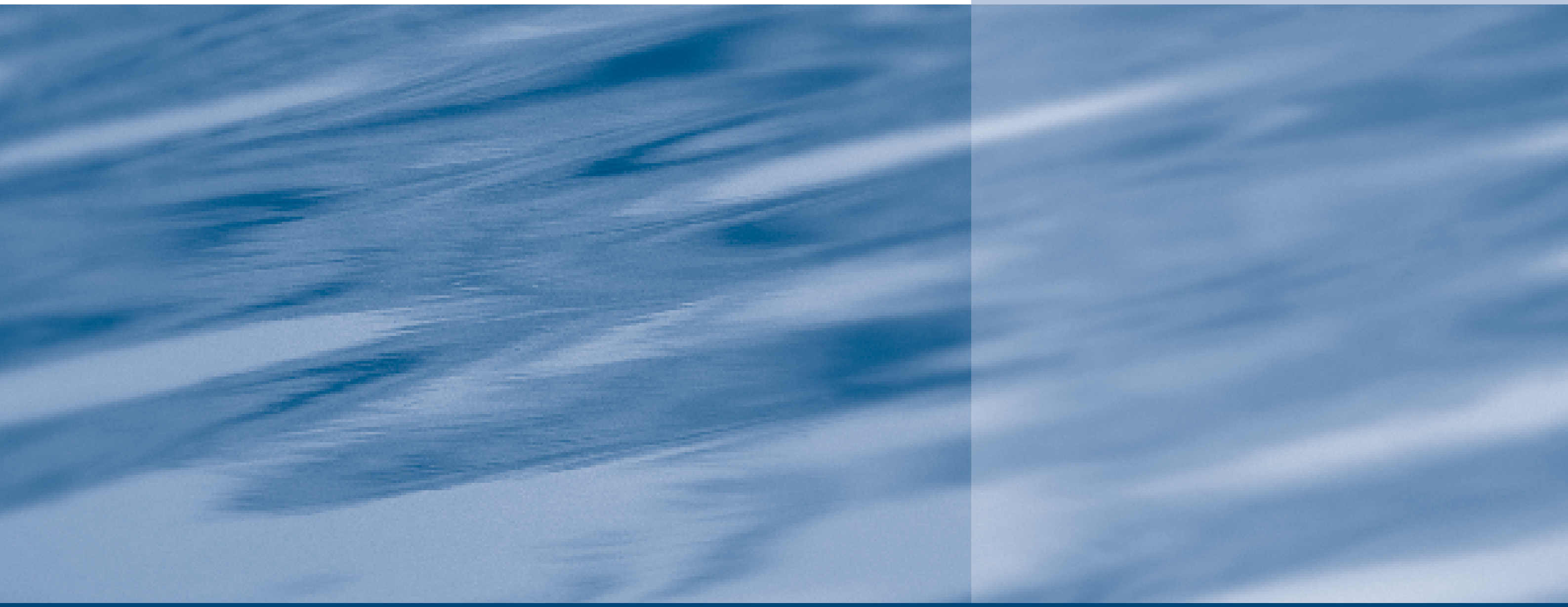

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Effect of climate change on salmon fisheries

Science Report W2-047/SR

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This report explores the influence of changes in freshwater and marine temperature on the age and growth characteristics of salmon stocks in England and Wales over the last 20-40 years. In doing so it seeks to identify potential links between these changes and the general decline in salmon abundance. It is intended to inform Fisheries staff and others on the likely effects of climate change on salmon.

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Professor Mike Depledge   Head of Science

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EXECUTIVE SUMMARY

This study explores the influence of changes in freshwater and marine temperature on the age and growth characteristics of salmon stocks in England and Wales over the last 20-40 years. In doing so it seeks to identify potential links between these changes and the general decline in salmon abundance.

The study reviews existing data on age, growth and temperature - concentrating on data collected in England and Wales but including information from Scotland, Northern Ireland and Ireland.

It also utilises scale collections from the Thames, Wye, Dee and Lune to produce new data on (back-calculated) length-at-age for pre-smolt (freshwater) and post-smolt (marine) stages, and generates 20-40 year time-series of water temperature data for these four rivers from in-situ readings and air-temperature records. The latter data were used to predict past and possible future changes in freshwater size-at-age based on the growth model of Elliott and Hurley (1997); future temperature profiles for this purpose were derived from the climate change scenarios of the UKCIP (2002).

The main conclusions of the study are summarised below.

In addition, the study makes a number of recommendations. These are primarily aimed at ensuring that age and growth data, currently collected at relatively low cost as part of larger, nationally supported monitoring programmes, continue to be collected as part of these programmes and are better utilised and reported. Such studies are important, as changes in freshwater or marine growth may be among the first signs that climate is having an unusual effect on salmonid populations. Detecting these changes and related traits (e.g. age at smoltification or maturation) will help in understanding and explaining associated fluctuations in abundance and inform fisheries management in a period of potentially unprecedented environmental change.

Past temperature change:

- In keeping with warming trends across the north Atlantic (Hughes and Turrell, 2003) and globally (IPPC, 2001), temperature records examined for rivers and coastal waters in England and Wales indicate both have been getting warmer over the last 20-40 years.

- In both cases, geographical differences in warming rates were evident (e.g. southerly sites appear to be warming faster than northerly sites). Temperature fluctuations among river and sea sites were also highly synchronous suggesting that large-scale climatic processes are influencing both freshwater and marine environments simultaneously.

Given these common patterns of freshwater and marine temperature change, and the importance of temperature to the biology of fishes, then coherent trends in the age and growth of pre and post-smolt salmon might be expected.

Pre-smolts:

- Growth predictions from the model of Elliott and Hurley (1997) suggest that pre-smolt (freshwater) growth rates on the Wye and Dee have improved in response to increasing temperatures, but not significantly so.

- These relatively stable growth predictions contrast the marked decline in mean smolt age of salmon evident on some rivers (Severn, Wye and Dee). This decline begins around the early 1980s but proceeds at different rates thereafter.

- This may indicate factors other than, or in addition to, temperature have been promoting faster growth in pre-smolt salmon on these rivers and, as a consequence, a decline in their mean smolt age.

Post-smolts:

- Common patterns of post-smolt (first-year marine) growth are apparent among salmon stocks around the UK and Ireland - including from rivers in England and Wales (Thames, Wye, Dee and Lune) as well as Scotland (east-coast rivers), Northern Ireland (Bush) and Ireland (Burrishoole).

- These common patterns are likely to be influenced by a mixture of fine and broad-scale environmental processes operating throughout the post-smolt period and could be indicative of shared trends in sea survival (Friedland *et al.*, 2000). However, no data are available in this study to confirm the link between post-smolt growth and survival and the existence of such a link is not evident elsewhere (Crozier and Kennedy, 1997).

- Sea surface temperature (SSTs) data (expressed in a variety of ways), were generally poorly associated with post-smolt growth patterns (this study) or with more direct measures of sea survival and adult abundance (SALMODEL, 2003). This does not mean that environmental temperature is unimportant for salmon in the sea, rather that other (perhaps more complex) factors have been the main cause of change and/or the temperature variables examined have poorly represented the true influence of temperature on salmonid biology/ecology.

- In contrast, the North Atlantic Oscillation (NAO) index was strongly correlated with patterns of PSG increment for 1SW salmon (this study). Year-to-to year variations in river and sea surface temperatures around England and Wales, and the NAO index were also highly synchronous. These relationships highlight the over-riding influence of the NAO as the dominant atmospheric process in the North Atlantic and one which appears to serve as a general surrogate for a number of climatic effects operating over land and sea (Dickson and Turrell, 1999).

- Global decline in abundance of Atlantic salmon is usually assumed to stem mainly from changes in the marine environment (Friedland 1998). However, the potential for large-scale processes, such as the NAO, to affect both freshwater and marine environments together may mean that the influence of freshwater factors in this decline have been understated.

- Like PSG increments, annual variations in adult weight-at-return data (Severn, Wye and Dee) were also highly synchronous, especially within sea age groups, but showed no strong associations with SST variables or the NAO index.

- Weak correlations between weight-at-return and PSG increment indicate the former is not heavily influenced by initial growth at sea. Cairns (2003) suggests that salmon aim to achieve a target weight prior to return and one of the consequences of this is that fish must compensate for poor initial growth by increased foraging activity but at the cost of greater susceptibility to predation.

- Relatively stable return weights for 1SW salmon (Wye and Dee) over the last 40 years are consistent with the target weight hypothesis; conversely, the weight of 2SW salmon appears to have been increasing in recent years (Severn, Wye and Dee).

Future temperature change

- Scenarios for future climate change (UKCIP, 2002) suggest that warming trends are likely to be far more severe in the coming decades than those experienced in the past – even under the best case 'low emissions' scenario.

- Growth predictions from the model of Elliott and Hurley (1997) based on temperature profiles forecast to the end of this century, indicate that on rivers in the south-west and north, freshwater growth rates could generally improve under the 'low emissions' scenario but may fall below current levels under the 'high-emissions' scenario as temperatures exceed optimum levels in the latter half of the century. On rivers in the south-east (represented by the Thames) - where warming is expected to be greatest - declining growth rates may result with adverse consequences for abundance and survival.

- Temperature increases are likely to have more severe consequences for trout in freshwater than salmon - as trout have the lower thermal tolerance of the two species (Davidson, Hazlewood and Cove, in press). However, for both species, warming is only one aspect of climate change that might prove detrimental at extreme levels; expected increases in the frequency of summer droughts and winter floods could also adversely affect survival and abundance.

- The effects of global warming on salmon in the sea are more speculative given our poorer knowledge of ocean processes and of the marine life of Atlantic salmon (Hughes and Turrell, 2003).

1. INTRODUCTION

Global decline in abundance of Atlantic salmon stocks in the last 30-40 years has been well documented. Much attention has focussed on the marine environment in looking for causes of this decline, and a number of studies have found associations between environmental parameters – particularly sea surface temperature (SST) and marine growth, survival and maturation of Atlantic salmon (Dickson and Turrell, 1998; Friedland 1998). However, the precise nature of any marine environmental effect remains unclear and the mechanisms involved are likely to be complex (Hansen *et al.*, 2003).

Among recent studies, Friedland *et al.* (2000) related synchronous patterns of survival for 1sea-winter (1SW) salmon from the North Esk (Scotland) and neighbouring Friggio (Norway) to May SSTs experienced by post-smolts soon after they entered the North Sea. They also reported a strong positive correlation between post-smolt growth increment (i.e. the increase in length – back-calculated from scale measurements - between the last freshwater annulus and the first sea annulus) and the survival rate of 1SW salmon returning to the North Esk.

Very few salmon rivers in England and Wales (or elsewhere in the north-east Atlantic) have facilities to monitor marine survival directly, or the time-series of data available on the North Esk and Friggio (see O'Maoileidigh *et al.*, 2003). However, the findings of Friedland *et al.* (2000) indicate that post-smolt growth (PSG) increment may serve as an index of marine survival which could be derived for a larger number of rivers where scale collections exist.

This study begins by identifying rivers in England and Wales where suitable scale collections are available. It seeks to utilise these to derive PSG increments, explore spatial and temporal trends in this variable and the influence of environmental factors (principally SST), and comment on the potential use of PSG increment as an indicator of marine survival. The study also examines trends in other growth data (weight-at-return) associated with individual scale samples.

Survival of salmon post-smolts at sea, and associated processes of growth and maturation, determine the abundance, size and age composition of returning adult spawners, and understanding how these processes have been (or could be) affected by marine climatic change is important for future stock management. However, while marine issues may be responsible for much of the decline in salmon abundance in the last 30-40 years, freshwater factors can not be ignored (Friedland 1998). Indeed large-scale atmospheric process may influence both marine and freshwater environments together. These include the effects of global warming on climate change (UK Climate Impacts Programme 2002) and, in the Atlantic sector, the influence of the North Atlantic Oscillation (NAO) as the dominant atmospheric force affecting weather patterns over land and sea (Dickson and Turrell, 1999).

Accordingly, this study also employs the same back-calculation methods used to derive PSG increments to examine trends in pre-smolt (i.e. freshwater) growth history and the influence of temperature changes on these.

The objectives of the study were as follows:

Overall Objectives

To explore spatial and temporal trends in back-calculated freshwater and post-smolt growth indices derived from historic salmon scale material collected in the last 10-15 years or more.

Specific Objectives

(i) To identify 4-6 rivers in England and Wales with historic scale samples collected over a common time-series of at least the last 10-15 years (e.g. Severn, Wye and Dee).

(ii) To obtain 'back-calculated' measurements of pre and post-smolt growth from the above material – preparing (e.g. cleaning) and sub-sampling where appropriate.

(iii) To explore patterns of back-calculated pre and post-smolt growth among sea age groups (i.e. 1 and 2 sea-winter fish) and, within and between rivers, relationships with catch and other indices of stock abundance and the influence of environmental variables (particularly freshwater and sea temperatures) on these.

(iv) To compare trends in adult size (length or weight) at return with back-calculated post-smolt growth in order to evaluate the sensitivity of the former as growth indicators. Pending a successful outcome from this, to examine time-series of sea age specific fish size data (e.g. from rivers where scale collections no longer exist) for common growth patterns.

(v) To assess the use of scale data in defining salmon stock characteristics/groupings across England and Wales, identifying and costing any additional monitoring requirements for this purpose.

Each of the Specific Objectives are first addressed in the following sections of the report:

Specific Objective (i) - Section 2.1
Specific Objective (ii) - Section 2.2
Specific Objective (iii) - Sections 3.1 and 3.2
Specific Objective (iv) - Sections 3.3 and 3.4
Specific Objective (v) - Section 5.5

2. METHODS

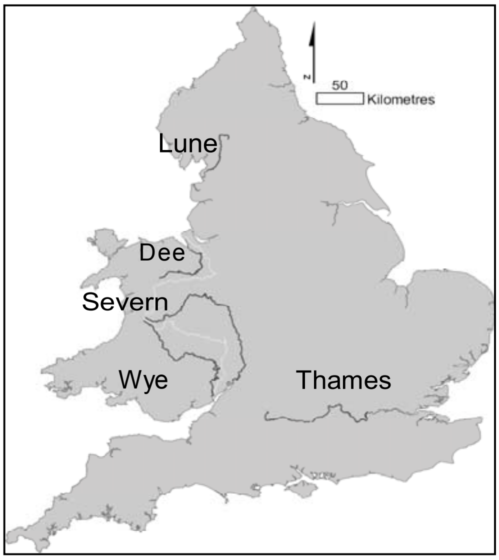
2.1 Study Rivers

A number of rivers in England and Wales were identified where salmon scales have been collected in the past and information recorded on age, weight, etc. These are summarised by sample size, method and year of capture in Appendix I.

In most cases, scales had been collected for only a few years. The Severn, Wye and Dee were notable exceptions where sampling of (primarily) rod and/or net fisheries had been carried out for 30 years or more. Unfortunately, many of the scale samples from these and smaller programmes have been discarded (e.g. virtually all from the Severn), as have age and other details from individual fish. However, on the Severn Wye and Dee, summary statistics describing smolt and sea age composition, weight and other details appear in published reports.

Only four rivers were identified where scale samples were still available and covered a period of 10 years or more. These were the Thames, Wye, Dee and Lune, all of which had samples from the 1980s and 1990s collected over 11-16 years. The location of these rivers, along with the Severn, is shown in Fig 1.

Figure 1 Location of study rivers



2.2 Back-Calculation

Radii measurements were taken from scales from the Thames, Wye, Dee and Lune in order to ‘back-calculate’ pre and post-smolt length-at-age and post-smolt growth increments. The methods used are described by Friedland *et al.* (2000). No analysis of Thames pre-smolt data was carried out because of the significant stocking programme on this river and the absence of any natural spawning.

Measurements were obtained from cleaned scales viewed under one of two microfiche readers (magnification x30). For each fish sampled, radii distances were recorded from a single selected scale and measured directly from the screen to the nearest 0.5mm.

On all four rivers, scales were measured from 1-sea winter (1SW) and 2SW salmon. Sampling effort was concentrated on the former, more dominant sea age group where (material permitting) up to 150 or so scales were measured per river per year. A lesser 'target' of 50 scales measured per river per year was set for 2SW fish.

However, in many cases insufficient scales were available to meet these nominal targets. Exceptions occurred on the Dee and the Wye where sub-sampling occurred in some years to provide numbers representative of the temporal distribution of the entire annual sample.

Scales were obtained from fish captured in a variety of ways – including by net, rod, trap and electrofishing. Numbers of fish from which scale radii measurements were taken are shown in Appendix II by smolt year, sea age group and method of capture.

3. RESULTS

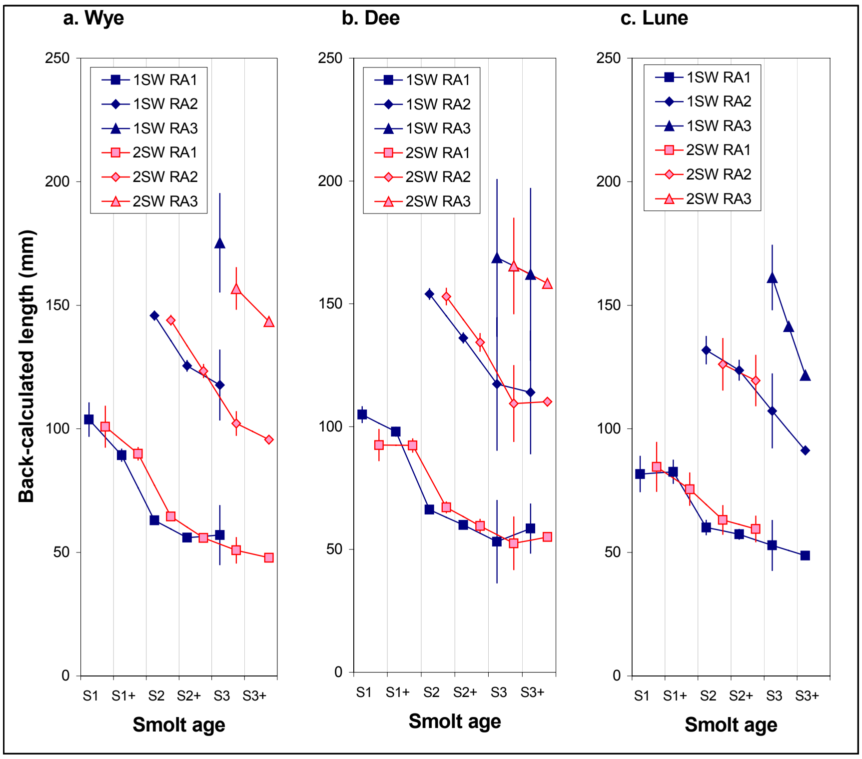
3.1 Pre-Smolt Growth

3.1.1 Freshwater length-at-age

Scale readings from the 1980s and 1990s for the Wye, Dee and Lune indicate that the majority of 1SW and 2SW fish (63-76%) surviving to return as adults had emigrated as 2-year old smolts (S2s). Most of the remainder were S1s with very few S3s (<2%). (Thames fish were excluded from this analysis as juvenile populations in this river are largely, if not entirely, maintained by stocking.)

Back-calculated mean lengths at each river annulus (RA) are summarised for the three rivers in Fig 2. Estimates are presented for 1SW and 2SW fish separately and ordered by eventual smolt age. The latter distinguishes between fish which did or did not exhibit 'run-out' (or '+' growth) on their scales (X-axis).

Figure 2 **Comparison of back-calculated lengths at each river annulus (RA) for fish of different smolt (S1-S3+) and adult age (1SW and 2SW) from the Wye, Dee and Lune (95% confidence limits shown around each estimate)**



It is evident from Fig 2 that freshwater 'growth' patterns among (i) fish from different rivers and (ii) fish from the same river but of different sea age, are generally very similar. It is clear, however that salmon on the Lune, for example, tend to be much smaller than fish of the equivalent smolt age on the Wye or Dee and this probably relates to the Lune's more northerly location. It is also apparent that fish emigrating as one year-old smolts (S1 or S1+) are significantly larger at river age 1 (RA1) than fish which emigrate after 2 or 3 years, and that the oldest smolts on any one river are usually the largest smolts (Fig 2). For example on the Wye, the average size of a 1SW salmon at smolt age S1 was 104mm compared to 146mm and 175mm at ages S2 and S3.

Fish which exhibit run-out are often significantly smaller when the last river annulus is laid down than fish of the same smolt age with no run out. However, run out growth may provide a means of making up this difference in freshwater size before a fish enters the sea.

3.1.2 Back-calculation of freshwater size

The observations described above conform to the general view of salmon growth in freshwater and in doing so give some assurance that the back-calculation technique employed provides a valid means of exploring growth history.

A more thorough check on the validity of this technique would involve comparison of actual measurements of smolt length with back-calculated (BC) estimates from the same fish recaptured as adults, but this would require individually marked smolts being recovered as adults. Where batch marked (e.g. microtagged) smolts have been released, an alternative approach is to compare the mean length of a batch of smolts with the BC lengths estimated from the same batch recovered as adults.

Sufficient tagging data of this sort do not currently exist for the Thames, Wye, Dee and Lune. However, data from wild smolt microtagging on the Wear, carried out by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) (Ian Russell pers. com.) have been examined to this end. This involved comparison of two years of smolt data (1986 and 1989) with the corresponding 1SW and 2SW adult data from the same smolt year class. All adults and smolts had been microtagged and only fish which appeared to have emigrated as 2 year old smolts (the great majority of the sample), and without run out growth, were examined.

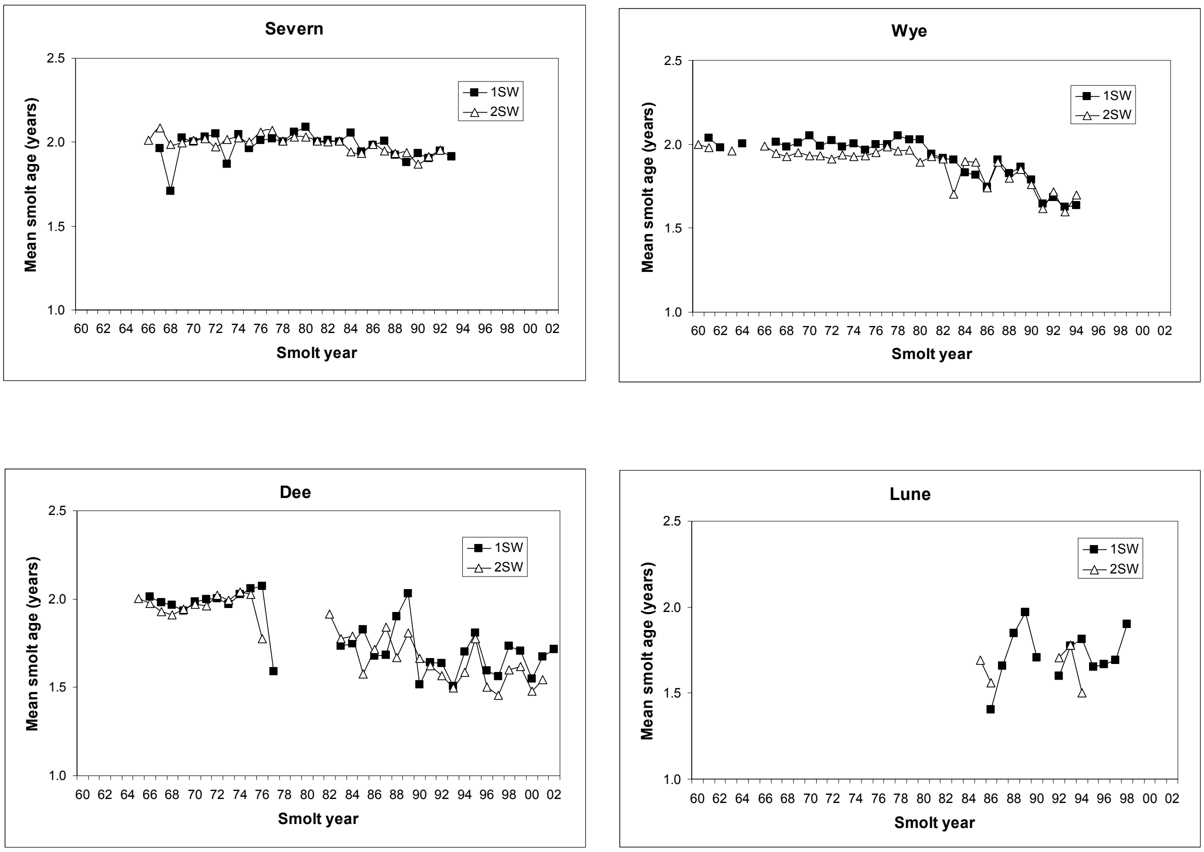
The measured and back-calculated mean lengths for these two groups of fish at 155mm and 154mm, respectively, (both smolt years and sea age groups combined) were not significantly different ($p=0.536$; $n1=64$ and $n2=129$). Hence, in this comparison at least, back-calculation from adult scales appeared to provide an accurate estimate of mean (S2) smolt length.

3.1.3 Mean smolt age

It is apparent from Section 2 that the age data available on some salmon rivers are more extensive than the scale material that now remains. On the Severn, Wye and Dee, information on the smolt age composition of returning adults (captured primarily by rod and net fisheries) has been published in annual reports extending back to the 1960s. Similar data are available for the Lune but only from the mid-1980s.

Annual variation in mean smolt age over the last 20-40 years is shown in Fig 3 for these four rivers. From this, it is evident that an overall decline in the mean smolt age of 1SW and 2SW salmon has occurred on the Severn, Wye and Dee since the 1960s. However, the onset of this decline does not appear until the 1980s, and has been notably less marked on the Severn. Examination of the data for time-periods common to each river confirm that no significant trends were apparent in mean smolt age during the period 1966-1977 (P>0.05) - with mean smolt age consistently around 2.0 during this time. However for the period 1982-93, significant negative trends ($p \leq 0.05$) were present in most cases – the exceptions being for 2SW salmon on the Wye (p=0.087) and 1SW salmon on the Dee (p=0.213). There was no evidence of a decline in mean smolt age on the Lune from the mid-1980s (p>0.05).

Figure 3 **Annual variation in mean smolt age of 1 and 2–sea winter (SW) salmon on the Severn, Wye, Dee and Lune, 1960-02**



3.1.4 Temperature and freshwater growth

Freshwater temperature data

Time-series of river temperature data were compiled for the Thames, Wye, Dee and Lune from a combination of: (i) *in situ* readings obtained from Environment Agency records and (ii) predicted monthly average values based on regression relationships between *in situ* readings and local air temperature records (after the method of Crisp, 1992). All air temperature data were extracted from the Meteorological Office web site www.metoffice.com

Air temperature records were usually more extensive than river temperature records, and predictions based on the former were used to complete gaps in the data set where *in situ* readings were absent. On each river system, temperature data were collected from a single main river site located in the lower third of the catchment. Information on the sources of temperature data and relationships used to convert from air to river temperature are summarised in Table 1. (Note: In some cases not all air or river temperature data were used to derive these relationships where monthly means were missing from annual data series.)

Table 1 Temperature data (^oC) for the Thames, Wye, Dee and Lune

a. Source and type of river temperature data:

River	Location (and grid reference)	Data type (and sampling method)	Period sampled
Thames	Teddington (TQ 1670 7150)	Single daily 'mid-day' (manual)	Jun 1986 to Dec 1999
Wye	Redbrook (S0 5286 1108)	Single daily 9.00am (automatic)	Jan 1996 to Dec 1999
Dee	Manley Hall (SJ 3481 4146)	Mean daily max/min (continuous chart)	Jan 1965 to Dec 1999
Lune	Lyon Bridge (SD 5815 6971)	Variable - 1 day per 2 months to 4 days per month (manual)	Feb 1980 to Dec 1999

b. Source and type of air temperature data:

River	Location (and grid reference)	Data type (and sampling method)	Period sampled
Thames	St. Jame's Park (TQ 2950 7970)	Mean daily max/min (manual)	Jan 1979 to Nov 1999
Wye	Malvern (SO 7830 4630)	Mean daily max/min (manual)	Jan 1960 to Dec 1999
Dee	N/A	N/A	N/A
Lune	Hazelrigg (SD 3740 8450)	Mean daily max/min (manual)	Jan 1979 to Nov 1999

c. Monthly mean air (X) to monthly mean river temperature (Y) conversion:

River	Regression relationship	R^2	P	N	Period
Thames	$Y = -0.8537+1.0599X$	0.972	≤ 0.05	72	Jan 1987 to Dec 1997
Wye	$Y = 1.0347+0.8808X$	0.965	≤ 0.05	47	Jan 1996 to Nov 1999
Dee	N/A	N/A	N/A	N/A	N/A
Lune	$Y = 2.0767+0.8332X$	0.838	≤ 0.05	57	Jan 1992 to Nov 1999

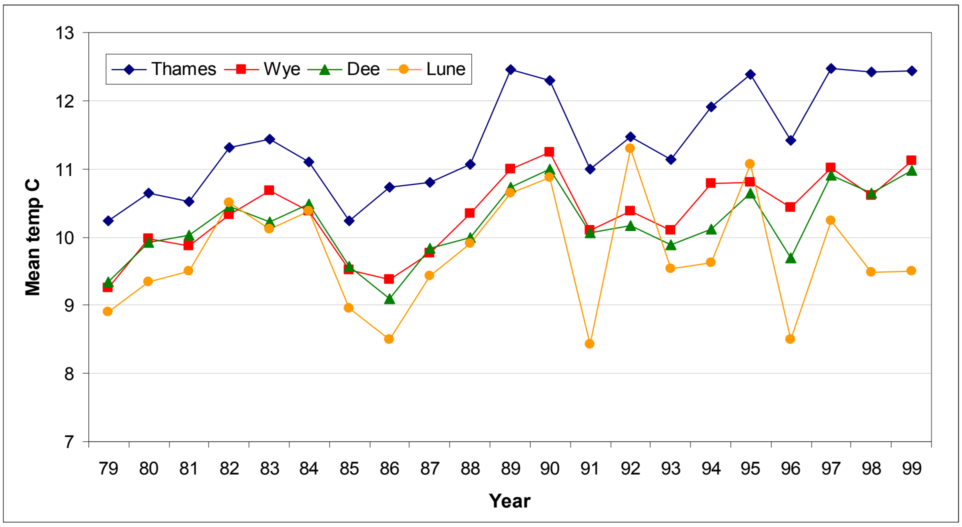
Temperature variation within and between rivers

Annual mean river temperatures for the Thames, Wye, Dee and Lune (derived from the data sets described above) are shown in Fig 4a for the period 1979-99. Over this common time-series, temperature records were highly correlated between all four rivers ($r=0.227-0.569$; $p=0.000-0.011$) and in all cases an increasing trend in annual mean temperature was apparent – significantly so ($p\leq 0.05$) except for the Lune ($r=0.090$; $p=0.660$). Log_{10} linear regression equations fitted to each of the data sets (Table 2a) indicated average increases in annual mean temperatures of 0.013-0.093 ^oC per year with a latitudinal gradient in the rate of increase (i.e. the Lune, as the most northerly river, had the smallest rate of increase and the Thames, as the most southerly, the greatest rate).

More extensive temperature time-series for the Wye and Dee, beginning in the 1960s, were also highly synchronous (Fig 4b) and also showed significant trends ($p \leq 0.05$) in annual mean temperature equivalent to average yearly increases of 0.031 and 0.020°C, respectively (Table 2b).

Figure 4 **Year-to-year variation in observed and/or predicted annual mean river temperatures:**

a. On the Thames, Wye, Dee and Lune for the period 1979-99



b. On the Wye and Dee for the period 1960-99

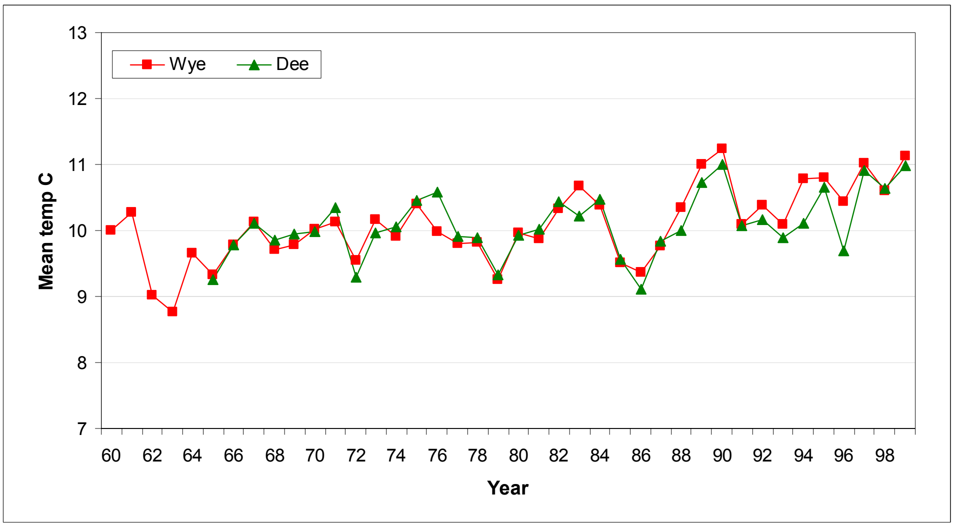


Table 2 Linear regression relationships between year (X) and annual mean river temperature (Y):

a. On the Thames, Wye, Dee and Lune for the period 1979-99

River	Regression relationship	R^2	P	N	Period
Thames	$Log_{10}(Y) = -5.986 + 0.0035405X$	0.569	0.000	21	1979-1999
Wye	$Log_{10}(Y) = -3.796 + 0.0024182X$	0.384	0.003	21	1979-1999
Dee	$Log_{10}(Y) = -2.463 + 0.0017447X$	0.227	0.029	21	1979-1999
Lune	$Log_{10}(Y) = -0.171 + 0.0005830X$	0.090	0.679	21	1979-1999

b. On the Wye and Dee for the period 1960-99

River	Regression relationship	R^2	P	N	Period
Wye	$Log_{10}(Y) = -1.6436 + 0.001337X$	0.409	0.000	40	1960-1999
Dee	$Log_{10}(Y) = -0.7096 + 0.000864X$	0.183	0.010	35	1965-1999

Predictions of past freshwater growth

The growth model of Elliott and Hurley (1997) was used to predict size-at-age for 1 and 2-year old juvenile salmon from the Thames, Wye, Dee and Lune based on monthly mean river temperatures. (The latter derived from the data sets already described.)

Where:

$$W_t = \left[W_0^{\,b} + bc \frac{(T - T_{LIM})\, t}{100\,(T_M - T_{LIM})} \right]^{1/b}$$

and

t = time in days
W_0 = initial fish mass
W_t = final fish mass (after t days at T ºC)
T = water temperature (ºC)

b = exponent for the power transformation of mass that produces linear growth with time = 0.31
c = growth rate of a 1g fish at the optimum temperature = 3.53
T_M = optimum temperature for growth = 15.94ºC
$T_{LIM} = T_L$ if $T \leq T_M$ or $T_{LIM} = T_U$ if $T > T_M$
T_L = lower temperature at which growth ceases = 5.99ºC
T_U = upper temperature at which growth ceases = 22.51ºC

In the absence of information on emergence date, or appropriate field length/weight measurements from any of the four rivers, a growth year of 1st April-31st March and an initial fish mass of 0.15g on the 1st May was assumed in all cases. (The latter based on data for the River Eden and described by Elliott and Hurley, 1997.) In applying the model it was also assumed that zero growth occurred from 1st October to 1st April in the first year. This followed comparisons of observed and expected salmon growth rates by Elliott and Hurley (1997), who found that model predictions were improved when growth cessation was imposed from mid-September to mid-March in the first year.

Fig 5 shows temperature-predicted mean lengths of salmon at river ages 1 and 2 for the Thames, Wye, Dee and Lune over the last 20 to 40 years. Mean weight predictions from the growth model were converted to length using the formula:

$$(L_nL_t) = \frac{(L_nW_t) - a}{d}$$

Where:

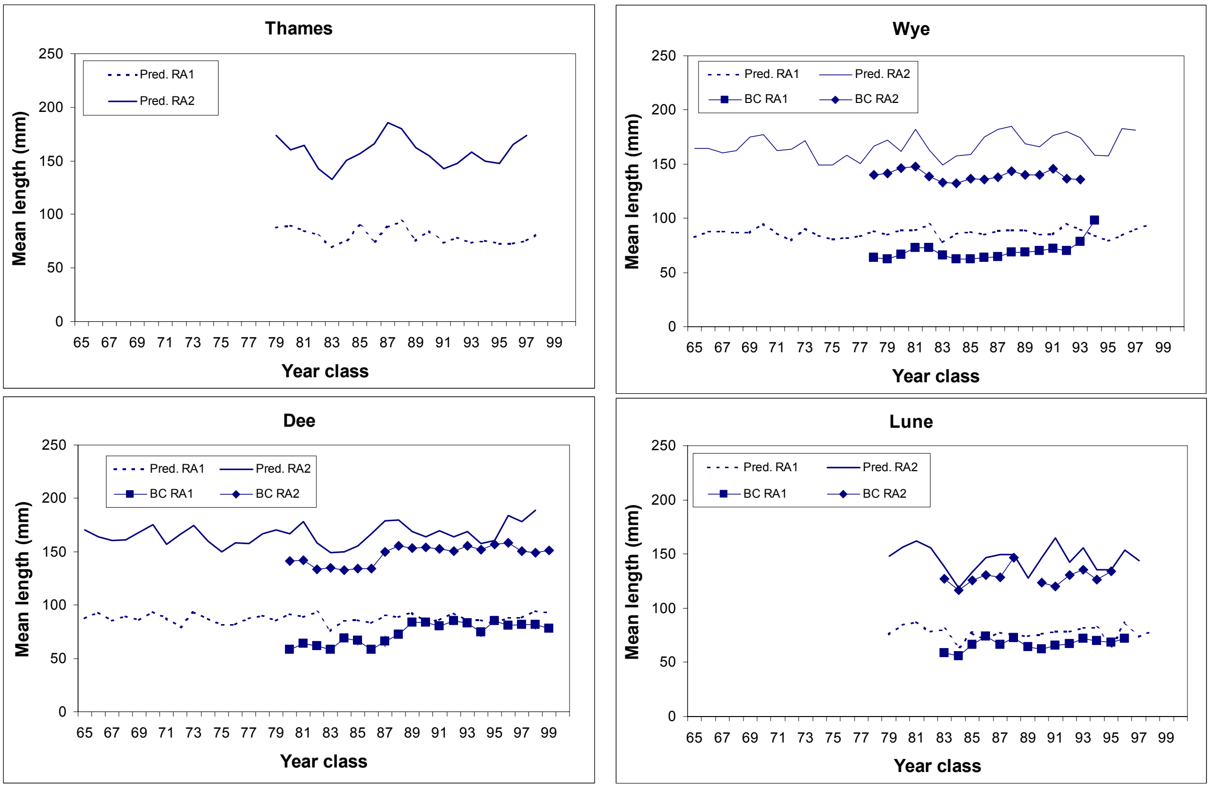
L_n = natural log
L_t = final length in cm (at time t)

and a (= -4.47) and d (=3.00) are obtained from the linear relationship between length (L) in cm and weight (W) in g for combined samples of Leven and Lune salmon published by Elliott and Hurley (1997), or:

$$(L_nW_t) = a + d\,(L_nL_t)$$

Back-calculated lengths for salmon of the same year class are also shown in Fig 5 (except for the Thames where salmon production is entirely maintained by stocking). These comprise mean lengths at river ages 1 and 2 and are based on data from both 1SW and 2SW adults combined.

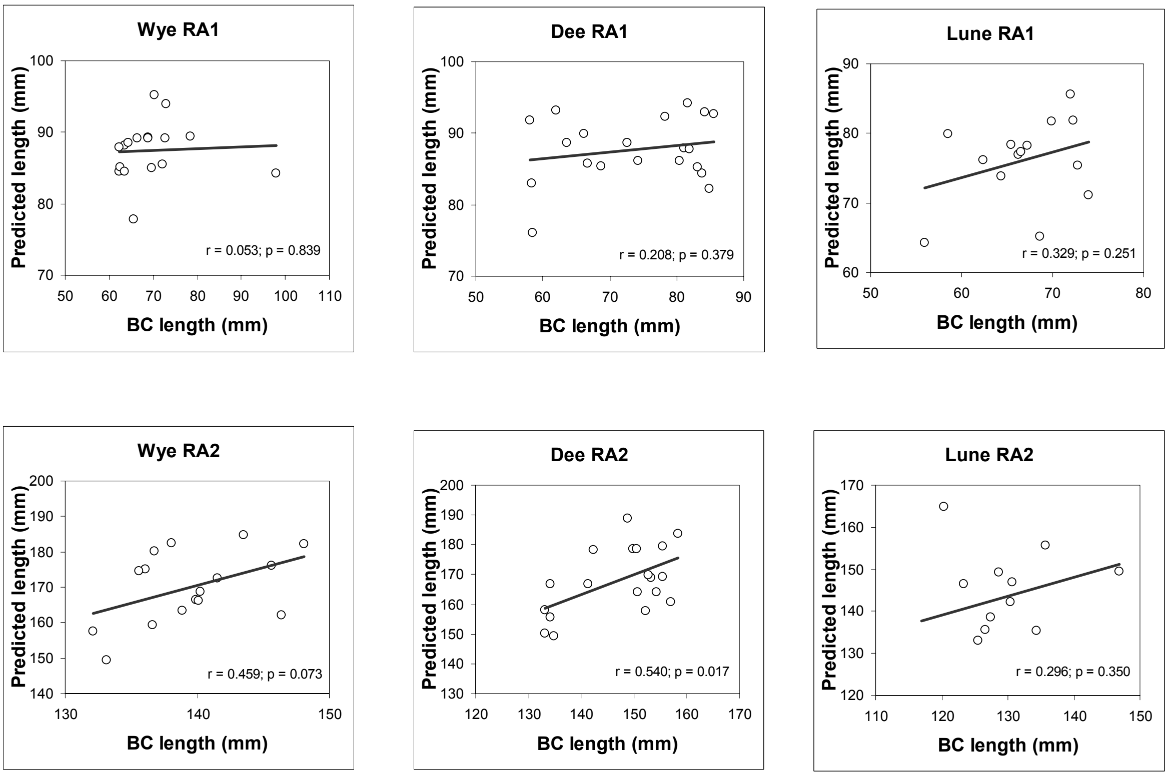
Figure 5 **Mean lengths of juvenile salmon at river ages (RA) 1 and 2 on the Thames, Wye, Dee and Lune; (i) predicted using the growth model of Elliott and Hurley (1997) and (ii) estimated by back-calculation (BC) from adult scales**



On the Thames, Wye and Dee, predicted lengths for salmon at river ages (RA) 1 and 2 showed no significant temporal trends over the time-series shown in Fig 5 ($\log_{10}$ transformed data; $p>0.05$). For the Wye and Dee this was the case when all data were examined (i.e. year classes 1965-1999) or just the years common to all rivers (i.e. year classes 1979-98). On the Lune however, predicted lengths for RA1 and RA2 fish over the 1979-98 period showed near-significant ($r=-0.423$; $p=0.063$) or significant ($r=-0.504$; $p=0.028$) downward trends, respectively.

Mean lengths estimated from back-calculation were generally less than those predicted from the growth model of Elliott and Hurley (1997), particularly so at river age 2 (Fig. 5). Temporal trends in back-calculated lengths ($\log_{10}$ transformed) were significant and positive for RA1 and RA2 fish on the Dee ($r=0.810$; $p=0.000$ and $r=0.721$; $p=0.000$, respectively) and for RA1 fish on the Wye ($r=0.605$; $p=0.010$) and Lune ($r=0.554$; $p=0.044$). Significant ($p\leq 0.05$) or near-significant ($0.10\geq p>0.05$) correlations were evident between predicted and back-calculated lengths of RA2 fish from the Dee ($r=0.540$; $p=0.017$) and Wye ($r=0.459$; $p=0.073$) (Fig 6).

Figure 6 Comparisons of back-calculated (BC) and temperature predicted lengths (Elliot and Hurley, 1997) for river age (RA) 1 and 2 salmon from the Wye, Dee and Lune



Predictions of future freshwater growth

Findings from the UK Climate Impacts Programmes (UKCIP, 2002) indicate that global and UK average temperatures have risen in the last 100 years and will continue to rise into this century due to past and present emissions of greenhouse gases (e.g. CO_2). The extent to which the UK climate will change in the latter half of this century will depend on the volume of greenhouse gases emitted over the next few decades.

The UKCIP (2002) has modelled four climate change scenarios for the UK corresponding to four global emission 'levels'. Namely: 'low emissions', 'medium-low emissions', 'medium-high emissions' and 'high-emissions'. Coupled to each scenario, average weather statistics have been predicted for three 30-year periods of 2011 to 2040 (or the '2020s'), 2041 to 2070 (the '2050s') and 2071 to 2100 (the '2080s'). These statistics indicate change in relation to the average 1961-90 (or '1970s') climate (UKCIP, 2002).

Average seasonal temperature changes for each scenario and in each 30-year period have been produced for a series of 50km squares covering the whole of the UK and Ireland and published on colour coded maps by the UKCIP (2002). These maps are available at www.ukcip.org.uk/scenarios/seasons/seasons.html and an example (for the 'high emissions' scenario) is shown in Fig. 7. In each case, the seasons 'spring', 'summer', 'autumn' and 'winter' correspond to the monthly periods: March-May, June-August, September-November and December-February, respectively.

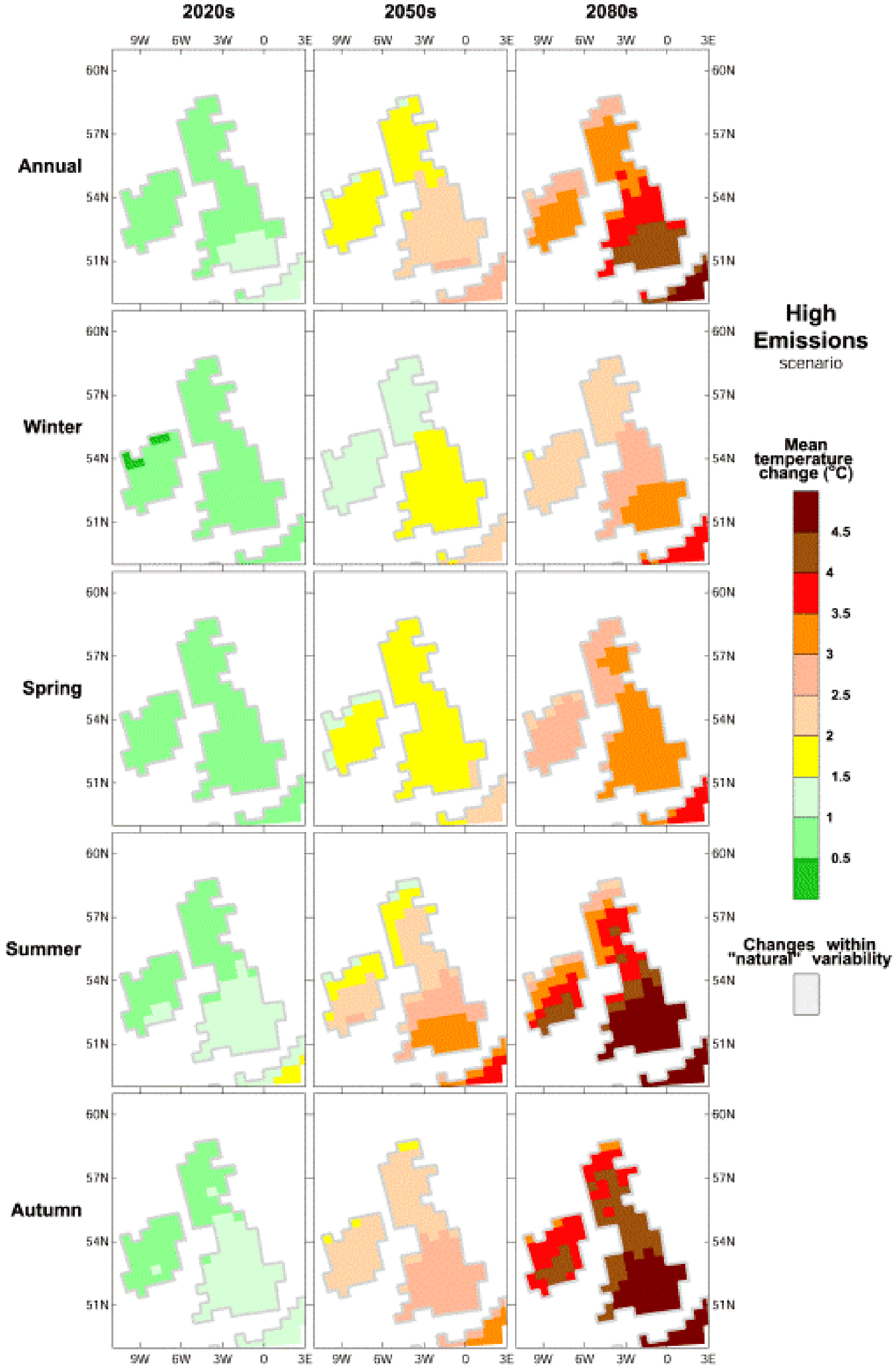
To explore the effect of possible future temperature changes on the growth of juvenile salmon in the Thames, Wye, Dee and Lune, predicted increases in seasonal temperatures for the extreme ('low' and 'high') emissions scenarios were obtained directly from the published maps of UKCIP (2002). (For each river, this involved selecting a single 50km square as representative of temperature changes in the catchment as a whole.) These temperature increases were then used to generate temperature profiles for the 2020s, 2050s and 2080s by adjustment relative to 'baseline' monthly average temperatures for the 1970s (i.e. the period 1961-90). Table 3 provides an example of the calculation of future temperature profiles for the River Wye, with the equivalent data for the Thames, Dee and Lune shown in Appendix III. Note that, in the absence of temperature data for the Thames and Lune for the 1960s and 1970s (see Table 1) monthly average temperatures for these decades were derived from 1980s values adjusted according to mean temperature increases observed on the Wye and Dee.

Temperature profiles derived for the 2020s, 2050s and 2080s, along with those from earlier decades, were used as inputs in the growth model of Elliott and Hurley (1997). Resulting growth predictions (Fig 8) indicate that for RA2 fish on the Wye, Dee and Lune, under the low emissions scenario, growth rates improve progressively through the 2020s and 2050s but decline (Wye and Dee) or level out (Lune) in the 2080s. In each case, growth rates to the end of this century remain above the 1961-90 average. Similar growth patterns occur on the Wye, Dee and Lune for the high emissions scenario up to the 2020s or 2050s, but thereafter growth rates decline (as temperatures begin to exceed the optimum for growth). On the Wye and Dee this decline results in growth rates well below the 1961-90 average by the 2080s. However, on the cooler, more northerly Lune - where the decline begins later and is less marked, the size attained by a 2-year old fish in the 2080s remains well above the 1961-90 average (Fig 8).

Growth predictions for the Thames (Fig 8), the most southerly river, differ markedly from the other three rivers in that predicted growth rates in the 2020s, 2050s and 2080s fall progressively below the 1961-90 average under both low and high emissions scenarios (the latter having the most severe consequences).

For RA1 fish (Fig. 8) growth patterns are broadly similar to those predicted for RA2 fish except that the tendency toward improved growth is less marked. For example, on the Wye and Dee, under both climate change scenarios, growth rates in the 2020s and 2050s are little changed from those predicted for the past. These differences in growth patterns among the two age groups probably arise because zero growth is assumed in the first year of life between 1st October and 1st April even though temperatures may allow growth to occur for at least part of this period. No such restrictions on growth are placed on fish in their second year.

Figure 7 Mean annual and seasonal temperature changes (on the 1961-90 average) for the 'high emissions' scenario (UKCIP, 2002)



Source: UKCIP02 Climate Change Scenarios (funded by DEFRA, produced by Tyndall and Hadley Centres for UKCIP)

Table 3 **Predicted monthly average river temperatures for the River Wye up to the 2080s, based on observed temperatures in the period 1961-90 and UKCIP (2002) modelled seasonal temperature increases for low and high emission scenarios**

	Mean river temperature (ºC)						
		Low emissions scenario			High emissions scenario		
Period	**1961-90**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Mar	6.5	7.2	7.6	8.0	7.2	8.0	9.1
Apr	8.6	9.6	10.1	10.5	9.6	10.5	12.0
May	11.5	12.8	13.4	14.1	12.8	14.1	16.0
Jun	14.2	15.1	16.0	16.5	15.6	17.0	18.8
Jul	16.0	17.1	18.1	18.6	17.6	19.1	21.2
Aug	15.7	16.7	17.8	18.3	17.2	18.8	20.8
Sep	13.6	14.9	16.2	16.9	15.6	17.5	19.4
Oct	10.7	11.8	12.8	13.3	12.3	13.8	15.3
Nov	7.2	7.9	8.6	8.9	8.2	9.3	10.3
Dec	5.5	6.7	7.3	7.3	6.7	7.8	9.0
Jan	4.4	5.4	5.8	5.8	5.4	6.3	7.2
Feb	4.6	5.5	6.0	6.0	5.5	6.5	7.4
Spring (MAM)	8.9	9.9	10.4	10.9	9.9	10.9	12.4
Summer (JJA)	15.3	16.3	17.3	17.8	16.8	18.3	20.3
Autumn (SON)	10.5	11.5	12.5	13.0	12.0	13.5	15.0
Winter (DJF)	4.9	5.9	6.4	6.4	5.9	6.9	7.9

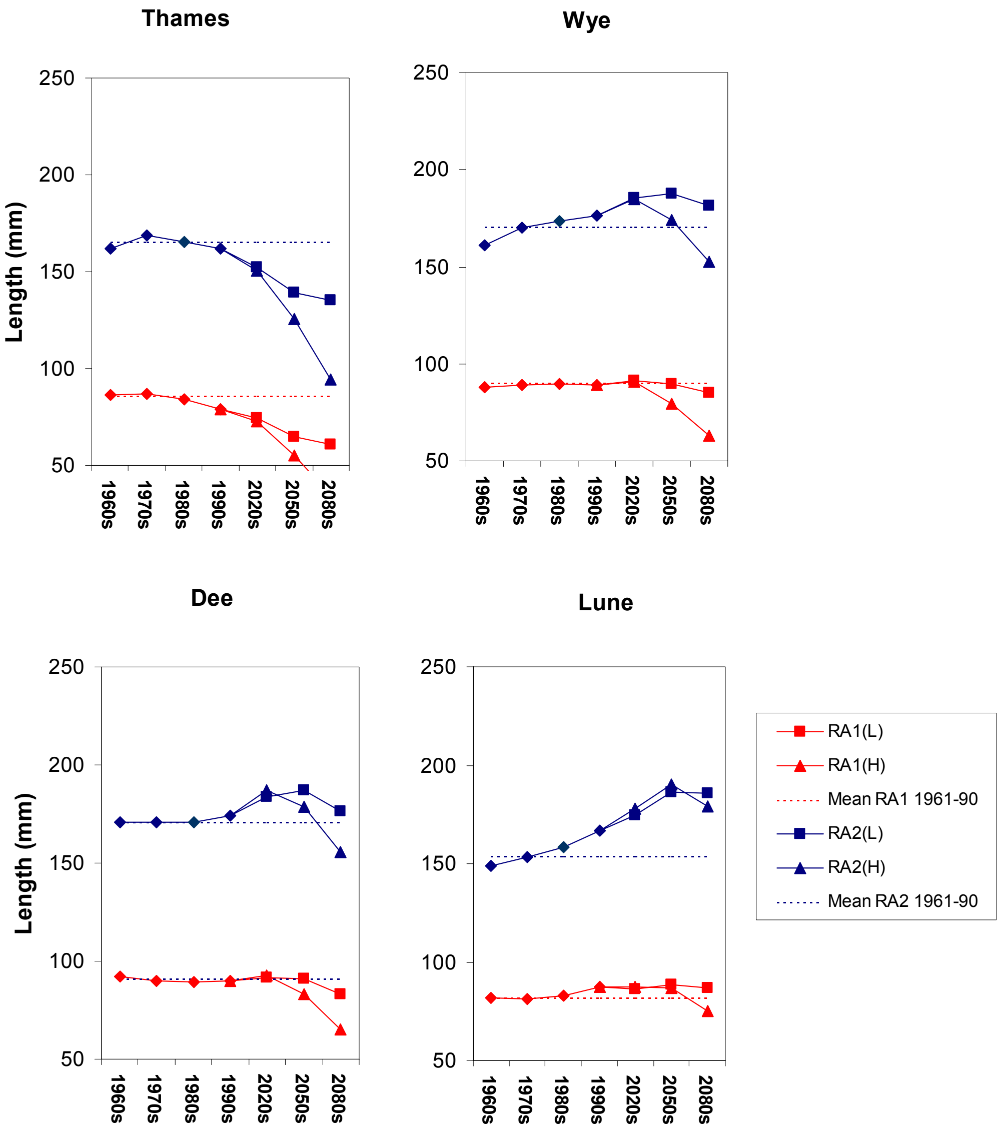
Table 3 **(Contd.)**

	Mean temp increase (ºC)		
Period	**2020s**	**2050s**	**2080s**
Low emissions scenario			
Spring (MAM)	1.0	1.5	2.0
Summer (JJA)	1.0	2.0	2.5
Autumn (SON)	1.0	2.0	2.5
Winter (DJF)	1.0	1.5	1.5
High emissions scenario			
Spring (MAM)	1.0	2.0	3.5
Summer (JJA)	1.5	3.0	5.0
Autumn (SON)	1.5	3.0	4.5
Winter (DJF)	1.0	2.0	3.0

Where, for example, the predicted March mean temperature (T) in the 2020s ($MarT_{2020s}$) is estimated as:

$$MarT_{2020s} = (MarT_{1970s} / SpringT_{1970s}) * SpringT_{2020s}$$

Figure 8 Predicted mean lengths of juvenile salmon at river ages (RA) 1 and 2 based on observed (1960s-1990s) and modelled (2020s-2080s) river temperature profiles on the Thames, Wye, Dee and Lune for the low (L) and high (H) emissions scenarios of the UKCIP (2002)



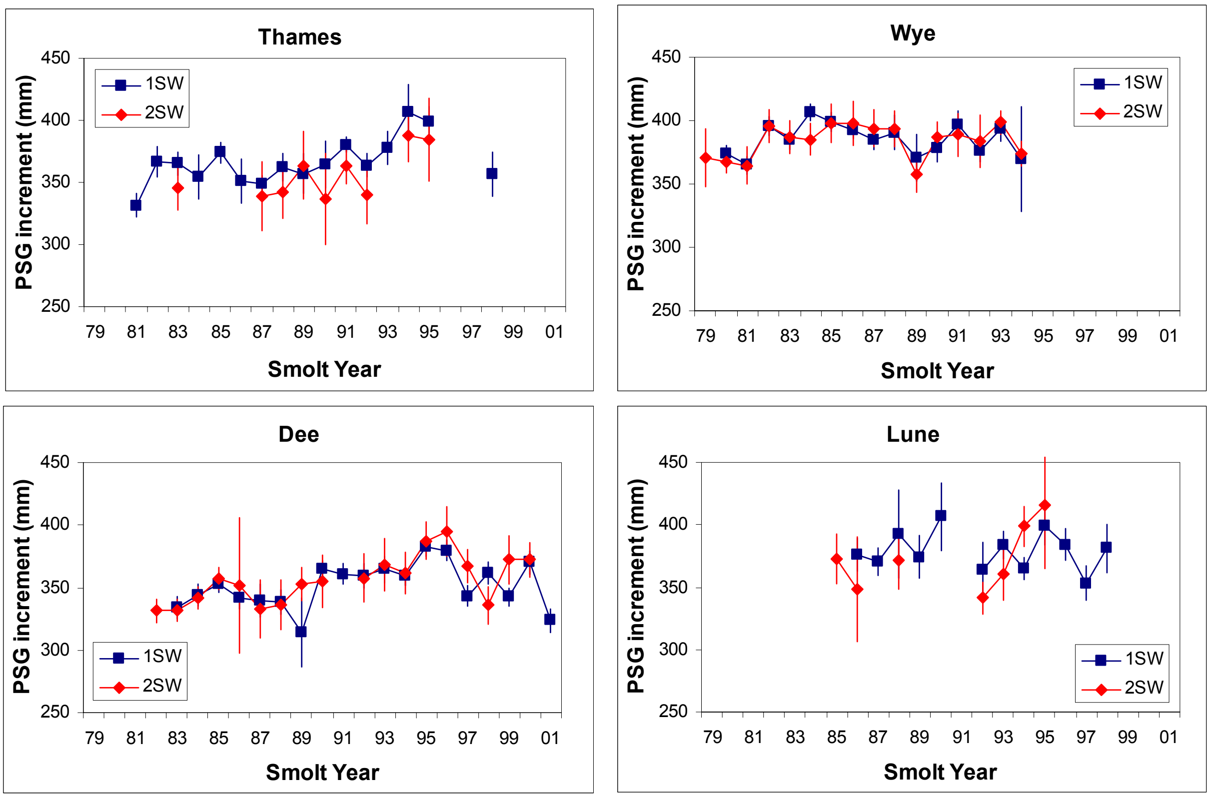
3.2 Post-Smolt Growth

3.2.1 Within and between river comparisons

England and Wales

Year-to-year variations in geometric mean post-smolt growth (PSG) increments for 1SW and 2SW salmon from the Thames, Wye, Dee and Lune are shown in Fig 9. Annual means were estimated from all back-calculation data irrespective of scale sample origin (i.e. whether collected from fish caught by net, rod, trap, etc – see Appendix II).

Figure 9 **Annual variation in mean post-smolt growth (PSG) increment for 1SW and 2SW salmon from the Thames, Wye, Dee and Lune, 1979-01 (95% confidence limits shown)**



Overall, mean PSG increments were very similar between rivers and sea age groups. For 1SW salmon, increments ranged from 354mm on the Dee to 387mm on the Wye, and for 2SW fish, from 355mm on the Thames and Dee to 385 mm on the Wye (Table 4).

Within-rivers, mean PSG increments for 1 and 2SW fish were highly correlated ($p \leq 0.01$) on the Thames, Wye and Dee (Table 5). Significant ($p \leq 0.05$) or near-significant ($0.10 \geq p > 0.05$) positive trends in PSG increment were also evident for 1 and 2SW salmon on the Thames and for 2SW fish on the Dee. In a number of cases, PSG increments were also strongly correlated between-rivers, suggesting a degree of synchrony in post-smolt growth patterns around the coast (Table 5).

Table 4 PSG increments (mm) for 1 and 2SW salmon from the Thames, Wye, Dee and Lune

1SW salmon	**Thames**	**Wye**	**Dee**	**Lune**
Sample period	1982-99	1981-96	1984-02	1987-99
Sample size	1479	1710	2492	758
Geometric Mean	367.0	386.9	354.3	377.7
Range	51-555	248-619	142-634	219-628

2SW salmon	**Thames**	**Wye**	**Dee**	**Lune**
Sample period	1982-99	1981-96	1984-02	1987-99
Sample size	239	1035	1022	309
Geometric mean	354.5	384.7	354.7	369.2
Range	223-542	112-650	165-743	201-596

Table 5 Correlation coefficients between PSG time-series for 1 and 2SW salmon from the Thames, Wye, Dee and Lune, 1979-01. [Note: All data were log$_{10}$ transformed and annual means from small samples (<10) were excluded from the analyses.)

	Smolt year	**Thames 1SW**	**Wye 1SW**	**Dee 1SW**	**Lune 1SW**	**Thames 2SW**	**Wye 2SW**	**Dee 2SW**
Thames 1SW	0.554**							
Wye 1SW	-0.067	0.121						
Dee 1SW	0.287	0.602**	0.168					
Lune 1SW	-0.144	0.096	0.343	0.403				
Thames 2SW	0.653*	0.860***	-0.334	0.305	-0.111			
Wye 2SW	0.235	0.189	0.781***	0.486	0.317	-0.596		
Dee 2SW	0.678***	0.684***	-0.276	0.621***	0.103	0.700*	-0.180	
Lune 2SW	0.482	0.858**	-0.275	0.559	0.445	0.900*	-0.456	0.535

*0.10≥ p>0.05; ** 0.05≥ p>0.01; ***p≤ 0.01

Scotland

Time-series of PSG data for net caught salmon from five Scottish east-coast rivers (Spey, Dee, North Esk, Tay and Tweed) (Fig 10) were provided by Maclean (pers comm). In a number of cases, mean PSG increments for 1SW salmon were highly correlated between-rivers at a significant (p≤ 0.05) or near-significant (0.10≥ p>0.05) level (Table 6 and Fig 11). [Note: unlike the PSG estimates for England and Wales, those for the Scottish rivers included freshwater growth as well as growth up to the end of the first sea-winter.]

Table 6 **Correlation coefficients between PSG data for 1SW salmon from Scottish east-coast rivers, 1979-98. [Note: All data were $\log_{10}$ transformed.)**

	Smolt year	Spey 1SW	Dee 1SW	N. Esk 1SW	Tay 1SW
Spey 1SW	0.013				
Dee 1SW	0.374	0.914*			
North Esk 1SW	-0.360	0.867***	0.865		
Tay 1SW	-0.568*	0.767**	0.875	0.824***	
Tweed 1SW	-0.735**	0.882***	0.743	0.896***	0.901***

*$0.10 \geq p > 0.05$; ** $0.05 \geq p > 0.01$; ***$p \leq 0.01$

Figure 10 **Location of study rivers with post-smolt growth data in England, Wales, Scotland and Ireland**

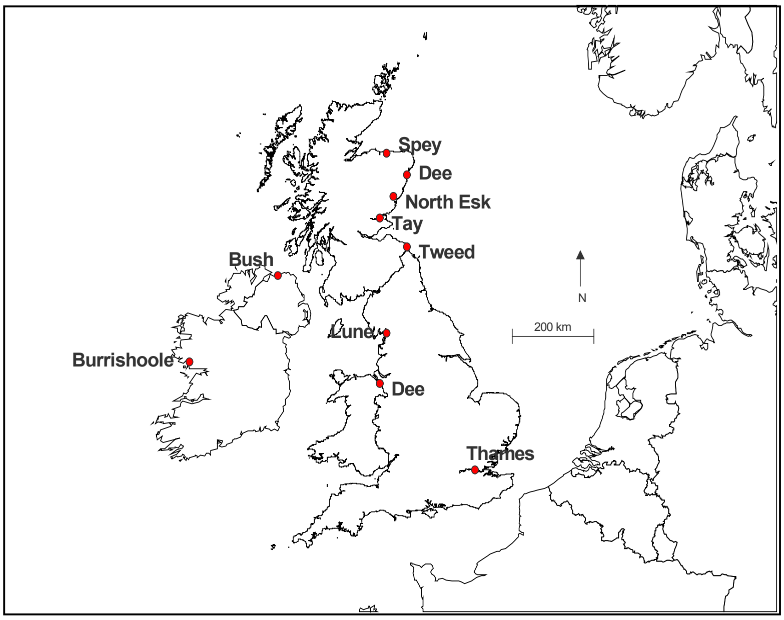
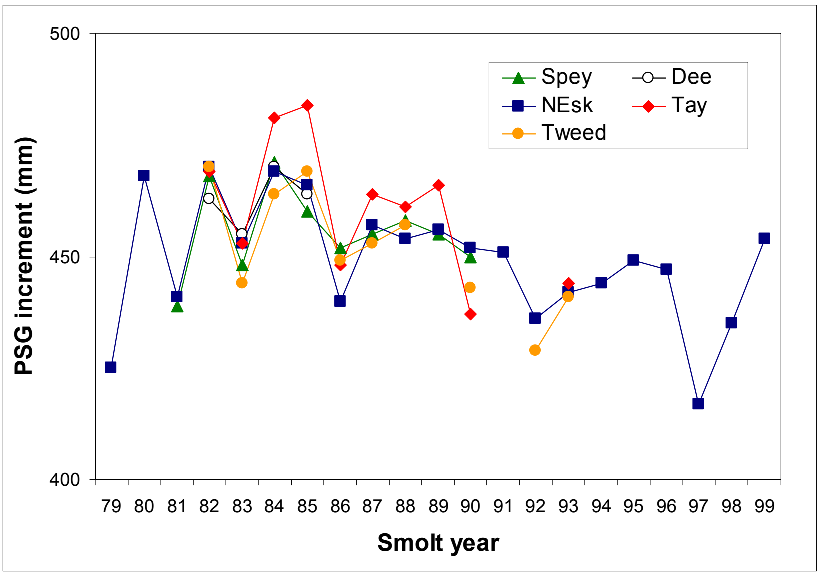


Figure 11 **Annual variation in PSG increment for 1SW salmon from the rivers Spey, Dee, North Esk, Tay and Tweed, 1979-1999**



Ireland

PSG data for 1SW salmon for Irish rivers were obtained for the Bush and Burrishoole (Fig 10) for the smolt years 1984-1992 and 1979-98, respectively. On both rivers, scales were sampled from trap and rod caught fish.

Data for the Bush were read directly from figures produced in Crozier and Kennedy (1999). These were derived using equivalent methods to those applied in this study (see Section 2.1) and published as annual mean PSG values for 1 and 2 year-old smolts separately. Both these variables ('Bush1' and 'Bush2', respectively) were used in subsequent analyses.
PSG data for the Burrishoole comprised mean inter-circuli spacings measured from scales for 'spring' and 'summer' growth periods during the first year at sea (methods and data described in McLoone, 2000). Both growth indices were used in subsequent analyses - represented as B'shoole1 and B'shoole2, respectively.

The Bush and Burrishoole PSG data are shown together in Fig 12. All four data sets showed negative trends over the time-series, significantly so ($P \leq 0.05$) for 'Bush1' and 'B'shoole2' (Table 7). Significant or near-significant correlations were also evident within and between-rivers (Table 7).

Figure 12 **Annual variation in PSG indices (arbitrary units) for 1SW salmon from the rivers Bush and Burrishoole, 1979-1998**

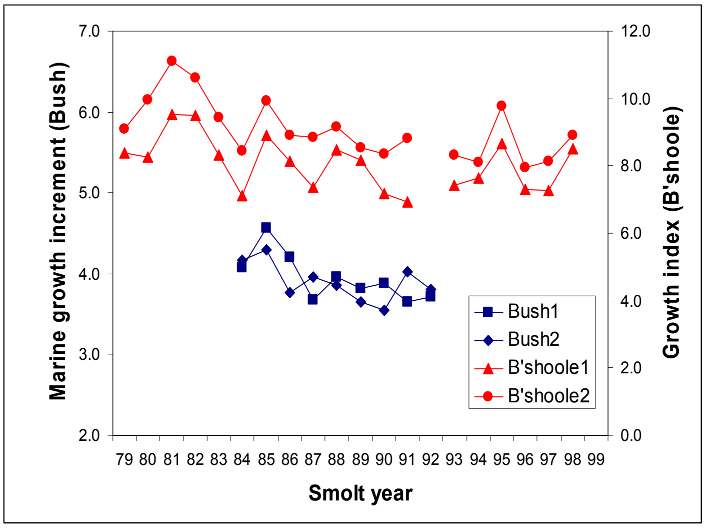


Table 7 **Correlation coefficients between PSG data for 1SW salmon from Irish rivers, 1979-98. [Note: All data were $\log_{10}$ transformed.)**

	Smolt year	Bush1 1SW	Bush2 1SW	B'shoole1 1SW
Bush1 1SW	-0.730**			
Bush2 1SW	-0.565	0.439		
B'shoole1 1SW	-0.444*	0.672*	0.109	
B'shoole2 1SW	-0.627***	0.646*	0.602	0.853***

*$0.10 \geq p > 0.05$; ** $0.05 \geq p > 0.01$; ***$p \leq 0.01$

All rivers

The correlation matrix for PSG data from all the above rivers (England, Wales, Scotland and Ireland) is given in Table 8 with associations summarised by the dendrogram in Fig 13. The latter was derived using cluster analysis (www.minitab.com); with the 'distance measure' (d_{ij}) between correlation variables defined after the 'correlation distance method':

$d_{ij} = 1 - p_{ij}$

but substituting '$1-p_{ij}$' where 'p' is the product-moment correlation coefficient between variables I and j, with an adjusted correlation probability value (p_{ij}); such that:

$d_{ij} = p_{ij}$ when p is positive; and
$d_{ij} = 2+p_{ij}$ when p is negative
In this way, d_{ij} is constrained between 0 and 2.

Clusters were formed using the 'single linkage method' with the 'similarity' (S_{ij}) between clusters I and j defined by:

$S_{ij} = 100(1-d_{(ij)})/d(max)$

Where d(max) =2

Table 8 **Correlation coefficients between PSG data for 1SW salmon from rivers in England, Wales, Scotland and Ireland 1979-99**

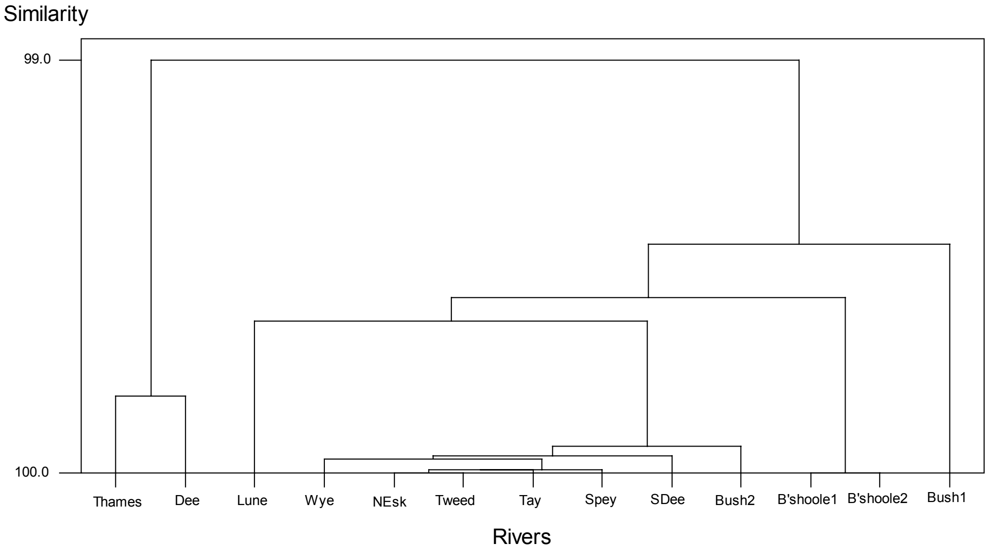
	Thames 1SW	Wye 1SW	Dee 1SW	Lune 1SW
Spey 1SW	0.520	0.819***	0.045	-0.337
Scots Dee 1SW	-0.454	0.995***	0.630	No data
North Esk 1SW	0.017	0.418	-0.195	0.586**
Tay 1SW	-0.091	0.478	-0.348	-0.662
Tweed 1SW	-0.041	0.781***	-0.392	0.319
Bush1 1SW	0.061	0.522	0.007	0.348
Bush2 1SW	0.290	0.808***	0.160	-0.545
B'shoole1 1SW	-0.219	-0.217	-0.140	0.264
B'shoole2 1SW	-0,314	-0.101	-0.064	0.432

*$0.10 \geq p > 0.05$; ** $0.05 \geq p > 0.01$; ***$p \leq 0.01$

	Bush1 1SW	Bush2 1SW	B'shoole1 1SW	B'shoole1 2SW
Spey 1SW	0.303	0.755**	-0.195	-0.225
Scots Dee 1SW	No data	No data	-0.449	-0.402
North Esk 1SW	0.391	0.588*	0.139	0.335
Tay 1SW	0.409	0.870**	0.357	0.443
Tweed 1SW	0.688*	0.755**	0.553	0.662*

*$0.10 \geq p > 0.05$; ** $0.05 \geq p > 0.01$; ***$p \leq 0.01$

Figure 13 **Dendrogram showing 'cluster' relationships based on probability values of correlations among post-smolt growth measures for 1SW salmon, 1979-01**



The tight cluster of Scottish east-coast rivers evident from Fig 13 highlights the strong similarities in post-smolt growth patterns among these rivers. The Wye and Bush2 join this cluster at a high level with other rivers linking at a lower level of 'similarity'. The latter include the Thames and the Dee, which initially form a separate cluster and are the last pair of rivers to link with the Scottish 'group'.

3.2.2 Sea surface temperature and marine growth

Variation in sea surface temperature within and between coastal sites

Monthly mean sea surface temperature (SST) data were obtained from Norris (2001) for sites close to the Thames, Wye, Dee and Lune. Details are given in Table 9.

Table 9 **Location and source of sea surface temperature data for the Thames, Wye, Dee and Lune**

River	Location	Source	Period available
Thames	Dover (51° 7'N, 1° 21'E)	District Council and CEFAS	1926-2000
Wye	Barry (51° 24'N, 3° 15'W)	CEFAS	1978-1999
Dee	Moelfre (53° 21'N, 4° 14'W)	CEFAS	1966-2000
Lune	Port Erin (54° 5'N, 4° 46'W)	University of Liverpool	1903-2000

Log_{10} linear regression equations fitted to these data for the period 1979-00, indicated average increases in annual mean temperature ranging from of 0.017°C per year at Barry to 0.082°C per year at Dover. Except for Barry, all relationships were significant at $p \leq 0.05$ (Table 10a).

Unlike the equivalent time-series of river temperature data (Section 3.1.4), there was no clear latitudinal trend in the rate of temperature increase among the four SST sites for the period 1979-00. However, such a trend was apparent for longer time-series of data (1960-00), ranging from 0.031°C per year at Dover (the most southerly site) to 0.014°C per year at Port Erin (the most northerly site) (Table 10b).

Annual variations in SST were highly synchronous between the four sites (Fig 14), with significant correlations evident among all data combinations (r=0.663-0.853; p=0.000-0.014).

Table 10 **Linear regression relationships between year (X) and annual mean SST (Y) at four sites close to the rivers Thames, Wye, Dee and Lune:**

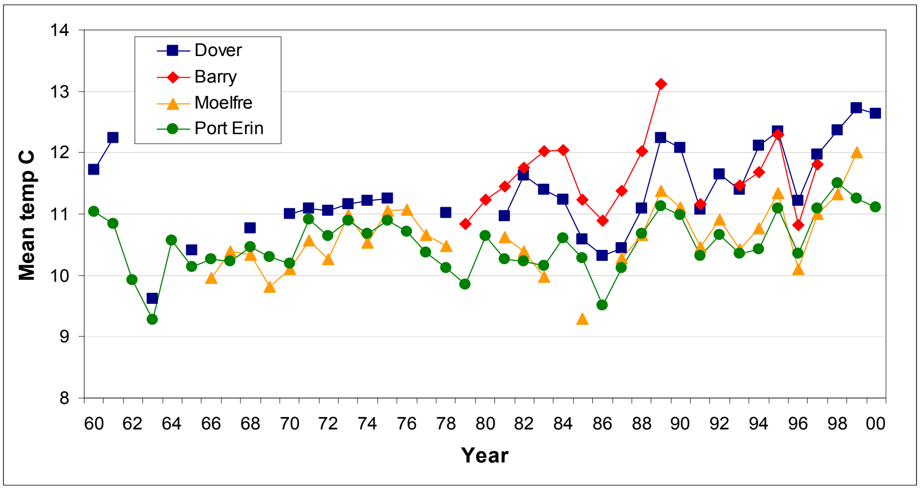
a. Years 1979-00

Site	**Regression relationship**	**R^2**	**P**	**N**	**Period**
Dover	$\text{Log}_{10}(Y) = -5.094 + 0.0030932X$	0.453	0.001	20	1981-2000
Barry	$\text{Log}_{10}(Y) = -0.191 + 0.0006315X$	0.029	0.517	17	1979-1997
Moelfre	$\text{Log}_{10}(Y) = -4.300 + 0.0009694X$	0.337	0.015	17	1981-1999
Port Erin	$\text{Log}_{10}(Y) = -3.039 + 0.0020422X$	0.424	0.001	22	1979-2000

b. Years 1960-00

Site	**Regression relationship**	**R^2**	**P**	**N**	**Period**
Dover	$\text{Log}_{10}(Y) = -1.3068 + 0.0011913X$	0.259	0.003	32	1960-2000
Moelfre	$\text{Log}_{10}(Y) = -0.8945 + 0.0003599X$	0.205	0.012	30	1966-1999
Port Erin	$\text{Log}_{10}(Y) = -0.1069 + 0.0005698X$	0.125	0.023	41	1960-2000

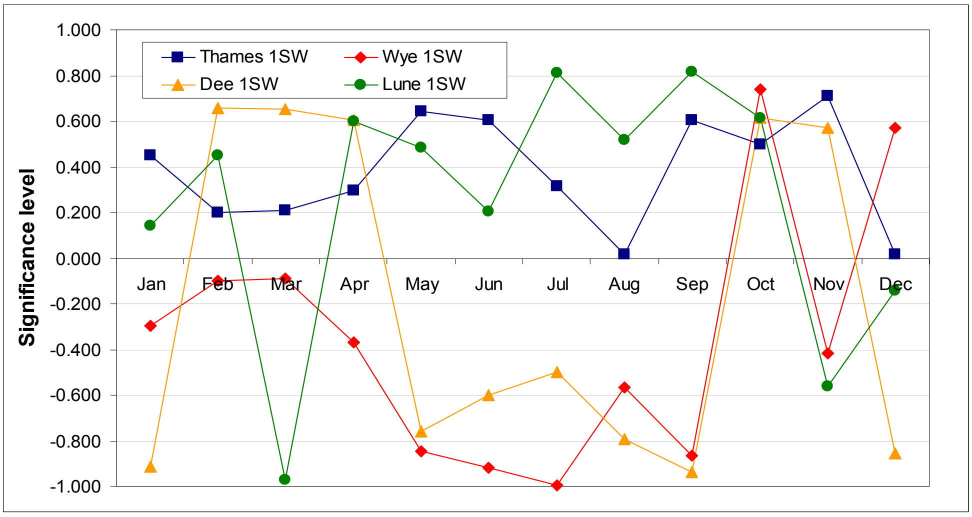
Figure 14 **Year-to-year variation in annual mean sea surface temperature at four coastal sites in England and Wales, 1960-00**



PSG and sea surface temperature

Correlations between PSG and mean monthly SST data from the four sites described above, revealed few significant relationships ($p \leq 0.05$) and no consistent pattern that might be indicative of an underlying biological process as opposed to chance association (Fig 15). Indeed few correlations had a significance level of $p \leq 0.20$ (this was also the case for 2SW fish).

Figure 15 **Significance level for correlations between mean monthly sea surface temperature and PSG increment for 1SW salmon from the Thames, Wye, Dee and Lune**



3.2.3 PSG and adult abundance

Correlations between PSG increment and adult abundance indices were explored on the assumption that the latter, like the former, may serve as potential indicators of sea survival.

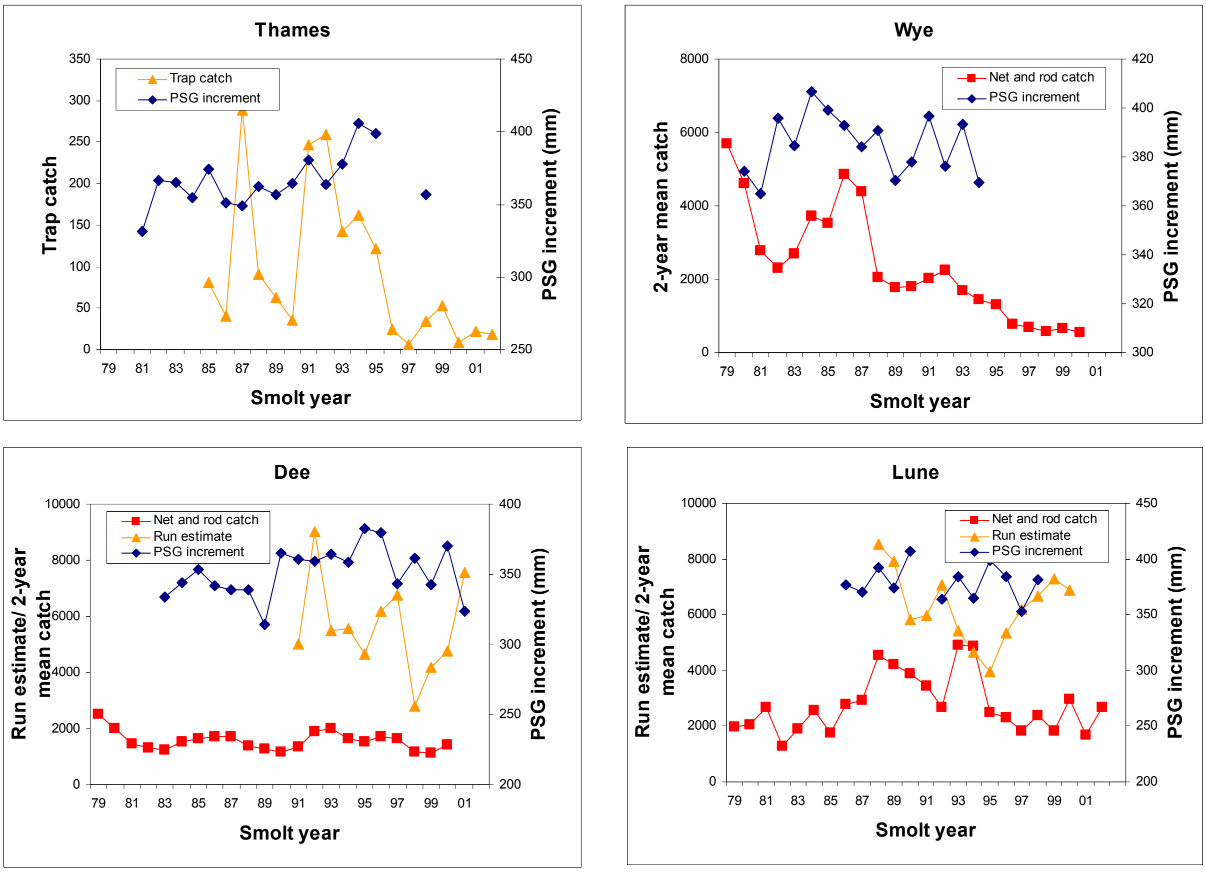
Indices of adult abundance comprised (i) net and rod catches on the Wye, Dee and Lune, (ii) trap catches on the Thames and (iii) run estimates on the Dee and Lune.

Combined net and rod catches of salmon on the Wye, Dee and Lune were examined for the period 1979-00 and expressed as a 2-year running mean catch plotted against smolt year (Fig. 16). [In the absence of information on sea age composition, the catch figures for smolt year ‘n’ were taken as the 2-year mean of catches in years n+1 (representing the 1SW return) and n+2 (representing the 2SW return).]

Run estimates were based on (i) trapping and mark-recapture on the Dee, and (ii) resistivity fish counts on the Lune.

There was no strong evidence on any of the four rivers that variations in PSG increments, catches and run estimates showed any common pattern over the 20-year time series (Fig 16).

Figure 16 Comparison of PSG increments, catches and run estimates for salmon from the Thames, Wye, Dee and Lune, 1979-00

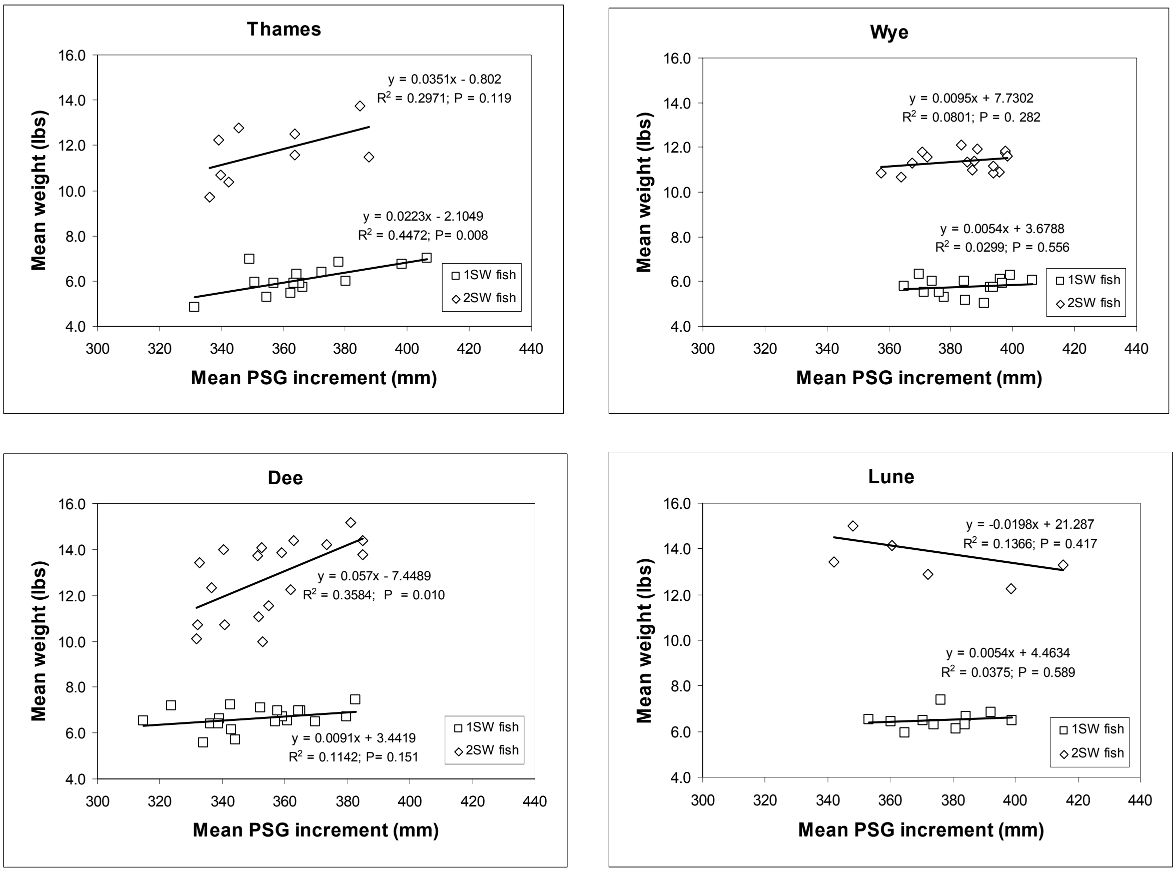


3.3 PSG and Adult Weight at Return

The availability of scale material from which to derive data on PSG increment is clearly limited in England & Wales (Section 2.1). Many of the scales collected from Wye and Dee salmon over the last 40 or more years, and virtually all from Severn fish, have been disposed of. However, extensive records giving details of weight-for-age remain for these rivers.

Comparisons of mean PSG increment with mean weight at return for the same group of fish (Fig. 17), indicated that while these two growth measures are usually positively related, such relationships were significant in only two cases (for 1SW salmon on the Thames and 2SW salmon on the Dee). Accordingly, weight at return would not appear to provide a consistently strong surrogate for PSG increment.

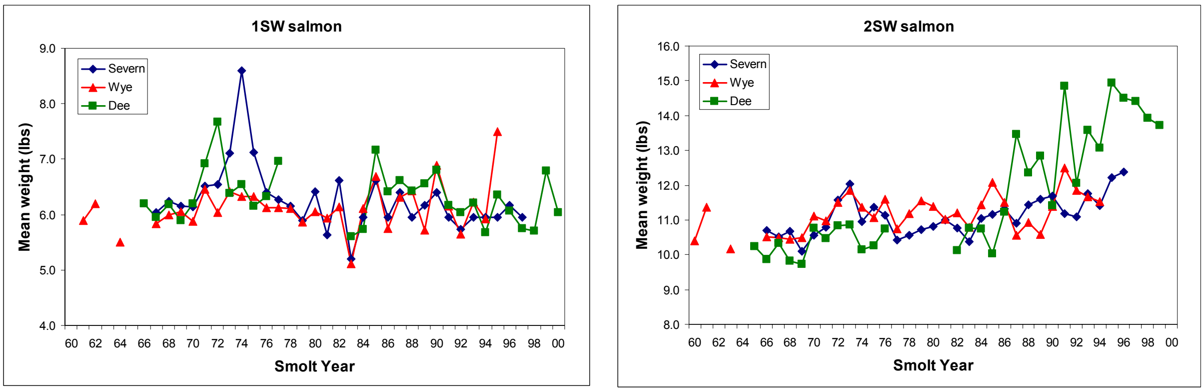
Figure 17 **Relationship between mean post-smolt growth increment and mean weight for 1SW and 2SW salmon on the Thames, Wye, Dee and Lune, 1983-98**



3.4 Historical Trends in Weight-at-Age

Fig 18 shows 40-year time-series of annual mean weight estimates for 1SW and 2SW salmon from the Severn, Wye and Dee. With the exception of recent data from the Dee trap, most of these estimates were based on net or rod caught fish (or a combination of the two) and were extracted directly or derived from summaries published in local fishery reports.

Figure 18 **Time-series of mean weight data for 1 and 2 SW salmon from the Severn, Wye and Dee originating primarily from fish captured by net and rod fisheries**



On all three rivers, significant positive trends (p≤ 0.002) in the recorded mean weight of 2SW salmon were evident over the last 40 years (Fig 18). On the Severn and Wye, the mean weight of 2SW fish appears to have increased gradually over the entire period, but on the Dee the rate of increase rose sharply after the 1985 smolt year (Fig 18). In contrast, trends in weight were less marked for 1SW salmon - except on the Severn where mean weights appear to have declined significantly over the time-series (p=0.038) (Fig 18).

Prior to the 1989 smolt year, Dee data for 2SW salmon originated solely from net caught fish (equivalent to the 1990 smolt year for 1SW salmon). After this time, all mean weight estimates were based on fish sampled at Chester Weir trap. Hence, the up-turn in the rate of weight increase recorded after 1985 did not simply coincide with the change from net caught to trap caught fish, or to any obvious change in net fishing practice.

In an attempt to make trap derived mean weight estimates for the Dee as compatible with earlier net fishery estimates as possible, the former were based only on fish captured between March and August. This matched the 1st March-31st August net fishing season up to 1994. After 1994, the start of the season was put back to the 1st May; then further delayed to the 1st June in 1999. [Note that the sampling protocol at Chester Weir was adjusted after 1992 when the weighing of early run MSW salmon - namely fish captured before the 1st July - effectively ceased in order to reduce handling of this sensitive run component. The resulting bias toward weighing later run (and larger) MSW fish exaggerates, to a small degree, the upward trend in weight of 2SW salmon after the 1991 smolt year (Fig 18).]

In a number of cases, mean weights of 1 and 2SW salmon were found to be significantly correlated – particularly among fish of the same sea age group (Table 11) - indicating a strong degree of spatial synchrony in this growth variable. However, there was little evidence of strong associations between weight-at-return and the SST variables described previously.

Table 11 **Correlation coefficients between mean weights of 1SW and 2SW salmon from the Severn, Wye and Dee; 1960-00. (All data $\log_{10}$ transformed.)**

	Severn 1SW	Wye 1SW	Dee 1SW	Severn 2SW	Wye 2SW
Wye 1SW	0.421***				
Dee 1SW	0.448**	0.435**			
Severn 2SW	0.124	0.521***	0.196		
Wye 2SW	0.097	0.228	0.134	0.522***	
Dee 2SW	-0.379*	0.229	-0.158	0.628***	0.354*

*$0.10 \geq p > 0.05$; ** $0.05 \geq p > 0.01$; ***$p \leq 0.01$

4. DISCUSSION

As ectotherms, fish normally have a body temperature near-identical to that of the surrounding water and therefore the rates of their biological functions are critically dependent on environmental temperature (Wood and McDonald, 1996). Accordingly, environmental temperature clearly has important consequences for the life history and survival of fishes - from the level of the individual up to that of the population or species. Perhaps the most predictable effects occur when temperature extremes are directly lethal to fish. In contrast, the consequences of sub-lethal temperatures - influencing processes such as growth and maturation - may be far more difficult to predict. A further level of complexity arises when considering the effects of temperature on the ecosystem as a whole and the implications for fish populations.

The primary focus of this study has been to explore the possible influence of temperature (as one aspect of climate change) on patterns of pre-smolt (effectively freshwater) and post-smolt (effectively marine) growth observed among salmon populations in England and Wales.

To do this, the study has identified a small number of rivers (Thames, Wye, Dee and Lune) where scale collections exist covering reasonable time-series of 10 to 20 years (Section 2.1), and has used these to generate new data on pre and post-smolt growth using back-calculation methods (Section 2.2). More conventional age and growth data (e.g. sea/river age, adult length/weight) have also been collated for these and other rivers (e.g. Severn).

The study has also extracted freshwater temperature records for lower main river sites on the Thames, Wye, Dee and Lune extending up to 40 years, estimating missing (monthly mean) temperatures by prediction from parallel series of air temperature records (Section 3.1.4). Near-shore sea-surface temperature records have also been examined from the data sets of Norris (2001).

4.1 Past Temperature Change

The temperature data examined in this study indicate that rivers and coastal waters in England and Wales have been getting warmer over the last 20-40 years.

On the Thames, Wye, Dee and Lune annual mean river temperatures appear to have increased by 0.3-1.9ºC over the last 20 years with the fastest rate of warming in the most southerly river (Thames) and the slowest rate in the most northerly (Lune) (Section 3.1.4). Similar warming trends are also evident from sea surface temperature (SST) data recorded at sites close to these rivers (Section 3.2.2).

These observations are in keeping with those of Hughes and Turrell (2003) who identified the period 1976-2000 as one of two periods of warming over the north Atlantic in the last century. (The other period: 1910-1945, pre-empts the salmon age and growth data examined in his study).

Such warming trends are not confined to the Atlantic area but are a global phenomenon. For example, Hughes and Turrell (2003) also note the findings of the Intergovernmental Panel on Climate Change (IPCC) who reported that global average surface temperatures (air and sea combined) increased by around 0.6 C during the 20th century. Warming trends in the northern hemisphere were even more significant, with the 1990s identified as the warmest decade of the 20th century and probably the warmest of the last millennium (IPPC, 2001).

It is also clear from this study that year-to-year fluctuations in annual mean temperatures are highly synchronous between sites - even though they are located several kilometres apart (Sections 3.1.4 and 3.2.2). This is the case not only among river and sea sites but between them, and suggests larger scale climatic processes influence both freshwater and marine environments simultaneously.

Given these common patterns of freshwater and marine temperature change, and the importance of temperature to the biology of fishes, then coherent trends in the age and growth of pre and post-smolt salmon might well be expected.

4.2 Freshwater Growth

The growth predictions for pre-smolt salmon generated for the Thames, Wye, Dee and Lune, using the model of Elliott and Hurley (1997), indicate that warming experienced in the last 20-40 years on these rivers (and presumably on other rivers within the same geographical range) has not resulted in marked increases in size-at-age.

Back-calculated (BC) lengths from adult scales on the Wye, Dee and Lune were compared with these predictions to provide some means (in the absence of direct measures of juvenile growth) of assessing their validity.

Overall, these comparisons indicated reasonable agreement between the two estimates in terms of absolute size, with 73% of BC lengths for age 1 and 2 fish (all rivers) being within 20% of the value predicted from the growth model, and 98% within 30%. This level of agreement was comparable with that found by Elliott and Hurley (1997) when they applied the same model to data from the Eden, and by Jensen *et al.* (2000) who applied the equivalent growth model for brown trout (Elliot *et al.* 1995) to data from populations around Europe.

In addition, there was some evidence from this study of synchrony in the inter-annual variability of BC and predicted growth estimates - at least in the case of 2 year-old fish on the Dee and Wye (Fig 6).

However, there were also differences between the two approaches; namely that: (i) BC estimates (except in 4 out of 98 cases) were always less than predicted estimates (as the growth model was based on fish fed on maximum rations, then any constraint on food availability in the wild could help explain this difference) and (ii) time-series of BC estimates showed significant positive trends ($p \leq 0.05$) in a number of instances whereas no significant positive trends were evident among predicted estimates.

Clearly, BC estimates of juvenile growth do not provide a true control against which to compare predicted estimates arising from the growth model, not least because BC estimates are unavoidably biased to represent only those pre-smolts which were able to survive to adulthood and not the ones which did not. BC estimates may also be affected by sampling bias associated with the method by which adult fish were captured and changes in that method through time, as well as possible inaccuracies in length measurements where these have been recorded by fishermen.

Similarly, a number of assumptions were made when applying the growth model which are unlikely to be realistic. For example, size and time at emergence were held constant in the model (represented as a starting weight of 0.15g on the 1st May), although in sea trout both these variables are known to fluctuate year-on-year and can significantly influence subsequent growth and survival (Elliott, 1984 and Elliott *et al.* 1999). Indeed emergence date has been shown to be influenced by temperature and climate change linked to the North Atlantic Oscillation (Elliott *et al.* 1999).

The model also imposed zero growth for the period 1st October-31st March in the first year following comparisons of observed and expected salmon growth rates by Elliott and Hurley (1997) on the Eden who found growth predictions improved following a similar restriction. However, while this may have been appropriate on the Eden where the population comprised mainly 'slow-growing' 2 year-old smolts, it may be less apt on rivers like the Wye and Dee which, over the last 20 years or so, appear to been producing significant numbers of 'faster-growing' 1-year old smolts (Fig 3).

Perhaps most importantly, using one source of lower main river temperature data to predict the growth of the population as a whole can only be broadly indicative of general trends as it ignores the complexity of river catchments – in terms of the temperature regimes which operate in different sub-catchments (influenced by factors such as altitude, aspect, shading by vegetation, etc.), the partitioning of total fish production among these sub-catchments and the behavioural response of fishes in avoiding adverse temperatures or in seeking out preferred conditions.

4.3 Marine Growth

4.3.1 Post-smolt growth

In examining marine growth, this study has focussed on the post-smolt phase, adopting the same measure of growth increment used by Friedland *et al* (2000) - who reported a significant correlation between post-smolt growth (PSG) increment and sea survival of 1SW salmon returning to the North Esk, Scotland, over a 40 year period.

In doing so, the study has sought, firstly, to identify adult scale collections for England and Wales from which PSG increment could be back-calculated and, secondly, to explore spatial and temporal trends in PSG increment as a potential indicator of marine survival.

For the first of these objectives, scale collections from only four rivers - the Thames, Wye, Dee and Lune were identified as suitable for further examination because of the extent of material available (10+ years). Among these four rivers, time-series of PSG increments were significantly or near-significantly correlated in a number of instances (Section 3.2.1).

Expanding the analysis to include post-smolt growth data from Scottish east-coast rivers (Maclean pers com), from the River Bush, N. Ireland (Crozier and Kennedy, 1999) and River Burrishoole, Ireland (McLoone, 2000), revealed further evidence of synchronous patterns in post-smolt growth (Section 3.2.1). This suggests that, overall, some of these correlations are more than chance occurrences but probably reflect the influence of common factors at sea on initial growth rate (and by association survival rate). [Clearly, some associations could occur by chance and so be of no biological significance. Others may be influenced by the different measures of post–smolt growth used among the different groups rivers, by measurement bias linked to the method of sampling (e.g. whether fish are obtained from rods, nets, traps, etc.) or by changes to the sampling method through the time-series.]

It is also apparent from these growth comparisons that the strength of association between PSG data from UK and Irish rivers does not always follow the pattern that might be anticipated on the basis of their spatial proximity (Figs 10 and 13).

The exception to this was among the Scottish rivers where post-smolt growth patterns were highly synchronous (Section 3.2.1) – probably reflecting the fact that the location of this group of rivers is so remote and distinctive from the rest. For example, they are the only rivers to enter the North Sea, they lie relatively close to one another along the coast, and, as a result, post-smolts from these rivers will enter a similar area of the sea and initially, at least, will take a different route to North Atlantic feeding grounds than fish entering from rivers in Ireland or the west-coast of England and Wales (Turrell and Shelton, 1993; Holm *et al.*, 2003).

The first days or weeks after entering the sea are likely to be among the most important for salmon post-smolts as the highest rates of natural mortality are believed to occur at this time (Friedland, 1998). In particular, survival during this period may be highly dependent on growth rate – with, for example, smaller fish considered to be more vulnerable to predation than larger ones (Doubleday *et al.*, 1979). It follows then, that fish entering common areas of the sea (such as those from Scottish east-coast rivers) are more likely to experience similar conditions for growth and survival.

While this explanation may be adequate for the Scottish situation, it is less convincing in other cases where the most coherent patterns of post-smolt growth appear to be shared by fish which enter the sea at quite different locations. For example, as is the case on the Wye where post-smolt growth patterns are more strongly associated with those of Scottish east-coast rivers than closer neighbours such as the Thames or Dee (Section 3.2.1).

Coherent growth patterns among distant river stocks should not be dismissed as simply a chance occurrence. The post-smolt growth period (as defined for most of the rivers examined in this study) covers a period of several months at sea - when fish from rivers across the north-east Atlantic will have time to mix together and experience common ocean environments. For example, most smolts from UK and Irish rivers are likely to emigrate to sea in spring (April May) and grow until the autumn - when the end of the post-smolt growth period is signified by the formation of the first sea annulus.

On the basis of observed post-smolt migration rates of 10-20 cm S^{-1}, Turrell and Shelton (1993) postulate that a smolt leaving a river in the North Sea in May, would arrive at Faroe sometime between August and November and could similarly reach the fishery grounds west of Greenland between January and October. Recaptures of post-smolts confirm that fish of southern European origin can reach areas off the Norwegian coast north of Iceland by the end of the first summer (Holm *et al.,* 2003). SALMODEL (2003) reported that one fish microtagged in a southern English river was recovered as far north as Jan Mayen island (around 70° N) – 2,000 km from its natal river and within 3 months of release.

In this way, similarities in post-smolt growth patterns among fish from UK and Irish rivers are likely to reflect a mixture of shared experiences in near and distant-water marine environments. However the first few days/weeks after sea entry may still be the most influential.

Finally, there was no evidence from this study that adult abundance indices – in the form of net and rod catches, trap catches or run estimates – might serve as useful surrogates for PSG increment (Section 3.2.3). However, this may not always be the case; for example, Maclean and Friedland (in prep) found that post-smolt growth patterns for the North Esk and neighbouring Dee were highly correlated among themselves and with local net catches – suggesting that both may reflect common trends in sea survival.

4.3.2 Adult weight-at-return

Data on size (and sea age) at return – usually recorded as the weight of fish caught by net or rod fisheries, are generally more widely available than estimates of PSG increment (or the scale material from which these were derived). Accordingly, 40-year time-series of weight data for 1SW and 2SW salmon from the Severn, Wye and Dee were examined in this study as (i) potential surrogates for post-smolt growth and (ii) as adult growth indices in their own right.

In exploring the former, it was apparent that while PSG increments were usually positively correlated with weight-at-return for 1 and 2SW fish, these correlations were rarely significant (Section 3.3). This indicates that final weight-at-return is not greatly dependent on the initial (post-smolt) growth rate at sea – even among 1SW salmon.

Cairns (2003) notes that uniformity in size-at-return seen among 1 and 2SW salmon on the Miramichi River, Canada over the last 20+ years may have arisen because fish aim to attain a specific target size at return which they achieve by adjusting their foraging intensity. Like the Miramichi, return weights for 1SW salmon on the Wye and Dee also appear to have remained relatively stable (i.e. have demonstrated no significant trend) over the last 40 years (Section 3.4). (Although, this wasn't so in the case for 1SW salmon on the Severn – where mean weight-at-return shows evidence of decline, or for 2SW salmon on any of the three rivers where mean weights appear to have been increasing over the time-series).

If the target weight hypothesis is valid then this could explain the weak relationships between PSG increment and return weight – with fish compensating for poor initial growth in the post-smolt phase. Conversely, if conditions for growth are good (as they appear to have been for 2SW salmon in recent years) and fish achieve their target weight earlier than usual - then there may be no disadvantage in putting on additional weight before return. Improved growth rates among 2SW salmon could also imply that marine survival rates have been improving for this group of fish, although there is little evidence for this from survival estimates collected from stocks across the north-east Atlantic (O'Maoileidigh *et al.,* 2003).

Cairns (2003) postulates that in poor growth years fish have to increase foraging activity to achieve a target weight and so will be susceptible to greater levels of predation (as the risk of detection by predators tends to increase the greater the foraging activity of the prey). Cairns (2003) also states that poor growth years may include years when SSTs are cooler than normal or the thickness of the warm sea surface layer is reduced, and suggests that in cooler conditions, fish - as ectotherms - are more susceptible to capture by endothermic predators (e.g. seals and sea birds).

Relationships between post-smolt growth rates and SSTs are discussed below, but no strong associations were found in this study between weight-at-return and various SST variables (Section 3.2.2). However, fluctuations in annual mean weight data for 1 and 2SW on the Severn, Wye and Dee were highly synchronous – particularly within sea age groups, suggesting that broad scale environmental factors have influenced final size at return.

4.3.3 Marine growth and temperature

Associations between near-shore SST data and post-smolt growth increment were examined for 1SW salmon from the Thames, Wye, Dee and Lune (Section 3.2.2). These revealed few significant correlations; indicating that temperature (at least when expressed as a simple monthly mean) had no marked influence on post-smolt growth. In the case of the Dee, other temperature variables were examined of potentially greater biological significance but were found to be equally uninformative (analyses not reported in detail here). These included (i) the difference between river and sea surface temperatures during the smolt migration; (ii) deviation from the 8-10C 'optimum' temperature identified by Friedland *et al.* (2000) as potentially important for sea survival; (iii) use of the Reynolds data series to explore associations with distant-water SSTs (see below).

SST data from a number of sources and expressed in various ways, were explored extensively in the SALMODEL (2003) project as potential predictor variables in models to forecast pre-fishery abundance (PFA) for stocks in the north-east Atlantic. Temperature variables ranged in complexity from observations at single sites, to construction of 'thermal habitat indices' in a manner similar to that used by ICES (2001) to predict PFA for North American salmon stocks.

The data sets used included the Reynolds Optimally Interpolated (ROI) Sea Surface Temperature data series and Reynolds Historical Reconstructed (RR) Sea Surface Temperature data series. Each was selected to provide coverage for large sectors of the north Atlantic (one of four 'blocks') where salmon were believed to be present at some stage during their marine migration. The ROI data series had a spatial resolution of 1° latitude by 1° longitude and a mixed temporal resolution of weekly and monthly means spanning 1981 to present (Reynolds et al., 2002). The RR data series was an extended version of the former covering the period 1950-99, but limited to 45° S to 69° N and providing readings at lower spatial and temporal resolutions (2° grid x monthly mean temperatures) (Smith et al., 1996).

Relationships between SST data (and other environmental variables including the 'North Atlantic Oscillation' and 'Gulf Stream North Wall') and abundance/survival data for salmon stocks from across the north-east Atlantic, were explored using a variety of analytical approaches (SALMODEL, 2003). These ranged from the use of simple correlation techniques (as in this study) to more novel statistical methods such as 'projection-pursuit regression'. [The latter approach - by creating 'composite' temperature indices helped avoid the problem of identifying meaningful relationships from the many significant, but possibly scientifically spurious correlations which may arise when numerous pairs of variables are examined.]

In some cases, (e.g. data for Northern Ireland; SALMODEL, 2003) regression analysis indicated that pre-fishery abundance could be predicted given suitable biological and environmental data - including SST data). However, in most instances, the number of significant correlations with SST and other data were no more than would be expected by chance (e.g. data for Ireland and Scotland; SALMODEL, 2003). Furthermore, where significant relationships were evident, these were generally inconsistent in terms of the monthly SST data which appeared most influential and whether associations were negative or positive.

SALMODEL (2003), developed models to predict PFA for north-east Atlantic stocks at West Greenland and at Faroes using temperature-preference habitat indices among the predictors (i.e. similar to those used in North American models; ICES 2001). They found that most of the predictive power was driven by the downward linear trend in the variable ‘log(PFA/Eggs)’ (a measure of survival rate) rather than indices of thermal habitat.

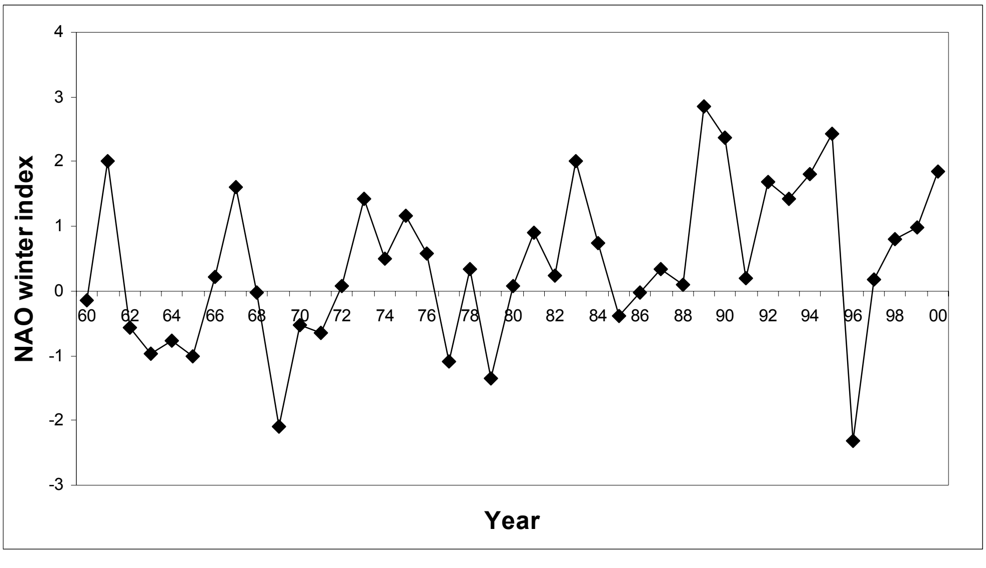
Generally, the findings from this study and SALMODEL (2003) indicate that variations in salmon survival, abundance and post-smolt growth have been little influenced by changes in SSTs in near or distant waters. Clearly, this does not mean that environmental temperature is unimportant for salmon in the sea. For example, Friedland *et al.* (2000) found that marine survival rates for 1SW and 2SW salmon from the North Esk, Scotland and Friggjo, Norway were both highly correlated with May sea temperatures - close to the time when smolts were entering the sea. Rather, (i) other (perhaps more complex) environmental factors have been the main cause of change and/or (ii) the temperature variables examined have poorly represented the true influence of temperature on salmon biology/ecology.

4.4 North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is the dominant recurrent mode of atmospheric behaviour in the North Atlantic sector throughout the year. It accounts for more than one-third of the total variance in sea-level pressure and represents the large-scale shift in atmospheric mass between a ‘high-index’ pattern, characterised by an intense Iceland Low with a strong Azores ridge to its south, and a ‘low-index’ pattern in which the signs of these anomaly cells reverse. The pressure difference between these two cells is the conventional index of NAO activity (Dickson and Turrell, 1999)

The NAO has exhibited considerable long-term variability (at decadal and other frequencies), which appears to be amplifying with time. Thus, the 1960s exhibited the most protracted and extreme negative phase of the Index; the late 1980s-early 1990s experienced the most prolonged and extreme positive phase, and the change from the low-index 1960s to the high index 1990s became the largest low-frequency change on record (Fig 19).

Figure 19 NAO Winter Index, 1960-00

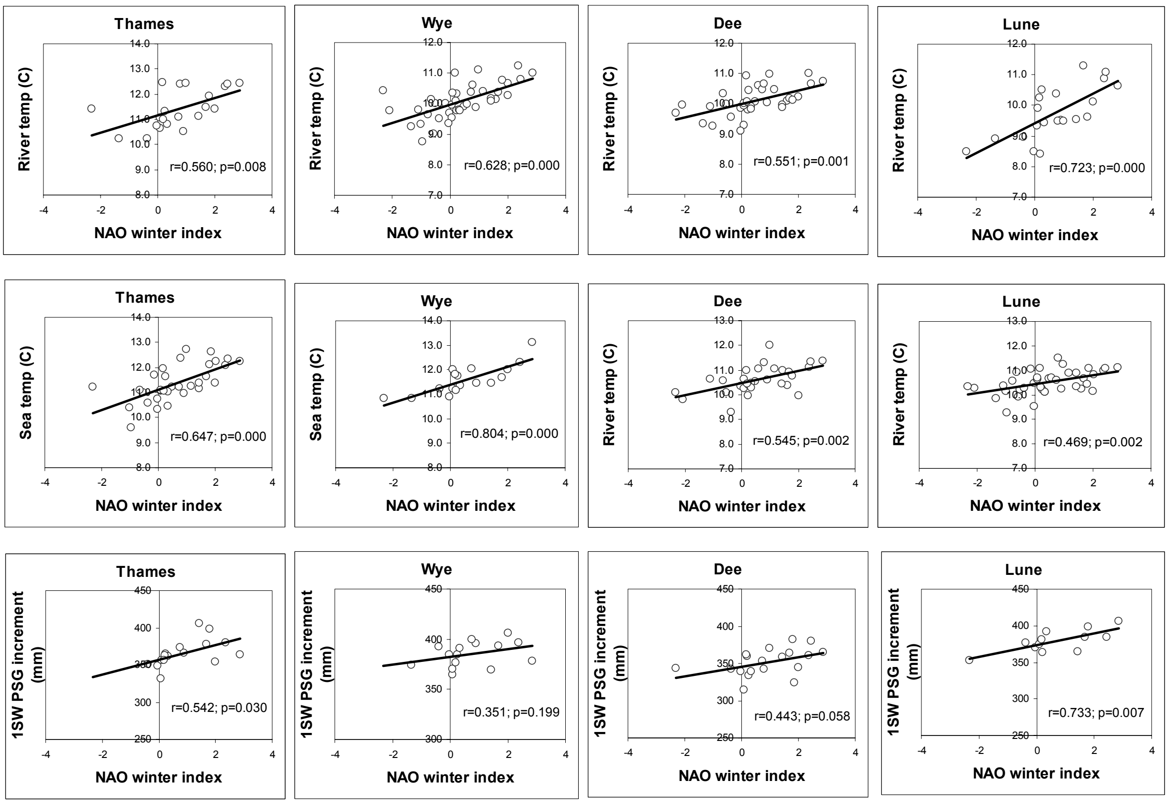


Dickson and Turrell (1999) describe how changes in the NAO Index produce a wide range of physical and biological response in the North Atlantic, including effects on wind speed, evaporation and precipitation, SST, ocean circulation, storminess, even production of zooplankton and fish recruitment. They explore how changes in the NAO index may have modified ocean conditions experienced by salmon over the last 40 years.

In this study, the NAO winter Index (equivalent to the mean index value for December to March) was found to be highly correlated with the river and sea surface temperature data associated with each of the four rivers; and (with the exception of the Wye) significantly or near-significantly correlated with PSG increments for 1SW salmon (Fig 20). (For the latter, the strength of association improved markedly when using the NAO index for the year following the smolt migration year, otherwise the NAO year corresponds to the year in which temperatures were recorded.)

It would seem then, that fluctuations in the NAO winter index are far more strongly associated with post-smolt growth patterns than any of the SST variables examined in this study. These associations suggest that the general shift toward a more positive phase of the index in the last 15-20 years may have improved post-smolt growth rates (and, as a possible consequence, sea survival rates). In contrast, when examined as part of the SALMODEL project, (SALMODEL, 2003) the NAO Index proved generally uninformative as a predictor variable for marine survival and adult abundance and was similarly ineffective in this study when compared with times-series of weight-at-return data (analyses not reported in detail here).

Figure 20 **Relationships between the NAO winter index, river and sea temperatures and PSG increments for 1SW salmon**



Where strong associations exist between the NAO index and fishery data, the nature of any effect, e.g. on salmon post-smolts, remains unclear because changes in the Index appear to give rise to such a variety of physical and biological responses (Dickson and Turrell, 1999). What is evident from the strong associations with temperature change described above (Fig 20), is that the NAO index can clearly influence freshwater and marine environments simultaneously. This may mean that freshwater factors have played a more significant role in the global decline of salmon than has been generally recognised particularly as freshwater effects could occur in parallel with marine effects and so potentially be 'masked' by them.

4.5 Future Temperature Change

Scenarios for future climate change (UKCIP, 2002) indicate that warming trends are likely to be far more severe in the coming decades than those experienced in the past. Even under the least severe 'low emissions' scenario, the future rate of global warming over the present century may be about four times that experienced during the twentieth century. For the 'high emissions' scenario, the future rate of warming may be about eight times that of the twentieth century (UKCIP, 2002).

For the UK, average temperatures by the 2080s may be 2 ^{o}C higher than the 1961-1990 baseline for the 'low-emissions' scenario and 3.5 ^{o}C higher for the 'high emissions' scenario. The south and east is expected to experience greater warming than the north and west and warming in summer and autumn should be greater than in winter and spring. By the 2080s for the high emissions scenario, parts of the south-east may be up to 5^{o}C warmer in summer (UKCIP, 2002). The future temperature profiles derived for the four rivers examined in this study (Section 3.1.4) should broadly reflect the spatial and temporal differences in warming patterns faced by the main salmon producing rivers in England and Wales (with the exception, perhaps, of rivers in the north-east of the country).

Applying the model of Elliott and Hurley (1997) to these temperature profiles indicates that growth of salmon in freshwater, for the 'low-emissions' scenario, could generally improve over the next 100 years, except in rivers in the south-east (the latter represented by the Thames). For the 'high-emissions' scenario, growth rates begin to decline as temperatures exceed optimum levels. This decline begins earliest and its effects are most severe in more southerly rivers, but even in a river as northerly as the Dee, size-at-age could fall well below that of recent years by the end of the century.

The relatively stable growth rates predicted for salmon on the Wye and Dee over the last 30-40 years are in marked contrast to the decline in mean smolt age apparent on both these rivers and (to lesser extent) the Severn since the 1980s (Fig. 3), and suggest that factors other than (or in addition to) a general rise in temperature may have been the main cause. Should growth rates for salmon in the UK improve as a result of global warming then further declines in mean smolt age may occur. However, the opposite effect could arise if warming results in declining growth rates – producing older mean smolt ages and fish of smaller size-at-age which are likely to experience higher mortality rates (e.g. because of starvation or greater susceptibility to predation) and, as a consequence, reduced abundance.

Elliott (1994) drew similar conclusions about the possible effects of global warming on growth and survival of juvenile trout, as did McCarthy and Houlihan (1997) who speculated about the positive and negative effects of warming on two contrasting salmon populations toward the extremes of the latitudinal range.

Warming trends have more severe consequences for trout than salmon because of their lower ‘thermal tolerance’ (Elliott 1994). Growth predictions for trout on the Thames, Wye, Dee and Lune (Davidson, Hazlewood and Cove, in press) appear less favourable than for salmon with marked reductions in growth rate evident from the 2020s onward - even under the low emissions scenario. Geographical differences in the growth rates of salmon and trout as a result of warming may already exist among rivers in England and Wales and could become more marked in the next few decades as temperatures rise. For example, on more southerly rivers (like the Thames) salmon and trout may already be growing at a slower rate than they were 30 years ago, and in the case of trout, the size attained by a 2 year old fish may be well below that of cooler rivers to the west and north (Davidson, Hazlewood and Cove, in press).

Whether growth predictions for the future will prove accurate is uncertain. Part of this uncertainty is linked to the predictions for temperature change and their application (in this case) to riverine environments. For example, while mean air temperature is expected to increase over the next 100 years, increases in river temperature may be less marked – a difference which is likely to be greatest on aquifer fed rivers (like the Thames and other ‘chalk’ rivers - many of which are located in southern England). Other sources of uncertainty stem from assumptions made in applying the growth model of Elliott and Hurley (1997) (Section 4.2). Also, physiological processes other than growth may be affected by temperature change with equally important consequences for salmon and other fish species (Wood and McDonald, 1997).

Furthermore, rising temperature is just one aspect of climate change expected as a result of global warming. Summers are likely not only to become hotter, but drier; and winters milder but also wetter - with more frequent episodes of intense rainfall leading to increased flooding (UKCIP, 2002). Increases in the frequency of both droughts and floods may adversely affect populations of juvenile and adult salmon in rivers. Global warming will also impact upon marine as well as freshwater environments (UKCIP, 2002), although for the former, the consequences for salmon are perhaps more difficult to predict - given our generally poorer understanding of ocean process and the species’ marine existence (Hughes and Turrell, 2003).

5 CONCLUSIONS

The main focus of this study has been to explore relationships between:

(i) **temperature** as a key environmental variable for fish and other ectotherms and a major component of climate change and

(ii) **growth** as one of the most important physiological responses to temperature change with significant consequences for life history and survival.

In doing so, it has been established that:

5.1 Past Temperature Change:

- Temperature records examined for rivers and coastal waters in England and Wales indicate both have been getting warmer over the last 20-40 years. These observations are in keeping with warming trends reported across the north Atlantic (Hughes and Turrell, 2003) and globally (IPPC, 2001).

- In both cases, geographical differences in warming rates were evident (e.g. southerly sites appear to be warming faster than northerly sites). Temperature fluctuations among river and sea sites were also highly synchronous suggesting that large-scale climatic processes are influencing both freshwater and marine environments simultaneously.

Given these common patterns of freshwater and marine temperature change, and the importance of temperature to the biology of fishes, then coherent trends in the age and growth of pre and post-smolt salmon might be expected.

5.2 Pre-Smolts:

- Growth predictions from the model of Elliott and Hurley (1997) suggest that pre-smolt (freshwater) growth rates on the Wye and Dee have improved in response to increasing temperatures, but not significantly so.

- These relatively stable growth predictions contrast a marked decline in mean smolt age of salmon evident on some rivers (Severn, Wye and Dee). This decline begins around the early 1980s but proceeds at different rates thereafter.

- This may indicate factors other than, or in addition to, temperature have been promoting faster growth in pre-smolt salmon on these rivers and, as a consequence, a decline in their mean smolt age.

5.3 Post-Smolts:

- Common patterns of post-smolt (first-year marine) growth are apparent among salmon stocks around the UK and Ireland - including from rivers in E&W (Thames, Wye, Dee and Lune) as well as Scotland (east-coast rivers), N-Ireland (Bush) and Ireland (Burrishoole).

- These common patterns are likely to be influenced by a mixture of fine and broad-scale environmental processes operating throughout post-smolt the period and could be indicative of shared trends in sea survival (Friedland *et al.*, 2000). However, no data are available in this study to confirm the link between post-smolt growth and survival and the existence of such a link is not evident elsewhere (Crozier and Kennedy, 1997).

- Sea surface temperature (SSTs) data (expressed in a variety of ways), were generally poorly associated with post-smolt growth patterns (this study) or with more direct measures of sea survival and adult abundance (SALMODEL, 2003). This does not mean that environmental temperature is unimportant for salmon in the sea, rather that other (perhaps more complex) factors have been the main cause of change and/or the temperature variables examined have poorly represented the true influence of temperature on salmonid biology/ecology.

- In contrast, the North Atlantic Oscillation (NAO) index was strongly correlated with patterns of PSG increment for 1SW salmon (this study). Year-to-to year variations in river and sea surface temperatures around E&W, and the NAO index were also highly synchronous. These relationships highlight the over-riding influence of the NAO as the dominant atmospheric process in the North Atlantic and one which appears to serve as a general surrogate for a number of climatic effects operating over land and sea (Dickson and Turrell, 1999).

- Global decline in abundance of Atlantic salmon is usually assumed to stem mainly from changes in the marine environment (Friedland 1998). However, the potential for large-scale processes such as the NAO to affect both freshwater and marine environments together may mean that the influence of freshwater factors in this decline has been understated.

- Like PSG increments, annual variations in adult weight-at-return data (Severn, Wye and Dee) were also highly synchronous, especially within sea age groups, but showed no strong associations with SST variables or the NAO index.

- Weak correlations between weight-at-return and PSG increment indicate the former is not heavily influenced by initial growth at sea. Cairns (2003) suggests that salmon aim to achieve a target weight prior to return and one of the consequences of this is that fish must compensate for poor initial growth by increased foraging activity but at the cost of greater susceptibility to predation.

- Relatively stable return weights for 1SW salmon (Wye and Dee) over the last 40 years are consistent with the target weight hypothesis; conversely, the weight for 2SW salmon appears to have been increasing in recent years (Severn, Wye and Dee).

5.4 Future Temperature Change

- Scenarios for future climate change (UKCIP, 2002) suggest that warming trends are likely to be far more severe in the coming decades than those experienced in the past – even under the best case ‘low emissions’ scenario.

- Growth predictions from the model of Elliott and Hurley (1997) based on temperature profiles forecast to the end of this century, indicate that on rivers in the south-west and north, freshwater growth rates could generally improve under the 'low emissions' scenario but may fall below current levels under the 'high-emissions' scenario as temperatures exceed optimum levels in the latter half of the century. On rivers in the south-east (represented by the Thames) - where warming is expected to be greatest - declining growth rates may result with adverse consequences for abundance and survival.

- Temperature increases are likely to have more severe consequences for trout in freshwater than salmon - as trout have the lower thermal tolerance of the two species (Davidson, Hazlewood and Cove, in press). However, for both species, warming is only one aspect of climate change that might prove detrimental at extreme levels; expected increases in the frequency of summer droughts and winter floods could also adversely affect survival and abundance.
- The effects of global warming on salmon in the sea are more speculative given our poorer knowledge of ocean processes and of the marine life of Atlantic salmon (Hughes and Turrell, 2003).

5.5 Futher Studies

Future climate change is likely to have significant consequences for freshwater fish in the UK. This study indicates that for 'cold water' species, like salmon, elevated river temperatures (as one aspect of climate change) could have mixed effects in time and space – with improved growth following small increases in temperature but depressed growth and reduced survival/abundance as temperatures exceed the optimum for growth.

Changes to freshwater or marine growth may be among the first signs that climate is having an unusual affect on fish populations. Detecting these changes and related traits such as age at smoltification or age at maturation will help in understanding and explaining associated fluctuations in abundance and inform fisheries management in a period of potentially unprecedented environmental change.

The Agency already routinely collects growth data for salmon (and trout) as part of sampling programmes whose primary aim is to monitor changes in abundance either from electrofishing surveys (juveniles); net and rod catch returns (adults) or trapping programmes (smolts and adults). These data include:

For all principal salmon rivers:

Juvenile length and age composition - collected on a site-by-site basis as part of the national juvenile monitoring programme. Sites are electrofished in summer either annually ('temporal sites') or 5-yearly ('spatial' sites).

Adult weight-at-return - for net (fish recorded by weight category) and rod caught fish (individual fish weights reported). Data submitted annually via the licence return for all salmon rivers. In many cases, weights are likely to be estimated by fishermen.

For 'index' monitored rivers (Tyne, Test and Itchen, Tamar, Dee and Lune) and other rivers with trapping programmes (Thames, Taff, Tawe):

Smolt length and age composition - Annual run sampling (Tyne, Test and Itchen, Tamar, Dee)

Adult length, weight and age composition - Annual run sampling (all the above rivers)

These growth data are collected at relatively low-cost and their collection should continue while the primary purpose of each sampling programme remains.

Where adult scales are collected, back-calculated pre and post-smolt lengths should be obtained to provide additional growth data for temporal and spatial comparisons. In the absence of resources for this work, scale samples should at least be stored to allow examination at a later date when funding allows. Similarly, surviving historic scale collections should be retained for future reference.

Age and growth data currently collected should be routinely analysed and reported nationally at an appropriate frequency (perhaps 5-yearly with an annual review of the effectiveness of each sampling programme), and also presented in the context of existing reporting on stock status (e.g. salmon report to ICES, 'State of the Nation's Fisheries' report).

The option of collecting adult scales from other rivers via net or rod fishermen is probably not a viable one given the experience of Harris (1995) whose attempts to meet the objectives of sea trout scale sampling programme using volunteer anglers met with limited success.

The feasibility of collecting more detailed (sub-catchment) river temperature data in conjunction with existing juvenile (and other ecological) monitoring programmes should be explored. Nominated sites should reflect different sub-catchment types within a river system (e.g. selected by aspect, tree cover, altitude, etc.) and different river systems across England and Wales broadly representative of expected geographical variations in future warming trends.

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Appendix I Salmon age data for rivers in England and Wales, 1970-02: Number of individual fish records shown by catch year

Method: Found dead	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Thames							5	14	7	3	4	7	2	3	2	4	4	2	1						58
Tyne												1	90	23	82	72	26	77	17						388
All	0	0	0	0	0	0	5	14	7	3	4	8	92	26	84	76	30	79	18	0	0	0	0	0	446

Method: Electrofished	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Thames						35	18	54	2	17	21	70	18	22	60	72	6	15							410
All	0	0	0	0	0	35	18	54	2	17	21	70	18	22	60	72	6	15	0	0	0	0	0	0	410

Method: UKN	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Conwy											26	35													61
Dee											1	7													8
Derwent									15	2															17
Eden									7																7
Ehen									3																3
Ellen									1																1
Lune									2								1								3
Severn	1		5	17	7	3	5		5	2	26	11	3			63	1	7							156
Wye			4	3	2	2																			11
All	1	0	9	20	9	5	5	0	33	4	53	53	3	0	0	63	2	7	0	0	0	0	0	0	267

Method: Net	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Avon									20	25	2	4													51
Conwy										14	11	3													28
Dee						201	180	290	121	71	128	46													1037
Itchen															16										16
Kent															10	3									13
Lune									72	91		52				172	71	31	22	27	33				571
North Northumbria								254	159	462															875
Ribble									4		8														12
Severn	84		150	94	214	133	137		183	652	799	728	528	461		472	321	286							5242
Solway									2	7	44	34													87
Tamar									83																83
Thames															1	1									2
Tyne								51			607	156													814
Wye			150	135	135	146																			566
All	84	0	300	229	349	480	317	595	644	1322	1599	1023	528	461	27	648	392	317	22	27	33	0	0	0	9397

Method: Rod	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Avon									4	6	26	13						24							73
Conwy									82	59	8	13													162
Dee							1	9		1		1													12
Eden										3		1													4
Exe		54																							54
Fowey		54																							54
Frome																		34							34
Kent															74	127	80	46	62						389
Lune										7	31	16	24	1	37	49	24	35	12	14					250
Severn	5		392	127	174	108	242		147	225	82	78	47	14		28	14	36							1719
Tamar							115	234	17																366
Test											21	2	48	75	97	48									291
Thames						3	4	7	3	5	5	8	1	1	7	10	9	14							77
Wye			50	70	66	27	729	828	626	1003	394	449	432	331	371	396	220	110							6102
All	5	108	442	197	240	138	1091	1078	879	1309	567	581	552	422	586	658	347	299	74	14	0	0	0	0	9587

Appendix I (contd.)

Method: Trap	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Dee								84	112				882	1230	1403	1644	1525	1134	1370	1190	731	591	921	1206	14023
Lune																2	58	136	63	47					306
Tawe													92	72	72	368	39	56	56	69					824
Thames						41	36	81	41	285	90	62	34	252	257	138	171	118			30				1636
All	0	0	0	0	0	41	36	165	153	285	90	62	1008	1554	1732	2152	1793	1444	1489	1306	761	591	921	1206	16789

Method: All	1970	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	All
Avon	0	0	0	0	0	0	0	0	24	31	28	17	0	0	0	0	0	24	0	0	0	0	0	0	124
Conwy	0	0	0	0	0	0	0	0	82	73	45	51	0	0	0	0	0	0	0	0	0	0	0	0	251
Dee	0	0	0	0	0	201	181	383	233	72	129	54	882	1230	1403	1644	1525	1134	1370	1190	731	591	921	1206	15080
Derwent	0	0	0	0	0	0	0	0	15	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
Eden	0	0	0	0	0	0	0	0	7	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	11
Ehen	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Ellen	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Exe	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54
Fowey	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54
Frome	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	0	0	0	0	0	0	34
Itchen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	16
Kent	0	0	0	0	0	0	0	0	0	0	0	0	0	0	84	130	80	46	62	0	0	0	0	0	402
Lune	0	0	0	0	0	0	0	0	74	98	31	68	24	1	37	223	154	202	97	88	33	0	0	0	1130
North Northumbria	0	0	0	0	0	0	0	254	159	462	0	0	0	0	0	0	0	0	0	0	0	0	0	0	875
Ribble	0	0	0	0	0	0	0	0	4	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	12
Severn	90	0	547	238	395	244	384	0	335	879	907	817	578	475	0	563	336	329	0	0	0	0	0	0	7117
Solway	0	0	0	0	0	0	0	0	2	7	44	34	0	0	0	0	0	0	0	0	0	0	0	0	87
Tamar	0	0	0	0	0	0	115	234	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	449
Tawe	0	0	0	0	0	0	0	0	0	0	0	0	92	72	72	368	39	56	56	69	0	0	0	0	824
Test	0	0	0	0	0	0	0	0	0	0	21	2	48	75	97	48	0	0	0	0	0	0	0	0	291
Thames	0	0	0	0	0	79	63	156	53	310	120	147	55	278	327	225	190	149	1	0	30	0	0	0	2183
Tyne	0	0	0	0	0	0	0	51	0	0	607	157	90	23	82	72	26	77	17	0	0	0	0	0	1202
Wye	0	0	204	208	203	175	729	828	626	1003	394	449	432	331	371	396	220	110	0	0	0	0	0	0	6679
All	90	108	751	446	598	699	1472	1906	1718	2940	2334	1797	2201	2485	2489	3669	2570	2161	1603	1347	794	591	921	1206	36896

Appendix II Numbers of fish from which scale radii measurements were obtained by smolt year, sea age group and capture method: Thames, Wye, Dee and Lune 1979-01

Thames

Smolt year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1SW salmon																							
Net															1								
Rod				3	2		5	3	3	2	2	2	1	1	4	1							
Trap			37	14	29	20	66	28	215	57	28	21	213	185	69	83	71	8	4	28			
EF					14	9	31	2	12		10			16	41		1						
Unkn			36	16	9	6	5	2	1	17	22	1	7	6	3	4	2						
Total	0	0	73	33	54	35	107	35	231	76	62	24	221	208	118	88	74	8	4	28	0	0	0
2SW salmon																							
Net																							
Rod										1			3										
Trap		1	1	2	6	4		8	13	15	7	8	52	24	4	18	12		2				
EF				2	2	2				5			3	8									
Unkn		2	3	1	3			1	1	12	3	3	1	1	1	4							
Total	0	3	4	5	11	6	0	9	14	33	10	11	59	33	5	22	12	0	2	0	0	0	0

Wye

Smolt year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1SW salmon																							
Net		126	93	111	102																		
Rod		26	51	37	20	159	154	162	140	46	44	52	79	160	129	11	2						
Trap																							
EF																							
Unkn		2	2	1	1																		
Total	0	154	146	149	123	159	154	162	140	46	44	52	79	160	129	11	2	0	0	0	0	0	0
2SW salmon																							
Net	24	42	24	44																			
Rod	24	19	30	7	57	60	57	54	56	55	53	54	68	53	153	96							
Trap																							
EF																							
Unkn	2	1	1	1																			
Total	50	62	55	52	57	60	57	54	56	55	53	54	68	53	153	96	0	0	0	0	0	0	0

Dee

Smolt year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1SW salmon																							
Net					109	108	194	81	38	92	31												
Rod							7																
Trap							58	46				146	143	147	145	142	147	150	150	149	144	136	129
EF																							
Unkn																							
Total	0	0	0	0	109	108	259	127	38	92	31	146	143	147	145	142	147	150	150	149	144	136	129
2SW salmon																							
Net				92	72	96	33	14	19	15													
Rod					1	2		1															
Trap						26	66				47	50	4	47	49	49	49	50	51	61	48	80	
EF																							
Unkn																							
Total	0	0	0	92	73	124	99	15	19	15	47	50	4	47	49	49	49	50	51	61	48	80	0

Lune

Smolt year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1SW salmon																							
Net								57	67		32				95	44	6	18	21	30			
Rod										13	5	17	1	25	31	16	23	9	13				
Trap															2	47	85	57	44				
EF																							
Unkn																							
Total	0	0	0	0	0	0	0	57	67	13	37	17	1	25	128	107	114	84	78	30	0	0	0
2SW salmon																							
Net							13	16		11				77	26	25	4	6	3				
Rod								1	2	4	7		3	18	8	12	3						
Trap															10	51	6	3					
EF																							
Unkn																							
Total	0	0	0	0	0	0	13	17	2	15	7	0	3	95	44	88	13	9	3	0	0	0	0

Appendix III Predicted monthly average river temperatures for the River Thames, Dee and Lune up to the 2080s, based on observed temperatures in the period 1960-90 and UKKCIP (2002) modelled seasonal temperature increases for low and high emission scenarios.

a. Thames

	Mean river temperature (ºC)						
		Low emissions scenario			High emissions scenario		
Period	**1961-90**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Mar	6.6	7.3	7.6	8.0	7.3	8.0	9.0
Apr	9.1	10.1	10.5	11.0	10.1	11.0	12.5
May	12.8	14.2	14.8	15.5	14.2	15.5	17.5
Jun	16.5	17.9	18.8	19.3	17.9	19.8	21.2
Jul	18.4	19.9	20.9	21.5	19.9	22.0	23.5
Aug	18.2	19.7	20.7	21.3	19.7	21.8	23.3
Sep	15.7	17.0	18.3	19.0	17.7	19.6	22.3
Oct	12.1	13.1	14.1	14.6	13.6	15.1	17.1
Nov	7.9	8.6	9.2	9.6	8.9	9.9	11.2
Dec	5.4	6.6	7.2	7.7	6.6	7.7	9.5
Jan	4.3	5.2	5.7	6.1	5.2	6.1	7.5
Feb	4.1	5.0	5.5	5.9	5.0	5.9	7.3
Spring (MAM)	9.5	10.5	11.0	11.5	10.5	11.5	13.0
Summer (JJA)	17.7	19.2	20.2	20.7	19.2	21.2	22.7
Autumn (SON)	11.9	12.9	13.9	14.4	13.4	14.9	16.9
Winter (DJF)	4.6	5.6	6.1	6.6	5.6	6.6	8.1

	Mean temp increase (ºC)		
Period	**2020s**	**2050s**	**2080s**
Low emissions scenario			
Spring (MAM)	1.0	1.5	2.0
Summer (JJA)	1.5	2.5	3.0
Autumn (SON)	1.0	2.0	2.5
Winter (DJF)	1.0	1.5	2.0
High emissions scenario			
Spring (MAM)	1.0	2.0	3.5
Summer (JJA)	1.5	3.5	5.0
Autumn (SON)	1.5	3.0	5.0
Winter (DJF)	1.0	2.0	3.5

b. Dee

	Mean river temperature (ºC)						
		Low emissions scenario			High emissions scenario		
Period	**1960-90**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Mar	5.9	6.6	6.9	7.2	6.6	7.2	8.2
Apr	8.4	9.3	9.8	10.3	9.3	10.3	11.7
May	12.1	13.5	14.2	14.8	13.5	14.8	16.9
Jun	15.1	16.0	16.5	17.5	16.0	17.5	18.9
Jul	16.6	17.6	18.1	19.2	17.6	19.2	20.8
Aug	15.9	16.9	17.4	18.4	16.9	18.4	19.9
Sep	13.3	14.6	15.8	16.5	15.2	16.5	19.1
Oct	10.5	11.5	12.5	13.0	12.0	13.0	15.0
Nov	7.2	7.9	8.6	9.0	8.3	9.0	10.4
Dec	5.7	6.8	6.8	7.4	6.8	7.9	9.1
Jan	4.8	5.8	5.8	6.3	5.8	6.7	7.7
Feb	4.4	5.3	5.3	5.8	5.3	6.2	7.1
Spring (MAM)	8.8	9.8	10.3	10.8	9.8	10.8	12.3
Summer (JJA)	15.8	16.8	17.3	18.3	16.8	18.3	19.8
Autumn (SON)	10.3	11.3	12.3	12.8	11.8	12.8	14.8
Winter (DJF)	5.0	6.0	6.0	6.5	6.0	7.0	8.0

	Mean temp increase (ºC)		
Period	**2020s**	**2050s**	**2080s**
Low emissions scenario			
Spring (MAM)	1.0	1.5	2.0
Summer (JJA)	1.0	1.5	2.5
Autumn (SON)	1.0	2.0	2.5
Winter (DJF)	1.0	1.0	1.5
High emissions scenario			
Spring (MAM)	1.0	2.0	3.5
Summer (JJA)	1.0	2.5	4.0
Autumn (SON)	1.5	2.5	4.5
Winter (DJF)	1.0	2.0	3.0

c. Lune

	Mean river temperature (ºC)						
		Low emissions scenario			**High emissions scenario**		
Period	**1960-90**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Mar	6.2	6.9	7.3	7.7	6.9	7.7	8.8
Apr	8.6	9.6	10.1	10.6	9.6	10.6	12.1
May	10.7	12.0	12.6	13.2	12.0	13.2	15.1
Jun	13.5	14.4	14.8	15.7	14.4	15.7	17.1
Jul	14.7	15.7	16.2	17.2	15.7	17.2	18.6
Aug	16.7	17.8	18.4	19.5	17.8	19.5	21.2
Sep	12.4	13.6	14.9	15.5	14.3	16.2	18.0
Oct	10.5	11.5	12.6	13.1	12.1	13.7	15.2
Nov	6.9	7.6	8.2	8.6	7.9	8.9	10.0
Dec	5.8	6.9	7.5	7.5	6.9	8.1	9.2
Jan	4.7	5.6	6.0	6.0	5.6	6.5	7.4
Feb	4.9	5.9	6.3	6.3	5.9	6.8	7.8
Spring (MAM)	8.5	9.5	10.0	10.5	9.5	10.5	12.0
Summer (JJA)	15.0	16.0	16.5	17.5	16.0	17.5	19.0
Autumn (SON)	9.9	10.9	11.9	12.4	11.4	12.9	14.4
Winter (DJF)	5.1	6.1	6.6	6.6	6.1	7.1	8.1

	Mean temp increase (ºC)		
Period	**2020s**	**2050s**	**2080s**
Low emissions scenario			
Spring (MAM)	1.0	1.5	2.0
Summer (JJA)	1.0	1.5	2.5
Autumn (SON)	1.0	2.0	2.5
Winter (DJF)	1.0	1.5	1.5
High emissions scenario			
Spring (MAM)	1.0	2.0	3.5
Summer (JJA)	1.0	2.5	4.0
Autumn (SON)	1.5	3.0	4.5
Winter (DJF)	1.0	2.0	3.0