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River temperature regimes of England and Wales: spatial patterns, inter-annual variability and climatic sensitivity

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Abstract:

Identification of the most sensitive hydrological regions to a changing climate is essential to target adaptive management strategies. This study presents a quantitative assessment of spatial patterns, inter-annual variability and climatic sensitivity of the shape (form) and magnitude (size) of annual river/stream water temperature regimes across England and Wales. Classification of long-term average (1989–2006) annual river (air) temperature regime dynamics at 88 (38) stations within England and Wales identified spatially differentiable regions. Emergent river temperature regions were used to structure detailed hydroclimatological analyses of a subset of 38 paired river and air temperature stations. The shape and magnitude of air and water temperature regimes were classified for individual station-years; and a sensitivity index (*SI*, based on conditional probability) was used to quantify the strength of associations between river and air temperature regimes. The nature and strength of air–river temperature regime links differed between regions. River basin properties considered to be static over the timescale of the study were used to infer modification of air–river temperature links by basin hydrological processes. The strongest links were observed in regions where groundwater contributions to runoff (estimated by basin permeability) were smallest and water exposure time to the atmosphere (estimated by basin area) was greatest. These findings provide a new large-scale perspective on the hydroclimatological controls driving river thermal dynamics and, thus, yield a scientific basis for informed management and regulatory decisions concerning river temperature within England and Wales. © 2013 The Authors. *Hydrological Processes* published by John Wiley & Sons, Ltd.

KEY WORDS   river water temperature; stream water temperature; regime classification; climatic sensitivity; air temperature; basin properties

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INTRODUCTION

In recent years, there has been an upsurge in river and stream temperature research (Hannah *et al.*, 2008a) as temperature is increasingly recognized as an important and highly sensitive variable affecting biological, chemical and physical processes in flowing waters (Caissie, 2006). Primary research challenges in the field of river temperature include improving understanding of thermal heterogeneity at different spatial and temporal scales, the nature of past variability and likely future trends (Webb *et al.*, 2008). The analysis of spatial and temporal variability in river temperature regimes is vital to (1) elucidate key controls and processes, (2) assess sensitivity to a changing climate and (3) inform management of land use, water resources and freshwater ecosystems (Moore *et al.*, 2005). In part, river temperature has attracted growing attention because water thermal

regimes may be highly sensitive to climate change. Instrumented records show significant river temperature warming (e.g. Webb and Walling, 1992; Caissie *et al.*, 2005; Webb and Nobilis, 2007; Kaushal *et al.*, 2010) and cooling (e.g. Arismendi *et al.*, 2012; Isaak *et al.*, 2012) over recent decades, and future projections (Webb and Walling, 1992; Webb and Nobilis, 1994; Mohseni *et al.*, 2003; van Vliet *et al.*, 2011) suggest profound potential impacts on freshwater ecosystems (Ormerod, 2009). Hence, environment managers and regulators urgently need information on space–time variability in river temperatures and a better understanding of the controlling factors as an important first step towards making well-informed decisions concerning the climatic sensitivity of river thermal regimes (Wilby *et al.*, 2010).

Drivers of river temperature dynamics are complex, with multivariate controls and process interactions spatially nested at macro (latitude, altitude and continentality), meso (basin climate and hydrology) and micro (micro-meteorology, channel geometry, riparian shading and substratum conditions) scales (Webb, 1996). Research on river temperature within England and Wales

has investigated (1) point-scale heat fluxes that fundamentally control water temperature (e.g. Webb and Zhang, 2004; Hannah *et al.*, 2008b), (2) micro-thermal variability within the water column (e.g. Clark *et al.*, 1999) and riverbed (e.g. Hannah *et al.*, 2009; Krause *et al.*, 2011), (3) the effects of forest canopies and forest clear-felling (e.g. Stott and Marks, 2000; Hannah *et al.*, 2008b) and (4) spatial and temporal dynamics across river temperature networks (e.g. Webb and Walling, 1992). This UK-based research has been restricted to the sub-basin scale; thus, no research exists on spatial and temporal variability and controls on river temperature at a larger scale (i.e. inter-basin to region and beyond).

Regimes describe the behaviour of hydroclimatological variables over the annual cycle or hydrological year, and they are useful tools for characterizing spatial and temporal variations in timing and magnitude of seasonal patterns (Bower *et al.*, 2004). The importance of the entire flow regime for maintaining and protecting the integrity of fluvial systems, rather than considering only the maximum, minimum or mean values, is well recognized with regard to the management of river discharge (e.g. Poff, 1996; Harris *et al.*, 2000; Kennard *et al.*, 2010). However, for river temperature, single metrics (particularly maxima, e.g. Picard *et al.*, 2003) and isolated months or seasons are used most commonly. These approaches consider the magnitude of thermal condition, which may limit aquatic stream organisms but ignore other potentially relevant characteristics, particularly the timing and duration of warmer and cooler episodes over the annual cycle (Chu *et al.*, 2010; Arismendi *et al.*, 2013). Spatial variability in multiple aspects of annual regime magnitude has been explored over a single calendar year in the Great Lakes Basin, Canada (Chu *et al.*, 2010), but, typically, consideration of river temperature variability across multiple years has been restricted to trend analyses (e.g. Webb and Walling, 1992; Webb and Nobilis, 1994, 2007; Kaushal *et al.*, 2010). Inter-annual variability/stability in the character of the entire river thermal regime has not been investigated to date. Therefore, there is a clear need to develop methods to assess the key attributes of annual river temperature regimes and their year-to-year dynamics.

To explore linkages between climate and river temperature, air temperature is commonly used as a proxy for net heat exchange at the air–water interface (Webb *et al.*, 2003). Across space, air–water temperature relationships are weaker for (1) upper headwater streams (Brown *et al.*, 2005; Hrachowitz *et al.*, 2010; Kelleher *et al.*, 2012), (2) locations with increased thermal capacity and longer water travel times (Webb and Nobilis, 2007) and (3) sites with major groundwater or anthropogenic inputs (Erickson *et al.*, 2000; O'Driscoll and DeWalle, 2006; Tague *et al.*, 2007; Webb and Nobilis, 2007; Webb *et al.*, 2008; Kelleher *et al.*, 2012). The strength of the

relationship between air and water temperatures increases from sub-daily to monthly timescales; but it is weakest for annual samples (Webb *et al.*, 2008) because river temperature is reported to display less year-to-year variability than air temperature (Pilgrim *et al.*, 1998; Erickson *et al.*, 2000; Webb *et al.*, 2003). There is a need to advance methods for rigorous, systematic analysis of dynamic air–water temperature links and to explore the controls on space–time patterns in the climatic sensitivity of river temperature.

Although there is a growing body of river temperature research, there remains limited understanding of large-scale spatial and temporal variability in climate–water temperature associations, and the modifiers of these relationships. Such research is essential for identification of the most temperature-sensitive river waters and to understand the controls on thermal sensitivity. To address these research gaps, this paper aims (1) to provide the first quantitative assessment of spatial patterns and inter-annual variability of the shape (timing) and magnitude (size) of annual river temperature regimes across England and Wales and (2) to assess the climatic sensitivity of river temperature regimes and understand the controls on river thermal sensitivity, including the potential moderating role of static basin properties. In addition to providing a new large-scale, long-term perspective and understanding of English and Welsh river temperatures, this paper seeks to make methodological innovations by testing a classification tool for annual regimes (Hannah *et al.*, 2000) on water temperature and a climatic sensitivity index (Bower *et al.*, 2004) for air–river temperature associations. Notably, this study represents the first application of the classification scheme and sensitivity index to annual river temperature regimes.

STUDY AREA CLIMATE

The countries of England and Wales have a temperate maritime climate. The highest air temperature is observed in July–August with the lowest air temperature in January–February. Air temperature is coldest in northern England and north-west Wales and warmest in South-eastern England, which reflects relief. High seasonality of the annual air temperature regime is observed inland, whereas in coastal locations, air temperature is warmer, but seasonality is reduced (Barrow and Hulme, 1997; Bower *et al.*, 2004).

DATA

River temperature

Time series of river water temperature from monitoring stations across England and Wales were extracted from the Environment Agency's Freshwater Temperature Archive. The Archive and its data holdings are described in detail by Orr *et al.* (2010). Sites were selected from the Archive to

provide a robust analysis with optimal spatio-temporal coverage across England and Wales. A total of 88 sites that had water temperature observations in ≥90% of all months over a common 18-year period (1989–2006 inclusive; Figure 1) were identified; water temperature was sampled on average 11.1 times per month over this time span. Monthly mean water temperature (°C) was calculated for each site for each month over the entire record to characterize annual thermal regimes and their year-to-year variability.

The potential influence of sampling frequency on the estimation of monthly means was evaluated systematically using data collected at the site monitored at the highest temporal resolution (i.e. River Dee at Pont Mwnwgl Y Llyn, 15-min intervals over 13 years). The mean was calculated for each possible combination of three samples in each month for all years (> 4.5 M resamples for each month in each year). Results indicated sampling frequency to have minimal impact on shape and magnitude of annual river temperature regimes (Figure 2).

Air temperature

Observations of daily minimum and maximum air temperature for the common data period (1989–2006) were obtained from the British Atmospheric Data Centre,
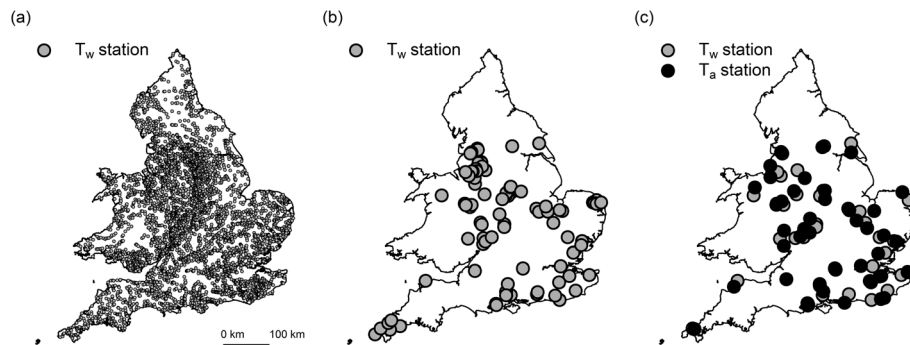
Figure 1. Maps of England and Wales showing (a) water temperature stations during the 1989–2006 common period, (b) water temperature monitoring stations within the common period with temperature samples in >90% of months and (c) paired air–water temperature monitoring stations
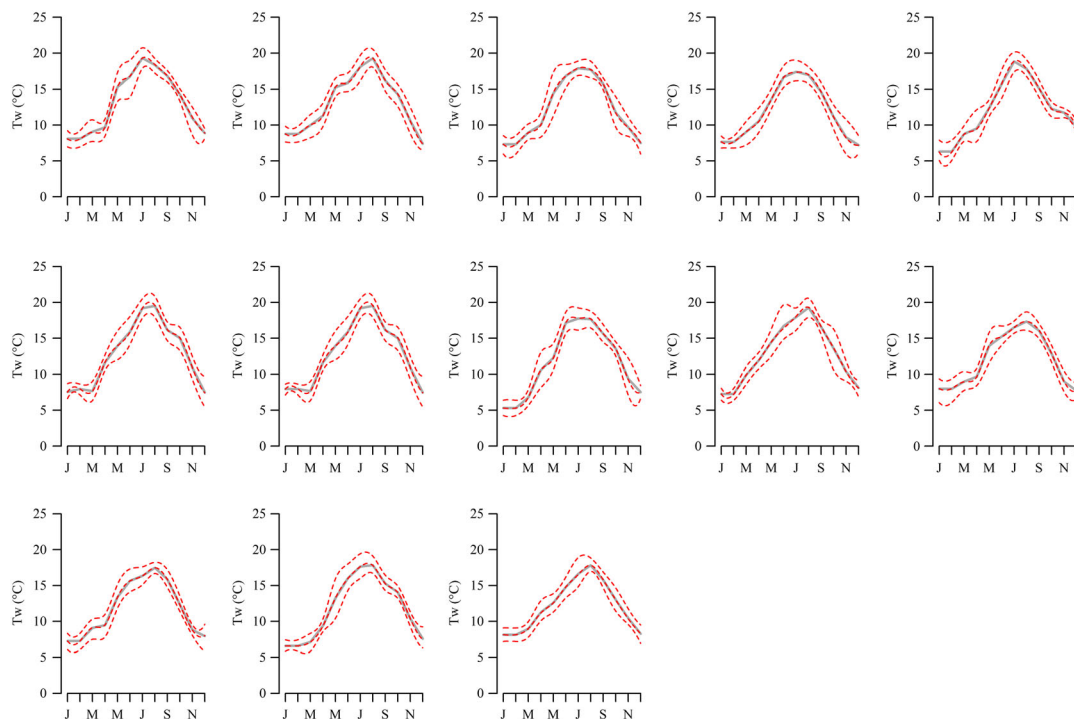
Figure 2. Influence of sampling frequency on the shape and magnitude of the annual river temperature regime for 13 years at Pont Mywnwygl Y Llyn on the River Dee. [Grey lines illustrate annual regimes based on monthly means calculated from continuous data recorded at 15 min intervals. Red lines show the 50th (median), 97.5th and 2.5th percentiles of monthly means calculated from all possible combination of 3 samples in each month in each year.]

MIDAS Land Surface Stations data set (UK Meteorological Office, 2006). River temperature sites were paired with the closest climate station, which yielded a total of 38 air temperature locations (Figure 1). The mean of minimum and maximum values for each station day provided estimates of daily averages (Bower *et al.*, 2004); monthly averages of mean daily air temperature (°C) were calculated to characterize annual regimes and their temporal stability.

Basin properties

River basin properties were selected to assess the potential role of hydrological controls in moderating spatial river temperature pattern and air–water temperature sensitivity. Properties were derived from two sources: (1) a 25-m resolution digital elevation model of England and Wales (University of Manchester/University of London, 2001) that was used to calculate basin area (km^2) and mean basin elevation (metres above sea level) and (2) the British Geological Survey Bedrock Permeability Index of England and Wales that was used to characterize average basin permeability as a measure of basin water storage and hydrological response time (Laize and Hannah, 2010). Basin properties for the 38 rivers selected for analysis of air–river temperature regime associations are summarized in Table I.

METHODS

The analytical procedure was divided into five linked stages: (1) regionalization of long-term average regimes for river and air temperature, (2) classification of annual regimes for each station-year, (3) quantification of inter-annual regime stability and (4) application of the sensitivity index (*SI*) to quantify linkage between air and river temperature classes.

Regime classification

As it was important to assess the timing (seasonality) and size of the annual river temperature regime, a hierarchical, agglomerative cluster analysis-based classification approach was used to group intra-annual patterns for river and air temperatures according to two key regime attributes: shape and magnitude. The regime classification procedure was developed by Hannah *et al.* (2000) and subsequently extended and evaluated for application to annual river flow and climate regimes (e.g. Harris *et al.*, 2000; Bower *et al.*, 2004). The shape classification identified stations (for regionalization) or station-years (to assess inter-annual regime variability) with similar regime forms, regardless of their magnitude. For the regionalization process, shape regimes were determined from long-term mean monthly values (i.e. the mean of observations in each month over the entire

study period) standardized separately for each station using *z*-scores (mean = 0, standard deviation = 1). To classify inter-annual shape regimes, monthly mean values (i.e. means of observations in months for individual years) were standardized for each station prior to classification.

The magnitude classification was based on four indices (i.e. the mean, minimum, maximum and standard deviation), regardless of their timing. For regionalization, the indices were derived from long-term mean monthly values at each station; and stations with similar magnitude regimes were grouped. Each index was *z*-scored to control for differences in relative magnitudes. Index values for inter-annual magnitude regimes were determined from monthly mean values in each station-year; and station-years with similar magnitude regimes were grouped. Each index was *z*-scored over the entire study period for each station to control for between-station differences in the indices. Classification of regime shape and magnitude was performed separately for air and river temperatures over the common data period (1989–2006). This is the first application of these methods to classify annual river water temperature regimes.

It is important to note that the methods applied herein yielded two separate sets of regime classifications: (1) the *regionalization* procedure grouped stations to examine spatial patterns and (2) the *inter-annual classification* grouped annual regimes for each station-year to identify patterns of year-to-year variability. Together, the two classification modes characterized spatial and temporal regime dynamics. The *regionalization* of long-term regimes provided a basis for structuring analyses of between-region and within-region patterns in inter-annual regime variability. The long-term average regime for a station was estimated from mean monthly values across all years for all 88 river temperature sites. *Annual regimes for each station-year* were characterized using monthly mean values for each station-year for a subset of 38 river temperature sites (i.e. closest locations paired with the 38 climate stations; Figure 1). Thus, regime shape and magnitude classes were identified for 702 station-years for both river and air temperatures. It is also important to note that (1) regime classes are not interchangeable between long-term and station-year regime classifications and (2) magnitude classes for regionalization identify absolute differences between stations whereas magnitude classes for station-years identify relative inter-annual variations at a station (Bower *et al.*, 2004). For all classifications performed, (1) inspection of the cluster dendrogram and agglomeration schedule identified the number of classes, and (2) Ward's algorithm yielded the most robust (Kalkstein *et al.*, 1987) and evenly sized classes.

Table I. Properties of 38 river basins selected for analysis of air–water temperature associations [River basins are listed in alphabetical order.]

Station name (river at site)	Mean basin		Basin area (km²)	Sampling frequency (month⁻¹)
	Elevation (masl)	Permeability		
Ditton Brook at Dart Bridge	98.1	3.5	179.8	3.7
Hundred Foot R. at Earith Bridge	14.2	2.0	1034.6	4.2
Moors R. at Hurn Bridge	48.6	3.6	7964.1	3.1
R. Ant at Wayford Bridge	30.9	3.0	4160.4	3.0
R. Avon at Lower Evesham	12.2	2.8	936.8	2.9
R. Avon at Stoneleigh Park	23.3	2.4	534.7	2.6
R. Chelmer at Langford	75.7	2.3	13867.1	5.3
R. Cuckmere at Sherman Bridge	17.1	1.9	4009.1	4.6
R. Darwin at Blue Bridge	65.8	2.5	423.4	6.1
R. Dee at Pont Mwnwgl Y Llyn	46.1	3.4	589.0	593.7
R. Derwent at Coultauds	73.2	3.0	3603.5	2.5
R. Eden at Clappers	19.3	2.0	4451.1	4.1
R. Erewash at Shipley Gate	69.3	2.4	22223.6	2.5
R. Goyt above Tame	98.0	2.8	1166.5	4.4
R. Hull at Hempholme	106.8	2.1	6153.5	10.5
R. Itchen at Gaters Mill	110.3	3.9	1441.7	3.9
R. Leam at Prince's Drive	45.6	2.6	65000.0	2.3
R. Mardyke at Thurrock	82.5	2.8	5614.1	4.5
R. Medway above Allington	45.1	2.0	3834.2	5.9
R. Nene at Littleport	86.8	2.9	9915.3	3.7
R. Perry at Mytton	40.3	2.4	14942.6	2.4
R. Roden at Roddington	107.3	1.5	19057.4	2.2
R. Rother at Blackwall Bridge	40.3	2.1	14942.6	4.4
R. Rother at Hardham	212.5	3.7	1918.2	6.9
R. Severn at Upton on Severn	160.9	2.6	4515.3	2.7
R. Stour at Bretts Bailey Bridge	255.0	3.6	1642.7	5.2
R. Stour at Iford Bridge	275.7	3.7	3289.5	4.7
R. Stour at Ingham	82.5	3.1	5614.1	5.7
R. Stour at Wixhoe	60.5	2.6	428.5	6.8
R. Test at Wherwell	35.4	3.9	2622.1	3.8
R. Thames at Caversham	127.5	2.9	4680.7	13.9
R. Trent at Yoxall Bridge	71.8	3.6	496.2	2.8
R. Umber above beach	31.0	2.7	210.0	2.7
R. Welland at Tinwell	132.0	2.7	496.9	4.8
R. Wharfe above Tadcaster	85.3	2.9	2589.6	6.6
R. Wye at Victoria Bridge	219.9	3.0	3173.9	3.5
Red R. at Gwithian Towans	3.5	3.2	115.2	4.8
Ten Mile R. at Denver	23.9	3.1	3448.0	4.4

Quantification of inter-annual regime stability and climatic sensitivity

The stability of inter-annual regimes at each site was assessed using the concept of equitability (E), which was a measure (values range from 0 to 1) of the probability of observing each regime shape or magnitude class against all the possible regime classes (Bower *et al.*, 2004) (Equation 1). Higher values indicated greater equitability (evenness).

$$E = \frac{-\sum_{i=1}^{n} P_i \ln P_i}{\ln n} \quad (1)$$

The *SI*, which quantifies the strength and direction of associations between air and river temperatures, was adapted by Bower *et al.* (2004) from an ecological index (Kent and Coker, 1992). From the concept of equitability, the *SI* considers the conditional probability, $P(Y_j|X_i)$, of observing a particular river temperature Y_j regime under each air temperature regime X_i and also the conditional probability, $P(X_i|Y_j)$, of a given air temperature regime prevailing for each river temperature regime. Equations (2) and (3) were used to calculate the equitability of regimes as the probability, $P(Y_j)$ and $P(X_i)$, of observing a particular river temperature regime and an air temperature regime, Y_j and X_i, respectively.

$$E(Y) = -\sum_{j=1}^{n_y} \left(\frac{PY_j \ln PY_j}{\ln n_y} \right) \quad (2)$$

$$E(X) = -\sum_{j=1}^{n_x} \left(\frac{PX_j \ln PX_j}{\ln n_x} \right) \quad (3)$$

The ratio of $E(Y) : E(X)$ identified one of two scenarios to produce a *SI* ranging from −1 to +1. Where $E(Y) \geq E(X)$, Equation (4) (positive scenario) returned a *SI* value between 0 and +1, which indicated that water temperature was more variable than air temperature. Where $E(Y) \leq E(X)$, Equation (5) (negative scenario) yielded a *SI* value between 0 and −1, which indicated that air temperature was more variable than water temperature. Values close to 0 indicated greater river temperature sensitivity to air temperature than those closer to ±1 (Bower *et al.*, 2004).

$$SI = \frac{1}{2(n_x n_y)} \left[-\sum_{i=1}^{n_x} \left[\left(\frac{PX_j \ln PX_j}{\ln n_x} \right) + \left(\frac{PY_j \ln PY_j}{\ln n_y} \right) \right] \right] \quad (4)$$

$$SI = -1 \\ - \frac{1}{2(n_x n_y)} \left[-\sum_{i=1}^{n_x} \left[\left(\frac{PX_j \ln PX_j}{\ln n_x} \right) + \left(\frac{PY_j \ln PY_j}{\ln n_y} \right) \right] \right] \quad (5)$$

Influence of basin properties on air–river temperature sensitivity

To assess potential modification of air–river temperature associations by basin properties: (1) the 38 paired water and air temperature stations were grouped by the long-term average river temperature regions, and (2) equitability, *SI* and basin properties were compared within and between regions.

RESULTS

Results are presented in three sections: (1) regionalization of long-term shape and magnitude regimes for river and air temperatures, to explore spatial patterns and identify regions that structure further analyses, (2) inter-annual river and air temperature shape and magnitude regimes, to assess between-region and within-region regime dynamics and air–river temperature sensitivity and (3) analysis of the influence of basin properties on air–water temperature regime sensitivity between and within regions.

Regionalization of long-term regimes

Regime shape and magnitude were classified using long-term (1986–2006) mean monthly river and air temperatures for 88 and 38 stations, respectively. The correspondence between river and air temperatures was explored for 38 paired stations.

Long-term regime shape. One river temperature regime and one air temperature regime were identified across all of England and Wales. Both regimes had similar forms of annual cycle. River temperature regimes peaked in July with minima in January; air temperature regimes exhibited an extended July–August maxima and January–February minima (Figure 3). Air temperature regimes demonstrated less variability between sites than river temperature (cf. composite averaged regime; Figure 3), indicating that air temperature was more spatially conservative than river temperature.

Long-term regime magnitude. Four and three clusters respectively provided a robust classification of the magnitude of air and river temperature regimes. The four river temperature regime classes ($R\text{-}Tw_x$) were characterized by variation in the indices as follows (Figure 4):

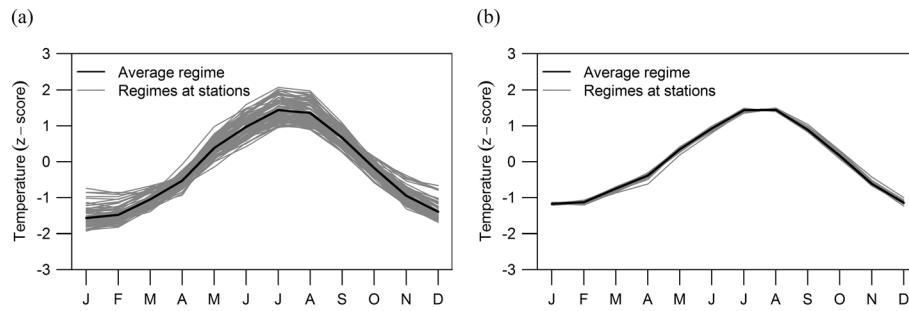|	
$R\text{-}w_1$	Cool – lowest mean and minimum and second lowest maximum and standard deviation (eight sites, 9%)
$R\text{-}Tw_2$	Moderate – moderate mean and lowest maximum, moderate minimum and standard deviation (30 sites, 34%)
$R\text{-}Tw_3$	Warm with low seasonality – highest mean and minimum, lowest maximum and standard deviation (17 sites, 19%)

Figure 3. Long-term (1989–2006) average standardised (z-scores) mean monthly temperature values for all (a) river temperature and (b) air temperature stations
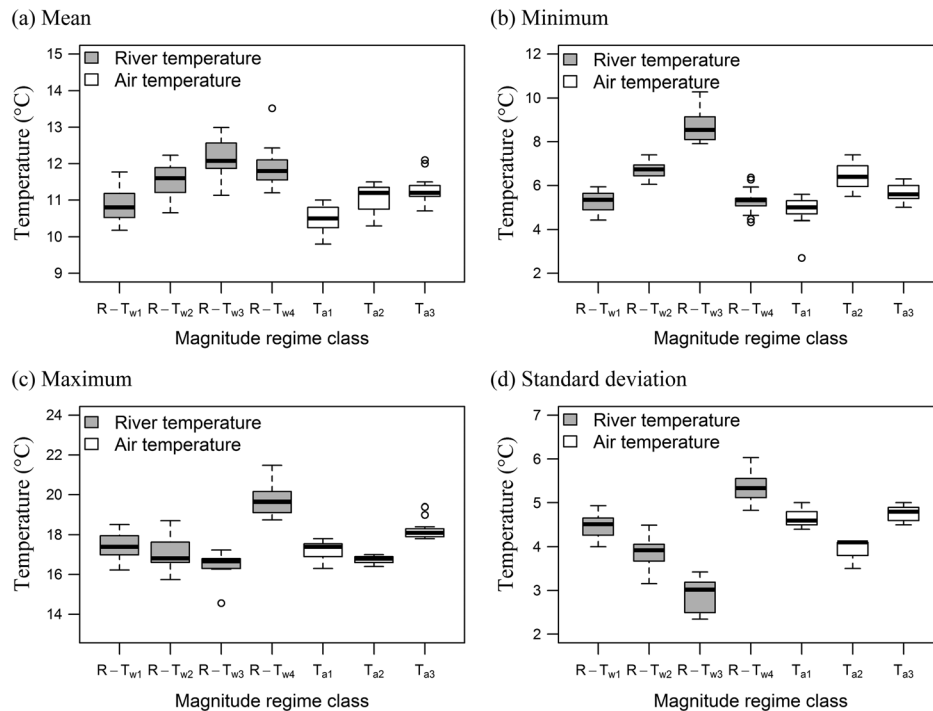

Figure 4. Box plots of annual (a) mean, (b) minimum, (c) maximum and (d) standard deviation for long-term average river and air temperature magnitude regime classes

$R\text{-}Tw_4$ Warm with high seasonality – second highest mean, moderate minimum, highest maximum and high standard deviation (33 sites, 38%)

Three air temperature classes were identified (Figure 4):

Ta_1 Cool – lowest mean and minimum, moderate maximum and high standard deviation (23 sites, 59%)

Ta_2 Warm with low seasonality – second highest mean, highest minimum, lowest maximum and lowest standard deviation (three sites, 8%)

Ta_3 Warm with high seasonality – highest mean, moderate minimum, highest maximum and standard deviation (13 sites, 33%)

Long-term regimes: spatial patterns and air–river temperature associations. Regionalization produced only one air class and one river temperature class, indicating no spatial variability in long-term river or air temperature shape regime across England and Wales. Therefore, the focus is on spatial patterns and air–river temperature associations for long-term magnitude regimes.

River and air temperature magnitude regimes displayed clear spatial differentiation across England and Wales (Figure 5); and dynamics of paired air–river temperature stations corresponded with the exceptions of central, southern England and two sites in the north-west. The coldest regimes were observed in the north (Ta_1 and $R\text{-}Tw_1$, $n = 13$), whereas those in the south displayed higher means and greater seasonality (Ta_3 and $R\text{-}Tw_3$, $n = 13$). Regimes in the south-west were characterized by
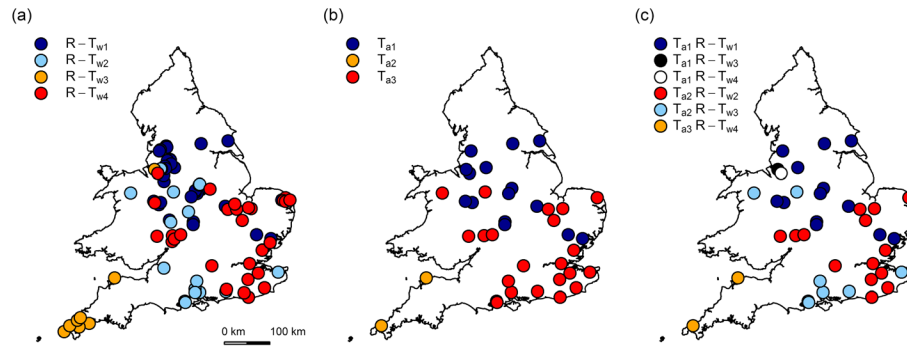
Figure 5. Maps of England and Wales showing distribution of long-term average (a) river temperature regime classes, (b) air temperature regimes classes and (c) associated air–river temperature regime classes at paired air–river temperature stations

high means and low seasonality (Ta_3 and R-Tw_4, $n = 2$). Three combinations of air and river temperature classes occurred for which air temperature contrasted with river temperature (Figure 5): (1) Ta_2 and R-Tw_2 ($n = 8$), which was a warm and highly seasonal air temperature with a moderate river temperature, (2) Ta_1 and R-Tw_3 ($n = 1$), which was a cold air temperature with a warm and highly seasonal river temperature and (3) Ta_1 and R-Tw_4 ($n = 1$), which was a cold air temperature with a warm and less seasonal river temperature.

Inter-annual regimes: variability and air–river temperature associations

Regime shape and magnitude of river and air temperatures were classified using monthly means for each year (1989–2006) across the 38 paired stations (i.e. 702 station-years). These regime classes provided the basis for: (1) quantification of inter-annual stability and (2) test application of the *SI* for linking air and river temperature regimes. The regionalization results (presented earlier) structured analyses of between-region and within-region inter-annual regime variability. As stated in the methodology, the long-term and annual regime classes were not the same; it must be noted that magnitude classes for regionalization were absolute (between stations) whereas magnitude classes for inter-annual regimes were relative (between years at a station).

Inter-annual shape regimes. Three inter-annual river temperature and four inter-annual air temperature shape regime classes were identified. River temperature shape regime classes (IA-Tw_x) were identified as follows (Figure 6):

IA-Tw_A Extended June–August maximum and January minimum with gradual warming and rapid autumn cooling (157 station-years, 22%)

IA-Tw_B July maximum and January minimum with rapid warming and gradual cooling (270 station-years, 38%)

IA-Tw_C August maximum and December minimum with gradual warming and rapid cooling (275 station-years, 39%)

Four inter-annual air temperature shape regimes (IA-Ta_x) were identified as follows (Figure 6):

IA-Ta_A Extended June–August maximum and November–February minimum with a very rapid rate of cooling (37 station-years, 5%)

IA-Ta_B July maximum and December minimum (240 station-years, 34%)

IA-Ta_C August maximum and December minimum (269 station-years, 39%)

IA-Ta_D August maximum and January minimum (156 station-years, 22%)

Associations between inter-annual air and river temperature shape regimes. As the regionalization identified single long-term average river and air temperature shape regimes, stations were not subdivided for analysis of associations between inter-annual classes. Annual frequencies of river and air temperature regime shape classes are summarized in Figure 7. There was no evidence of a trend in the occurrence of either river or air temperature regime over the 18-year study period. Very limited spatial differentiation was observed in patterns of air temperature shape regime occurrence across all sites in each year of the study period. In any given year, one of the four air temperature shape regimes predominated at >90% of stations. Regime IA-Ta_C predominated in seven years, IA-Ta_D in six years, IA-Ta_B in four years and IA-Ta_A in one year only. Greater spatial differentiation was observed in patterns of river temperature shape regimes (cf. air temperature), although a predominant river temperature shape regime was identified across >50–92% of stations in
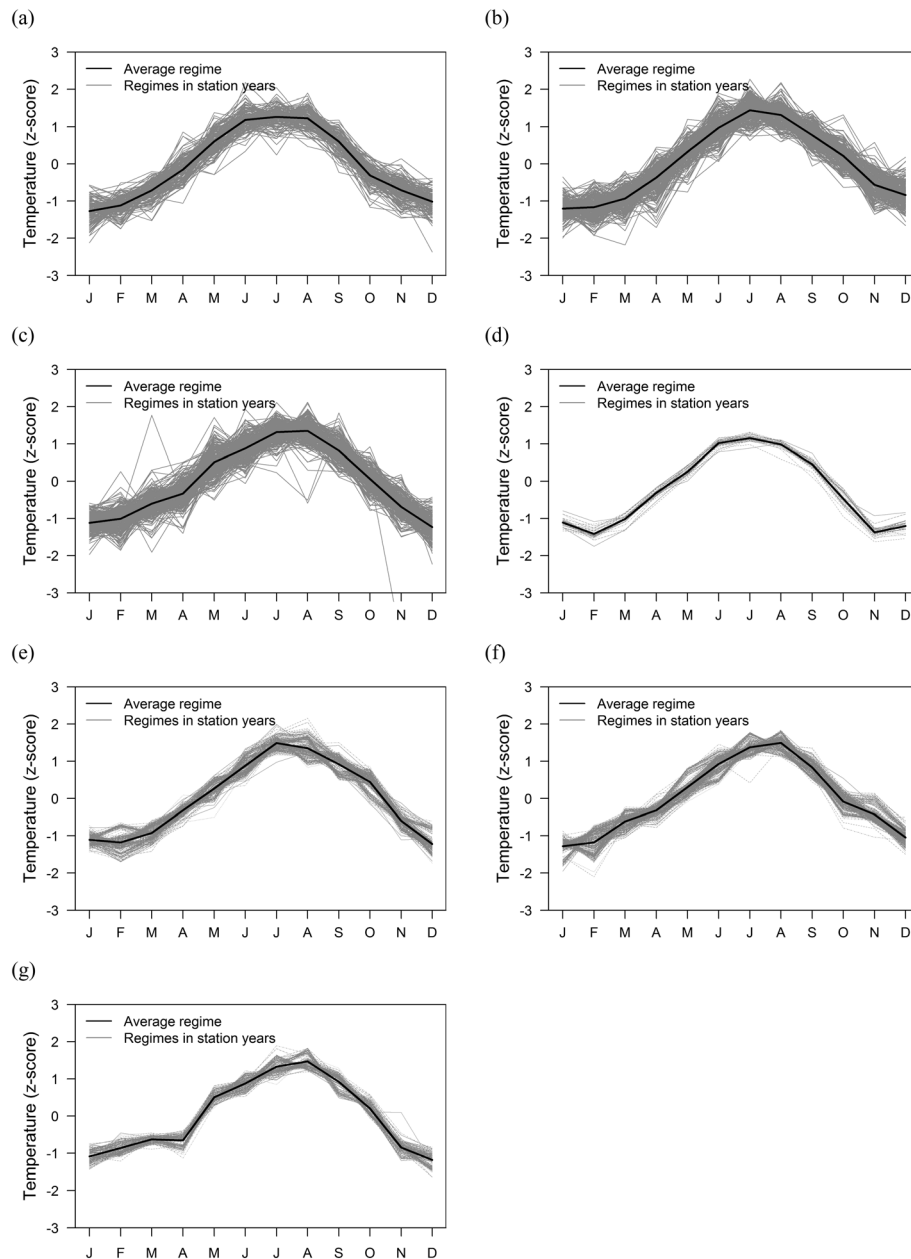
Figure 6. Standardized (z-score) monthly average temperature values for regimes in station-years (a) $IA\text{-}Tw_A$, (b) $IA\text{-}Tw_B$, (c) $IA\text{-}Tw_C$, (d) $IA\text{-}Ta_A$, (e) $IA\text{-}Ta_B$, (f) $IA\text{-}Ta_C$ and (g) $IA\text{-}Ta_D$

all years except 1997, 2003 and 2004. Regime $IA\text{-}Tw_C$ predominated in six years, $IA\text{-}Tw_A$ in seven years and $IA\text{-}Tw_B$ in two years. Equitability (E) quantified the evenness of regime occurrence at each station. Values of E were on average very high with 0.87 ± 0.2 and 0.89 ± 0.5 for river and air temperature regimes, respectively. This indicated that river and air temperature shape regime occurrences were highly variable between years and that all regimes occurred reasonably evenly at each station over the study period.

Annual frequencies of river and air temperature shape classes within England and Wales are summarized in

Figure 7. The SI quantified the strength and direction of the association between air and river temperature regimes. SI values were positive at all stations, indicating that river temperature regime shape was more variable than air temperature regime shape. The absolute magnitude of SI values averaged 0.35 ± 0.3, which indicated moderate sensitivity of river temperature to air temperature.

Inter-annual magnitude regimes. Five inter-annual river temperature and four inter-annual air temperature magnitude regime classes were identified. Inter-annual
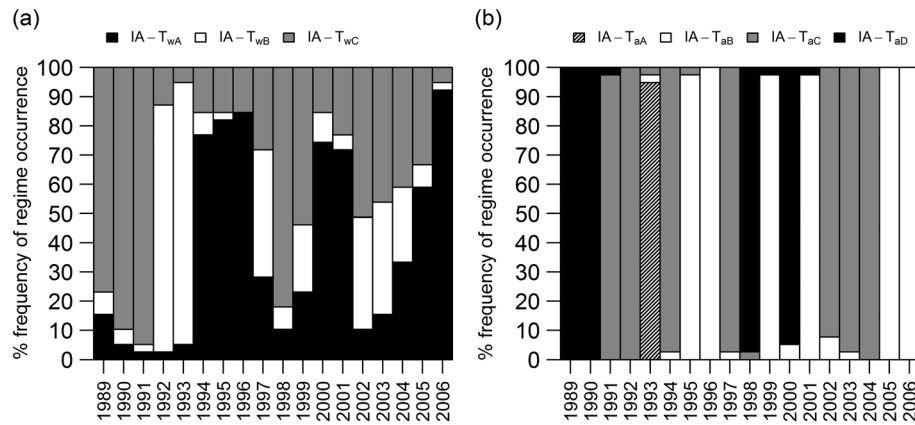
(a)

(b)

Figure 7. Percentage frequency of occurrence of each inter-annual shape regime in each study year for (a) river temperature and (b) air temperature

river temperature magnitude regime classes ($IA\text{-}Tw_x$) were identified as follows (Figure 8):

$IA\text{-}Tw_1$ Cool – low mean, low maximum, minimum and moderate standard deviation (133 station-years, 19%)

$IA\text{-}Tw_2$ Moderate – moderate mean, lowest maximum, highest minimum, lowest standard deviation (175 station-years, 25%)

$IA\text{-}Tw_3$ Moderate with high seasonality – moderate mean, high maximum, lowest minimum and high standard deviation (71 station-years, 10%)

$IA\text{-}Tw_4$ Warm – moderate mean, high maximum, moderate minimum and standard deviation (224 station-years, 32%)

$IA\text{-}Tw_5$ Warm with high seasonality – highest mean and maximum, moderate minimum and highest standard deviation (99 station-years, 14%)

Inter-annual air temperature magnitude regimes ($IA\text{-}Ta_x$) were identified as follows (Figure 8):

$IA\text{-}Ta_1$ Cool – lowest mean, low maximum, low minimum and moderate standard deviation (198 station-years, 28%)

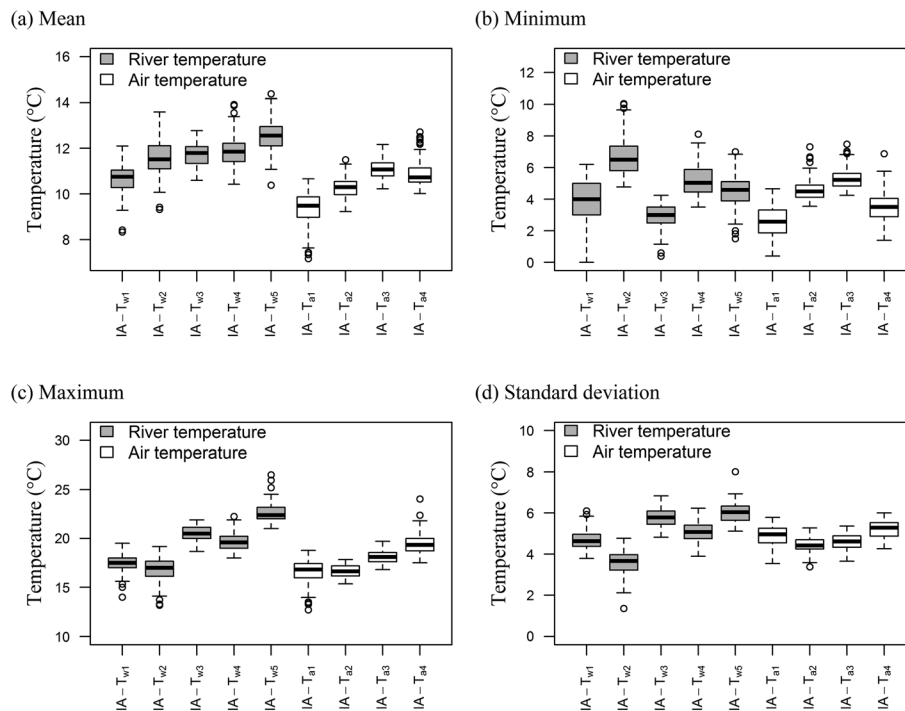(a) Mean

(b) Minimum

(c) Maximum

(d) Standard deviation

Figure 8. Box plots of annual (a) mean, (b) minimum, (c) maximum and (d) standard deviation for inter-annual river and air temperature magnitude regime classes

IA-Ta₂ Moderate – moderate mean, moderate maximum, high minimum and moderate standard deviation (158 station-years, 23%).

IA-Ta₃ Warm – highest mean, high maximum, high minimum and moderate standard deviations (182 station-years, 26%)

IA-Ta₄ Warm with greatest seasonality – high mean, high maximum, low minimum and highest standard deviation (164 station-years, 23%)

Associations between inter-annual air and river temperature magnitude regimes. Regionalization identified four long-term average river temperature regions ($R\text{-}Tw_1$–$R\text{-}Tw_4$) for which stations were pooled for analysis of associations between inter-annual regimes of river and air temperature magnitudes. Annual frequencies of river and air temperature magnitude classes in each region are summarized in Figure 9. There was no apparent trend in either river or air temperature regime magnitude for any region.

Distinct differences in the frequency of occurrence of inter-annual river temperature magnitude regimes were observed between regions (Figure 9). All inter-annual magnitude regimes occurred within $R\text{-}Tw_1$ only; $IA\text{-}Tw_1$ occurred most frequently, followed by $IA\text{-}Tw_4$, $Ia\text{-}Tw_2$, $IA\text{-}Tw_3$ and $IA\text{-}Tw_5$ (Figure 9). Within region $R\text{-}Tw_2$, all inter-annual regimes except $IA\text{-}Tw_3$ occurred; $IA\text{-}Tw_2$ occurred most frequently, followed by $IA\text{-}Tw_4$, $IA\text{-}Tw_1$ and $IA\text{-}Tw_5$ (Figure 9). Within region $R\text{-}Tw_3$, all regimes except $IA\text{-}Tw_2$ were observed; $IA\text{-}Tw_4$ occurred most frequently, followed by $IA\text{-}Tw_5$, $IA\text{-}Tw_3$ and $IA\text{-}Tw_1$ (Figure 9). Within region $R\text{-}Tw_4$, regime $IA\text{-}Tw_2$ predominated across the majority of stations and station-years, followed by $IA\text{-}Tw_4$ (Figure 9). Consequently, equitability was greatest within region $R\text{-}Tw_1$ (0.71 ± 0.11), followed by $R\text{-}Tw_3$ (0.70 ± 0.07), $R\text{-}Tw_2$ (0.49 ± 0.11) and $R\text{-}Tw_4$ (0.18 ± 0.32).

For air temperature, all inter-annual magnitude regimes occurred in each region; equitability was high and varied little between regions (cf. river temperature regimes). Equitability was greatest within $R\text{-}Tw_3$ (0.88 ± 0.14), followed by $R\text{-}Tw_4$ (0.86 ± 0.13), $R\text{-}Tw_1$ (0.81 ± 0.27) and $R\text{-}Tw_2$ (0.74 ± 0.33). Differences in the frequency of
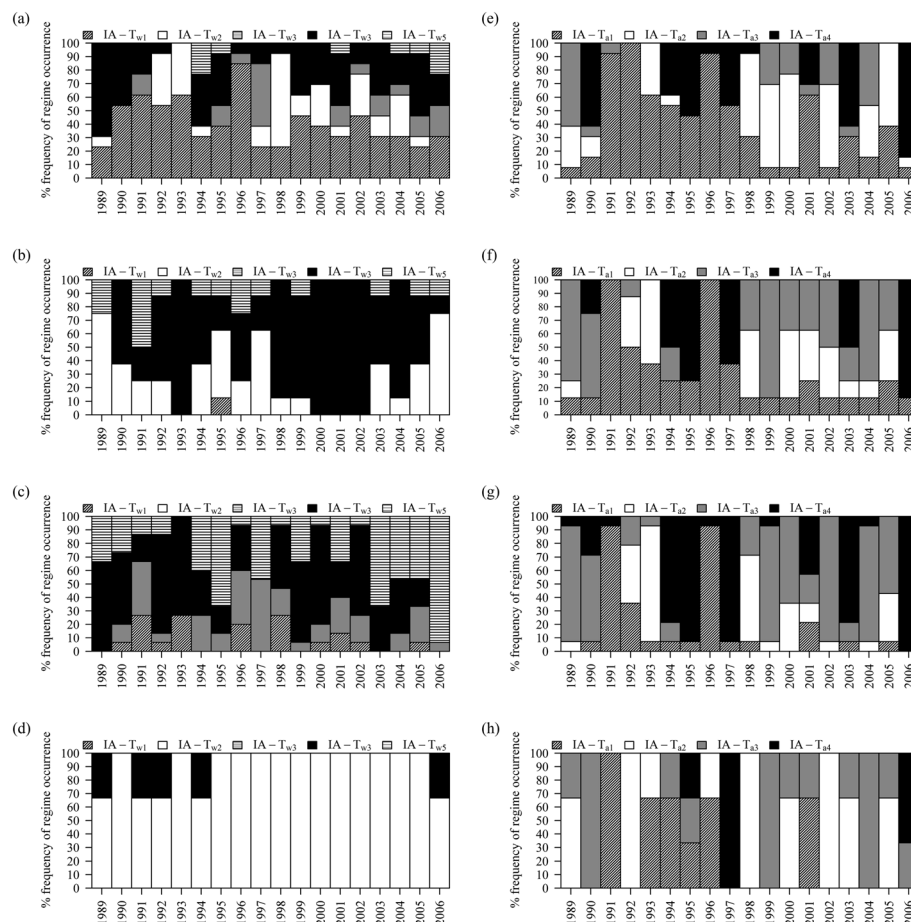

Figure 9. Percentage frequency of occurrence of each inter-annual magnitude regime in each study year for river temperature in (a) $R\text{-}Tw_1$, (b) $R\text{-}Tw_2$, (c) $R\text{-}Tw_3$ and (d) $R\text{-}Tw_4$ and air temperature in (e) $R\text{-}Tw_1$, (f) $R\text{-}Tw_2$, (g) $R\text{-}Tw_3$ and (h) $R\text{-}Tw_4$

regimes were observed between regions (Figure 9) but were not as pronounced as differences for river temperature. In $R\text{-}Tw_1$, regime $IA\text{-}Ta_1$ occurred most frequently, followed by $IA\text{-}Ta_2$, $IA\text{-}Ta_4$ and $IA\text{-}Ta_3$ (Figure 9). The frequency of inter-annual air temperature regime occurrence was similar in regions $R\text{-}Tw_2$ and $R\text{-}Tw_3$ (Figure 9) because stations within these regions formed the same long-term average air temperature region (Figure 6); $IA\text{-}Ta_1$ occurred most frequently followed by $IA\text{-}Ta_3$, $IA\text{-}Ta_2$ and $IA\text{-}Ta_4$. In $R\text{-}Tw_4$, inter-annual regime $IA\text{-}Ta_1$ occurred most frequently, followed by $IA\text{-}Ta_2$, $IA\text{-}Ta_3$ and $IA\text{-}Ta_4$.

The strength and direction of inter-annual associations between river and air temperature regime magnitudes were quantified using the *SI* and the number of synchronous air–river temperature regime switches. All stations within regions $R\text{-}Tw_1$, $R\text{-}Tw_2$ and $R\text{-}Tw_3$ were associated with negative *SI* values; therefore, river temperature was not as variable year to year as air temperature. Within region $R\text{-}Tw_2$, 12 stations had negative *SI* values, but two stations had positive *SI* values; thus, at a minority of stations, river temperature was more variable than air temperature between years.

Region $R\text{-}Tw_3$ was associated with the greatest absolute *SI* values (Figure 10) and the least synchrony of air–river temperature regime switches from year to year, five on average. Region $R\text{-}Tw_2$ had a *SI* of 0.68 and displayed an average of nine synchronous air–river temperature switches. Regions $R\text{-}Tw_1$ and $R\text{-}Tw_4$ had the lowest *SI* values and the most synchronous air–river temperature regime switches; on average, stations within $R\text{-}Tw_1$ had a *SI* value of 0.56 and displayed ten synchronous switches. Stations within $R\text{-}Tw_3$ had a *SI* value of 0.52 and displayed 11 synchronous switches.

Influence of basin properties on air–water temperature regime sensitivity. Mean basin permeability (a measure of basin water storage and response time), basin area and mean basin elevation were compared across the four long-term average river temperature regions for magnitude (Figure 9). For basin area, stations within $R\text{-}Tw_4$ were characterized by the smallest basins and lowest sensitivity to air temperature. Region $R\text{-}Tw_2$ was associated with the most permeable geologies and was the second least sensitive to air temperature. $R\text{-}Tw_4$ was situated on the second most permeable geologies. Regions $R\text{-}Tw_1$ and $R\text{-}Tw_3$ were
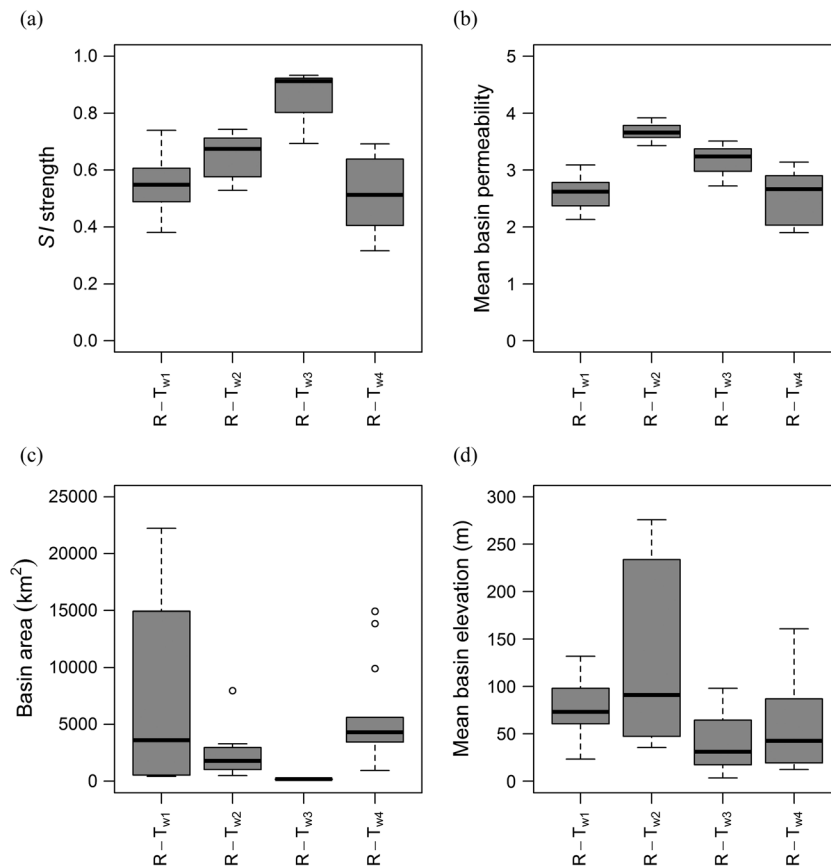

Figure 10. Box plots showing (a) *SI* strength, (b) mean basin permeability, (c) basin area and (d) mean basin elevation for for river temperature stations in each region

situated on the least permeable geologies and contained the largest basins. For mean basin elevation, a considerable range of values was observed for all regions, especially $R\text{-}Tw_2$.

DISCUSSION

This paper has quantified the space–time links between the shape and magnitude of air and river temperature regimes within England and Wales and identified the role of basin properties in modifying these associations. Static basin properties were not found to influence river temperature shape regimes; therefore, the discussion of the role of the river basin in modifying river temperature is confined to regime magnitude.

Shape regimes

No spatial differentiation of regime shape occurred within England and Wales as only one river regime and one air temperature regime were identified in the regionalization process. Broad temporal correspondence of air and river temperature dynamics was observed both intra-annually and inter-annually. For long-term regimes, river and air temperatures displayed maxima in July and minima in January, but air temperature maxima (minima) continued into August (February). The observed discrepancy between the timing of maximum and minimum regime features is attributable probably to the dominance of summer river flow by baseflow (i.e. groundwater) contributions (Marsh *et al.*, 2007; Tague *et al.*, 2007; Payn *et al.*, 2012). The thermal dynamics of groundwater are slightly influenced by intra-annual variability in air temperature, whereas runoff is influenced by intra-seasonally variable meteorological conditions (O'Driscoll and DeWalle, 2006; Tague *et al.*, 2007; Herb and Stefan, 2011). Hence, maximum air temperature continued through August, whereas river temperature declined from its annual maximum in July potentially because of changing hydrological sourcing of river flow.

Inter-annually, river temperature regimes varied more than air temperature regimes, and the *SI* quantified moderate links between air and river temperatures. Moderate correspondence suggests that basin controls modified links between air and river temperatures, but because the regionalization process did not discern regional-scale variability in the long-term average regime, it is likely that these controls were basin specific and that the strength of their influence was variable between years (i.e. they were not static), explaining also why river temperature varied more than air temperature. Inter-annually variable discharge and hydrological sourcing of river flow (i.e. from runoff or groundwater) would generate varied thermal capacity and initial water temperature for atmospheric warming/cooling (Poole

and Berman, 2001). Therefore, responsiveness of river temperature to air temperature would be varied between years. A lack of previous research on the variability of river temperature seasonality and links with air temperature hampers the comparison of these results for regime shape with studies conducted elsewhere.

Magnitude regimes and their modification by basin properties

For regime magnitude, spatially distinct regions of long-term average air and river temperature dynamics were observed. Bower *et al.* (2004) and Chu *et al.* (2010) also observed variability of air and river temperature magnitudes at regional scales. Intra-annual dynamics of air and river temperature regimes corresponded broadly within most regions, although some exceptions occurred. Air temperature regimes were warmer and varied less between seasons across a north to south-west gradient within England and Wales (as observed by Bower *et al.*, 2004) in response to reducing altitude and continentality (Barrow and Hulme, 1997). River temperature regimes became warmer and varied less between seasons across a north to south-west gradient too, with the exception of moderate regimes within $R\text{-}Tw_2$ (located in the south-east) that were observed under warm and highly seasonal air temperature regime Tw_2. Stations within $R\text{-}Tw_2$ were located on the most permeable geologies (i.e. predominantly on the Chalk in central southern England; Marsh *et al.*, 2000) and received larger influxes of groundwater. Groundwater contributions in these regions would have contributed cooler water to river flow during summer and warmer water during winter (Story *et al.*, 2003; Hannah *et al.*, 2004; O'Driscoll and DeWalle, 2006; Tague *et al.*, 2007; Chu *et al.*, 2010; Kelleher *et al.*, 2012) and so dampened the magnitude and inter-seasonal variability of the long-term average annual river temperature regime.

Inter-annually, clear regional spatial differentiation was observed in the occurrence of river temperature magnitude regimes and in the strength of links between air and river temperatures. River temperature regimes were least stable between years and displayed the strongest (yet weaker compared with shape) links with air temperature in regions $R\text{-}Tw_1$ and $R\text{-}Tw_4$, where stations were situated on the least permeable and also largest basins. River temperature regimes were most stable and displayed the weakest links with air temperature in regions $R\text{-}Tw_2$ and $R\text{-}Tw_3$, where stations were located on the most permeable geologies and smallest basins, respectively. These results were consistent with studies conducted on North American and continental European rivers. Runoff sourced from groundwater in Pennsylvanian and Oregon streams, USA, was less variable and less sensitive to variability in air temperature in comparison with those sourced from shallow sub-surface flows (O'Driscoll and

DeWalle, 2006; Tague *et al.*, 2007). Reduced sensitivity of headwater streams to air temperature was observed in the Aberdeenshire Dee, Scotland (Hrachowitz *et al.*, 2010), and River Danube, Austria (Webb and Nobilis, 2007), and small Pennsylvanian streams were shown to be less sensitive to changes in air temperature than larger streams (Kelleher *et al.*, 2012). The thermal dynamics of headwater streams were similar to those of groundwater because they were likely to be located closer to the river source and water had insufficient exposure time to equilibrate with the atmosphere (Edinger *et al.*, 1968; Poole and Berman, 2001; Tague *et al.*, 2007; Kelleher *et al.*, 2012). Furthermore, stations on small headwater catchments may be forested (e.g. Hrachowitz *et al.*, 2010), so that downstream warming may have been reduced or interrupted (Poole and Berman, 2001; Moore *et al.*, 2005).

Although more sensitive to air temperature than smaller basins, larger basins did not exhibit strong links between thermal dynamics and air temperature as would be expected if they had reached atmospheric equilibrium. Only moderate air–river temperature links were observed, for which a number of causes may be hypothesized: (1) dynamic basin properties (e.g. discharge and changing hydrological sourcing of runoff; see Discussion sub-section on Shape regimes) varied the strength of air–river temperature between years; (2) larger basins within England and Wales (i.e. predominantly 'mesoscale basins', 10^2–10^3 km^2 in size; Cappel *et al.*, 2012) were smaller than so-called large river basins in continental Europe (e.g. Webb and Nobilis, 2007) and North America (e.g. Kelleher *et al.*, 2012), and thus because of shorter travel times (Mohseni & Stefan, 1999), river temperature may not have enough time to fully equilibrate with the atmosphere; (3) thermal capacity was greater at stations in larger basins owing to higher discharge (Poole and Berman, 2001), and thus, response to air temperature variations was weakened (as demonstrated by Webb *et al.*, 2003 in the Exe basin, UK).

CONCLUSIONS AND IMPLICATIONS

This study is innovative in presenting: (1) an assessment of large-scale spatial and temporal variability of the shape (timing) and magnitude (size) of annual river temperature regimes within England and Wales, (2) a quantification of their associations with air temperature regimes and (3) the identification of basin controls that modified the strength of air–river temperature links.

The application of a regime classification methodology (after Hannah *et al.*, 2000) and sensitivity index (after Bower *et al.*, 2004) proved to be useful tools for identifying spatial and temporal patterns in annual air and river temperature regimes and assessing the strength of air–river temperature links. Observed patterns of, and

associations between, river and air temperature regimes within England and Wales were explained by physically meaningful basin controls, which modified the climatic signal in similar ways to those observed in North American (e.g. Tague *et al.*, 2007; Kelleher *et al.*, 2012) and continental European rivers (e.g. Webb and Nobilis, 2007). Thus, the methods applied herein to annual river temperature regimes have wide potential applicability for the assessment of large-scale hydroclimatological interactions.

Future changes in river temperature are anticipated in response to a changing climate (Webb and Walling, 1992; Webb and Nobilis, 1994; Mohseni *et al.*, 2003; van Vliet *et al.*, 2011). This study represents an important first step in identifying the locations within England and Wales and dynamics of annual river temperature regimes, which may be impacted most (i.e. those most sensitive to air temperature change). The results suggest that the regime shape will be most sensitive to a changing climate, followed by regime magnitude in the largest and least permeable basins. Regime magnitude in the smallest and most permeable basins is anticipated to be least sensitive. The outcomes of this study contribute new knowledge to the scientific basis for making informed regulatory and management decisions regarding river temperature within England and Wales.

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