HYDROLOGICAL PROCESSES
Hydrol. Process. **29**, 752–766 (2015)
DOI: 10.1002/hyp.10181

Detecting changing river temperatures in England and Wales

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Abstract:

Changes in water temperature can have important consequences for aquatic ecosystems, with some species being sensitive even to small shifts in temperature during some or all of their life cycle. While many studies report increasing regional and global air temperatures, evidence of changes in river water temperature has, thus far, been site specific and often from sites heavily influenced by human activities that themselves could lead to warming. Here we present a tiered assessment of changing river water temperature covering England and Wales with data from 2773 locations. We use novel statistical approaches to detect trends in irregularly sampled spot measurements taken between 1990 and 2006. During this 17-year period, on average, mean water temperature increased by 0.03 °C per year (±0.002 °C), and positive changes in water temperature were observed at 2385 (86%) sites. Examination of catchments where there has been limited human influence on hydrological response shows that changes in river flow have had little influence on these water temperature trends. In the absence of other systematic influences on water temperature, it is inferred that anthropogenically driven climate change is driving some of this trend in water temperature.

KEY WORDS water temperature; trends; climate change; freshwater ecology

Received 4 August 2011; Accepted 24 February 2014

INTRODUCTION

Evidence for recent global warming comes mainly from observations of air temperature and near-surface sea temperature (Brohan *et al*., 2006; Hansen *et al*., 2006), but freshwater ecosystems are considered to be highly sensitive to temperature change (Bates *et al*., 2008; Yvon-Durocher *et al*., 2010). Some aquatic species, such as salmonid fish, have thermal limits that determine the success of spawning, migration and survival (Hari *et al*., 2006; Wehrly *et al*., 2007). Temperature also affects fish growth rates, in turn, influencing fish size, for example, changing the age at which salmon migrate out to sea and potentially abundance (Russell *et al*., 2012). Warming could lead to less suitable conditions for cold and cool-water-adapted salmonid species (Isaak *et al*., 2012; Webb and Walsh, 2004). Other freshwater species, including some macroinvertebrates, tolerate only a narrow range of temperature (Durance and Ormerod, 2007). Water temperature also regulates the amount of dissolved oxygen in rivers and the rate of biological and chemical processes with direct impacts on water quality and indirect impacts on biological responses (Whitehead *et al*, 2009).

The temperatures experienced by freshwater plants and animals cannot necessarily be determined from air temperature. Daily and annual cycles in water temperature are controlled by dynamic energy and hydrological exchanges at the water surface, air interface, streambed and banks (Hannah *et al*., 2008; Webb *et al*., 2008). Air temperature is sometimes used as a first approximation of water temperature. However, while water and air temperatures can covary, the strength of the relationship varies regionally, through time, and can be highly site specific (Hannah *et al*., 2008; Garner *et al*., 2013). Heat fluxes at the water surface are driven by solar radiation, net long-wave radiation, evaporation and convection (Caissie, 2006). Radiative fluxes generally account for the greatest proportion of heat inputs to rivers in the summer but not necessarily in the winter and can be highly variable locally (e.g. Webb and Zang, 1997; Hannah et al., 2004; Webb *et al*., 2008). On a

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sunny summer day, a tree canopy can change the energy flux to a net loss of heat compared with a net gain without the canopy (Johnson, 2004). River flow can also influence the relationship between air and water temperature (Webb *et al.*, 2003). Simplified approximations based on air temperature do not provide detail of the thermal regime experienced by aquatic organisms. To understand climate impacts on freshwater ecosystems, we need to examine water temperature directly from observations.

One reason why long-term trends in river water temperature are not well reported may be that water temperature has not been sampled with the same spatial or temporal intensity as air temperature. For example, observations of water temperature collected during research studies on thermal dynamics tend to be limited in space and time or aimed at understanding land use impacts. Most assessments of river water temperature trends and variability have been site specific or have considered only a small number of sites (e.g. Langan *et al.*, 2001; Bartholow, 2005; Hari *et al.*, 2006; Moatar and Gailhard, 2006; Webb and Nobilis, 2007; Kaushal *et al.*, 2010). Routine observations of water temperature over longer time periods tend to be collected as part of water quality monitoring or to investigate impacts of pollution at affected sites. Consequently, network design and sampling frequency are unlikely to have been optimized for trend detection; such sites are often sampled infrequently.

Generalization about overall trends is, therefore, problematic because of heterogeneous controls (Webb *et al.*, 2008) and a lack of data. Spatial variation in river temperature is affected by local climate gradients, valley slope, elevation, aspect, hill shading, channel incision and morphology, surface–groundwater interactions, catchment and riparian vegetation cover (Caissie, 2006; Webb *et al.*, 2008; Toone *et al.*, 2011). Temporal trends in water temperature can be driven not only by climatic change but also by human interventions such as water abstraction, impoundment, wastewater discharges, land use change (particularly woodland cover), channel management and river flow regulation. The sensitivity of river response to potential drivers of temperature change is much less certain but may be affected by factors such as the volume and temperature of groundwater inputs, catchment and channel size (Garner *et al*, 2013).

Long-term studies of water temperature in large European and US rivers suggest that up to two thirds of warming over the 20th century may have been because of human-induced changes in the flow regime, discharges of treated wastewater, heated water and urbanization (Webb and Nobilis, 1994; Huguet *et al.*, 2008; Kaushal *et al.*, 2010). The broadest scale investigation of 40 sites across North America (Kaushal *et al.*, 2010) acknowledged that human activities were likely to have had a significant impact on observed river warming and that causes of change are hard to quantify and attribute. A more recent study suggests that systematic warming is not being observed and calls for a better instrumented network to detect change more reliably (Arismendi *et al.*, 2012).

The sensitivity and recent rates of change in river water temperature are of interest because air temperature has risen by 1 °C since the 1980s across the UK (Jenkins *et al.* 2009). England and Wales have, like many countries, a large spatial network of irregularly sampled water quality monitoring sites with potential for trend detection despite not being designed for this purpose. Long time series are rare, and the problems of looking at a limited number of sites make attribution of change difficult. Using a large data set with extensive spatial coverage ensures that any systematic changes are likely to result from large-scale drivers. A significant challenge in examining time series of irregularly sampled data is identifying suitable statistical techniques. The so-called spot sampled data would be inappropriate for examining changes in many commonly measured hydrological variables such as discharge or sediment load that are highly variable over short time scales. In contrast, water temperature tends to change more slowly, so spot samples can provide information on trends.

This study uses novel statistical techniques to show that irregularly sampled data can be used to detect trends. Having developed trend model capability, we exploit a large number of sites to look at trends over a wide spatial area. We take a tiered approach to investigating trends starting with an assessment of annual changes in river water temperature for 2773 sites across England and Wales between 1990 and 2006 (when data were extracted) to show short-term trends. We undertake detailed analysis on a smaller set of sites that is used to explore the drivers of observed changes addressing a series of questions:

- Are there regional trends in river water temperature from 1990 to 2006?
- Could the trends be the result of errors associated with sampling methods?
- Can trends in river water temperature be explained by changes in river flow?
- How do changes in water temperature relate to changes in air temperature?
- How do water temperature changes between 1990 and 2006 compare with longer term changes and to changes in air temperature?
- What are the recent trends in river water temperature across England and Wales?

METHODS

Data collection and quality

This study is based on a data set collected by the Environment Agency (since 2013, water temperature in

Wales has been monitored by Natural Resources Wales). This water temperature archive contains 42 million temperature measurements at around 30 000 sites. Subdaily data (hourly and 15-min sampling) are available for 351 sites, but most spot measurements are typically taken twice a month, between 08:00 and 16:00 h. Some records span several decades, but the average length is 14 years. Data were collected as part of monitoring where temperature is one of many variables used to determine water quality. Sample collection was performed by trained field staff following a standard procedure with regularly maintained equipment, sampling at known sites. No guidance was given on the time of day of sampling; this and irregular sampling could introduce systematic bias (Toone *et al.*, 2011). We consider these issues but take no account of other potential errors such as changing observer and sampling depth.

Spot measurements are taken from a multiuse probe that detects temperature, dissolved oxygen and pH. The probe is held in the water column until readings stabilize; temperature is recorded to the nearest 0.1 °C. During high flows, a container of water is taken from the river, and temperature is measured immediately in the same manner. Equipment is pooled with regular performance checks (Table I). Temperature cannot be recalibrated, but inaccurate equipment was replaced. Details of the most numerous of the 1500 instruments in use are based on an equipment survey in 2003 (Table I).

We selected 2773 sites from the archive for analysis. These were sites that had at least 250 individual measurements across more than 120 months, starting on or before 1 January 1990 and extending to at least 31 December 2006. We removed records with one or more years of missing data or records with improbable extreme values (greater than 35 °C or less than 1 °C). Freezing temperatures are sometimes experienced in upland headwaters in rivers in England and Wales; however, high elevation sites are underrepresented in our data set with only six sites above 300 m. Temperatures below 1 °C are more likely to be errors. Inclusion of sites with larger amounts of missing data would have introduced greater uncertainties to subsequent trend analyses.

From the 2773 sites, we selected a subset of 231 sites (predominantly spot sampled) located within 63 'benchmark catchments'. These catchments are subject to only minimal impacts on the flow regime, and there have been no known major land use changes that might cause systematic hydrological changes (Bradford and Marsh, 2003; Hannaford and Marsh, 2006, 2008). The benchmark catchments cover most of the country and are representative of the range of rivers across England and Wales. We use these benchmark sites to analyse water temperature trends where there are fewer local anthropogenic influences, compare water temperature and river flow changes with trends in nearby air temperature and explore seasonal trends. We also compare recent trends to longer term trends (seven sites) and trends derived from spot sampling with trends derived from daily sampling (one site).

Water temperature trend analysis

River water temperature data typically exhibit strong periodicity and often nonlinear patterns of change. Methods such as the Mann–Kendall test or linear regression, which assume monotonic and linear trends

Table I. Details of most commonly used instruments

Date	Equipment (no. in use in 2003)	Accuracy	Resolution	Calibration
Spot measurement equipment				
1970s	Thermometers	±1 °C	0.5–1 °C	Annual check regionally (checked against each other in a bucket of water)
ca 1991	YSI 55 (503) introduced nationally	±0.2 °C	0.1 °C	Annual check against thermometer
2002	YSI 556 (214) introduced for pH monitoring	±0.15 °C	0.01 °C	Monthly temperature checks (everywhere) and annual check against calibrated lab thermometer (accuracy 0.005 °C only one region).
December 2010	YSI proplus	±0.15 °C	0.01 °C	Monthly temperature checks (everywhere) and annual check against calibrated lab thermometer (accuracy 0.005 °C, everywhere).
After 2004	Eutech (230) scan 2/pH test30	±0.1 °C	0.5 °C	Monthly checks
Continuous or long-deployment equipment				
After 1998	YSI 6920	±0.15 °C	0.01 °C	Monthly checks
After 1995	Hydrolab DS3	±0.15 °C	0.01 °C	Monthly checks

respectively, may therefore provide a poor fit to the data. Instead, additive models were used to identify trends in temperature time series (Ferguson *et al.*, 2008). Additive models do not prescribe any particular form for the trend. The shape of the trend is estimated from the data via a penalized regression. Models were fitted separately to each of the 2773 sites.

To identify trends in the 2773 sites, we used an additive model (Equation (1)) with trend ($f_1(\text{time}_i)$) and seasonal ($f_2(\text{doy}_i)$) components

$$y_i = \beta_0 + f_1(\text{time}_i) + f_2(\text{doy}_i) + \varepsilon_i, \quad \varepsilon = N(0, \sigma^2\mathbf{\Lambda}) \quad (1)$$

where y_i is the observed water temperature, time_i the time, in days, since monitoring started at an individual site, and doy_i is day of the year for the ith observation. The seasonal smooth ($f_2(\text{doy}_i)$) used cyclic cubic spline bases, to allow a smooth transition between December and January, and remained constant through time, not varying with the trend. The seasonal smooth was not allowed to vary over time. The model residuals, ε, were assumed to be drawn from a zero-mean Gaussian distribution with variance σ^2 and correlation matrix $\mathbf{\Lambda}$. The introduction of the correlation matrix allows the relaxation of the independence assumption for the residuals, enabling the model to account for residual temporal autocorrelation. A continuous time, first-order autoregressive process (CAR1) was assumed for $\mathbf{\Lambda}$, which allows the model to handle observations that are irregularly spaced in time and describes the degree to which the correlation between any two observations declines exponentially as a function of their temporal separation.

Model 1 (Equation (1)) was modified to include time of day of sampling (tod) as an additional model term ($f_3(\text{tod}_i)$) for the subset of sites (231 sites) within the benchmark catchments. Model 2 (Equation (2)) thus avoids a situation where any systematic variation in sampling time present in the data could bias the modelled trend

$$\begin{aligned} y_i &= \beta_0 + f_1(\text{time}_i) + f_2(\text{doy}_i) + f_3(\text{tod}_i) + \varepsilon_i, \\ \varepsilon &= N(0, \sigma^2\mathbf{\Lambda}) \end{aligned} \quad (2)$$

The more complex model (Equation (2)) was only applied to the 231 sites in the benchmark catchments because the time of sampling had not been reliably recorded in all 2773 sites from England and Wales, and the model could then not be consistently applied across the larger data set. For two sites, model 2 failed to converge; hence, results for only 229 sites are presented.

To investigate whether water temperature trends were different for each season, at the benchmark sites, we also fitted an additive model that allowed the trend component to interact with a season fixed effect

$$\begin{aligned} y_{ij} &= \beta_0 + \beta_j \text{season}_\text{j} + f_j(\text{time}_i) + f_2(\text{doy}_i) \\ &\quad + f_3(\text{tod}_i) + \varepsilon_{ij}, \\ \varepsilon &= N(0, \sigma^2\mathbf{\Lambda}) \end{aligned} \quad (3)$$

where the single trend term has been replaced by j trend terms, one for each season ($f_j(\text{time}_i)$). The parametric term for the jth season ensures that each seasonal trend is defined as the long-term variation in temperature about the mean temperature for that season. The within-year variation ($f_2(\text{doy}_i)$) again remains fixed in time. Models for 12 sites failed to converge, so results for seasonal analysis are presented for 219 sites only. Seasons are defined as the winter (December to February), spring (March to May), summer (June to August) and autumn (September to November).

The individual model terms are additive, and therefore, the individual contributions from each term to the fitted values of the model can be determined. This allows the isolation of the trend component in order that the degree of change in water temperature over the long term can be extracted from each fitted model, independent of variation within year and within day. To do this, we obtained predictions from each model at the daily time step and isolated the trend component of these predictions. The change in temperature reported for the period 1990 to 2006 was computed as the difference between the isolated trend component at the start and end of the period. For the model exploring seasonal trends in water temperature (Equation (3)), the previously mentioned procedure was performed separately on the contribution to the fitted values of the individual seasonal trend terms.

Results of the trend analysis are presented as the difference in °C between the start and end of the time period. Water temperature is commonly expressed in measurements of daily mean, minimum and maximum values. Our data represent spot samples of water temperature, and our models decompose these data into an estimate for the time-of-day effect, the day-of-year effect and the effect of longer-term change, plus ε. Hence, models 2 and 3 are for the expectation of water temperature from a spot sample taken on any day of the year, at any time of the day (not extrapolated beyond the times of day of the observations), at any point between the start and end of the observed time series. Put simply, our models provide an estimate for the water temperature that could have been observed on any given day during the period of the time series.

The fitted smooths in Equations (2) and (3) are subject to uncertainty, as given by the standard errors of the coefficients for each smooth, $\boldsymbol{\beta}$. Hence, the difference in water temperature between 1990 and 2006 is also subject to uncertainty. A 95% confidence interval on the difference in temperature was calculated by means of sampling from the posterior distribution of the coefficient estimates for the trend smooth (or smooths in the case of model 3 where there is a trend per season). The coefficients for the trend smooth (or smooths) are distributed multivariate normal with mean vector $\boldsymbol{\beta}$ and covariance matrix $\boldsymbol{\Omega}$, whose diagonal elements are the standard errors of the coefficients $\boldsymbol{\beta}$. This distribution is the posterior distribution of the smooth(s). A single random sample from this distribution multiplied by the linear predictor matrix of the model yields a new trend that is fully consistent with the estimated trend given its uncertainty. From this new trend, the difference in estimated water temperature between 1990 and 2006 was computed in the same way as for the fitted model. This process was repeated for a total of 10 000 random samples from the posterior distribution of the smooth(s) to produce a distribution of 10 000 estimates of the change in water temperature at a single site. The lower 0.025 and upper 0.975 probability quantiles of this distribution were taken as the 95% confidence interval on the estimated change. It should be noted that sampling from the posterior distribution in this way yields a simultaneous confidence interval on the entire fitted trend(s) and is therefore a more rigorous assessment of uncertainty than that provided by the usual pointwise confidence interval. The simultaneous confidence interval remains conditional upon the estimated smoothing parameters for each smooth; accounting for this additional source of uncertainty, however, invariably makes little difference to the interval (Wood, 2010).

All models were fitted using the Mixed GAM Computation Vehicle (mgcv) package (Wood, 2004, 2006) for the R statistical software (R Core Development Team). Coefficients for each smooth term and the model fixed effects, plus the parameter for the correlation matrix, were all estimated via a linear mixed model representation of the additive models described in the preceding texts (Wood, 2004, 2006) using restricted maximum likelihood (REML). The number of degrees of freedom for each of the smooth terms in the models was also determined during model fitting. Where a linear trend was present in the data at a particular site, as opposed to a nonlinear trend, the degrees of freedom for the trend could be penalized back to a single degree of freedom term representing the linear trend via the REML fitting. Where a nonlinear trend described the data better, the degree of smoothness (complexity) of the fitted smooth terms was estimated as a parameter in the model, again using REML (Wood, 2011).

Trends in flows in benchmark catchments

To assess changes in flow at the benchmark catchment gauging stations over the years 1990 to 2006, we calculated trend magnitude at each site using the Theil–Sen nonparametric estimator of slope (Theil, 1950; Sen, 1968). This method is widely used and reported in literature relating to hydroclimatic trend testing, e.g. in a recent assessment of streamflow trends across Europe (Stahl *et al.*, 2010); the technique is described fully therein or in widely available standard references on trend testing, e.g. Kundzewicz and Robson (2000). Annual and seasonal river flow data sets were derived for all benchmark catchments in England and Wales. Following Hannaford and Marsh (2006, 2008), the Mann–Kendall trend test was employed, which – although unsuitable for the water temperature data – is suitable for flow trend variation because the availability of consistent daily flow data means that seasonal and annual averages can be derived accurately. However, as the records are short, conventional significance testing was not performed. The effects of multidecadal variability (Chen and Grasby, 2009; Hannaford *et al.*, 2013) and long-term persistence (Cohn and Lins, 2005) indicate that significance testing in short hydroclimatic time series is of limited value. In this instance, we wished only to compare the direction of trend in flow with the direction of trend in water temperature. Consequently, the magnitude of the trend was computed, using the Theil–Sen nonparametric estimator of slope (Theil, 1950; Sen, 1968). The slope was used to find the absolute change over the period in question, which was then expressed as a percentage of the long-term average flow to account for the widely varying magnitude of absolute run-off across England and Wales.

Comparison with air temperature

To investigate the degree to which water and air temperatures co-vary, we created time series of air temperature from a 5-km grid of interpolated daily mean temperature data for the UK land area (Perry and Hollis, 2005) downloaded for the period 1990–2006 (UKCP09). Benchmark water temperature sites were overlaid on the air temperature grid, allowing extraction of time series for grid cells that most closely corresponded to the locations of water temperature sites. We fitted additive models as described in the Section on Water temperature trend analysis to time series of daily air temperature at each site. There was no need to include the time of day component because air temperatures are presented as daily means. Change statistics in the fitted air temperature trends were computed for each air temperature site in the same manner as the change statistics for the models described in the Section on Water temperature trend analysis in the preceding texts for water temperature. Pairs of change statistics (for air and water) were compared using a linear regression at each of the 231 sites.

RESULTS AND DISCUSSION

This section first considers average trends in river water temperature across England and Wales before exploring possible explanations for these trends.

Trends in river water temperature across England and Wales

Additive models fitted to the data from each site show that 86% of the 2773 sites across England and Wales warmed between 1990 and 2006. There may be some spatial structure to the distribution of warming and cooling sites, with apparent clustering of sites with cooling trends such as in Somerset in south-west England (Figure 1). These may indicate other local influences but would need more investigation to be sure whether such clusters represent controls such as changes in discharge or abstraction or sampling or equipment issues. No attempt has been made here to understand local drivers of change for the wider data set other than to note that the dominance of apparent warming is widely distributed. The average total change for all 2773 sites between 1990 and 2006 is 0.52 °C (±0.01 standard error of the mean), which gives a mean increase for England and Wales of 0.03 °C per year.

It is clear that rates of change across the 2773 sites are spatially variable (Figure 1), and about 82% of sites changed by less than 1 °C, but some sites, approximately 18%, increased by more than 1 °C (solid line, Figure 2). The distribution of rates of change in all 2773 sites is compared with rates of change in the 231 sites located in the benchmark catchments (dashed line, Figure 2). There are fewer sites in the benchmark catchments that exhibit higher rates of temperature increase compared with the larger data set, which may suggest that very high rates of change are linked to more heavily modified sites. Further, site-based information would be required to explore these changes in more detail.

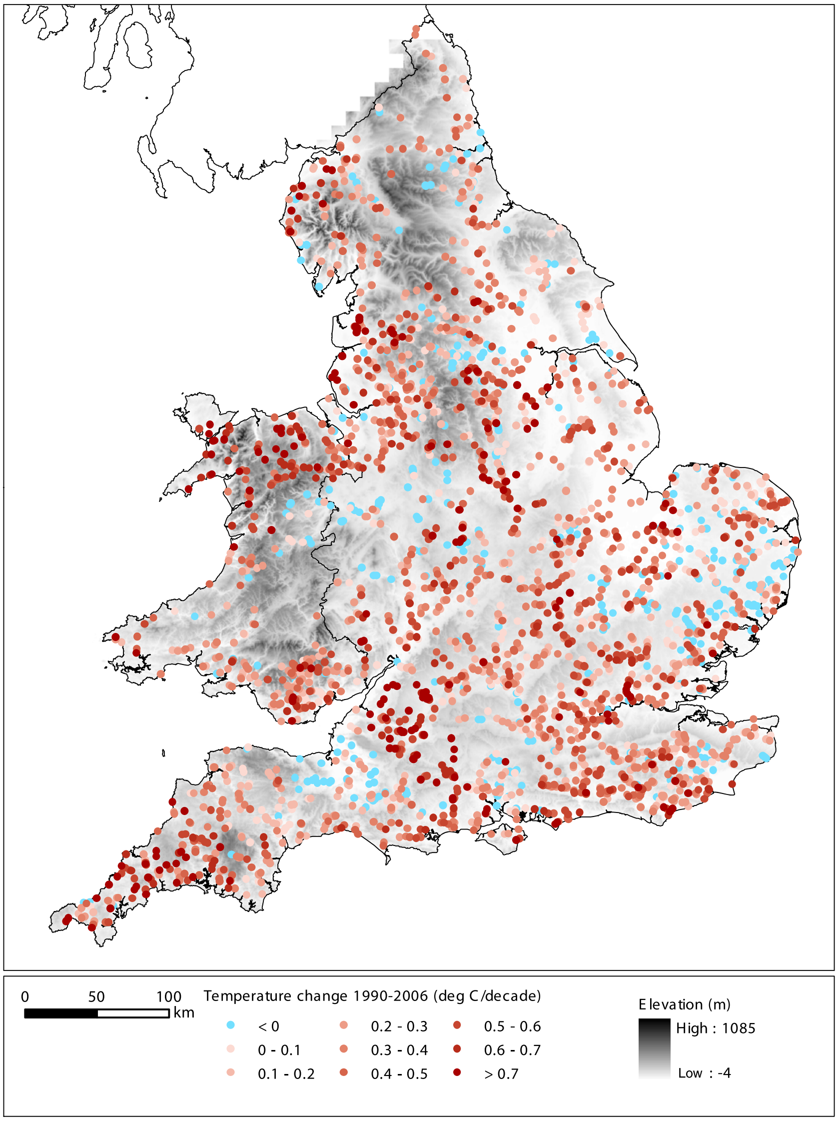

Figure 1. Estimated mean annual river temperature change (°C/decade) between 1 January 1990 and 31 December 2006

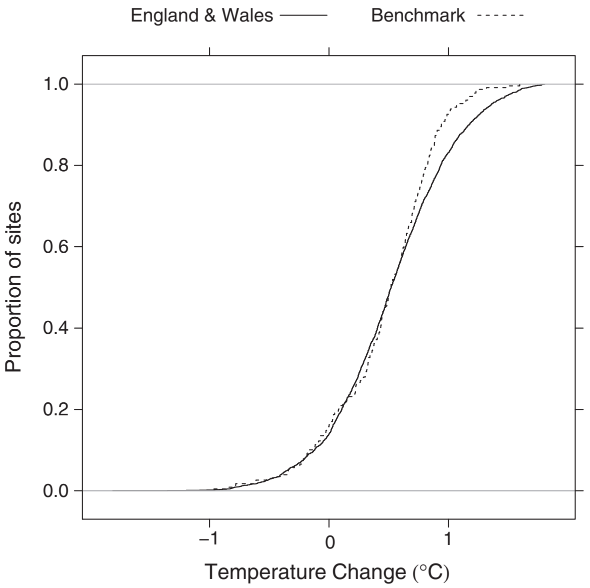

Figure 2. Frequency distribution [empirical cumulative distribution function (ECDF)] of the amount of change at 2773 sites across England and Wales (national) and for 231 sites in hydrologically undisturbed (benchmark) catchments

Influence of water temperature sampling on trends in temperature

Sources of error in water temperature measurements that could lead to apparent trends in temperature may include the following: discontinuous sampling where whole months or seasons are undersampled, infrequent (e.g. fortnightly) sampling where extremes of temperature are not detected, systematic changes in the time of day of sampling or changes in the method of sampling and/or the type of instrument and systematic drift in instrument performance.

Systematic changes in observer, sampling depth and equipment calibration could lead to trends over time. We cannot correct for changes in observer, but because sampling protocols have remained unchanged, staff members are trained and instruments regularly tested, we would not expect systematic trends. Equipment is pooled so that observers could be using different equipment so that any systematic errors in equipment are likely to be randomly distributed across sites within a region and should not be able to persist for more than 1 year when temperature checks are carried out.

Systematic changes in the time of sampling could lead to trends in temperature particularly during the summer; water temperature tends to peak late in the afternoon. Sampling between 08:00 and 16:00 h reflects the need to visit sites in daylight. We evaluated the effect of time of sampling for the benchmark catchments by incorporating this as an additional term in the additive models. This reveals the same patterns of change in benchmark catchments when time of day is included in the models (not shown). This suggests that the overall picture for England and Wales is robust (Figure 1). The analysis shows that sampling time of day does affect the magnitude of the trend at some sites, but there is no systematic change in trend when sampling time of day is not included in the model (not shown). Indeed, there is no reason to believe that the time of sampling has changed systematically across England and Wales; some sites may be sampled later in the day at some times as sampling rounds change, but other sites would be sampled earlier. However, sampling time of day should be considered as a matter of course, particularly when trend analysis is based on a small number of sites.

To test the influence of fortnightly sampling on temperature trends, one of the few daily water temperature series was sampled randomly 100 times to simulate a typical fortnightly sampling regime. For this site, temperature trends from additive models obtained from twice monthly sampling are presented alongside the trends found in daily sampled data (Figure 3). The thick line shows the fitted trend in daily temperature at a single site from 1 January 1990 to 31 December 2006. The thin (grey) lines are the trends fitted to 100 random time series for the same site, chosen to simulate the effect of irregular spot sampling on the detectable trend component. The overall direction of the trend appears to be very similar, but at a number of points, the simulated data series seem to underestimate or overestimate the magnitude of the trend (Figure 3). The main effect of infrequent as opposed to daily sampling is thus an increase in the uncertainty of the trend in the data, but the overall direction of the trend remains consistent. This suggests that fortnightly sampling was sufficient to characterize trends in water temperature, at least at this site over this time period.

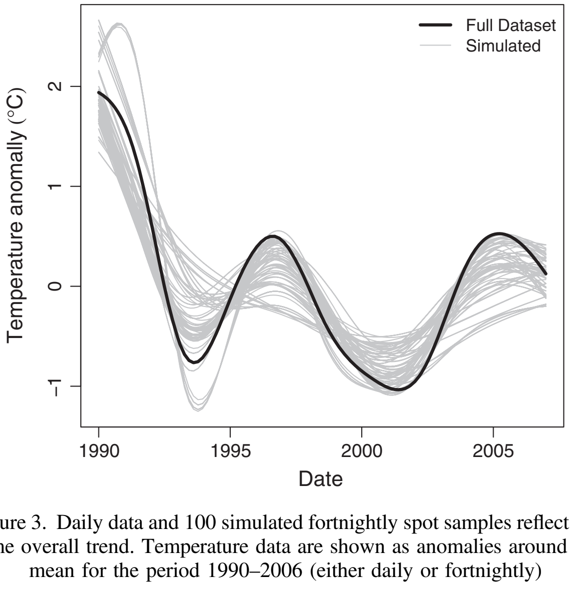

Figure 3. Daily data and 100 simulated fortnightly spot samples reflect the same overall trend. Temperature data are shown as anomalies around the mean for the period 1990–2006 (either daily or fortnightly)

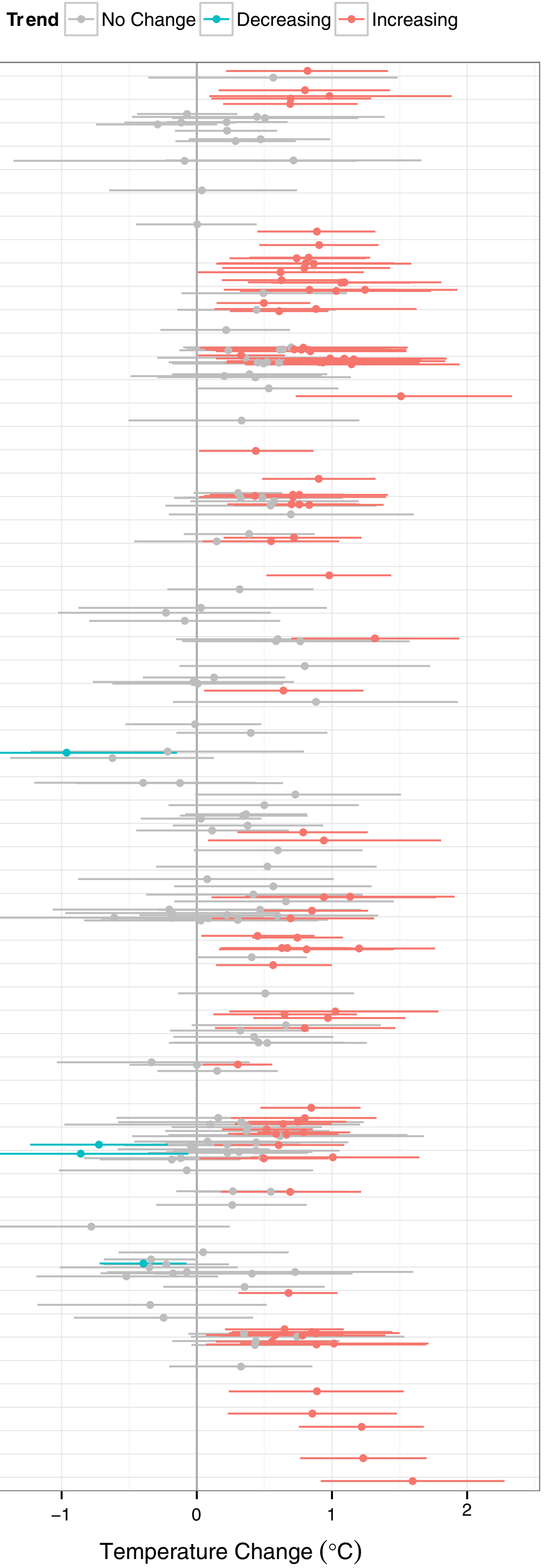

Figure 4. Rate of annual temperature change at 231 sites within benchmark catchments between 1990 and 2006 [sites, grey circles, are presented within catchments listed from north (Coquet) to south (Tiddy); lines represent 95% confidence interval for each site]

Any investigation of anomalous data at a single site would have to consider the possibility of changes in observer and the quality of the data, but this is not necessary for a large sample because such changes would not lead to systematic biases across the data set as a whole. Therefore, sampling errors can be ruled out as a cause for the overall trend in water temperature across England and Wales, although they add to the uncertainty in the analysis of individual sites.

Influence of river flow on water temperature

Local trends in water temperature could be induced by many factors mainly related to abstractions and discharges described in the introduction. For example, where abstraction leads to increased temperature in the summer as a result of increased net incoming radiation or discharges affect temperature through changes in thermal capacity and advection (including groundwater and hyporheic water) (Caissie, 2006). Release of discharges warmer than river water could lead to increased water temperatures as could some land use changes. Catchment properties may also influence river sensitivity to future change (Caissie, 2006), but for the present analysis, these are assumed to be constant, and the influence of local channel properties at individual sites is blended within the large sample set. Thus, changes in climate and flow are the most likely potential drivers for modelled water temperature trends.

River flow influences water temperatures, so it is important to be able to discount the effect of human activities such as water abstractions or heated discharges from power stations for example. In the UK, truly 'pristine' catchments are extremely rare, but the benchmark catchments have only minimal influence of human disturbance on their flow regimes (Bradford and Marsh, 2003). As such, any river temperature trends in benchmark catchments are unlikely to be the result of direct human-induced modification of flow regimes.

Annual changes in water temperature in the 231 benchmark catchments are comparable with the wider network of 2773 sites (Figure 4). The distribution of rates of change suggests that around 88% of sites have warmed, but most of these were not statistically significant (Figure 5). Statistically significant decreases in temperature were observed at 4 sites (2%), whereas significant increases were observed at 95 sites (41%); 130 sites (56%) had nonsignificant trends (Figure 4). The average change in mean temperature at the benchmark sites is 0.035 °C per year between 1990 and 2006 (Figure 2). The cause of variation in the rates of change between sites within some of the benchmark catchments would require more detailed analysis of site conditions than has been undertaken here (Figure 4).

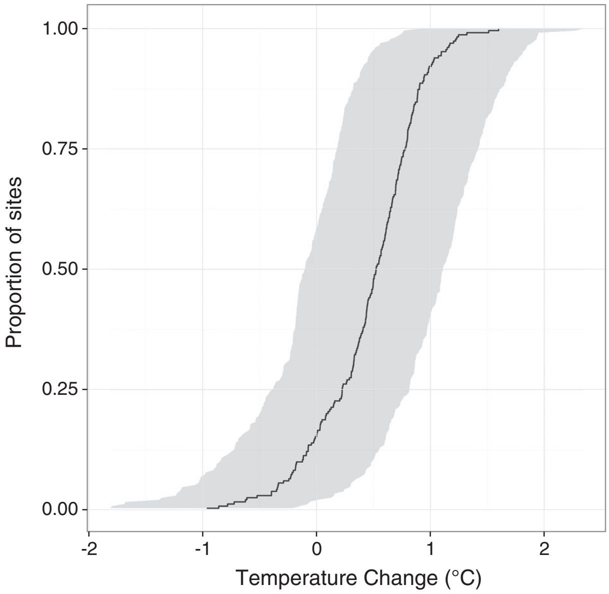

Figure 5. Empirical cumulative distribution function of annual water temperature change (1990–2006) in 231 benchmark catchments predicted by Equation (2), the single trend model (solid line). A 95% simultaneous confidence interval on the temperature change is indicated by the shaded region

There are apparent seasonal variations in water temperature change at benchmark sites (Figure 6; Table II). Annual temperature changes are primarily driven by increases in autumn (September to November) and winter (December to February) with 90% of benchmark sites showing increasing trends in both seasons, although only 24 and 34% of these were statistically significant in autumn and winter respectively (Table II). In the spring (March–May), 70% of sites warmed, but less than 50% warmed in the summer (June–August) with far fewer of these being significant, 19 and 6% for the spring and summer respectively (Table II; Figure 6).

The spatial distribution of temperature change in annual time series (Figures 7 and 8) is most similar to change observed in the spring (Figure 9). Warming is observed throughout England and Wales in autumn and winter, whilst cooling is observed across many areas in the summer, with the exception of north and western coastal areas (Figure 8).

There are no clear associations between annual temperature and annual flow trends (Figure 8) or in equivalent seasonal relationships (Figure 9). Within the study period, annual flow trends show increases in most northern and eastern regions, with the strongest increases in the east and weak decreases in south-west Britain. Whilst there are positive and negative trends and some tendency towards increasing flows overall, most trends are weak, except in the east of England and Wales. In general, autumn flows increased and winter flows decreased, while mixed patterns are observed in the

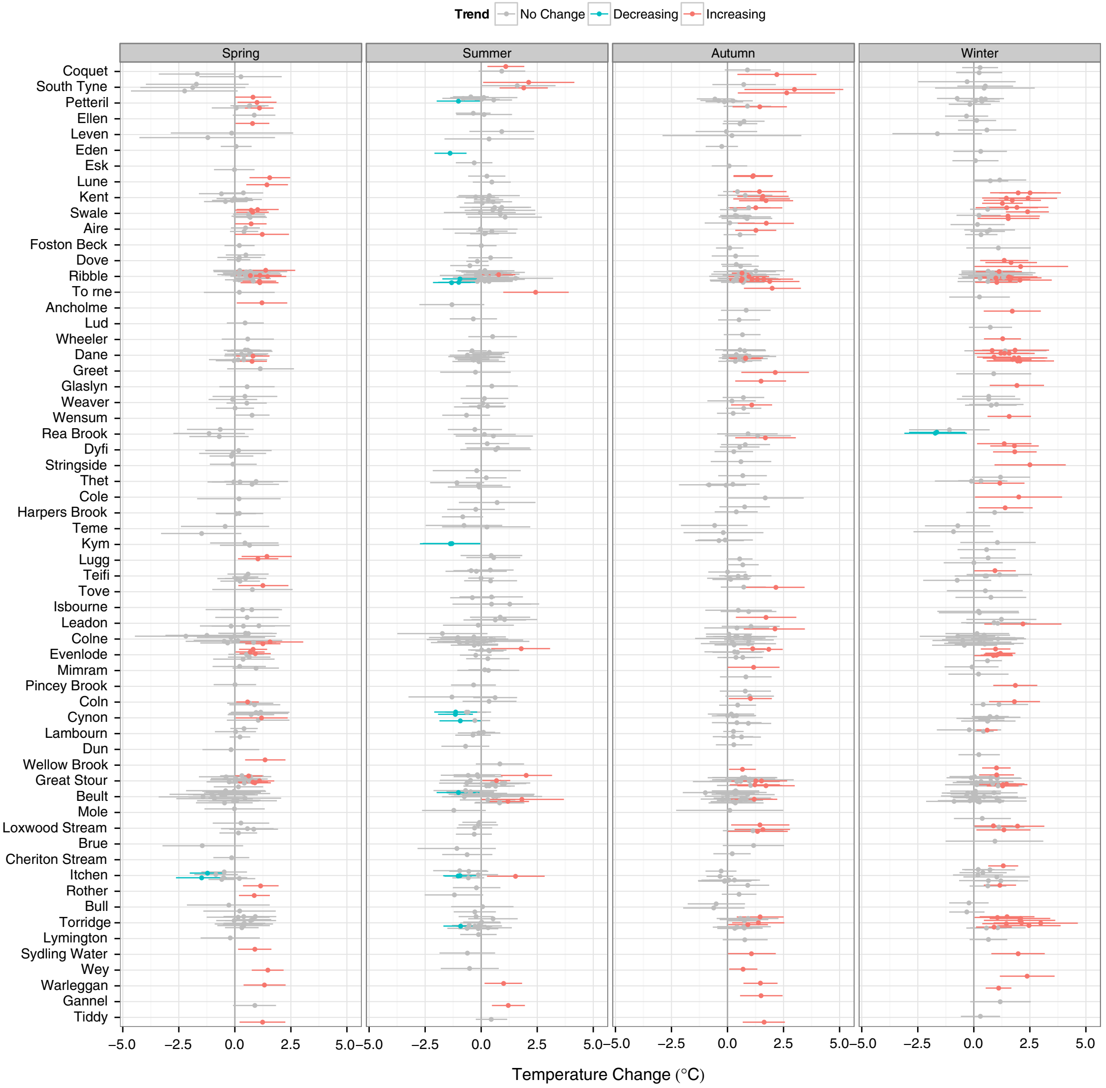

Figure 6. Rate of seasonal temperature change at 229 sites within benchmark catchments between 1990 and 2006 [sites, grey circles, are presented within catchments listed from north (Coquet) to south (Tiddy); lines represent 95% confidence interval for each site]

Table II. Seasonal temperature changes in 219 benchmark catchments with 95% confidence intervals

Season	Mean temperature change	SE	No significant change [number (%) of sites]	Significant decrease at [number (%) of sites]	Significant increase at [number (%) of sites]
Spring	0.266	0.105	176 (80)	2 (1)	41 (19)
Summer	−0.022	0.085	192 (88)	14 (6)	13 (6)
Autumn	0.700	0.070	167 (76)	0	52 (24)
Winter	0.855	0.010	142 (65)	2 (1)	75 (34)

spring and summer (Figure 10). This does not match changes in seasonal water temperature trends, which increased in both autumn and winter. The purpose of this analysis is not to try to understand the relationship between changes in flow and temperature in detail but to look for systematic trends. The analysis suggests that there is no direct relationship between the changes in water temperature and flow over this 17-year period (Figure 10). This does not discount the possibility that flow changes at individual sites may be important. However, we do not see systematic changes in flow, whereas we do see systematic changes in water temperatures. We therefore conclude that changes in flow can be discounted as a major driver for the observed temperature increases.

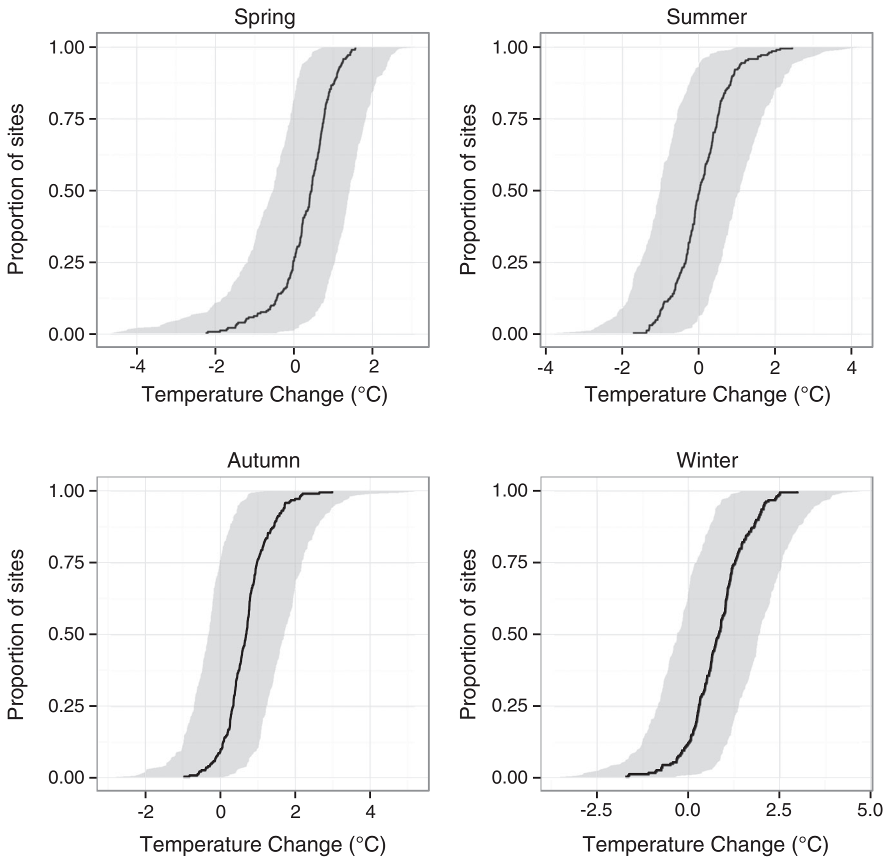

Figure 7. Empirical cumulative distribution functions of seasonal water temperature change (1990–2006) in 229 benchmark catchments predicted by Equation (3), the seasonal trend model. A 95% simultaneous confidence interval on the temperature change is indicated by the shaded region

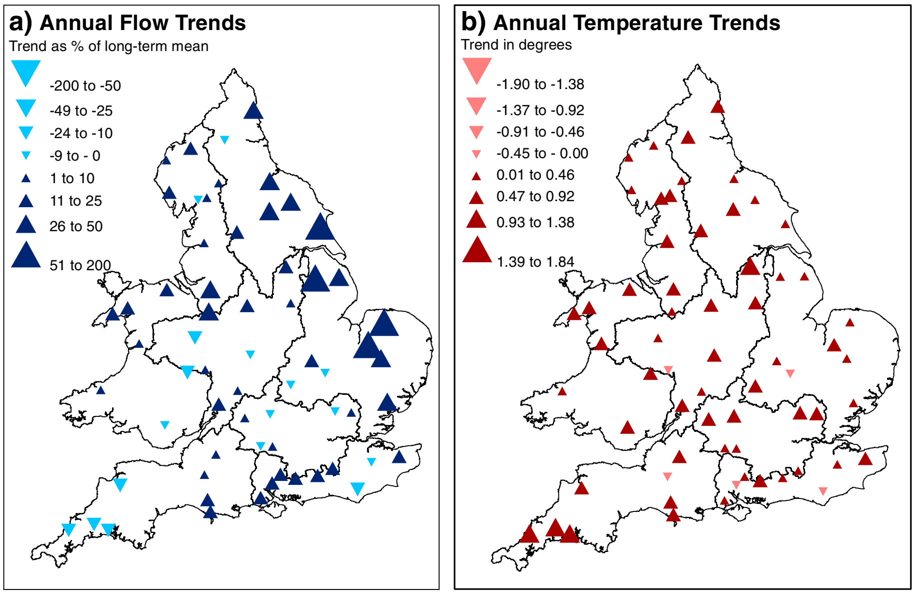

Figure 8. Annual flow and temperature variation in 63 benchmark catchments. (a) Flow trends are in blue and (b) temperature trends in red. Upward (downward) pointing triangles indicate increasing (decreasing) trends over the period 1990 to 2006. Flow trends are expressed as a percentage of the average for 1990 to 2006 to account for the wide variations in absolute run-off cross England and Wales

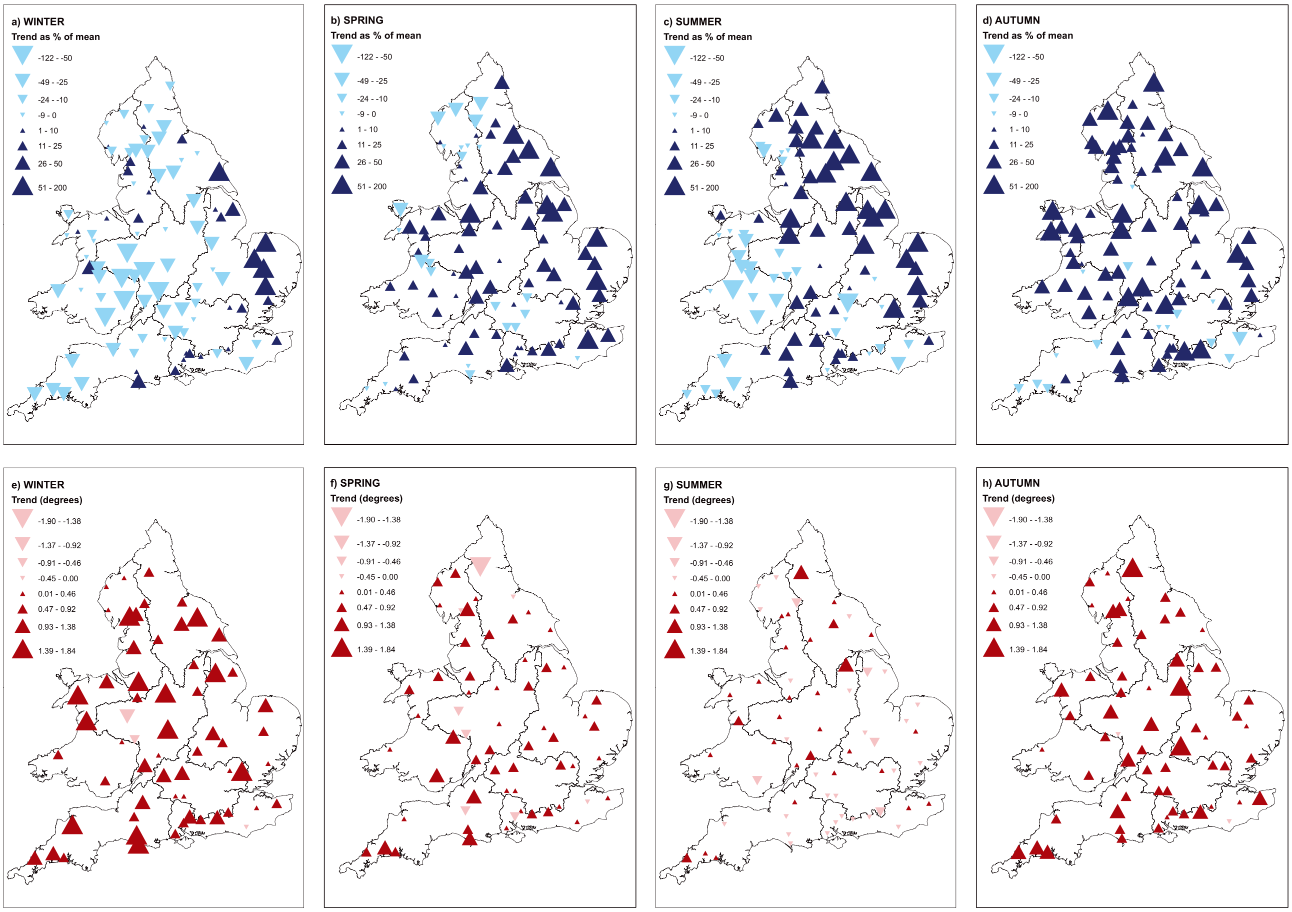

Figure 9. Relationship between seasonal flow and temperature trends in 63 benchmark catchments. Temperature trends are shown as total change between 1990 and 2006. Flow trends are in blue and temperature trends in red. Upward (downward) pointing triangles indicate increasing (decreasing) trends over the period 1990 to 2006. Flow trends are expressed as a percentage of the average for 1990 to 2006 to account for the wide variations in absolute run-off cross England and Wales

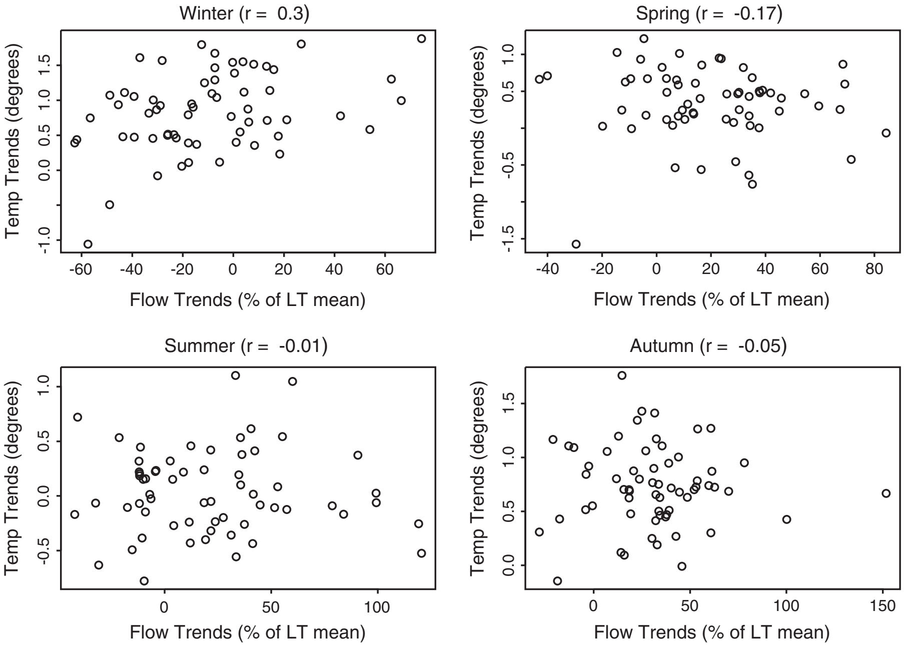

Figure 10. Relationship between seasonal change in flow and temperature in 63 benchmark catchments

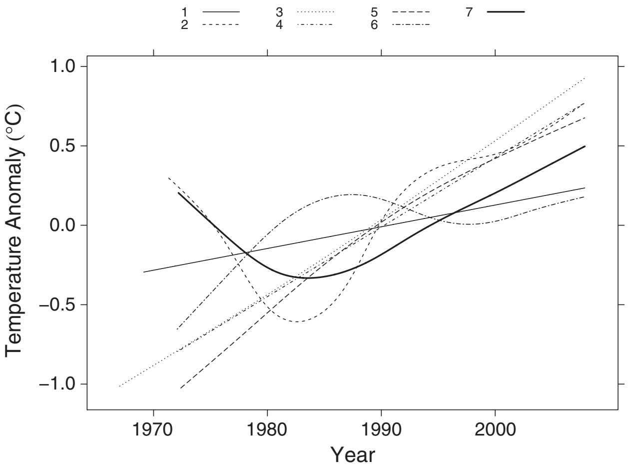

Figure 11. Temperature trends for seven sites from 1970 to 2006. (1) River Calder, NW England; (2) River Ribble, NW England; (3) River Wellow, SW England; (4) River Evenlode, Midlands, England; (5) River Glyme, Midlands, England; (6) River Lambourn, South England; (7) River Coln, West Midlands, England

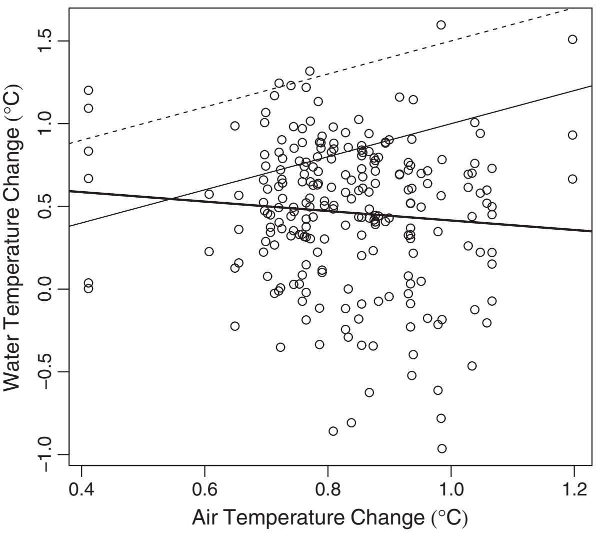

Figure 12. Relationship between the change in air and water temperature for 229 sites in benchmark catchments. The 1 : 1 line is depicted by the thin solid line. Those sites where water temperature has increased by 0.5 °C or more than the change in temperature fall above the dashed line. The thick solid line is the fitted linear regression model ($F_{1227} = 1.1719$, $p = 0.1911$), indicating no relationships between the change in air and water temperature during 1990–2006 at the benchmark sites

Relationship of recent warming with longer term water temperatures and air temperatures

Seven sites with longer records from across England and Wales were selected to explore trends over a longer time period (Figure 11). Trends were determined using the procedure described in the Section on Water temperature trend analysis in the preceding texts using Equation (1). The result is a series of trends; some of which are linear and some are not. All sites show a warming trend since 1990: Most of these are essentially linear, but there is much more variability between 1970 and 1990. This limited analysis suggests that most warming has occurred between 1990 and 2006, but further work is needed to look at longer records of water temperature.

The rates of change in water temperature are comparable with those reported for UK air temperatures (e.g. Jenkins *et al*., 2009). Furthermore, the widespread warming of rivers since the 1990s followed a period of variability around a more stable mean that is consistent with long-term changes in air temperature. The Central England Temperature (CET) has risen by 1 °C since the 1980s, after a period of long-term stability over the majority of the 20th century (Jenkins *et al*., 2009). However, trends in air and water temperature differ at some sites (Figure 12). This may be a result of using derived air temperatures that do not reflect catchment wide or *in situ* values (Johnson, 2003) or, more likely, different processes driving temperature. Further work would be required to investigate sites where water temperature increases appear to outpace increases in air temperature. This would be difficult over a large area because water temperature is fundamentally the integration of local processes over a period of days or months, whereas air temperature is the integration of regional processes. Observed warming in annual mean CETs since 1950 is very unlikely to be because of natural climate variations alone and is consistent with the modelled response to anthropogenic forcing (Karoly and Stott, 2006). We suggest that the same regional climate changes are driving higher river temperatures. Approximately half of the January–March warming over Europe is estimated to be because of large-scale climate variability in the Northern Annular Mode (NAM) for the period 1968–1999 (Thompson *et al*., 2000). The North Atlantic Oscillation (NAO) – the Atlantic arm of the NAM (Woollings and Hoskins, 2008) – was in a positive phase over this period, resulting in warm and wet winters across the UK. Reasons for what was a prolonged positive phase of the NAO are not yet clear (Woollings and Hoskins, 2008), but this pattern of behaviour is found in some projections of anthropogenic climate change (IPCC, 2007).

CONCLUSIONS

Understanding thermal heterogeneity in watercourses over a range of temporal and spatial scales is an ongoing challenge (Webb *et al*., 2008). Our regional analysis of 2773 sites shows increases in water temperature from 1990 to 2006 at a large number of sites. A novel application of additive models allowed trends to be discerned despite the lack of continuous sampling, permitting the use of a much larger data set than is normally available for this type of study.

There is apparent widespread warming over this short time period. The most likely causes are the following: (1) a response to climate warming, (2) systematic changes in river flows or (3) systematic changes in land use (especially woodland cover) and (4) systematic sampling error or equipment failure. We have ruled out changes in flow and land use by using the benchmark catchments, and we find no evidence of systematic sampling problems that leaves climate warming as a likely driver of warming in the rivers of England and Wales.

These results show not only rapid change over a relatively short time period but also significant spatial variations in the signal. Further work is needed to understand the processes that are leading to these increases and whether they are acting differentially between locations. Preliminary analysis suggests no strong relationships between static catchment characteristics and rates of warming, but improved representation of likely controlling variables would allow more detailed investigation of physical controls. It would also be valuable to investigate the sites that demonstrate cooling; this may reveal errors in water temperature data, sites where tree planting has taken place or perhaps thermal refugia.

Understanding the basis of observed heterogeneity in water temperature and the relative sensitivity of rivers to climate change may signpost actions to ameliorate heating of rivers and subsequent impacts on their water quality and ecosystems. Further work is needed to examine how trends reported here relate to extreme temperatures and flows, given that low flows and heat waves often coincide noting that irregular sampling techniques will always be poor at characterizing and detecting extreme temperatures that occur infrequently.

Finally, river water temperature provides a further indicator of climate variability and change that may already be affecting the freshwater environment. Hence, there is an ongoing need for systematic temperature monitoring (particularly at underrepresented locations such as uplands), alongside routine recording of emerging ecosystem responses such as the frequency of occurrence and abundance of thermally sensitive species. This work is guiding evaluation of existing water temperature monitoring networks.

ACKNOWLEDGEMENTS

The work was funded by the Environment Agency of England and Wales under two projects SC070035 and SC090901. The views expressed are those of the authors and do not necessary represent the position of the Environment Agency.

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