DAVID A. LAVERS[1, 2*+], DAVID M. HANNAH[3], CHRIS BRADLEY[3]

[1] Department of Meteorology, University of Reading, UK

[2] The Walker Institute, University of Reading, UK

[3] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham. B15 2TT. UK

Revised manuscript submitted to

Journal of Hydrology

12th December 2014

[*]Contact author: email: dlavers@ucsd.edu; Tel.: 001 858-534-3320

[+]Current affiliation: Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California

ABSTRACT

Groundwater is an important water resource and globally it represents the largest distributed store of freshwater. In southern England, groundwater is a major source for public water supply, and many aquifers have recently experienced both extreme low and high groundwater levels. In this paper, we use observations of precipitation, river discharge and groundwater levels (1964 to 2010) and an atmospheric reanalysis to explore the large-scale climate patterns preceding the nine highest and lowest March river discharge and groundwater levels in the chalk catchment of the River Lambourn (Berkshire Downs, southern England). Peak monthly precipitation is shown to occur from October to January, while the highest river discharge and groundwater levels are found from February to April. For high discharge / groundwater levels, composite anomaly patterns of the mean sea level pressure show a stronger than average pressure gradient across the North Atlantic Ocean, with enhanced water vapour transport across southern England. For the lowest discharge / groundwater levels, a blocking high pressure system is found across the British Isles deflecting storms and precipitation to the north. Significantly, the intra-composite variability suggests that different sequences of atmospheric states may lead to high and low discharge / groundwater events.

1. Introduction

Groundwater is an increasingly important water resource: globally groundwater represents the largest distributed store of freshwater (Taylor et al., 2013). Groundwater discharge sustains river base flow (Winter et al., 1998) and supports characteristic groundwater-dependent ecosystems (Boulton, 2005; Boulton & Hancock, 2006). In the context of changes in the frequency and magnitude of hydrological extremes, groundwater abstraction has helped sustain human water security during periods of rapid population 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 drought events, and particularly rainfall during those periods that account for the majority of groundwater recharge (Marsh et al., 2007; Bloomfield & Marchant, 2013). Conversely in some river catchments, seasonal increases in groundwater levels may lead to prolonged inundation of low-lying land, and groundwater flooding following high recharge (Hughes et al., 2011; Négrel & Petelet-Giraud, 2005) as experienced in southern England during the winter of 2013/14.

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

One of the key difficulties when seeking to quantify climate – riverflow – groundwater relationships is accurate estimation of groundwater recharge. Woldeamlak et al. (2007) highlight the sensitivity of groundwater levels in a catchment in North Belgium to recharge, and the implications for increased flood risk. However, recent studies indicate considerable uncertainty in projected estimates for groundwater recharge. Herrera-Pantoja & Hiscock (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 southern England (ranging very widely between -26% to +31% of current levels). The significance of this is spatially variable, depending upon the characteristics of individual catchments, as demonstrated by work on the chalk catchment of the River Pang in southern England (Peters et al., 2006; Tallaksen et al., 2009). This research has demonstrated the degree to which drought events can be attenuated and delayed in permeable catchments, and emphasises the importance of catchment properties in determining the variability in drought 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.

Despite the importance of groundwater, relatively few studies have investigated the linkage between groundwater systems and the large-scale atmospheric circulation (e.g. Anderson & Emanuel, 2008). Commonly river baseflow has been used as a groundwater proxy, although in some catchments fluctuations in groundwater levels have been 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 statistically significant wavelet coherence on multi-annual to decadal time scales between monthly groundwater-level time series (in three boreholes along a northeast to southwest transect across England) and the North Atlantic Oscillation (NAO), East Atlantic Pattern and 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 used coarse large-scale climate indices, such as the NAO, to investigate climate-groundwater connections. However, studies of European precipitation and river flow have shown climate diagnostics with fixed centres-of-actions are unable to capture important, dynamic and informative subtleties in atmospheric controls driving hydrological response (e.g. Kingston et 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 permeable catchment (the River Lambourn, Berkshire, UK) that is unaffected by abstraction. To meet this aim, the following objectives are addressed to:

- Determine the seasonal cycle in rainfall, groundwater levels and river flow in the Lambourn catchment;
- Investigate the climatic 'states' that contribute to periods of high and low river flows and groundwater levels. Use composite analyses to reveal the large-scale atmospheric conditions that yield extreme groundwater levels and peak river discharges;
- Improve process understanding of the groundwater response to hydroclimatological drivers.

2. Data and Methods

2.1 Atmospheric data

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 meteorological/oceanic observations into the short-range forecasts of a fixed version of a Numerical Weather Prediction model. In this study, the mean sea level pressure (MSLP), specific humidity q (in kg / kg), and the zonal and meridional (u and v) wind fields (in ms^{-1}) on pressure levels at a monthly resolution for 1964 to 2010 were retrieved from the Twentieth Century Reanalysis (20CR) at a 2.0°×2.0° resolution (Compo et al., 2011). The MSLP is a useful indicator of where low pressure and extratropical storm activity occurs, while the upper tropospheric wind field at 250 hPa highlights the location of the jet stream and storm track (a region in which extratropical cyclones tend to develop). It is within these storms that atmospheric moisture transport predominantly occurs in mid-latitude regions, a quantity that 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:

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

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.

2.2 River Lambourn catchment description

We focus on the catchment of the River Lambourn, which covers ~234 km^2 of the West Berkshire Downs in southern England. The catchment is largely rural (pasture) with rolling 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 southeast (Figure 1). The catchment is entirely underlain by the Chalk formation, which dips at a shallow angle to the southeast. The Chalk is characterised by an upper zone of active groundwater movement, for example, through solution enlarged fractures, which overlies a deeper zone of regional groundwater movement (Bradford, 2002). It is groundwater discharge from the upper zone that largely sustains the flow of the River Lambourn and its tributary stream. The Lambourn is relatively unaffected by groundwater abstraction and as such is listed as a benchmark catchment by the UK National River Flow Archive (NRFA).

The catchment was also studied intensively during two research campaigns: (1) the Thames Groundwater Scheme (1967–1976) and (2) the UK Lowland Catchment Research (LOCAR) programme (2000–2006) (Grapes et al., 2005; Griffiths et al., 2006; Butler et al., 2012).

2.3 River Lambourn catchment data

A surrogate index of monthly mean groundwater (hereafter, GW) levels was generated for the period from September 1964 to August 2010 as the mean of GW levels observed manually at 4 boreholes (locations given in Figure 1). Our approach recognises the observation by Peters et al. (2006) of the difficulty in characterising an aquifer using data from one key borehole. The methodology used to derive the mean catchment GW series is summarised in the supplementary material as there were occasional periods when concurrent data were not available for all 4 boreholes. In most years, GW levels exhibit a strong seasonal 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 30 August 2010 (46 years); the river flows were averaged to yield a monthly river flow series. Herein, we regard the start of the water year as September because Bower et al. (2004) identified this to be the month of minimum river flow across the UK. Furthermore, as significant precipitation in September can eradicate soil moisture deficits that develop during the summer, we feel it is appropriate that the start of the autumn climate season is used as the 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., 2007). The monthly atmospheric fields corresponding to these high and low years (for each month) were then used in a composite analysis. Composite analysis has the benefit of 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 mean (1965 to 2010) from each of the nine atmospheric fields, and then finally averaging the anomaly fields. These anomalies highlight the average departures from the climatological mean that led to the extreme events.

3. Results and discussion

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

Boxplots of monthly precipitation, discharge and GW level are shown in Figure 2a, b and c, respectively. Typically precipitation peaks in autumn and winter (October to January), 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 discharge and GW level distributions occur from February to April. As the upper quartile of 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 preceding discharge and GW level in March.

As expected, there is a strong association between monthly discharge and GW level, quantified by a Spearman Rank correlation ρ of 0.88 over 1965–2010. In March, the correlation ρ between discharge and GW level is 0.83 (Figure 2d). The close link between GW and discharge is confirmed by the similarity between the top and bottom March events for both. For the highest discharge / GW levels seven out of nine years are the same. For discharge, these are 2001, 1995, 2007, 1994, 1967, 1988, 1975, 2003, 1977; and, for GW levels, these are 2001, 1995, 2003, 1994, 2007, 1975, 1988, 1969, 2008 (years are given in their order of magnitude). For the lowest discharge / GW levels eight out of nine years are the 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 our analysis on the lowest discharge / GW levels only investigates the lower tail of the distribution for the period when GW recharge would be expected, rather than examining the absolute low flows (and GW levels), which normally occur in the late summer and early autumn.

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 for the nine highest March discharges. (A lagged analysis of 6 months is considered to be appropriate primarily because the GW borehole sites used are situated in the more productive 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 the North Atlantic Ocean (especially from December to February) and lower than normal pressure across the British Isles. The resultant westerly (or zonal) wind pattern would advect moisture into southern England. In Figure 3, the larger than average IVT (red colours) is situated to the south of the low pressure anomaly, but a significant signal is not observed in moisture transport. A 90% confidence interval has been calculated around the composite 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 acknowledge that this is a small sample size to make strong assertions on the IVT patterns 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.

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

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

For the lowest nine March discharges, a strong positive MSLP anomaly exists (especially from November to February) to the west of the British Isles (Figure 6). This 'blocking high'-like pressure anomaly (with MSLP anomalies of 7 hPa in January; Figure 6c) precludes extra-tropical cyclones from affecting southern England, and their associated water vapour 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 reduced precipitation receipt and lower discharge. The 250 hPa zonal wind anomalies in Figure 7 highlight how the jet stream region of anomalously strong upper-level winds, and thus the storm track, is located to the north of Britain (especially in December and January; 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.

4. Conclusions

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

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

For highest March river discharge / GW levels a stronger than normal pressure gradient 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 Lambourn (Lavers et al., 2011), but the results in this study suggest that their order or spacing in time is variable. Typically, the lowest March discharge/ GW levels have stronger than normal pressure situated over the British Isles, which is also known as a blocking high pressure system. This atmospheric set up acts to deflect storms, their moisture transport and precipitation to the north of the British Isles. By comparing the atmospheric patterns between the highest and lowest events (discharge and GW), an important result to highlight is how the composite anomaly patterns are not the opposite of each other, which suggests that the system studied is behaving in a non-linear manner.

The analysis undertaken raises important questions for future research. Firstly, do similar non-linear patterns between high and low river flow / GW levels occur in other months where GW recharge is expected, such as, January, February, and April. Secondly, what types of patterns exist in catchments of differing geology (e.g., sandstone), where the response of GW and river flow may be more attenuated. Thirdly, to what extent do the results that we present here advance the goal of forward modelling conditions of both extreme high and low GW and river flow conditions. If successful, the latter could enable improved conjunctive management of GW and surface-water resources in permeable catchments with respect to both GW flooding, and drought. Fourthly, if models of hydroclimatological connections can be developed for GW / river flow in catchments unaffected by abstraction, they can be used to assess 'natural' system variability and thus (a) quantify the potential effects of abstraction in impacted catchments and (b) provide a basis for defining environmental flows.

Acknowledgements

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 UK National River Flow Archive, based at the Centre for Ecology and Hydrology in Wallingford UK, for kindly providing the daily river flow data, and the British Geological Survey for provision of the groundwater level data. We are very grateful for the helpful and constructive comments of Dr. John Bloomfield and an anonymous reviewer on this paper.

References

Anderson, W.P. and R.E. Emanuel. 2008. Effect of interannual and interdecadal climate oscillations on groundwater in North Carolina. *Geophysical Research Letters*, 35, L23402, doi: 10.1029/2008GL036054

Bloomfield, J.P., and B.P. Marchant. 2013. Analysis of groundwater drought building on the standardised precipitation index approach. *Hydrol. Earth Sys Sci*, 17: 4769-4787.

Boulton, A.J. 2005. Chances and challenges in the conservation of groundwaters and their dependent ecosystems. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 15: 319–323

Boulton, A.J. and P.J. Hancock. 2006. Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. *Australian Journal of Botany*. 54: 133-144.

Bower, D., Hannah, D.M. and McGregor, G.R. 2004. Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes*, 18: 2515-2543.

Bradford R.B. 2002. Controls on the discharge of Chalk streams of the Berkshire Downs, UK. *The Science of the Total Environment*, 282-283, 65-80.

Butler, A.P., A.G. Hughes, C.R. Jackson, A.M. Ireson, S.J. Parker, H.S. Wheater and D.W. Peach. 2012. Advances in modelling groundwater behaviour in Chalk catchments. Geological Society, London, Special Publications 364: 113-127.

Compo, G. P., et al. 2011. The Twentieth Century Reanalysis Project, *Quarterly Journal of the Royal Meteorological Society*, *137*(654), 1-28.

Crosbie, R.S., W.R. Dawes, S.P. Charles, F.S. Mpelasoka, S. Aryal, O. Barron and G.K. Summerell. 2011. Difference in future recharge estimates due to GCMs, downscaling methods and hydrological models. *Geophysical Research Letters*, 38 L11406.

El Janyani, S., N. Massei, J-P. Dupont, M. Fournier and N. Dörfliger. 2012. Hydrological responses of the chalk aquifer to the regional climatic signal. *Journal of Hydrology*, 464-465: 485-493.

Gleeson, T., Y. Wada, MFP Bierkens, and LPH van Beek. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488 197-200.

Grapes, T.R., C. Bradley and G.E. Petts. 2005. Dynamics of river – aquifer interaction along a chalk stream: the River Lambourn, UK. *Hydrological Processes*, 19: 2035-2053.

Green, TR. M. Taniguchi, H Kooi, JJ Gurdak, DM Allen, KM Hiscock, H. Treidl, and A. Aureli. 2011. Beneath the surface of global change: impacts of climate change on groundwater. *Journal of Hydrology*. 405: 532-560.

Griffiths, J., A. Binley, N. Crook, J. Nutter, A. Young, and S. Fletcher. 2006. Streamflow generation in the Pang and Lambourn catchments, Berkshire, UK. Journal of Hydrology. 330: 71-83.

Herrera-Pantoja, M. and K.M. Hiscock. 2008. The effects of climate change on potential groundwater recharge in Great Britain. *Hydrological Processes*. 22: 73-86.

Holman, I.P., M. Rivas-Casado, J.P. Bloomfield and J.J. Gurdak. 2011. Identifying non-stationary groundwater level response to North Atlantic ocean-atmosphere teleconnection patterns using wavelet coherence. *Hydrogeology Journal*. 19: 1269-1278.

Holton, J. R. 1992. An Introduction to Dynamic Meteorology (Third Edition).

Hughes, A.G., T. Vounaki, D.W. Peach, A.M. Ireson, C.R. Jackson, A.P. Butler, J.P. Bloomfield, J. Finch, and T.S. Wheater. 2011. Flood risk from groundwater: examples from a Chalk catchment in southern England. *J. Flood Risk Management*, 4, 3, 143-155.

Jackson, C.R., R. Meister and C. Prudhomme. 2011. Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology*. 399: 12-28.

Kingston, D. G., G. R. McGregor, D. M. Hannah, and D. M. Lawler 2006, River flow teleconnections across the northern North Atlantic region, Geophys. Res. Lett., 33, L14705, doi:10.1029/2006GL026574.

Kingston, D.G., McGregor, G.R., Hannah, D.M. and Lawler, D.M. 2007. Climatic controls on New England streamflow. J. Hydrometeorol., 8: 367-379.

Kingston, DG., & RG Taylor. 2010. Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile basin, Uganda. *Hydrology Earth System Science*, 14: 1297-1308.

Kurylyk, B.L., and K.T.B. MacQuarrie. 2013. The uncertainty associated with estimating future groundwater recharge: a summary of recent research and an example from a small unconfined aquifer in a northern humid-continental climate. *Journal of Hydrology*, 492: 244-253.

Lavers D., Prudhomme C. and Hannah D.M. 2010. Large-scale climate, precipitation and British river flows: identifying hydroclimatological connections and dynamics, *Journal of Hydrology*, 395, 242–255 DOI:10.1016/j.jhydrol.2010.10.036.

Lavers, D. A., R. P. Allan, E. F. Wood, G. Villarini, D. J. Brayshaw, and A. J. Wade. 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophys. Res. Lett.*, 38, L23803, doi:10.1029/2011GL049783.

Lavers, D., Prudhomme, C., and Hannah, D.M., 2013. European precipitation connections with large-scale mean sea-level pressure (MSLP) fields. *Hydrological Sciences Journal*, 58 (2), 310–327.

Marsh, T., Cole, G., and Wilby, R. 2007. Major droughts in England and Wales, 1800-2006. *Weather*, 62 (4) 87-93.

Négrel, Ph. and E. Petelet-Giraud. 2005. Strontium isotopes as tracers of groundwater-induced floods: the Somme case study (France). *Journal of Hydrology*. 305: 99-119.

Peters, E., Bier, G., Van Lanen, H.A.J, and Torfs, P.J.J.F. 2006. Propagation and spatial distribution of drought in a groundwater catchment. *Journal of Hydrology*, 321: 257-275.

Tallaksen, L.M., Hisdal, J. and Van Lanen, H.A.J. 2009. Space-time modelling of catchment scale drought characteristics. *Journal of Hydrology*, 375: 363-372

Taylor, RG, B. Scanlon, P. Döll, M. Rodell, R. Van Beek, Y. Wada, L. Longuevergne, M. Leblanc, JS. Famiglietti, M. Edmunds, L. Konikow, TR Green, J. Chen, M. Taniguchi, MFP Bierkens, A. MacDonald, Y. Fan, RM Maxwell, Y. Yechiele, JJ Gurdak, DM Allen, M. Shamsudduha, K. Hiscock, PJ-F. Yeh, I Holman and H. Treidel. 2013. Ground water and climate change. *Nature Climate Change*, 3, 322-329.

Winter, T.C., J.W. Harvey, O.L. Franke and W.M. Alley 1998. Ground water and surface water: a single resource. US Geological Survey Circular 1139, 79pp.

Woldeamlak, ST., O. Batelaan, & F. De Smedt. 2007. Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium. *Hydrogeology Journal*, 15: 891-901.

Figures

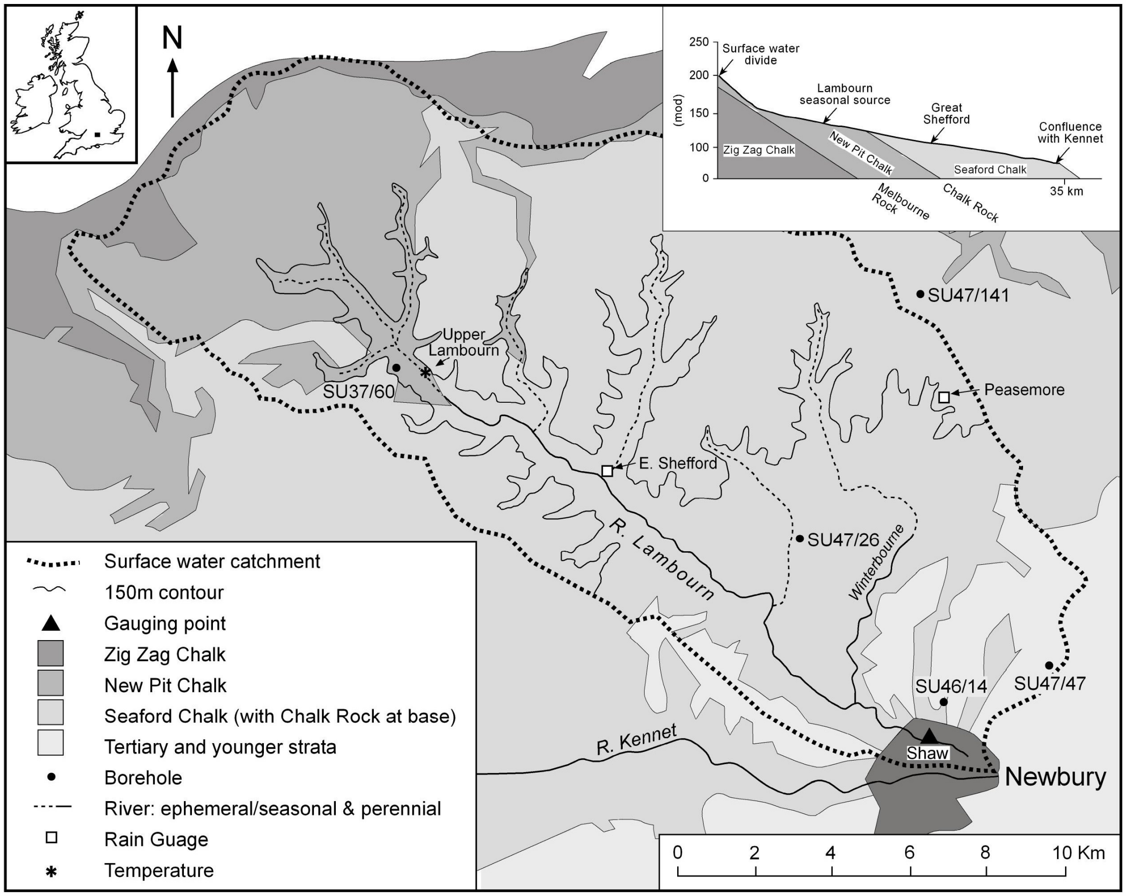


Figure 1: A map of the River Lambourn basin (after Grapes *et al.*, 2005).

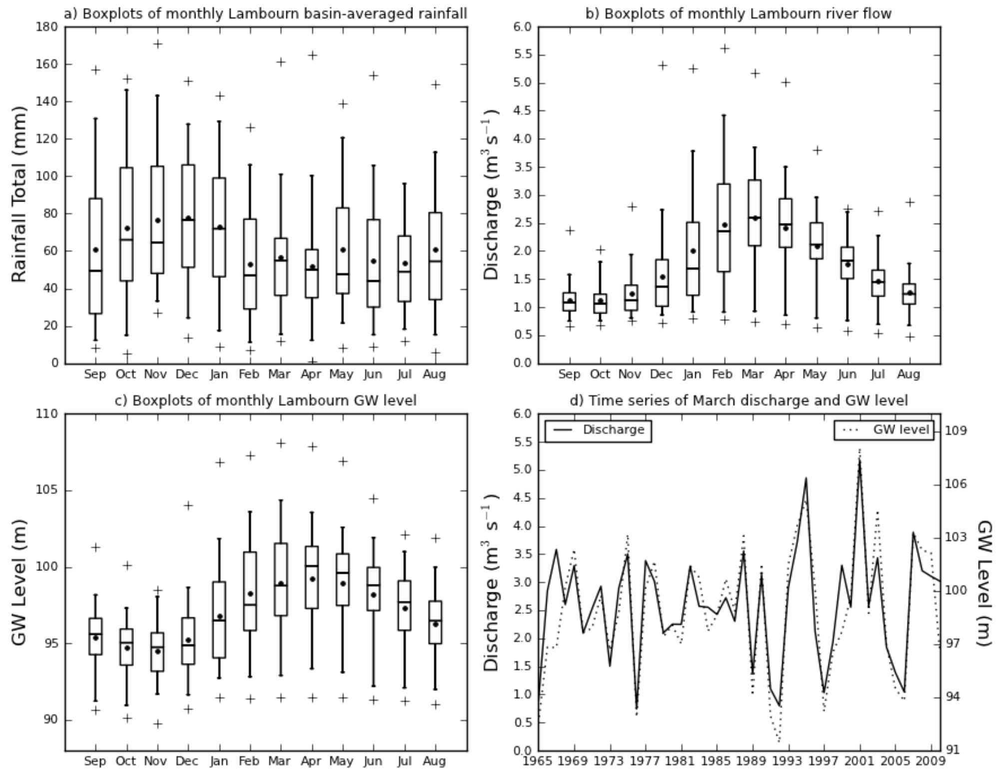


Figure 2: Boxplots of monthly (a) rainfall, (b) river flow, (c) groundwater (GW) levels, and (d) time series of March discharge (solid line) and groundwater levels (dashed line) for the river Lambourn basin (over the period 1965–2010). For panels a–c the line in each box is the median, the dot in each 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.

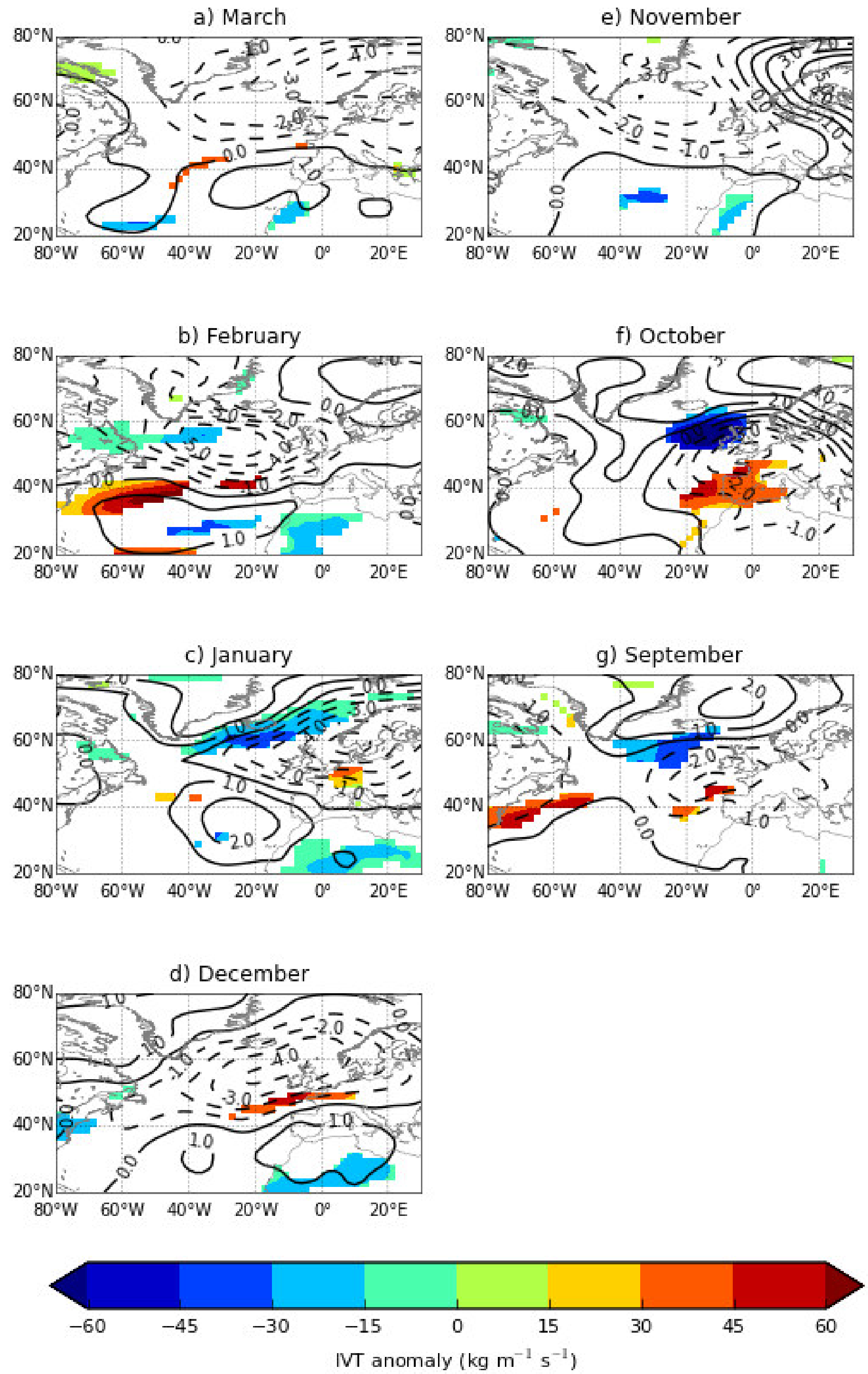
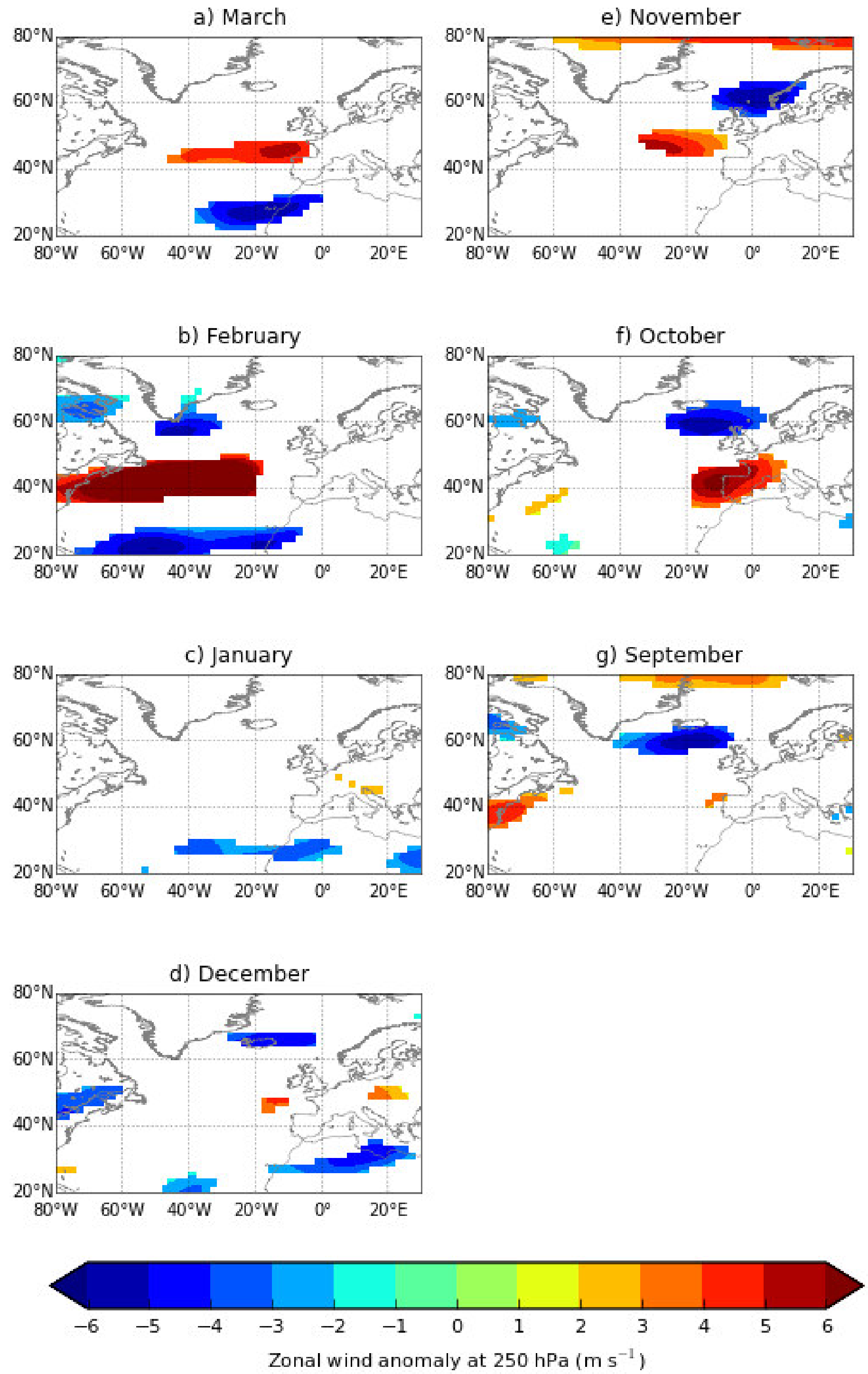
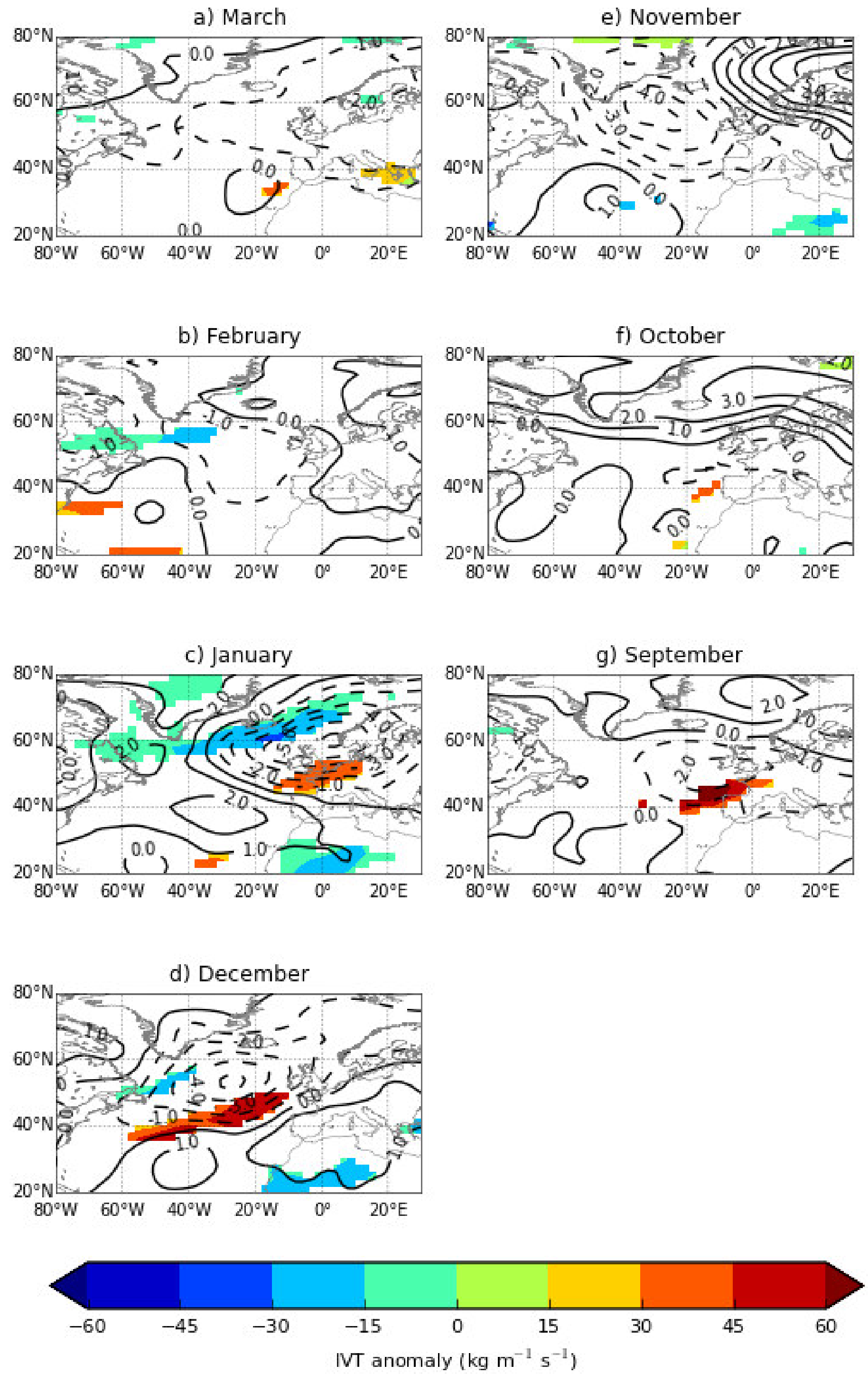

a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W
60°W
40°W
20°W
0°
20°E
−60
−45
−30
−15
0
15
30
45
60
IVT anomaly (kg m⁻¹ s⁻¹)

Figure 3: Composite monthly mean anomaly fields of the IVT (in kg m^{-1} s^{-1}) and MSLP (contours; in hPa) before the top nine March river flows. Coloured regions identify areas where the IVT composite mean is different from zero at the 10% confidence level.


a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W
60°W
40°W
20°W
0°
20°E
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
Zonal wind anomaly at 250 hPa (m s^{-1})

439

Figure 4: Composite monthly mean anomaly fields of the zonal wind at 250 hPa (in ms^{-1}) before the top nine March river flows. Coloured regions identify areas where the composite mean is different from zero at the 10% confidence level.



a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W
60°W
40°W
20°W
0°
20°E
−60
−45
−30
−15
0
15
30
45
60
IVT anomaly (kg m^{-1} s^{-1})

445

Figure 5: Composite monthly mean anomaly fields of the IVT (in kg m^{-1} s^{-1}) and MSLP (contours; in hPa) before the top nine March GW levels. Coloured regions identify areas where the IVT composite mean is different from zero at the 10% confidence level.

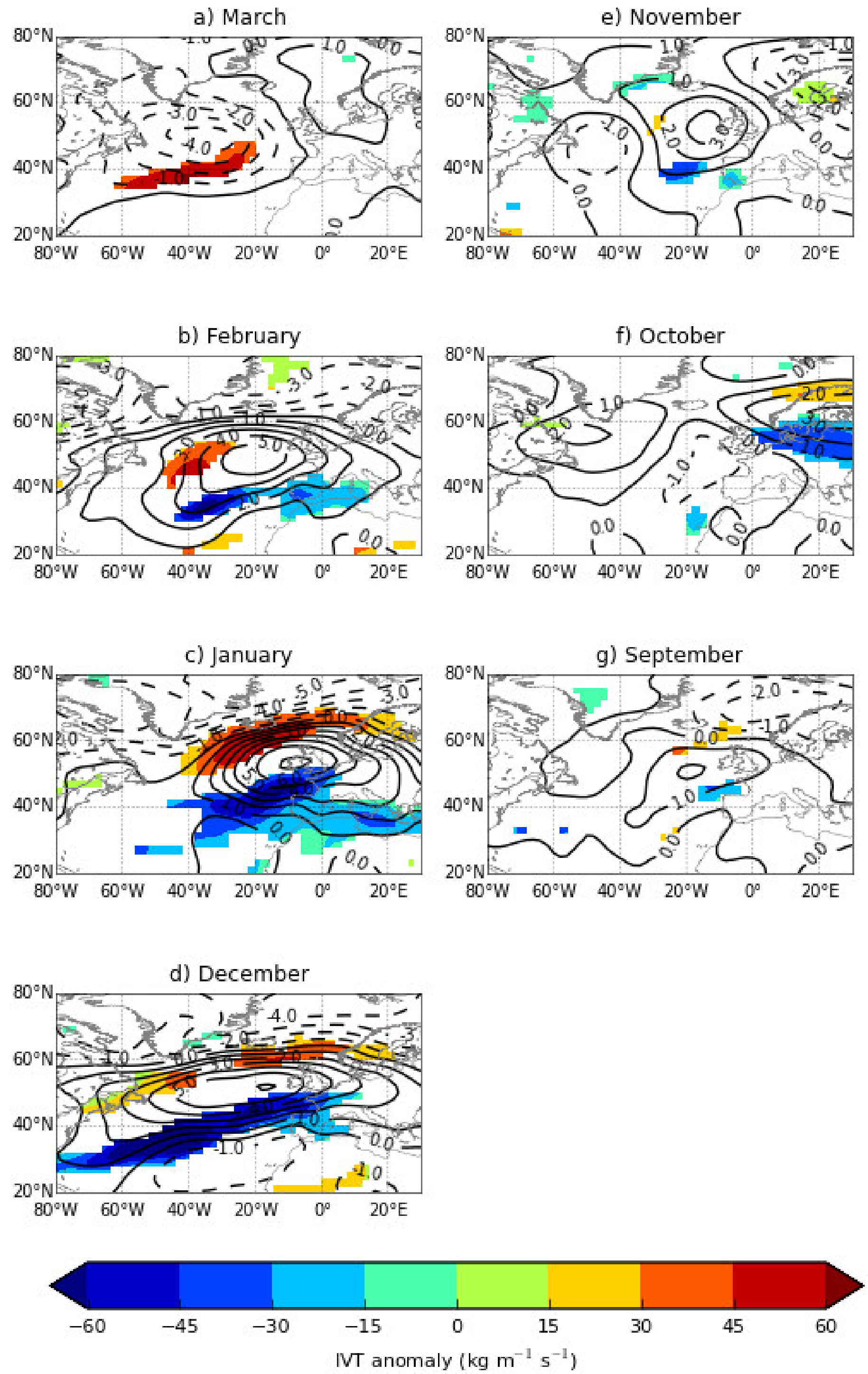
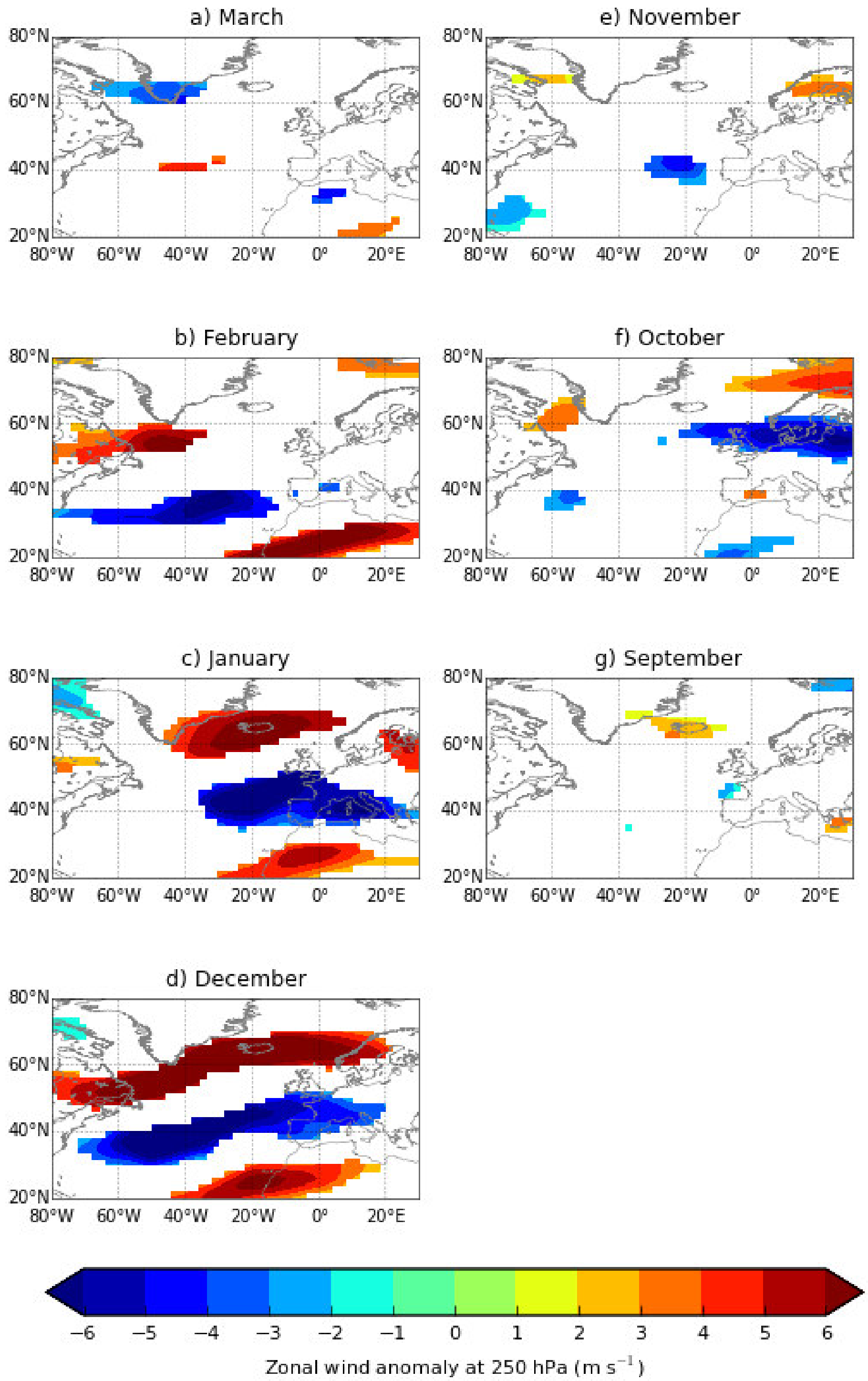

a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W 60°W 40°W 20°W 0° 20°E
−60 −45 −30 −15 0 15 30 45 60
IVT anomaly (kg m^{-1} s^{-1})

Figure 6: Composite monthly mean anomaly fields of the IVT (in kg m^{-1} s^{-1}) and MSLP (contours; in hPa) before the lowest nine March river flows. Coloured regions identify areas where the IVT composite mean is different from zero at the 10% confidence level.


a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W 60°W 40°W 20°W 0° 20°E
−6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
Zonal wind anomaly at 250 hPa (m s^{-1})

457

Figure 7: Composite monthly mean anomaly fields of the zonal wind at 250 hPa (in ms^{-1}) before the lowest nine March river flows. Coloured regions identify areas where the composite mean is different from zero at the 10% confidence level.

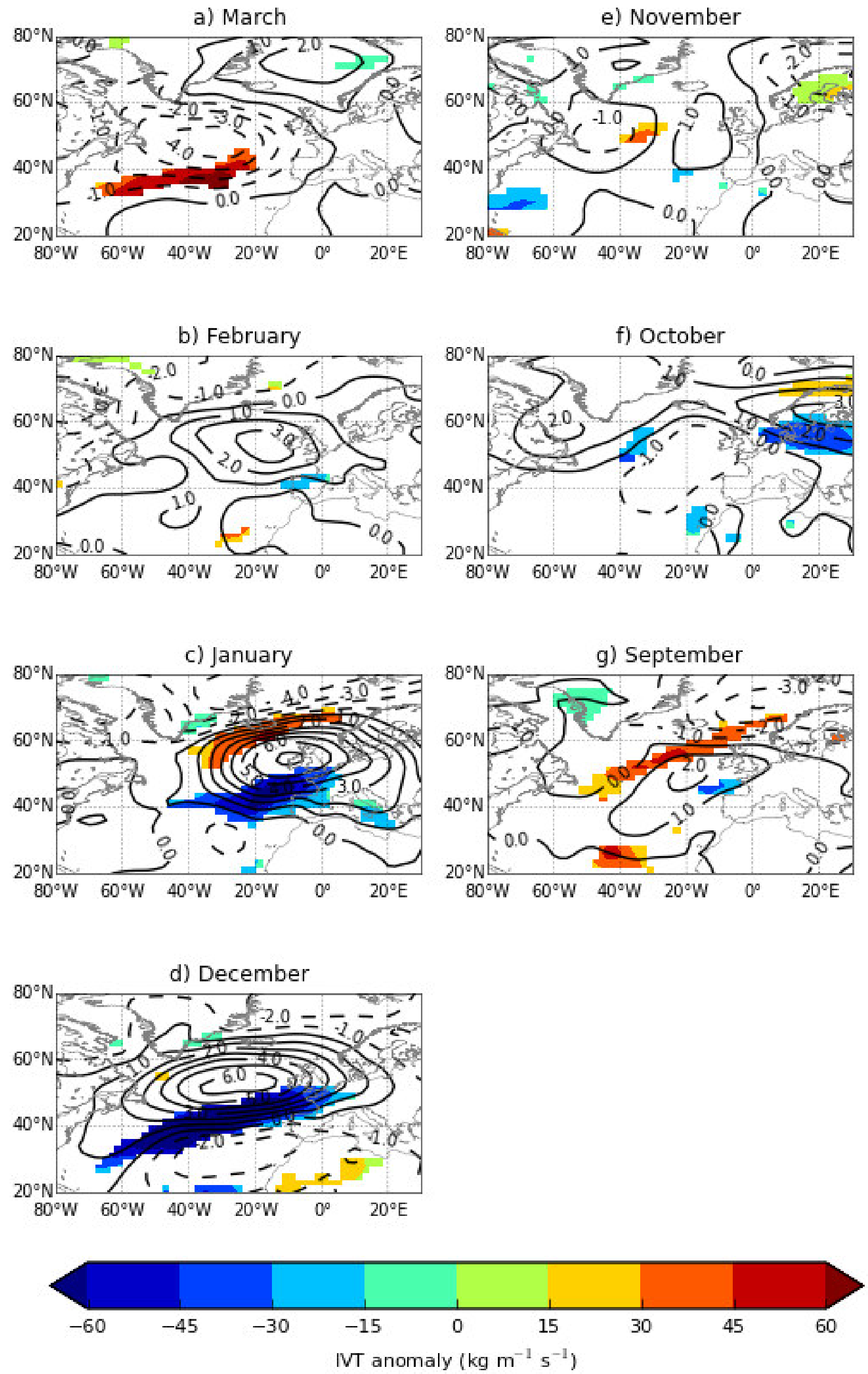

a) March
e) November
b) February
f) October
c) January
g) September
d) December
80°N
60°N
40°N
20°N
80°W
60°W
40°W
20°W
0°
20°E
−60
−45
−30
−15
0
15
30
45
60
IVT anomaly (kg m^{-1} s^{-1})

Figure 8: Composite monthly mean anomaly fields of the IVT (in kg m^{-1} s^{-1}) and MSLP (contours; in hPa) before the lowest nine March GW levels. Coloured regions identify areas where the IVT composite mean is different from zero at the 10% confidence level.

Linking variations in groundwater level in southern England to large-scale atmospheric circulation

DAVID A. LAVERS[1*+], DAVID M. HANNAH[2], CHRIS BRADLEY[2]

[1] IHR-Hydroscience & Engineering, The University of Iowa, Iowa City, IA, USA

[2] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham. B15 2TT. UK

HIGHLIGHTS

1). Strong pressure gradient is over North Atlantic Ocean during high groundwater events.

2). A blocking high pressure system is found across Britain during low groundwater events.

3). Varying sequences of atmospheric patterns cause high and low groundwater levels.