Changing water temperatures: a surface water archive for England and Wales

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Abstract
The temperature of water in lakes, rivers and streams has a fundamental influence on aquatic organisms, ecological processes and the potency of many pollutants. We expect water temperature in the UK to increase under projected climate change, but rates and spatial variation of change remain unclear for inland waters. It is also unclear how we might manage land and river flow regimes to modify river temperature where this may be desirable, for example, to protect fish from lethal temperatures. Although water temperature broadly correlates with air temperature, the drivers of surface water temperature involve dynamic heat (energy) exchanges at the water surface and river bed and complex hydrological fluxes. To date, published reports of water temperature change in British rivers have been based on a limited number of sites: these have provided useful monitoring data on the thermal processes of rivers but rather less about the thermal regime of rivers. Our understanding of river thermal spatio-temporal variability and processes remains incomplete. In part, this has been related to a lack of long-term data across a range of different environments. The Environment Agency has recently created a surface water temperature archive for England and Wales based on measurements at over 30 000 sites, with observations extending back to between <5 and 30 years. The archive is being used to assess post-1990 trends in water temperature across England and Wales. Here, we briefly describe the archive and its potential uses. We present preliminary observations of the variation in river water temperature across England and Wales and the changing relationship between water and air temperatures at and between sites. We also illustrate the potential for exploring ecological response to changes in water temperature.

Introduction

Inland water temperature is expected to be significantly altered by future climate change with profound potential impacts on freshwater ecosystems (Bates *et al.*, 2008; Ormerod, 2009). We know that many 'natural' environmental factors affect the variation of water temperature between and within rivers, and that thermal properties are also modified by anthropogenic impacts. However, gaps in knowledge remain about the scales of variation in temperature regime and the controls on this variation (Hannah *et al.*, 2008; Webb *et al.*, 2008). Even greater gaps exist in our understanding of how aquatic ecosystems will be modified by changing temperature (Wilby *et al.*, in press). Lack of water temperature data often leads to the use of air temperature as a proxy with the potential for fundamental misinterpretation and a risk of incorrect attribution of causation (Johnson, 2003).

Whilst models of water temperature in river catchments do exist (e.g. Caissie, 2006) their application has not yet led to widespread characterisation of thermal regimes. Water temperatures do not follow air temperatures exactly due to complex atmospheric and hydrological controls (Hannah *et al.*, 2008), so that direct observations of water temperature are required for reliable tracking of thermal cycles and trends. To this end, the Environment Agency commissioned a pilot study (Hammond and Pryce, 2007) and subsequently development of a wide-ranging surface water temperature archive for freshwater and estuarine sites in England and Wales (des Clers *et al.*, in press).

It is intended that the archive will support investigation of ecological response to historic and contemporary variations in temperature and that it will contribute to predictions of how inland water ecosystems will respond to future changes in temperature. In general, climate change impact assessments to date have tended to use air temperature as a proxy for water temperature (e.g. Conlan *et al.*, 2007; Durance and Ormerod, 2007; Webb and Walsh, 2004) and frequently to explore changes in hydrology and temperature separately. In England and Wales, the Environment Agency has detailed and extensive hydrometric monitoring networks and a range of widely applied hydrological models of rivers that have enabled characterisation of hydrological regimes across a wide geographical range. Developing similar information on thermal regimes would advance our ability for a more interactive approach to understand and predict the impacts of climate change on water quality variables, particularly dissolved oxygen levels, ecological processes and community composition. The archive also provides a basis for benchmarking and monitoring of environmental change that may be particularly useful in understanding changing water quality and ecological variation.

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Surface water temperature archive

The archive is a unique database that brings together for the first time 42 million temperature records from 30 580 sites across England and Wales. At this scale and intensity of data capture we believe this is globally unmatched. Most of the temperature records were collected coincidentally with hydrometric or water quality data; sampling intervals are predominantly fortnightly or monthly, but 351 sites have sub-daily or continuous sampling. Although for many sites, the time series are of relatively short duration (average length of 14 years), there are at least 3000 sites with records from before 1990. The temperature records have not been subject to intensive quality control and the use of individual site data must be treated with some caution. Nevertheless, the majority of records were obtained from spot samples registered by trained staff following a standardised sampling procedure; temperature measurements were taken from a probe immersed in the water column (waiting for readings to stabilise) and recording temperature to the nearest 0.1°C. In some circumstances, such as during very high flows, or where access is difficult a container of water was taken from the river and temperature recorded immediately using the same method as used in-stream.

The archive contains temperature records for rivers (28031 sites), canals (789 sites), coastal waters (268 sites), lakes (966 sites), estuaries (457 sites) and drains (57 sites). The archive has notably few higher elevation sites. There are 500 sites above 300 m but only 6 of these are included in the subset of 'high quality' sites used for trend analysis described below; this is the main under-represented component of the data-set. The distribution and duration of records from river sites are shown in Figure 1.

A subset of 2772 river sites with at least 250

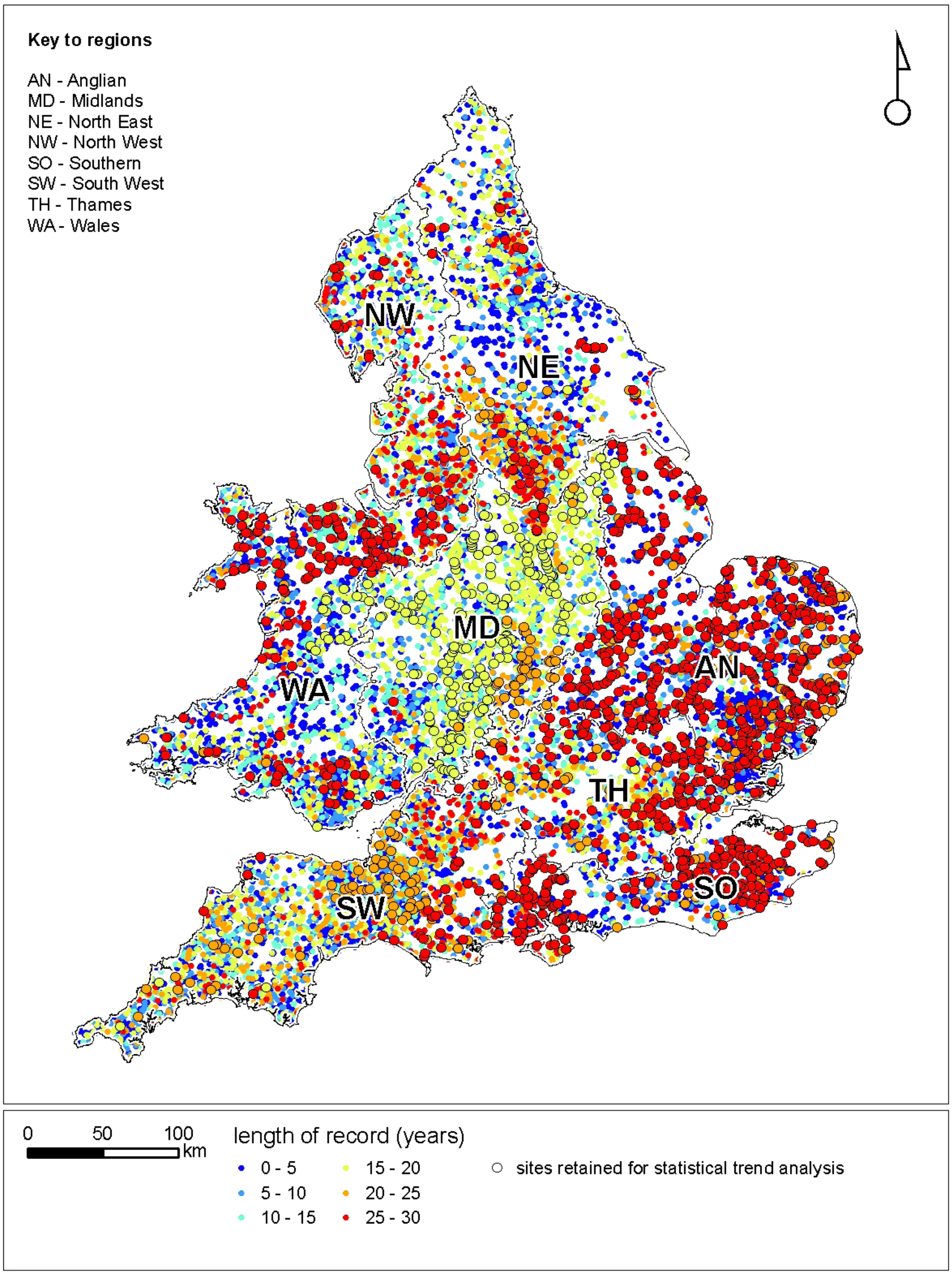

Figure 1 *Distribution of river water temperature monitoring sites in Environment Agency regions across England and Wales (NW = North West; NE=North East; MD=Midlands; WA=Wales; TH=Thames; SO=Southern; SW=South West; AN=Anglian). Sites with records from different time intervals are distinguished. Large circles denote sites where temporal trends (1990 to 2006) have been estimated (from des Clers et al, in press).*

samples taken in more than 120 months between 1985 and 2006 was selected to assess thermal trends over time; the sites are marked by ringed, larger circles in Figure 1. The methods used to gauge trends are described fully in des Clers *et al.* (2010, in press). In summary, additive models with a continuous-time autoregressive process for the residuals were developed to identify trends and patterns in the temperature time series (Ferguson *et al*., 2007, 2008). This modelling approach has several important advantages over linear regression models. It allows for the lack of independence of the observations in time and can accommodate non-linear patterns and trends. The inclusion of smooth functions of covariates allows more flexible relationships than the linear parametric approach allowing the data themselves to control the form of the trend and other patterns fitted to the observations. A number of alternative models were fitted to the actual spot temperature measurements for each site in the Surface Water Temperature Archive with enough data (see Figure 1). The Likelihood ratio test was used to determine whether there were significant trends in the temperature time series for each site. We use the best-fitting model for each site to simulate a continuous daily temperature time series for the site.

These models were not used to 'fill-in' missing periods of data or supplement the measured data in any way. A cyclical smoother is included to model seasonal variation in water temperature. As the models were fitted to the irregular daily spot samples, the modelling time-step is daily and predictions from the model can be produced at this time-step. A likelihood ratio test was used to determine whether there were significant trends in the temperature time series for each site. These models thus indicate typical likely temperatures on the days when no measurements were made based solely upon the observed water temperature data and the fitted additive model.

Applications of the archive

The archive provides information about the changing thermal state of the freshwater environment as well as being a valuable resource for wider analytical research. Although there is variation in sampling duration and intensity at different sites, the sheer extent of the archive and its spatial coverage open up possibilities for studying the thermal properties of rivers in new ways. Here we outline some preliminary analyses of the temperature inventory. These examples should be viewed as exploratory and are chosen to illustrate features of the archive rather than give a definitive statement about the thermal regime of rivers in England and Wales.

Exploring the thermal regime of rivers across England and Wales

For the first time, it is now possible to characterise the thermal regime of rivers at a national (England and Wales) scale with an overview of the variation in thermal regime within and between rivers. Preliminary analysis suggests that fixed physiographic and regional hydro-climatic variables explain only a limited amount of the variation, and there is clearly substantial scope to explore this in more detail (des Clers *et al.*, 2010; Simpson *et al.*, 2010).

For example, Figure 2 shows summary statistics for mean, minimum, maximum and range of water temperature at 2832 sites with at least 250 temperature samples between 1990 and 2006. Simpson *et al.* (2010) suggest that infrequently sampled data, such as those used to construct this Figure, give realistic mean values but tend to underestimate extremes. Figure 2 uses a common colour scheme to map z-scores, with blue colours indicating negative z-scores (site values below the average for England and Wales), and red colours indicating positive z-scores (higher than average site values). These maps begin to show the macro-scale variation in river water temperature characteristics in relation to general controls. For example, there is evidently an altitude effect on the mean site water temperature, since green and blue dots in Figure 2(a) occur in Wales, the Pennines, and Dartmoor, implying temperatures about 2ºC cooler than the national average of 11ºC, while red dots occur in the Fens and Somerset Levels (about 2ºC warmer). Minimum temperatures (Figure 2(b)) are clearly higher along the south and south-west coast, and there is a suggestion of a latitudinal effect, although complicated by maritime influences. This latter influence results in lower maximum temperatures (Figure 2(c)) and a lower overall temperature range in the south and south-west coastal rivers. Generally, a west-east increase in temperature range appears in Figure 2(d) to be superimposed on the effects of other controls (Cooper, 2010).

Understanding these spatial patterns in response to the static underlying influences of location, topography and geology could help to define benchmark conditions relevant for the reference states in designations for the Water Framework Directive. In addition, providing a basis for assessing the effects of departures from these states caused by more short-term, dynamic effects on water temperature, such as water abstraction, land cover change, and industrial impacts. These all need to be understood before the subtle medium-term signal of climate change can be identified.

Whilst the strength of the archive lies in its density of sample sites and wide spatial coverage, it is nevertheless possible to examine local diurnal fluctuations in sufficient detail to explore relationships with air temperature, river flow or water quality variables. There are about 300 sites distributed across England and Wales that have automatic monitoring stations collecting sub-daily information. A selection of sites is presented in Figure 3 together with the mean, minimum and maximum temperature record from the Central England (air) Temperature time series (CET) (Manley, 1974 and Parker *et al.*, 1992). This indicates that although diurnal fluctuations may be quite similar between rivers that are geographically separated, water temperatures can be quite different by several degrees. The difference is apparent when compared to the daily average CET.

In the absence of information on river heat exchange processes, water temperature has been related to air temperature as a surrogate variable for energy exchange. However, the nature of air–water temperature relationships has been critically appraised recently (e.g. Johnson, 2003; see review by Webb *et al.*, 2008). Strong covariance between air and water temperatures is illustrated for a site on the River Coquet at Warkworth Dam in north-east England which was sampled quasi-monthly from April 1973 to December 2006 (Figure 4). In general, the relationship between the Coquet water temperature and the daily air temperatures from the central England temperature time series for the days when water temperatures are recorded is linear, but the slope of this relationship varies from month to month. Apparent outliers in Figure 4 may reflect the known non-linearity of the relationship between air and water temperature at high and low temperatures (Webb *et al.*, 2008). This may be due to discharge moderation (i.e. change in thermal capacity) influencing air-water temperature relationship. As previously stated, whilst broad correlations exist, water temperature is controlled by dynamic heat (energy) exchanges at the water surface and river bed and complex hydrological fluxes. This demonstrates that a simple annual model would not be appropriate, but that a model drawing on seasonal differences in the relationship between water and air temperatures is

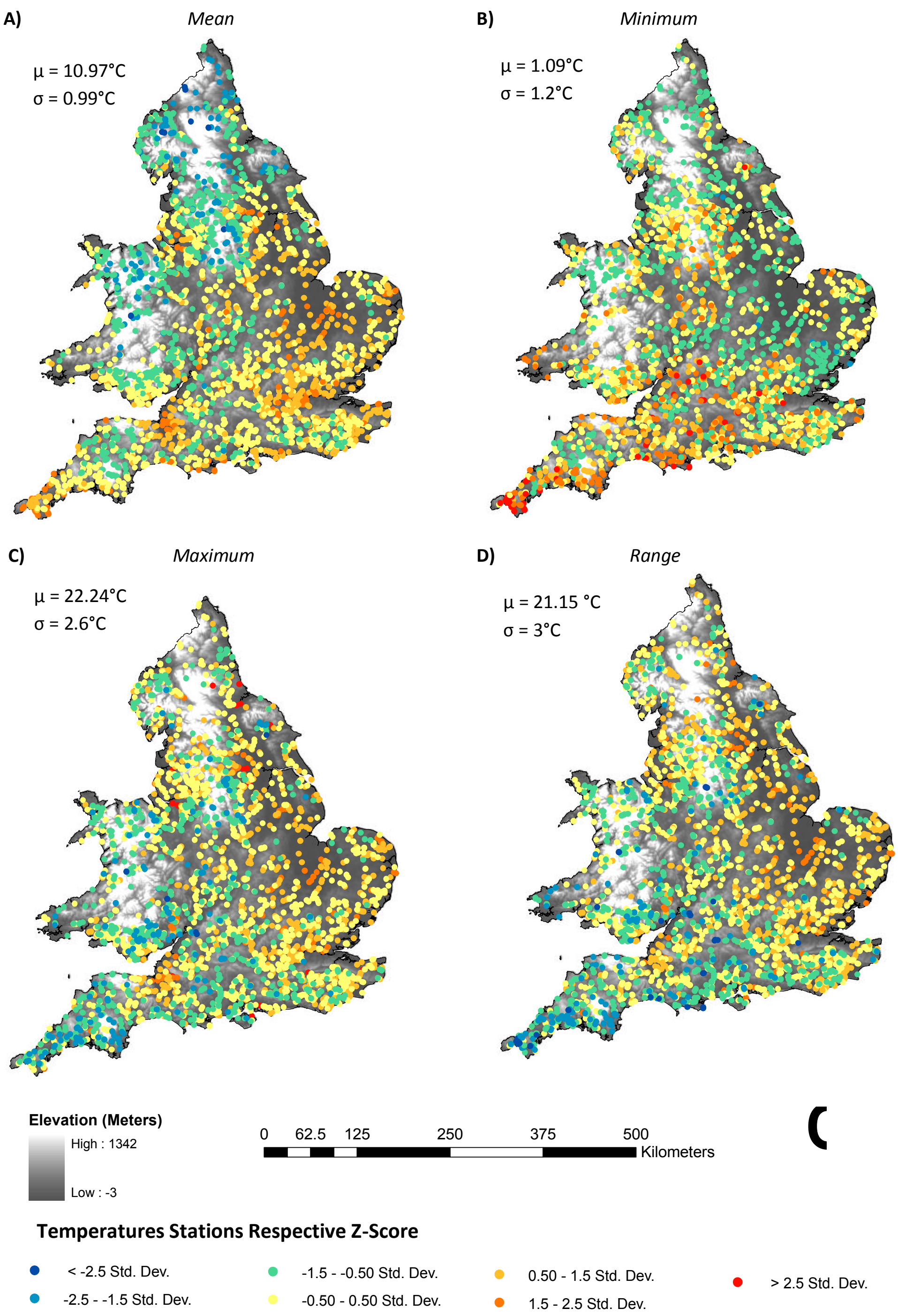

Figure 2 *Spatial distribution of values derived from water temperature data from 1990-2006; a) Mean, b) Minimum, c) Maximum and d) Range. Each map gives the England and Wales mean (μ) and standard deviation (σ) for the variable mapped, and each site is mapped as a z-score (obtained by subtracting the England and Wales average from the site value, and dividing by the England and Wales standard deviation), and colour-coded by the general key for z-scores (blue for negative site z-values below the England and Wales average, red for positive site z-values (above the average) (Cooper, 2010).*

necessary to capture shifting climatic and hydrological conditions over the yearly cycle would be an improvement.

Rivers can have very different water temperature responses to air temperature fluctuations; and the controls on this variation are not necessarily clear. For example, two rivers shown in Figure 5 illustrate that whilst neither have a discernible diurnal variation in winter as might be expected, the site on the River Trent (in black) has no significant variation in summer either. This may be a factor of channel size, discharge or other local controls and the archive should enable some exploration of within catchment and downstream variation in river sensitivity to solar radiation.

Thermal thresholds for ecological response

Among the applications that we anticipate for the archive are to assess the degree to which thermal variation has contributed to ecological variation in England and Wales in the past and to make predictions about future biological response to changing temperature regime. Ultimately, we hope that this will be a resource to inform climate change adaptation planning by, for example, developing the evidence to support measures that might be used to ameliorate the potentially damaging impacts of high temperatures on freshwater ecology (e.g. Wilby *et al.*, in press), as well as water quality (Whitehead *et al.*, 2009). However, we recognise that predicting ecological response is complex and driven by changes in variables other than water temperature (e.g. Malcolm *et al.*, 2008).

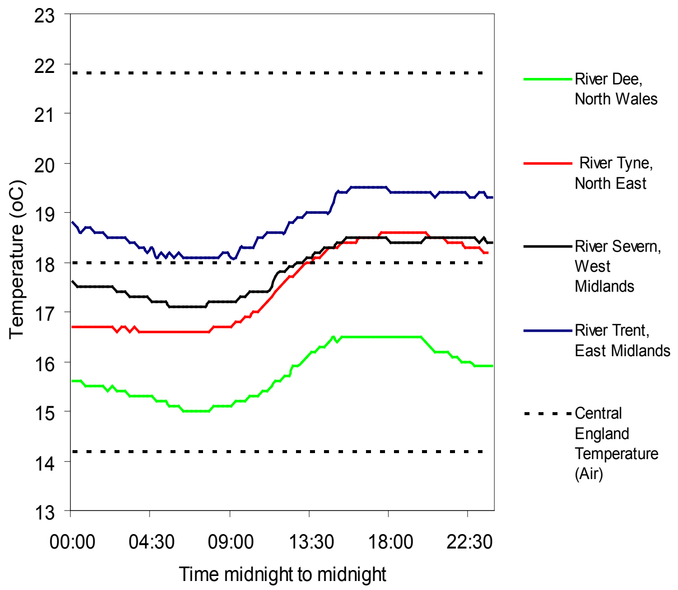

Figure 3 *Observed water temperatures for 24 hours on 8th July 2003 (recorded every 15 minutes). Maximum, minimum and mean daily air temperatures from the Central England Temperature series are shown in dotted lines.*

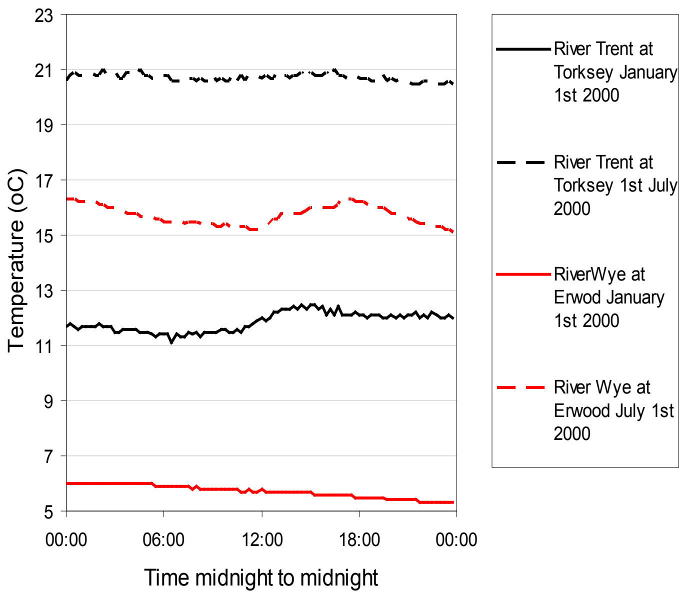

Figure 5 *Summer and winter diurnal patterns in contrasting rivers with continuous (15minute interval) sampling*

Ecological responses to changes in thermal regime vary according to species resilience and resistance but can include local extinction, migration and changes in behaviour and physiology (e.g. Parmesan, 2006). Often the trigger for change is not well understood but, for temperature or drought sensitive species, bioclimatic envelope modelling can be used for preliminary prediction (e.g. Pearson and Dawson, 2003). Such approaches assume that species distributions are in equilibrium with 'baseline' or current climates which may not always be appropriate (Heikkinen *et al.*, 2006). They are nevertheless helpful in considering potential changes in range and distribution. The surface water temperature archive may contribute to such assessments for certain freshwater species that could help identify the sensitivity of 'reference condition' used in assessments of ecological status under the Water Framework Directive. Here we present an example of how

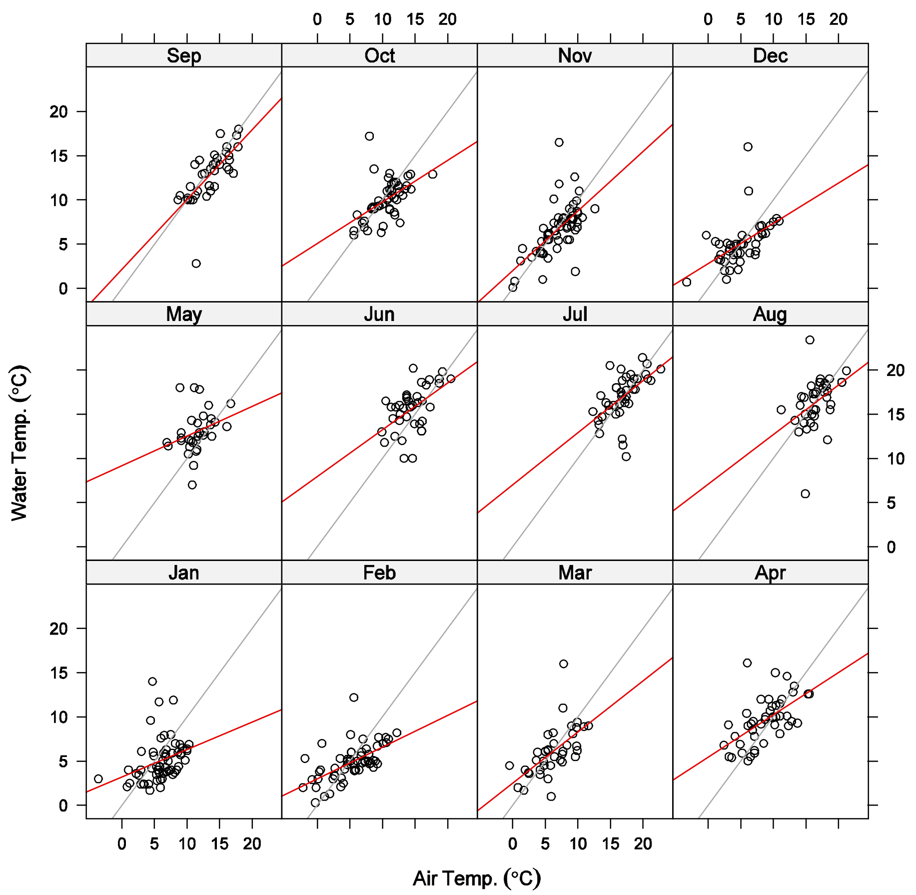

Figure 4 *Changing monthly relationship between mean daily Central England air temperature and simulated daily water temperature of the river Coquet at Warkworth Dam, 1973-2007. Red lines show the least squares regression fit; grey lines show the 1:1 relationship line between air and water temperatures.*

the archive can be used to identify changes in ecologically-meaningful thermal thresholds.

Salmonid fish have well-documented temperature optima and critical thresholds acting at different stages of their life-cycle (e.g. Wherly *et al.*, 2007; Solomon and Lightfoot, 2008). Consequently, it is possible to look at how these thresholds have been exceeded at specific locations. For this example, we selected rivers where there are Atlantic salmon (*Salmo salar*) populations currently present; these rivers have salmon action plans in response to the National Salmon Strategy to promote their conservation (Cefas and Environment Agency, 2008).

We chose the following two thermal thresholds to represent potential pressure on different life stages of salmon and to illustrate changing conditions.

- Below 10°C: this is the existing Freshwater Fish Directive temperature standard for salmonid waters during the spawning season (Turnpenny and Liney, 2006; UKTAG, 2008)
- Above 20°C: values that may constitute thermal barriers reducing the number of upstream migrating adults in the southern regions of England and Wales (Solomon and Sambrook, 2004; Turnpenny and Liney, 2006).

Models fitted to observations of water temperature at irregularly sampled time intervals enabled us to produce simulations of daily temperatures between 1990 and 2006 for each site (described earlier). This provides a basis to compute the number of days per year, by taking an average over 1000 simulation runs, when the water temperature is above or below a given threshold. The estimated number of days tends to underestimate the actual observations of high and low temperatures so that our results here are a conservative estimate (Simpson *et al.*, 2010).

We identified 437 river sites from the 2772 sites where we had undertaken trend analysis for the period 1990 to 2006 that are within 150 m of a salmon action plan river. We found that 88% of the sites have experienced a decrease in the number of days when the water temperature was less than 10°C. On average, the decrease is much higher for South West sites, with 1.2 fewer days per year (12 days less per decade) over the 1990-2006 period (Table 1). Not all this decrease may be in the peak spawning season, or even relevant for a particular stretch of river where fish may have changed their spawning times. However, despite adaptive mechanisms that change the timing and length of spawning periods, a general decreasing trend in the numbers of optimal temperature days is likely to put pressure on some populations. A detailed analysis by region, catchment and site is needed to assess the actual constraint this imposes on the salmon's reproductive potential. But if we know what the thermal character is for the reference state relative to location, altitude, geology, then we can potentially predict this for all rivers, and can estimate the total loss of suitable thermal habitat in terms of river length.

The models also revealed that the number of days when the water temperature is below 10°C decreases linearly with the average daily temperature which may be a useful predictor of future changes. For example, a 0.33°C increase in mean temperature is associated with an 8-day reduction in the number of days per year <10°C in Wales (Figure 6).

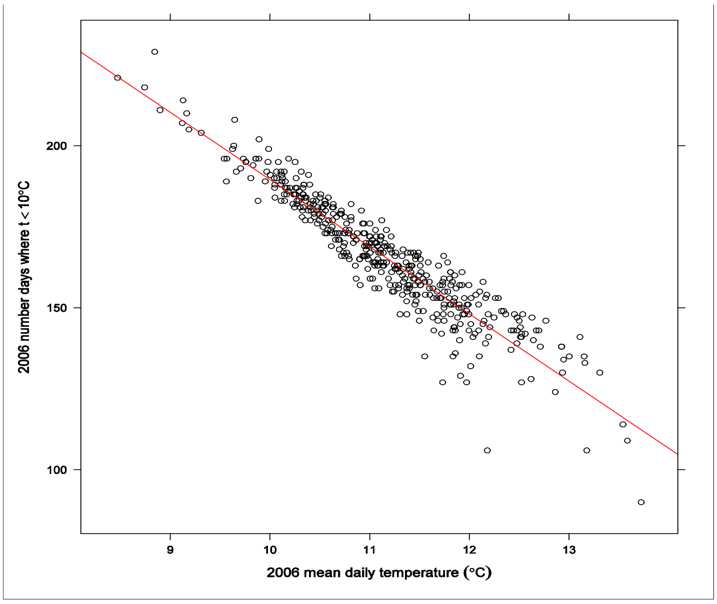

Figure 6 *Average number of days per year when t<10°C with estimated mean daily temperature for 2006 in 437 sites in salmon rivers across England and Wales*

For the higher threshold, 15 sites on the River Thames had a simulated mean daily temperature in excess of 20°C in 2006 (Figure 7). It should be noted that in general 2006 was a warm year, with a relatively high number of hot

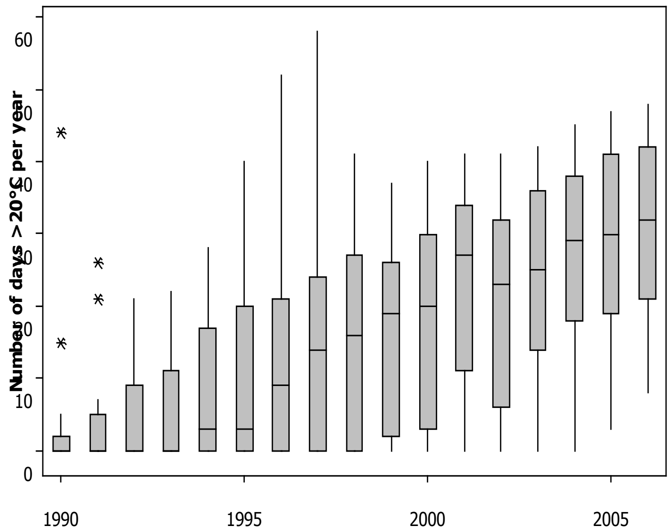

Figure 7 *Box whisker plot of the modelled number of days per year >20°C for 15 sites on the River Thames between 1990 and 2006*

Table 1 *Frequency of days when daily mean temperature is <10oC (from des Clers et al, 2010)*

EA Region	*Number of sites*	*1990 to 2006 change °C /decade*	*2006 mean temp*	*Average days <10°C 2006*	*1990 to 2006 change days/decade*
Anglian	1	0.50	12.32	148	-8
Midlands	57	0.21	11.18	167	-5
North East	36	0.20	10.18	187	-4
North West	57	0.37	10.52	181	-7
Southern	14	0.09	11.49	153	-2
South West	96	0.42	11.39	157	-12
Thames	65	0.29	12.22	148	-6
EA-Wales	111	0.33	10.87	171	-8

days. Changes over time in the Thames region suggest that a 0.5°C increase in mean annual temperature will lead to 20 more days with temperatures >20°C. This relationship will vary between catchments and the number of hot days compared to the mean temperature may be fewer elsewhere, as was observed in the Welsh River Wye in 2006 (des Clers *et al.*, in press).

Concluding remarks

Water temperature variables are often overlooked in environmental and ecological studies. Simple relationships with air temperature, especially when air temperatures are taken from sites some distance away from water bodies, may provide poor and potentially misleading substitutes. The surface water temperature archive, created by the Environment Agency, has direct measures of water temperature at broad spatial and temporal scales and could be used to improve our understanding and predictive capacity of the thermal regimes of surface waters.

The archive highlights the value of long-term and widely distributed temperature monitoring alongside other variables. However, there is scope for designing a network of sites to capture extreme temperature variation more effectively and to cover some of the under-represented water bodies, for example sites above 300 m altitude. This could include the use of intensive sub-daily measurements for limited periods of time. Greater insights can also be gained from co-locating measures of other environmental parameters, particularly flow and biological sampling. Future monitoring will also need to consider the importance of multiple factors at single sites and within a catchment, for example to capture the impacts of flow abstractions or release.

Acknowledgements

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