Scoping Study into Adaptation of the Tasmanian Salmonid Aquaculture Industry to Potential Impacts of Climate Change

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Scoping Study into Adaptation of the Tasmanian Salmonid Aquaculture Industry to Potential Impacts of Climate Change

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Associate Professor Stephen Battaglene[1]
Professor Christopher Carter[1,2]
Dr Alistair Hobday[3]
Dr Vincent Lyne[3]
Associate Professor Barbara Nowak[1,2]

[1]Tasmanian Aquaculture and Fisheries Institute, Marine Research Laboratories, University of Tasmania, Private Bag 49, Hobart Tasmania, 7001
[2]Tasmanian Aquaculture and Fisheries Institute, National Centre for Marine Conservation and Resource Sustainability, University of Tasmania
[3] Climate Adaptation Flagship, CSIRO Marine and Atmospheric Research, Castray Esplanade Hobart, Tasmania, 7000

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List of Abbreviations

ABARE - Australian Bureau of Agricultural and Resource Economics

AD - Apparent Digestibility

AGD - Amoebic Gill Disease

AOGCM - Atmosphere Ocean General Circulation Model

Aquafin CRC - Aquafin Collaborative Research Centre

BOD - Biological Oxygen Demand

BOM - Bureau of Meteorology

CSIRO - Commonwealth Scientific and Industrial Research Organisation

DGC - Daily Growth Co-efficient

DE - Energy Digestibility

DP - Protein Digestibility

EAC - East Australian Current

FRDC - Fisheries Research and Development Corporation

GCM - Global Climate Model

GMO - Genetically Modified Organism

GR - Growth Ration

HAB - Harmful Algal Blooms

IPCC - Intergovernmental Panel on Climate Change

MOU - Memorandum of Understanding

MJ - Mega Joule

PUFA - Polyunsaturated Fatty Acids

RCM - Regional Climate Model

RLO - Rickettsia-like Organism

RNA - Ribonucleic Acid

SBT - Southern Blue fin Tuna

SGR - Specific Growth Rate

SST - Sea Surface Temperature

TGC - Thermal Growth Co-efficient

TSGA - Tasmanian Salmonid Growers Association

1 Executive summary

This scoping study was conducted under the Australian Government's *National Agriculture & Climate Change Action Plan: Implementation Programme*[1] which identifies and supports initiatives for coordinated action on climate change. The objectives of the study were to:

a) Identify and review key climate change information needs as they relate to the Tasmanian salmonid aquaculture industry;

b) Scope the likely impacts of climate change as they relate to the Tasmanian salmonid aquaculture industry; and

c) Scope possible solutions for adaptation and identify viable industry development opportunities.

The Tasmanian salmonid farming industry is Australia's largest and most valuable seafood producer, currently producing 26,000 tonnes of Atlantic salmon at an estimated farm gate value of $272 million. Fish are farmed in geographic regions that sometimes have average water temperatures approaching the upper thermal limits for salmon production. Fish growth is extremely fast resulting in a production advantage compared to many northern hemisphere regions. However, the rapid expansion of the industry is potentially restricted by control and management of disease, competition from overseas producers, availability of water in which to farm and environmental changes. There is concern that ocean warming associated with climate change could result in the thermal limit being exceeded for a portion of the year in some Tasmanian regions, even while the rest of the year is more optimal for production. Additional impacts of climate change, such as availability of freshwater, extreme storm events and increases in jellyfish blooms, may also have consequences for the salmon industry.

The project is presented in three parts: Part A *Predictive modelling* is a review of models that can inform understanding of future environmental conditions, identification of key environmental variables, and a summary of potential delivery mechanisms; Part B *Salmon performance at higher temperatures* is a review of impacts on salmonid health and nutrition; Part C *Alternate species and solutions* discusses adaptation strategies, attributes of new species, biosecurity and other challenges.

The *Predictive modelling* section provides a summary of the range of prediction approaches that may be used at the three time scales of interest, short (months to seasonal), medium (several years) and long (decades), and their relative advantages and disadvantages. The approaches comprise three categories, statistical modelling,

[1] The National Agriculture & Climate Change Action Plan and its implementation are actions of the National Climate Change Adaptation Framework agreed by the Council of Australian Governments in April 2007 (www.coag.gov.au).

dynamical downscaling, and ensemble analysis of climate models. Climate models are generally referred to as Global Climate Models (GCMs), and different models are produced by science agencies around the world. Australia, through CSIRO, maintains one GCM. Climate variables relevant to salmon performance are identified. However, some key variables are not available from the present generation of GCMs for the temporal and spatial scales that are relevant to the salmonid industry. In general, the spatial scale of current GCMs is too large, and does not show the variation observed *in situ* farm temperatures. Despite this coarse resolution, GCM predictions for changes in key variables: annual sea surface temperatures, seasonal wind speed, rainfall and solar radiation are provided for the three growing regions as general indicators of change. It is likely that average sea surface temperatures at the inshore farm locations are underestimated by the GCMs, and the average change in southern Tasmanian waters by 2030 could be treble the annual 1^{o}C predicted by GCMs. An increase of 3^{o}C against a baseline of 11 to 18^{o}C is used for boundary setting in the rest of the study. Other predictions of interest to farmers are winter wind speeds increasing by up to 5% and summer rainfall decreasing by 5%. Examples of supplementary information sources for key meteorological and oceanographic variables together with their respective information timescales are documented.

The *Salmon performance at higher temperatures* section highlights the general lack of knowledge about effects of higher water temperatures and other environmental changes related to climate change on farmed Atlantic salmon, especially larger fish in sea cages. There is a wealth of overseas research based on colder temperatures, but this has been conducted mainly on small fish, and often for different species of salmonids. Australia will need a sustained research effort to address this knowledge gap for the salmonid industry. It is clear that rising water temperatures associated with global warming will increase thermal stress and disease outbreaks unless new treatments are developed. In the short term, outbreaks of most current diseases including Amoebic Gill Disease (AGD), Rickettsia-like Organism (RLO) infections, and Marine Flexibacteriosis are likely to intensify. In particular, AGD could be an increasing problem, not only because of the immune suppression and environmental conditions favouring the disease, but also due to reduced fresh water availability for treatment. Development of a vaccine against AGD and selective breeding for AGD resistant stock are longer term solutions currently being examined. Research is also required to determine the performance of currently used vaccines at higher temperatures and the development of new vaccines which will support immunity at increased temperatures.

Increased water temperature will impact on salmonid growth and nutrition directly through the influence of temperature on growth and indirectly via specific nutritional and physiological processes that affect growth. Relationships between temperature and feed intake, growth and growth efficiency have been broadly researched for several salmonid species. Feed intake, growth and growth efficiency show a skewed bell-shaped curve with increasing temperature. Growth is described as the net result of energy expenditure increasing exponentially and feed intake increasing to a maximum from where it decreases. This approach is adequate for providing a generalised view about the effect of temperature but does not provide resolution that may be necessary on farms or take account of multiple secondary factors. The influence of temperature on digestive efficiency is relatively small and the negative effects of higher temperature are more likely at extreme temperatures. These may affect specific nutrients or ingredients such as saturated fats or complex carbohydrates. High temperatures will also affect the flesh quality and lipid profile of farmed fish.

The challenges to fish health and nutrition can be offset by improved selective breeding. Selective breeding for increased tolerance to higher water temperatures is now possible with the establishment of an industry breeding program. Breeding Atlantic salmon to tolerate higher temperatures will become integral to the general selection strategy for maintaining the excellent growth rates and fish wellbeing currently achieved. The Tasmanian industry will not consider genetically modified organisms (GMOs).

The *Alternate species and solutions* section suggests that relocation of existing grow-out facilities to areas with significantly cooler temperatures would involve open-ocean offshore operation but operating costs are currently prohibitive and new technology would be required. The industry has plans to double production within five years which will necessitate new leases in more exposed locations irrespective of climate change. Benefits of moving offshore include better water quality, the possibility of fewer disease outbreaks and fewer seal predation problems. Disadvantages, beyond increased costs, include operational logistics, freshwater bathing and storm damage. Removing the environmental challenges of climate change by evolving the industry into one using shore based grow-out facilities using recirculation technology is technically feasible but the economics do not currently justify production of large salmon in recirculation systems. There are a number of native species available for culture using new generation recirculation technology but none currently operate in Tasmania. The importation of exotic fish species is not considered a viable option for Australian aquaculture under the current environmental regulations. Some native species have potential as new species candidates for Tasmanian sea cage culture. Alternative species will only supplement, not replace, the need to farm salmonids. There is no current evidence for the commercial feasibility of new species. The most promising new candidates are: striped trumpeter; southern blue fin tuna; and yellowtail kingfish. Sea cage trials using cultured striped trumpeter are currently being undertaken. Diversifying into alternative species will require establishment of a commercial marine fin-fish hatchery, zoning of new water for marine farming and overcoming new health, wild fish interactions and marketing challenges.

Other aspects of climate change which are likely to impact on the Tasmanian salmon industry include the cost of energy and feeds. These factors are covered in depth in other studies and are not dealt with in the current report. Climate change may also impact competitors to the Tasmanian industry, with a range of impacts in other production regions. A long-term strategy should also consider this international perspective.

2 Introduction

2.1 Background

One of the major challenges to Australian agriculture is ongoing and future climate change. An analysis of comparative risks is important for identifying priorities for adaptation action and planning. The Australian Government, is developing strategies to increase the resilience of the agricultural sector; strategies that build on the existing capacity of agriculture to adapt to change and identify steps that need to be taken to prepare for and manage the risks and opportunities presented by a changing climate.

The Australian Government's *National Agriculture & Climate Change Action Plan: Implementation Programme*[2] identifies and supports initiatives for coordinated action on climate change. This action will help to improve the adaptive capacity of the sector to climate change, mitigate its greenhouse gas emissions and inform future development of national climate change policies and programmes.

Projects undertaken as part of the *National Agriculture & Climate Change Action Plan: Implementation Programme* seek to build on existing Australian Government and industry initiatives and involve a close partnership with landholders, industry organisations, and research providers. They focus on areas where climate change management is a priority issue for farmers. Terms used in the report are defined in Appendix 8.1.

The Tasmanian salmon industry is one of Australia's largest and most valuable aquaculture industries. However, the rapid growth of the Atlantic salmon industry is potentially restricted by control and management of disease, availability of water in which to farm, competition from overseas producers and environmental changes. The Tasmanian salmon industry is subject to environmental influence, and hence impacts of climate change on the environment, during both freshwater rearing and the marine grow-out phases of production. Freshwater rearing facilities are located in several regions, and have both closed recirculating and flow-through systems. Marine grow-out facilities are located in the south-east, west coast and northern Tasmania. Pending the advent of alternative treatments, freshwater is also required in large quantities during the grow-out phase as a bathing treatment in the control of Amoebic Gill Disease (AGD).

[2] The National Agriculture & Climate Change Action Plan and its implementation are actions of the National Climate Change Adaptation Framework agreed by the Council of Australian Governments in April 2007 (www.coag.gov.au).

2.2 Project development

The Tasmanian Salmonid Industry is recognized as proactive and well organised, and in a position to consider climate impacts on future operations. Following submission of a proposal to address potential impacts, this scoping project was initiated. The project started with a workshop between key salmon industry representatives and research providers on the 1st December 2007 to clarify the terms of reference and objectives of the study. The impact of climate change on energy and feed costs was acknowledged as an important factor. However, it is one affecting many industries and is covered in detail in other studies and is only briefly mentioned in the current report.

A draft report was provided to industry and feedback sought. A workshop was convened on the 23 rd July to disseminate information to industry and to refine the final report, with particular attention to the clarification of the findings, and the next steps for this industry. Information derived through the project will provide the basis for development and implementation of industry-specific strategies to maintain the viability of temperate aquaculture production in Tasmania in the face of climate change.

2.3 Project objectives

(a) Identify and review key climate change information needs as they relate to the Tasmanian salmonid aquaculture industry;

(b) Scope the likely impacts of climate change as they relate to the Tasmanian salmonid aquaculture industry; and

(c) Scope possible solutions for adaptation and identify viable industry development opportunities.

The project was conducted in three parts:

A. *Predictive modelling*

1. review of the prediction methods for inshore coastal temps and freshwater supply (Chapter 4.1)
2. review of the likely change in the environmental variables of interest to salmon farmers (Chapter 4.2)
3. review of the delivery mechanisms (Chapter 4.3)

B. *Salmon performance at higher temperatures*

1. Health (Chapter 5.1)
   a. salmonid immune response and resistance to diseases
   b. outbreak of diseases currently affecting salmon in Tasmania
   c. potential effect of temperature changes on vaccination
   d. potential emerging pathogens and diseases due to climate change
2. Nutrition (Chapter 5.2)

a. growth and feed conversion at higher temperatures
b. marine protein / oil substitution

C. *Alternate species for local conditions* (Chapter 6)
1. choice of available species in Australia
2. attributes which make an alternative species attractive
3. biosecurity relating to co-habitation with salmon
4. identify opportunities and challenges for new species development

The overall study was co-ordinated by the Tasmanian Aquaculture and Fisheries Institute and involved close collaboration with industry and key research providers from CSIRO.

2.4 Climate change

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning over 800,000 years (IPCC 2007; Luthi et al. 2008). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. As a result, average temperature is expected to increase in the future (Figure 2.1). Impacts are already observed on land and in the ocean. Average global temperatures in eleven of the last twelve years (1995 - 2006) are warmer than any year since 1850. The 100-year linear trend (1906 to 2005) is 0.74°C. The linear warming trend over the last 50 years (0.13°C per decade) is nearly twice that for the last 100 years (IPCC 2007). A similar pattern has been observed for Australia (Figure 2.2).

Predictions for future climate are generally obtained from global climate models (GCMs), which simulate the future environment based on projected greenhouse gas emissions. While there is a range of potential futures, depending on the emission scenario and climate model used, change in the next 30 years does not vary depending on the model used, as the warming will be due to gasses already in the atmosphere. Data available from most GCM predictions are relatively coarse, with a temporal resolution of one month, and a spatial scale of 1-2 degrees of latitude and longitude (~120-240 km) (Hobday et al. 2007; IPCC 2007). As a result, confidence in local-scale predictions, particularly where there is variation in the environment over quite small distances, will be low.

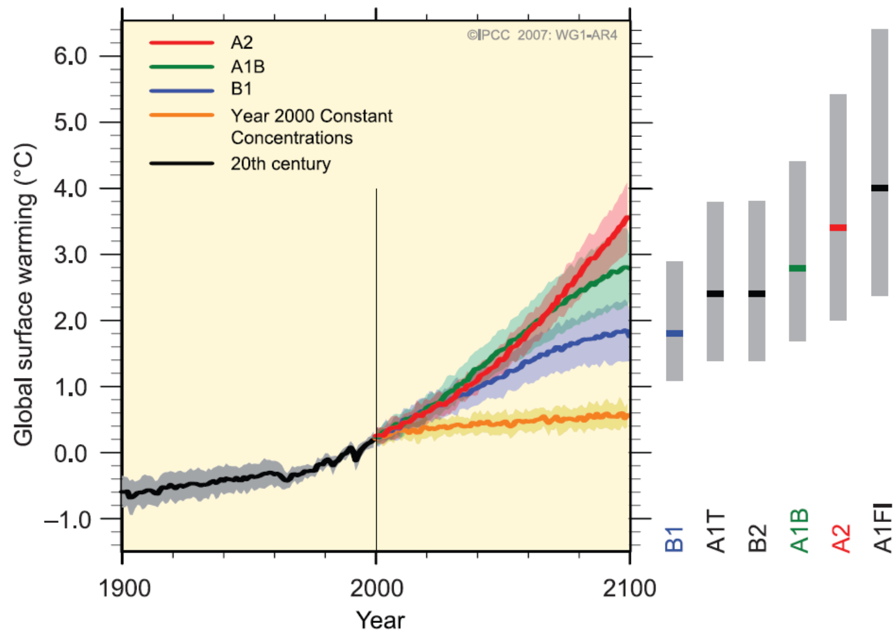

Figure 2.1. Potential increase in global surface temperatures according to a range of GCM and greenhouse gas emission scenarios. ***Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the*** *likely* ***range assessed for the six SRES marker scenarios. The assessment of the best estimate and*** *likely* ***ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.*** **Figure SPM.5. from IPCC (2007).**

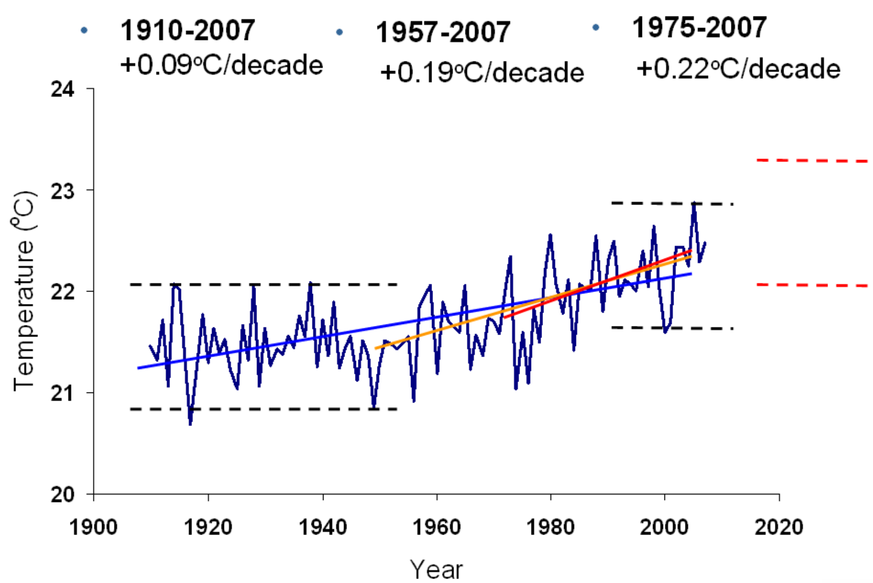

Figure 2.2 Trend in average temperature for Australia. Note the increase in the rate of warming in recent years, and the range of averages in the last decade versus the first half of the 20th century (Mark Howden, CSIRO, unpublished data).

In the ocean, observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise. It is now clear that global warming will impact most human activities in the coming years (IPCC 2007).

Climate variability, operationally defined as interannual change in the environmental conditions, has always been a factor for many Australian aquaculture businesses. That inherent variability, however, is now accompanied by a directional change in climate attributed to human activity altering the composition of the atmosphere (IPCC 2007). Recent evidence suggests that climate change is already affecting Australian marine life and consequently Australian fisheries and aquaculture (Hobday et al. 2007, Hobday et al. 2008; Hobday and Poloczanska 2007; Poloczanska et al. 2008). For example, the waters of south-eastern Australia have warmed at almost four times the global average over the last 100 years (Ridgway 2007), and as a result, this region is seen as particularly vulnerable to the impacts of climate change (Lyne et al. 2005; Hobday et al. 2007).

Climate change will affect a range of environmental variables directly and indirectly due to an increase in greenhouse gas in the atmosphere. With respect to the Tasmanian salmonid industry, these changes may include impacts on air and water temperature, ocean currents and chemistry (lower pH), winds, nutrient supply, freshwater inputs, sea levels, rainfall and extreme weather events. These in turn are likely to affect key biological attributes of commercially important species including their phenology (e.g. maturation schedule) and physiology (e.g. growth rates); location of suitable habitat; and structure and dynamics of aquatic communities (e.g. jellyfish blooms) (Hobday et al. 2007).

2.5 Time and space scales

The time and space scale of information desired by salmon stakeholders varies from days to years and from regions to individual farms. Different approaches are required across the range of time scales, and climate predictions allow appropriate business decisions to be made. Predictions involve risk, and as in all future business decisions, assessment of the risk and certainty of the prediction is required before deciding to take a particular business decision.

Time scales: Three time scales were identified in discussion with the salmon industry.

1. Short time scales (months to seasonal). For example, a prediction made in September, might be “surface water temperature this coming January will be 2°C warmer than the long term average (18.2°C)”.
2. Medium time scale (~ 4 years, as a production cycle from eggs to harvest takes four years). For example, the predicted water temperature in the marine grow-out facility in year 4 is desirable.
3. Long time scales (decades ~ 20-30 years). For example, a prediction might be “the average summer water temperature in the years 2020-2030 is likely to be 2.2°C warmer than the average for the period 1990-2000 (18.2°C)”.

Uncertainty will be associated with each prediction, and could be in the form of the 95% confidence level of the prediction. This would appear as: “the sea surface temperature (SST) estimate for the coming January is 20.2°C (95% confidence limits 19.4 - 20.6°C).”

Spatial scales: Three grow-out regions are of interest to the salmon industry, together with the freshwater catchments that supply water for health management and hatcheries:

1. south-east
2. west coast
3. northern Tasmania

The report uses as a worst case, a sea surface temperature increase of 3.0°C by 2030, for investigating potential impacts in the following sections. If the rate of warming is slow, it will take longer to reach this increase than if the rate is rapid. This increase in temperature for the ocean off eastern Tasmania is likely to be seen by 2030-2100 (Hobday et al. 2007). Predictions on how fast the temperature changes are used in some sections, as this rate of change is important to determining the effects on fish health, nutrition, husbandry and the practicality of alternative species adoption.

2.6 Atlantic salmon farming industry in Tasmania

The salmon farming industry in Australia produced 26,000 tonnes of Atlantic salmon in 2007/08 at an estimated farm gate value of $272 million (Figure 2.3). Between 2002-03 and 2006-07, the volume and real value of farmed salmonid production in Tasmania increased by 10 000 tonne and $154 million (ABARE 2008). Farming began in Tasmania in 1981 using rainbow trout and then Atlantic salmon in 1984 as a joint venture project between the state government a Norwegian company Noraqua and industry. Farming developed quickly due to the establishment of a large hatchery, the use of proven European hatchery technology, a high level of government involvement, excellent cage culture sites, and good water quality (Treadwell et al. 1991). Today three species are farmed in sea cages: Atlantic salmon (90%), rainbow trout (9%) and brook trout (1%). Tasmania produces over 95% of sea cage salmonid production in Australia with a fledgling industry in South Australia. Over the five years to 2006-07 there has been a 65% increase in the volume of salmonid production in Tasmania, the effect of which has been compounded by a 28% increase (in real terms) in unit price accounting for 57% of the state's total gross value of fisheries production. The current study only relates to the Tasmanian industry which is a major regional employer of around 1200 people. There are currently five salmon farming companies, three with large vertically integrated businesses. The industry plans to double production in the next five years and is targeting growth around 12.5% p.a. (Personal Communication, Jungalwalla, P., 2008). Grow-out facilities are located in the south-east (~50% production, Channel and Huon, Tasman Peninsula), west coast (~45% production, Macquarie Harbour) and northern Tasmania (~5% production, Tamar River) (Figure 2.4).

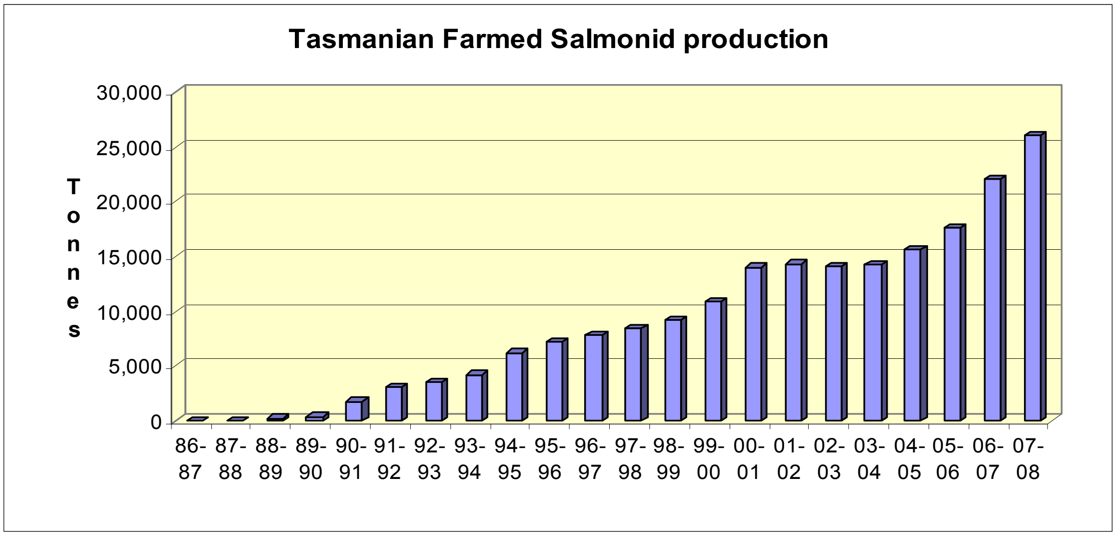

Figure 2.3 Annual Tasmanian farmed salmon production from 1986 to 2008 in tonnes. Data supplied by the TSGA. Note that production data differs from ABARE statistics and is more up to date.

Salmonids are farmed towards their upper thermal limit and growth rates are extremely fast, with a production cycle taking around 30 months. There are four large freshwater recirculation hatcheries in Tasmania and several smaller flow-through hatcheries providing over seven million smolts per year. The *Marine Farming Planning Act 1995* provides a statutory planning process for the development of marine farming in State Waters. This planning process delivers Marine Farming Development Plans that determine specific zones where marine farming leases are allocated. Most salmon farming regions are currently at or near maximum development with regard to their respective marine farming development plans and if the industry is to expand as planned, new zones will be required, perhaps in less sheltered waters. Leases are subject to strict conditions for pre and post farming environmental monitoring, input registers, predator control, health surveillance, and general farming conditions. The Tasmanian Fish Health Surveillance Program monitors all salmonid marine farming operators in a structured surveillance and monitoring program.

World production of salmon is now over 1.2 million tonnes (Table 2.1). The Australian market for Atlantic salmon is only 1.2% of global supply. The majority of Australian salmon (88%) is sold on the domestic market, with only a small portion exported overseas, mostly to Japan and south-eastern Asia.

Tasmanian growers in 2003 estimated that production costs over the previous four years had risen by as much as 50%, exacerbated by significant increases in feed prices and poor growing conditions, caused by low rainfall and high water temperatures. The rapid growth of the salmon industry during the latter half of the 1990's and the poor growing conditions resulted in a series of challenges that threatened the sustainability and profitability of the industry. These challenges included the cost, control and management of disease, particularly AGD, jellyfish and algal blooms in some seasons; the high cost of providing year-round supply of fish to the markets; the interaction of cage aquaculture on the environment and the cost of monitoring and compliance of managing seal predation; the increasing cost of salmon food; and global changes in sea water temperatures.

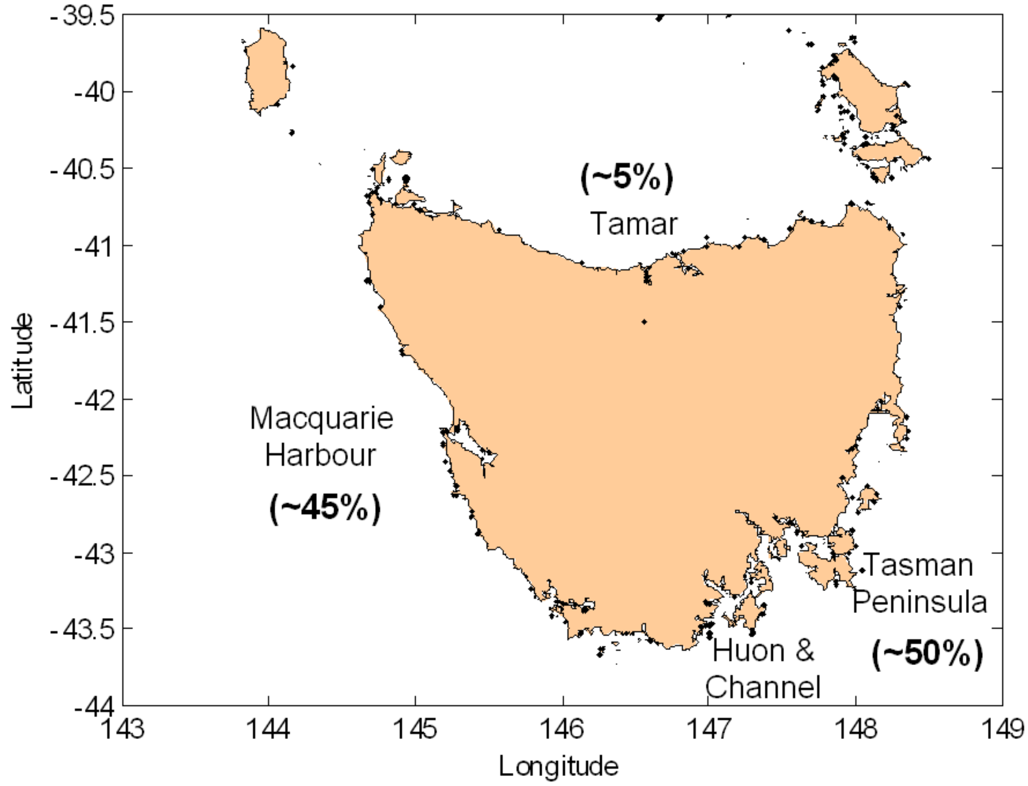

Figure 2.4 Major growing areas for Atlantic salmon in Tasmania, and production for the three regions identified for this study.

Table 2.1 World production of cultured Atlantic salmon from 2001 to 2006 (source: Globefish 2007). Values are in 1000's of tonnes.

	2001	2002	2003	2004	2005	2006
Norway	438.2	445.0	507.4	537.0	573.0	600.0
Chile	253.9	265.0	280.5	343.0	379.0	370.0
UK	138.5	138.0	145.6	139.0	119.0	125.0
Canada	91.4	117.0	90.2	87.0	103.0	115.0
Faeroe Is.	43.9	42.0	56.3	38.0	16.0	13.0
Australia	**12.2**	**13.0**	**14.0**	**15.0**	**16.0**	**16.0**
Ireland	23.3	22.0	16.3	12.0	12.0	15.0
USA	20.8	15.0	16.3	14.0	10.0	10.0
Others	3.1	3.0	4.6	3.0	3.0	3.0
Total	**1025.3**	**1060.0**	**1131.2**	**1188.0**	**1247.0**	**1270.0**

The industry has attempted to overcome some of these challenges by forming a peak-body - the Tasmanian Salmonid Growers Association (TSGA). The TSGA has an MOU with the Fisheries Research and Development Corporation (FRDC) that provides a greater certainty of intent in relation to the planning, funding and managing of R&D and the adoption and commercialisation of research results. This proactive approach should also facilitate effective decision making around climate change issues.

The main endemic diseases of concern are: Amoebic Gill Disease (AGD); Vibriosis, Marine Aeromonas disease; Yersiniosis; and Rickettsiosis (RLO). Management of AGD in particular is estimated to cost industry $20 million per year. Predators and pests of salmon or their feed include seals, cormorants and seagulls, and jellyfish (blooms in intermittent years). Management and relocation of seals is estimated to cost $15 million per year.

Opportunities to enhance cost efficiency cover a wide spectrum, including selective breeding, extension of harvesting season by management of the development and maturation of the fish, improved feeds, feeding strategies and feed delivery techniques, cage technologies and net fouling management, prevention of predation, maintenance of fish health by means of better epidemiology, improved husbandry and development of more cost-effective treatment, vaccines and dietary supplements, and refinement of harvesting and processing methods. Of particular importance to the challenges of global climate change was the establishment of an improved selective breeding program in 2004.

2.6.1 Atlantic salmon and temperature

The preferred temperature range for Atlantic salmon in sea cages is 16-18ºC. It has been suggested that 18.9ºC is above the optimum temperature for growth and development of Atlantic salmon in sea water. However, post-smolt salmon (0-14 weeks after transfer to sea water) showed signs of thermal stress at 18ºC, in particular these fish had higher proportions of neutrophils (suggesting stress) and lower proportions of immunoglobulin positive cells (suggesting immunosuppression) in peripheral blood compared to the groups in lower temperatures. Atlantic salmon farmed in a warmer climate can adapt to higher temperatures, which could explain the discrepancy between studies. However, even current summer temperatures can affect salmon production in Tasmania. The upper critical temperature range for salmonids is considered to be 20-34ºC. Upper incipient lethal temperature is 27.8ºC. For juvenile salmonids in fresh water lethal temperature has been determined to be 29.2ºC (see literature review Appendix 8.2 for details).

2.6.2 Current temperature range and expected future temperatures

Overall, most Australian salmon farms reported the maximum water temperature in winter to be 11ºC and the maximum summer temperature as 18ºC (at 5 m depth). However, in extreme conditions, water temperatures over 22ºC do occur in summer months of some years. Using our best estimates from current modelling (see below) an increase of 3ºC in the surface water temperature in Northern Tasmania could increase temperatures up to 25ºC in summer and to 14ºC in winter.

2.6.3 Temperature control in salmon farming

It is expected that in the nearest future all Tasmanian salmon hatcheries (including brood stock holding) will be temperature-regulated due to the planned introduction of water recirculation and temperature control. This is essential to ensure supply of good quality smolts as high temperatures have been shown to have a detrimental impact on egg quality and production (King and Pankhurst 2000; King and Pankhurst 2004). However, salmon in sea cage grow-out facilities will be exposed to ambient water temperature and therefore can be greatly affected by global warming. The report therefore focuses on the effects of high temperature on the grow-out stage, particularly in sea cages.

2.6.4 Genetic solutions

Saltas, on behalf of the Tasmanian salmon industry and in partnership with the CSIRO Food Futures Flagship, commenced the development of a selective breeding program in 2004. The selective breeding program will use targeted mating to gradually raise the frequencies of desired performance traits in Tasmania's Atlantic salmon stocks. The key selection traits are currently growth rates, maturation, resistance to amoebic gill disease, and carcass characteristics (Personal Communication Elliott, N., 2008). Other countries have had breeding programs for much longer but it is unlikely any genetically improved stocks are available with higher temperature tolerance because they are operating at lower temperatures than those experienced in Tasmania. Current regulations limit the opportunity to import new genetic material to booster salmon stocks in Tasmania. However, CSIRO research has established the existence of substantial genetic variation in Tasmania's Atlantic salmon stocks. On this basis, and with the strong selection intensity being applied in the breeding program, gains in the order of 10% per generation are expected for the key commercial traits (Personal Communication Elliott, N., 2008). Clearly as water temperatures continue to rise in Tasmania the selection for temperature tolerance will become integral to the general selection strategy for maintaining the excellent growth rates and wellbeing currently achieved.

The Tasmanian Government and salmon industry has worked hard at a clean green image and despite changes by the Federal Government, the State government has vowed not to let Canadian salmon imports into the state. Genetically modified organisms (GMOs) and the use of transgenic salmon have been completely ruled out by industry as potential solutions to climate change challenges.

2.6.5 Climate change predictions for salmon farming overseas

In order to understand the impact of climate change on salmon farming in Australia it is important to understand the impact on the world salmon farming industry. Detailed studies have only recently started. The rest of the world's salmon producers will have the advantage of seeing what happens in Tasmania, as upper temperatures may be experienced here first. The possible impact of climate change on Norwegian salmon farmers indicates that some fish farms will have to be relocated pole ward (north in Norway) and farming technology modified to reduce the undesirable effects of higher temperatures (Bergh et al. 2007). Climate studies suggest sea temperatures in Norway will rise by 2-4 ^{O}C over the next century, with fluctuations in fjords being greater due to stratification from increased freshwater runoff, precipitation will increase throughout the year, particularly in autumn, and tidal range will increase by about 80 cm (Bergh et al. 2007). More extreme weather is predicted, which will require development of stronger cages and anchoring systems; particularly to reduce escapement of fish during storms. The impact on the main parasites, such as sea lice, is at present unknown. However, increases in brackish water may lead to more sea lice. The reported prevalence of AGD is increasing around the world, possibly related to the advent of higher average temperatures (Young et al. 2007, 2008). The predicted impact on other diseases is outlined in Chapter 5. The frequency and intensity of extreme situations of temperature stress are considered most important for future study (Bergh et al. 2007). Vaccination of salmon in Norway when temperatures are high raises the frequency of adverse side effects on the quality of salmon flesh and deformed vertebrate (Bergh et al. 2007).

Norway has diversified into new species over the past 30 years with Atlantic cod production steadily increasing (Moksness et al. 2004). Francisellosis, arguably the most serious disease problem facing Norwegian cod farming is expected to increase with climate change (Bergh et al. 2007). Farming of warmer water species such as sea bass and turbot is expected to increase and a larger number of farmed species is predicted with targeted adaptations to local effects of climate change (Bergh et al. 2007).

3 Predictive modelling review

Vincent Lyne and Alistair Hobday

3.1 Introduction

3.1.1 Scope of review

The future climate is not known, but can be estimated by predictive modelling approaches. This section provides a review of methods for predicting the value of key variables, such as water temperature, at the location of the farm sites at the range of time scales identified. The original intention was to review the prediction methods suitable to provide forecasts at a range of time and space scales of interest to industry, including:

i. statistical modelling
ii. regional downscaling
iii. ensemble analysis of climate models
iv. relocatable fine-scale models
v. local mechanistic hydrodynamic models

As the review progressed, overlaps between the modelling approaches facilitated consolidation to three modelling approaches for this review:

i. statistical modelling, including statistical downscaling
ii. dynamical downscaling, including hybrid methods
iii. ensemble analysis of climate models

In the remainder of this chapter, each of these approaches is reviewed with regard to a number of attributes in four general categories. The results from this review will be of use in selecting modelling approaches that may be investigated in detail for future implementation.

3.1.2 Review Methodology

Weather and climate prediction studies and modelling approaches date back over a century and with the intense effort now expended to study climate change, this vast and rapidly growing field of endeavour cannot be completely covered in this limited review. This review therefore draws heavily on key review and primary articles of relevance to this study. Two IPCC review articles were particularly important: Wilby et al. (2004) on *Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods* and a companion study by Mearns et al. (2003) on *Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments.* Taken together, these two articles summarise the extensive range of modelling and prediction studies which were conducted up to the time the reviews were written. Since then many more papers and reports have been produced on the topic and thus we completed an additional literature review using a few key terms to locate the most relevant new material (using keywords: *Salmonid, Climate Change, Aquaculture, Climate Prediction, Seasonal Forecasts, Operational Forecasts)*. Due to the pace of scientific effort, we recommend that if any new studies are initiated, a thorough literature review is conducted to ensure that effort is not unnecessarily being duplicated or wasted. Notably this review of the international literature did not find a single reference to the use of climate predictions for aquaculture operations. While this could be due to missed literature or examples, it is likely to reflect Tasmania's unique position with respect to salmonid aquaculture and the recognition that climate change impacts will make a difference to future operations. Indeed, at this stage there are very few fisheries worldwide that use environmental information for real-time management (but see Hobday and Hartmann 2006) let alone future decision-making (Hobday 2006).

3.1.3 Geographic Context

The south-east region of Australia is considered vulnerable with regard to climate change (see for example, Cai et al. 2005; Lyne et al. 2005; Hobday et al. 2007; Ridgway 2007). A short description of this system is relevant to the choice of prediction approaches, and is also related to the success or failure of different prediction methods. Analyses of results from the CSIRO Mark 3 global climate model by Cai et al. (2005) suggest that the ecological changes observed in the oceans off eastern Tasmania (Lyne et al. 2005; Hobday et al. 2007; Ling et al. 2008) are linked to changes in wind stress curl forcing a southern extension of the East Australia Current (EAC) system. The observed trend in warming and extension of the EAC is predicted to continue, and these changes are part of wider oceanic changes and impacts on marine ecosystems of the entire South Pacific (Ridgway et al. 2007). Cai et al. (2005) conclude that the warming observed off eastern Australia / Tasmania is the highest for the entire Southern Hemisphere.

Confounding these climate change trends in south-east Australia are strong quasi-decadal cycles that have defied consistent explanation (Lyne et al. 2005). For example, the south eastern coast of Tasmania is subjected to the influences from the East

Australia Current from the north, the Tasman Sea circulation from the east, the Antarctic Circumpolar circulation to the south and the deeper incursions of Antarctic Intermediate Waters at depths of 1000m or so (Ridgway 2007). It is difficult to disentangle all of these influences and to reconcile the observation that part of the cycle which appears to be phase locked to sunspot cycles (Thresher R., CSIRO, personal communication). Additional discussion in Lyne et al. (2005) focused on the climate influences in this region.

At the scale of the farm sites, forecasting studies have in the past been conducted by CSIRO for Tassal Ltd, the largest salmonid producer. The study found that both regional and local predictor variables were necessary to enhance the predictive power of their statistically based forecasts. Biannual instabilities in the statistical relationships were also discovered and an explanation has yet to be found, although it is reasonable to conclude that Tasmania is under the influence of more than one climate regime. This is a key area for future climate research, as it impacts on the ability of model predictions for the future.

As discussed previously, three time scales of interest were identified in discussion with industry

1. Short time scales (months to seasonal)
2. Medium time scale (several years)
3. Long time scales (decades)

The predictive capability across these time scales varies (Figure 3.1) and the approach that delivers the best prediction may also vary. Some time scales are less predictable than others, and the best technique for each time scale may not provide the same level of confidence for the future.

Currently, statistical forecasting methods exist for short time scales and model forecasts for the long time scale can be derived from GCM data (IPCC 2007). The difficult scale is the medium term (Figure 3.1). In Tasmania, this time scale is particularly problematic because of the range of climate influences discussed above. For example, with regard to statistical prediction, if a postulated phase relationship with the sun-spot cycle continues to hold, the medium term may in fact be highly predictable, however, without an understanding of why that correlation exists, there is a real risk that it is fortuitous and may breakdown in future. In fact, a relationship between sun-spot cycle and Hobart air temperature is evident only after the mid-1970's (V. Lyne unpublished data), and may not be present into the future.

The different farm sites located in different regions of Tasmania are likely to respond differently to changes in climate so downscaling studies will be required for each site (and possibly for the different regions of Tasmania). This in turn demands good records of local weather and climate related variables (water temperature, water / river flow, air temperature, winds, insolation, rain), along with, if possible, water quality variables (BOD, oxygen, chlorophyll, turbidity, dissolved organic matter), preferably at the surface and at depth. Salmonid farmers are encouraged to continue, or initiate efforts, on collection of environmental variables at their farm sites. These data will be invaluable in future prediction efforts.

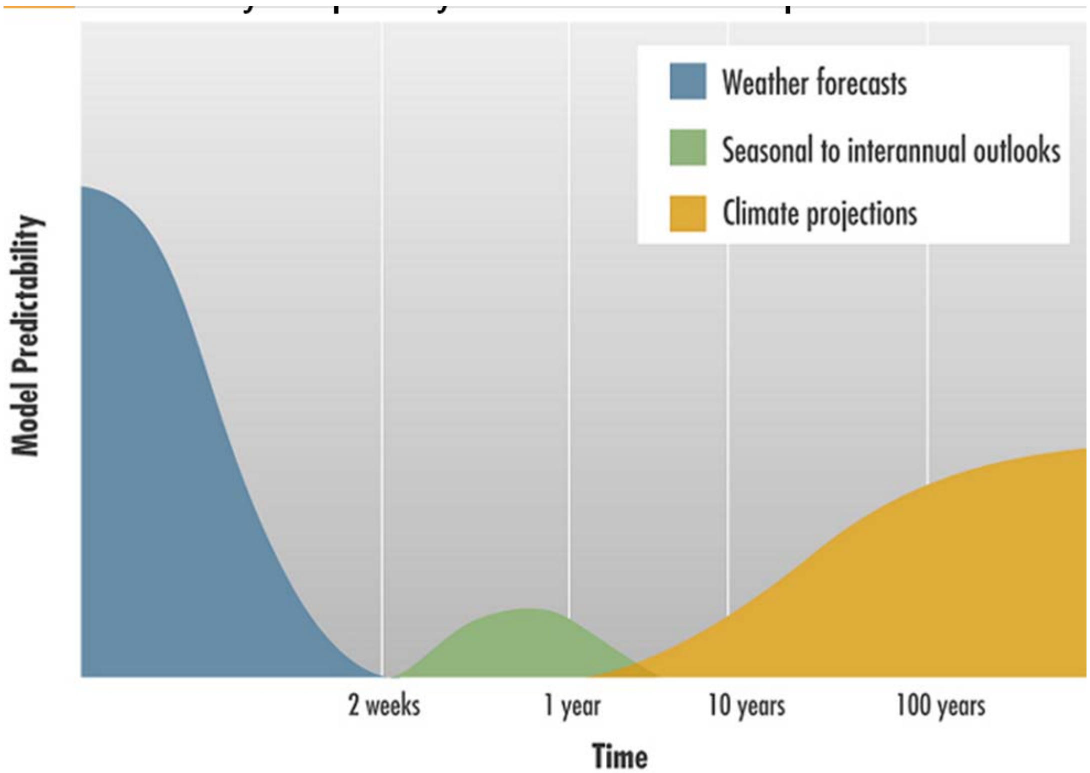

Figure 3.1 Illustration of the ability using models to predict the future conditions for times in the future, including weather forecasting models (what will be the air temperature in Hobart next week), seasonal projection models (will next summer be a rainy one) and climate projections (will the temperature in 100 years be 3 degrees warmer than this year) (source Rohan Nelson, CSIRO).

3.2 Modelling approaches for climate prediction

Modelling approaches fell into three categories, statistical modelling, dynamical downscaling, and ensemble analysis of climate models. Climate models are generally referred to as Global Climate Models (GCMs), and different models are produced by science agencies around the world. For example, in the IPCC 4th assessment, over 20 GCMs were evaluated in producing predictions of climate change (IPCC 2007). The possible warming prediction varies according to the model selected, and the future greenhouse gas scenario (Figure 2.1). As a result, several models may be considered to make a prediction (ensemble analysis). These models are quite coarse (a spatial scale of 2 degree resolution), and so dynamical downscaling represents an approach to derive predictions for a smaller scale. In this approach, the GCM is used to provide boundary conditions for a higher resolution model that covers the region of interest, and thus allows prediction at the site of interest. Finally, statistical modelling, which also exists in many forms, may for example involve relating a variable (e.g. water temperature) collected away from the site of interest (farm) to the values of that variable at the site. The variable may also be derived from a GCM, and using a known relationship be converted to a value for the site of interest.

In reviewing the three modelling approaches, information was gathered to inform future selection of an approach to deliver climate predictions for the Tasmanian salmonid industry in each region and time scale. A range of attributes in four general categories were investigated (Table 3.1). Not all attributes were relevant or could be determined for all modelling approaches so instead we focused upon the key strengths and limitations of each method in the following subsections. A full description of each model against the attributes listed in Table 3.1 is provided in Table 3.4.

Table 3.1 Information for attributes in four categories was gathered for each modelling approach to review the applicability for predictions relevant to the Tasmanian salmonid industry.

Application Issues	Capabilities and Limitations	Skill	Costs
o Model setup and update o Model portability/distribution o Input data provision o Form of outputs o Delivery options and mechanisms o Delivery updating issues o Availability of pilot projects for demonstration o Computation requirements o User requirements o Feedback and customisation	o Scale: Spatial, temporal, variables o Resolution: as per Scale o Utility o Stability of predictions o Assumptions o Treatment of finer scales o Extreme events capability o Capacity building needs	o Skill evidence o Forecast range o Forecast accuracy (data versus model) o Treatment of uncertainty/ variability	o Input data o Model setup and runs o Output delivery o Feedback and updates o Cost versus accuracy/resolution o Management o Operational costs

3.2.1 Statistical modelling including statistical downscaling

Statistical modelling comprises a very large discipline. For the purposes of this review, the approach can be generalised as follows: calculate a relationship between two variables (predictor and response variable), and then use this relationship to translate values of the known variable into values of the response variable when it is unknown. Statistical modelling could, for example, involve relating a variable (e.g. water temperature) collected away from the site of interest (farm) to the values of that variable at the farm site. The variable may also be derived from a GCM, and using a known relationship converted to a value for the site of interest.

Statistical downscaling, a category of statistical modelling, involves at least two models of different scales: a larger model, such as a regional model (such as Bluelink) or a Global Circulation Model (such as the CSIRO model, or any other IPCC model), which provides context (and boundary conditions) for a local fine-scale statistically-based model. The larger model captures the regional context within which the local model resolves the variation / variability due to fine-scale dynamics or statistical associations. The statistical model generally involves a response variable (the variable to be predicted - e.g. water temperature at the farm site) which is then related to predictors derived from the large scale model (such as sea-surface temperature for the ocean grid cells surrounding the particular region of Tasmania under investigation). Wilby et al. (2004) provide a summary of the state of statistical downscaling (as of 2004) and much of the review is still of relevance today. The strengths and weaknesses of the various statistical downscaling methods are summarised in Table 3.2.

Table 3.2. Strengths and weaknesses of the main statistical downscaling methods after Wilby et al. (2004). The "Comments" column contains comments with regard to the intentions of this study.

Method	Strengths	Weaknesses	*Comments*
Weather typing (e.g. analogue method, hybrid approaches, fuzzy classification, self organizing maps, Monte Carlo methods).	Yields physically interpretable linkages to surface climate Versatile (e.g., can be applied to surface climate, air quality, flooding, erosion, etc.) Compositing for analysis of extreme events	Requires additional task of weather classification Circulation-based schemes can be insensitive to future climate forcing May not capture intra-type variations in surface climate	*Successfully applied the analogue method for seasonal cycle as part of overall prediction scheme for Tassal Ltd in previous CSIRO project.*
Weather generators (e.g. Markov chains, stochastic models, spell length methods, storm arrival times, mixture modelling).	Production of large ensembles for uncertainty analysis or long simulations for extremes Spatial interpolation of model parameters using landscape Can generate sub-daily information	Arbitrary adjustment of parameters for future climate Unanticipated effects to secondary variables of changing precipitation parameters	*Metrics such as degree-days may require investigation of generators for "spell length" and other non-stochastic phenomena.*
Regression methods (e.g. linear regression, neural networks, canonical correlation analysis, kriging).	Relatively straightforward to apply Employs full range of available predictor variables 'Off-the-shelf' solutions and software available	Poor representation of observed variance May assume linearity and/or normality of data Poor representation of extreme events	*Non-linear methods are readily available and provide more robust predictions but considerable expertise is required to formulate the models and to select/condition the data.*

Wilby et al. (2004) note a number of key assumptions when downscaling climate model output for current and projected climates (Hewitson and Crane 1996; Giorgi et al. 2001), which we summarise as follows:

(i) Predictors relevant to the local "response variable" should be adequately reproduced by the larger climate model at the spatial scales used to condition the downscaled response(s) relationship.

(ii) The variables in the predictor set must include the (larger scale) "signals" that will change as a consequence of climate change. For example, if lower atmosphere moisture saturation is going to be affected by climate change and it is important to rainfall prediction, then it must be included as part of the training set.

(iii) The predictors used for determining future local climate should not lie outside the range of the climatology used to calibrate the downscaling model. This is particularly problematic for climate change, where temperatures will be higher than ever seen before.

Key issues to be considered in implementing statistical downscaling are (Wilby et al. 2004):

- *Choice of statistical method*
- *Choice of predictors*
- *Extremes*
- *The tropical regions*
- *Feedbacks*
- *Recognising situations where statistical transfer function may be unstable*

The key stages of statistical downscaling are presented in the flowchart below (Figure 3.2**)** taken from Wilby et al. (2004). In our experience, the data collation, data handling and model calibration / verification stages are the most time and resource consuming phases. However, the impact assessment and "policy response" phases are equally important for informed decision making and these must be incorporated where possible in the overall design of the prediction scheme and its implementation.

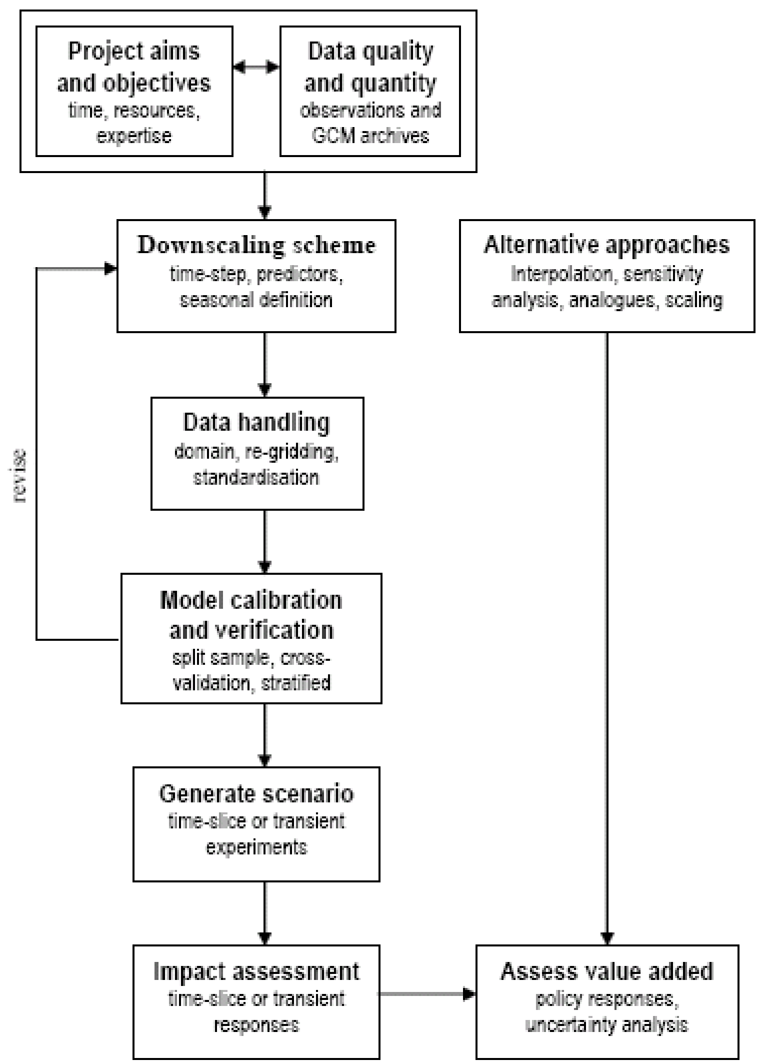

Figure 3.2. Key stages and decision points in designing and implementing a statistical downscaling scheme (from Wilby et al. 2004).

3.2.2 Dynamical downscaling

Dynamical downscaling describes the nesting of a high resolution circulation model within a larger model, such as a regional model, or a GCM (Figure 3.3). Both models typically consist of a set of linked 3-dimensional grid cells (model domain) and the transfer of mass and behaviour of each variable within each cell is dictated by a set of equations. For example, the heating of water within each cell might be dictated by an equation incorporating the effect of sunlight, cooling, and loss and input of the water to and from other cells.

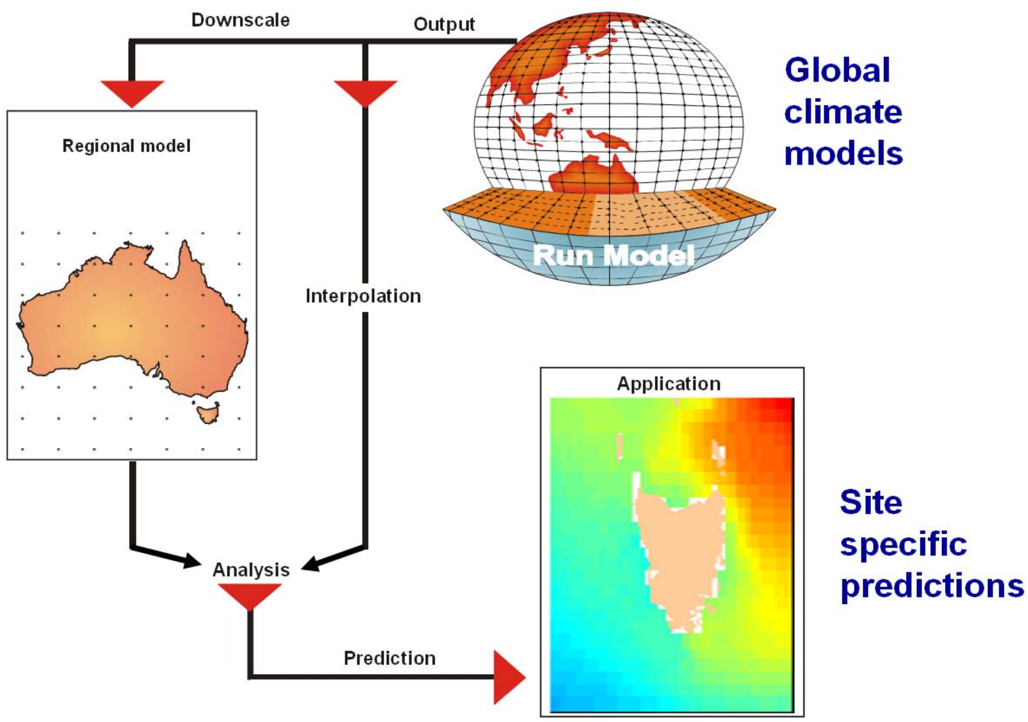

Figure 3.3 . Conceptual diagram showing the relationship between models involved in downscaling. Output from a global climate model (GCM), provides data for either downscaling using a regional model, or interpolation, to a finer scale. Predictions can then be made at a fine scale. (Figure modified from BOM, 2003 unpublished data).

Mearns et al. (2003) present downscaling guidelines for using information from Regional Climate Models (RCM), where the larger context is provided by a Global Circulation Models (GCMs), relative advantages and disadvantages are summarized in Table 3.3.

Table 3.3. Summary of climate models, their uses and their relative advantages and disadvantages (from a summary by Mearns et al. 2003)

Scenario type or tool	Description/Use	Advantages*	Disadvantages*
Climate model based: Direct AOGCM (Atmosphere-Ocean Global Circulation Model) outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically-based models (1, 2) • Long integrations (1) • Data readily available (5) • Many variables (potentially) available (3)	• Spatial information is poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4, 5) • Large control run biases may be a concern for use in certain regions (2)
High resolution/stretched grid AGCM (Atmosphere Global Circulation Model)	• Providing high resolution information at global/continental scales	• Provides highly resolved information (3) • Information is derived from physically-based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4, 5) • Problems in maintaining viable parameterizations across scales (1,2) • High resolution is dependent on SSTs and sea ice margins from driving model (AOGCM) (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Regional models	• Providing high spatial/temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information is derived from physically-based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2, 4)	• Computationally expensive, and thus few multiple scenarios (4, 5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Statistical downscaling	• Providing point/high spatial resolution information	• Can generate information on high resolution grids, or non-uniform regions (3) • Potential for some techniques to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1, 2) • Demands access to daily observational surface and/or upper air data that spans range of variability (5) • Not many variables produced for some techniques (3, 5) • Dependent on (usually biased) inputs from driving AOGCM (2)

- Numbers in parentheses under Advantages and Disadvantages indicate that they are relevant to the numbered criteria described. The five criteria are: 1) *Consistency* at regional level with global projections; 2) *Physical plausibility and realism*, such that changes in different climatic variables are mutually consistent and credible, and spatial and temporal patterns of change are realistic; 3) *Appropriateness* of information for impact assessments (i.e. resolution, time horizon, variables); 4) *Representativeness* of the potential range of future regional climate change; and 5) *Accessibility* for use in impact assessments.

Mearns et al. (2003) provide a set of recommendations relevant to the current project, and are modified as follows:

1. The requirements for climate information and the constraints imposed by available resources (funding, computing, data, skills) must be carefully considered in making an informed decision on whether or not high resolution information is required and if so, what approach will be used. They suggest that this phase requires considerable judgment, and in particular how to deal with uncertainty in spatial scale amongst a range of uncertainties which may need to be allowed for in the study.
2. Regional models should be developed and implemented by modellers experienced in this field of research.
3. The added value of higher resolution models should be assessed in relative comparison to the skill of the coarser scale model. In other words, does the fine-scale model have added prediction skill?
4. Uncertainty associated with spatial scale should be kept in perspective in relation to other uncertainties affecting the predictions, and the fact that there are a number of ways of getting finer scale predictions, and these all have their own uncertainties.
5. Take advantage of existing Regional Climate Model (RCM) output. Many experiments (at least with $2xCO_2$) have been performed over many regions and these provide a least cost method for investigating the utility of climate model information.

The question of the relative value of using dynamical versus statistical downscaling revolves around the added value of dynamical approaches (deterministic hydro dynamical models, portable fine-scale models, nested models) versus the cost in setting up, running and analysing results from a dynamical model. For particular applications, such as monsoonal rainfall prediction, statistical models out-perform dynamical ones (Hastenrath 1995). Dynamical models also appear to be weaker at seasonal scales (Rodwell 1997). Problems with nested models may arise from boundary artefacts (in time and space) in changing from the large to the fine scale model and in error propagation through the boundary from the large scale to the fine scale. Hybrid downscaling approaches are also possible but these involve both types of models and can consequently be more costly but offer the possibility of better resolution and accuracy (Gershunov et al. 2000). These issues are summarized in Table 3.4.

A regional model that may be useful for dynamical downscaling (and short-term forecasting and developing statistical models for climate predictions) is under development at CSIRO. The Bluelink regional ocean model is still in development, however, substantial progress has been made in developing data assimilation methodology to provide a "clean" set of predictions for such attributes as SST and sea level, known as the reanalysis product. Overall, Oke et al. (2008) find that SST in the reanalysed product is within 0.4-0.9ºC of observed values. The value of this product from a forecasting perspective is that it can be used at times when cloud or other factors may cause problems in receiving SST or other remotely sensed data. A further advantage is that the modelled product can reduce the noise inherent in remotely sensed data but the disadvantage is that if the "noise" is actual small-scale variability, then it will be smoothed. Consequently, this type of product is best used to characterise the large scale regional variations in SST and sea level. This approach is also preferred in downscaling as it provides a characterisation of the larger scale fields that is not affected by the small scale structures and / or noise. In the coming year this model will be nested within a GCM (CSIRO Mk 3.5) to generate fine-scale predictions, an approach which will be of great interest to the salmon industry.

3.2.3 Ensemble Analyses

Climate models produce different results depending on the construction of the model. This difference may be due to several factors, including (i) structural, such as the size of the grid cells or the number of vertical layers, (ii) mechanistic, with different equations for the same processes, such as mixing of ocean waters, or (iii) scope, such as the inclusion or absence of say, freshwater inputs. This uncertainty can be reduced by simultaneously considering a range of models, or the same model with a range of conditions, to derive a prediction - ensemble analysis.

In the simplest sense, deriving the average temperature from say, nine GCMs, for a region in southern Tasmania would be an example of an ensemble analysis. Models can be weighted according to criteria, such as match to observed patterns, or analysed without weighting (Cai and Cowan 2007).

An example of ensemble analyses provides some important guiding points. Alexandru et al. (2007) used seasonal statistics from the Canadian RCM, generated using differences in initial conditions, to show that internal variability depends strongly on synoptic precipitation events coupled to the spread of geopotential highs. While decreases in domain size reduce internal variability, geographic variation in the distribution and amplitude of precipitation still remain. Large values of internal variability for precipitation suggest possible repercussions of internal variability on seasonal statistics. Alexandru et al. (2007) suggest that a minimum of 10 ensemble members are required for a robust estimation of seasonal-mean value in mid-latitude North American summer regions where internal variability is large.

Overall, ensemble pooling can provide higher skill for larger regions because the best model may vary with season and region (Goddard et al. 2001). Rather than just simple averaging, better predictions are possible from weighted models where the weights are chosen on the basis of previous model performance (Goddard et al. 2001). Improved performance can also result from selecting a combination of different models rather than just increasing the number of models considered in the ensemble (Pavan and Doblas-Reyes 2000).

3.3 Summary of Model Approaches

Based on our review of each method against the attributes listed in Table 3.3, and discussions with relevant staff at CSIRO, the comparison of the various prediction methods as they may apply to this project are summarised in Table 3.4**.** Note that simple statistical and statistical downscaling approaches are treated separately in this summary table.

Table 3.4. Summary of the attributes of the various prediction methods as they may apply to salmonid aquaculture operations in Tasmania.

	Simple Statistical Models	Statistical Downscaling	Dynamical Downscaling	Ensemble Analyses (of GCM for example)
Application Issues				
Effort in model setup and update	Lowest	High	Very High	Low (if based on existing models)
Model portability/distribution	High	Low	Very Low	High
Input data required	Very High	High	High	Low (if already exists)
Form of outputs	Single value	Maps possible	Mapped	Distribution of values
Delivery options and mechanisms	Web possible - easy	Web possible - easy	Web possible - more complex maps	Web possible /more complex maps & distributions
Delivery updating issues	Needs input updated	Needs larger model input	Needs larger model input	Run models to generate results
Availability of pilot projects for demonstration	Results available	Not available	Not available	Possible
Computation requirements:	Low	Low	High	Very High to generate GCM results
Computer/software	Desktop	Desktop	Desktop/Cluster	Supercomputer for GCM Desktop for ensemble
Prediction times	Short	Short	Long	Very Long
User requirements	Can include	Can include	Hard	Very Hard
Feedback and customisation	High	High	Low	Very Low
Capabilities and Limitations				
Scale: Spatial, temporal, variables	Flexible	Flexible	Gridded	Coarse grids and times
Resolution: as per Scale	Points	Points	Fine grid	Coarse grid
Utility	High	High	Very High	Needs testing
Stability of predictions	Depends on model	Depends on model	Subject to boundary errors	Stable
Assumptions	Historical dataset includes future conditions	See text	See text	See text
Treatment of finer scales	Not considered	Not considered	Implicit in grid scale	Not considered
Extreme events capability	Possible but needs customisation	Possible but needs customisation	Local possible, synoptic relies on larger model	Depends on models
Capacity building needs	Low	Medium	Very High	Very High for models Medium for analyses
Skill				
Skill evidence	High	NA for Tas	NA for Tas	NA for Tas
Forecast range	Up to 3 months	No experience	No experience	No experience
Forecast accuracy (data vs model)	Under 0.2°C generally	No experience	No experience	No experience
Treatment of uncertainty/variability	Probability based	Probability based	Poor	Probabilistic
Costs				
Input data	High	High	Low	Low
Model setup and runs	Low	High	Very High	Very High
Output delivery	Low	Low	High	Very High
Feedback and updates	Flexible	Flexible	Difficult	Difficult
Cost vs accuracy/resolution	Data dependent	Depends on larger model and data	Higher resolution - higher cost	Higher accuracy requires more testing
Management	Low	Low	High	Very High
Operational costs	Very Low	Low	Very High	Very High

Recommendations

With regard to the Tasmanian salmonid industry, we make the following suggestions with regard to prediction of environmental conditions

1. Statistically-based approaches appear to offer the most immediate value for local predictions.
2. Statistical downscaling may also be possible provided access to Bluelink and other regional climate model predictions can be gained.
3. For south-east Tasmania, the intermediate timescale of a few years appears to be the most difficult to predict because of the uncertainty surrounding the observed quasi-decadal cycles.
4. South-east Tasmania may experience greater impacts from climate change due to the predicted southward excursion of the East Australia Current in response to the southward shifts in the wind fields. Recommendations contained in the CSIRO report by Lyne et al. (2005) could be implemented as part of current climate research.
5. The subject of synoptic patterns, extreme events and running sequences of high temperature events needs further investigation to determine options for predicting them.

3.4 Future values of environmental variables of interest to salmon farmers

Variables relevant to salmon performance in grow-out cages have been identified (Table 3.5), but our review indicates that these key variables are not available from the present generation of global climate models (GCM) for the temporal and spatial scales that are needed. Thus, there is a need for work on the appropriate statistical prediction methods, as listed above.

Table 3.5. Explanation of variables from historical and global climate models (GCM). Note the mismatch of time and space scales between the historical observations and the GCM data.

Variable Type	Available from historical records	Available from GCM for future predictions	Desirable from GCM in future
Water temperature	Mean, max, average daily	Monthly average	Daily mean, minimum and maximum
Air temperature	Mean, max, average daily	Monthly average	Daily mean, minimum and maximum
Rainfall	Daily	Monthly average	Daily total
Extreme events	Unknown	None	Unknown

Alternative approaches to prediction do exist using air temperature data, and examples are provided (Figure 3.4). Using this example, as the threshold for counting the degree days increases from 15°C to 17°C, the plot goes from linear (i.e. mean and degree days linearly related) to a threshold-type relationship where the degree days ramps up quickly. Increasing the tolerance of salmon from 15 to 17°C is critical in substantially reducing their exposure and hence vulnerability to stress from sustained high temperature events. Alternatively, an increase from 15 to 17°C in the mean can have significant degree day impacts. As an illustrative example in interpreting Figure 3.4, suppose you have three strains of fish adapted to temperatures of 15°C, 16°C and 17°C respectively. For a mean temperature of say 17°C, the 15°C fish experiences 60 degree days of stress, the 16°C fish experiences 30 degree days and the 17°C fish experiences less than 10 degree days. So, in this case a one degree tolerance change has a very significant degree days effect.

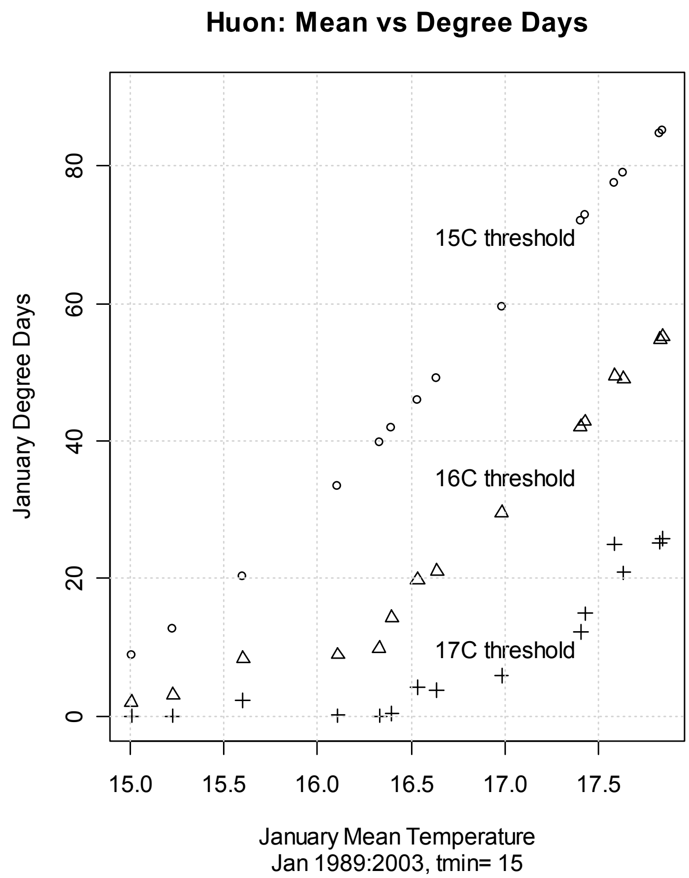

Figure 3.4. Relationship between mean monthly sea surface temperature (data available from a GCM) and the sea surface degree days above 15°C, 16°C and 17°C for the Huon region. Consider the 3-day example where temperatures were 15.5°C, 16.5°C and 17°C = 0.5 + 1.5 + 2.0 = 4 degree days.

Global Climate Model output for related variables is available for the following scenarios: Low emissions (B1 scenario), medium (A1B) and high (A1FI). Based on the high emission scenario for Tasmania, some temperature predictions for 2030 are possible (Figure 3.5**)**.

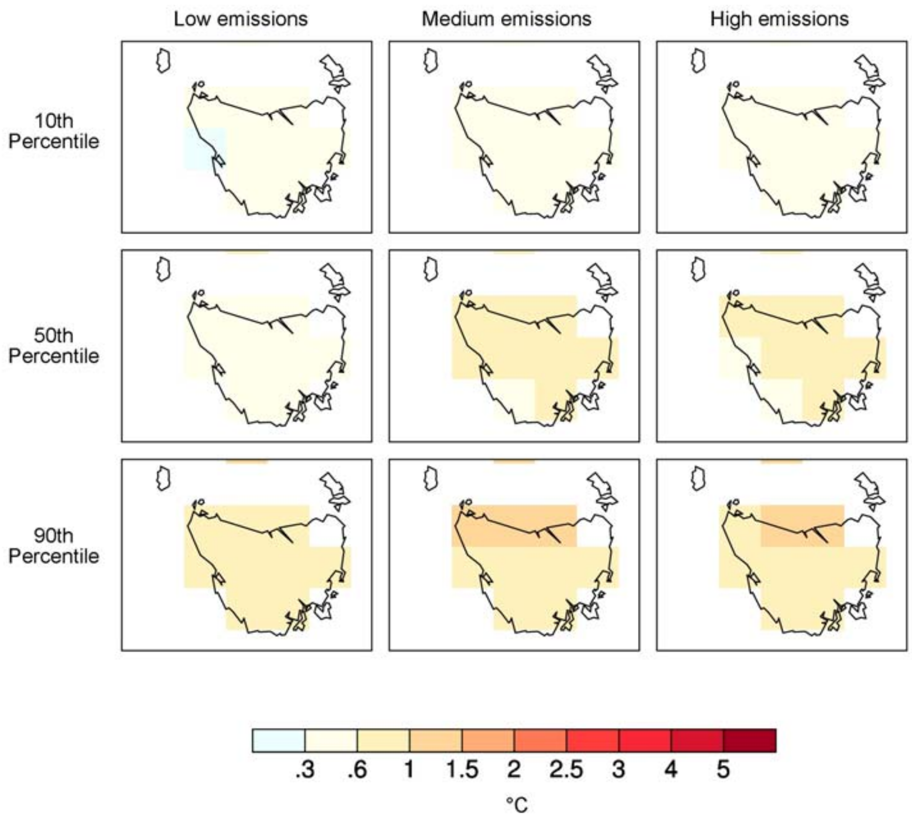

Figure 3.5 Predicted change in summer air temperatures by 2030. Projections are given relative to the period 1980-1999. The projections give an estimate of the average climate around 2030, taking into account consistency among climate models. Individual years will show variation from this average. The 50th percentile (the mid-point of the spread of model results) provides a best estimate result. The 10th and 90th percentiles (lowest 10% and highest 10% of the spread of model results) provide a range of uncertainty. Source: http://www.climatechangeinaustralia.gov.au/images/projections/300/tas3by350_s1_tas.jpg

Values for changes in these related variables (Table 3.1) by 2030, summarised in Table 3.6, have been used as minimum estimates for Part B and Part C of this project. However, some values almost certainly underestimate the future change, based on observed historical rates of change compared to the observed global warming. For example, observed sea surface temperature (SST) warming in eastern Australia in the period 1944-2002 was 2.28°C century^{-1} (Ridgway 2007) compared to a global warming trend of ~0.6°C century^{-1}. Thus, the region of eastern Australia is warming at more than 3 times the global rate. As a result, we believe that SST is one variable that is likely underestimated, and the change in southern Tasmanian waters by 2030 could be double that predicted by the GCM output presented Figure 3.5. For other variables, particularly for down welling radiation, models predict almost no change for all seasons.

Table 3.6. Summary of changes in GCM variables by the year 2030 for Tasmania based on the high emission scenario (A1F1) and the 50th percentile estimate from many models. An arrow indicates the positive or negative change. The three areas are those identified as of interest to salmon industry. ↓ = decrease, ↑ = increase, ↕ = increase or decrease.

Variable	Northern Tasmania	South-eastern Tasmania	Western Tasmania
Water temperature - annual	↑ 0.6-1°C	↑ 0.6-1°C	↑ 0.3-0.6°C
Windspeed - summer	↓ 2-5%	↕ 2%	↕ 2%
Windspeed - autumn	↕ 2%	↕ 2%	↕ 2%
Windspeed - winter	↑ 2-5%	↑ 5-10%	↑ 2-5%
Windspeed -spring	↕ 2%	↑ 2-5%	↕ 2%
Air temperature - summer	↑ 0.6-1°C	↑ 0.6-1°C	↑ 0.3-0.6°C
Air temperature - autumn	↑ 0.6-1°C	↑ 0.6-1°C	↑ 0.6-1°C
Air temperature - winter	↑ 0.3-0.6°C	↑ 0.3-0.6°C	↑ 0.3-0.6°C
Air temperature - spring	↑ 0.6-1°C	↑ 0.3-0.6°C	↑ 0.3-0.6°C
Rainfall - summer	↓ 2-5%	↓ 2-5%	↕ 2%
Rainfall - autumn	↕ 2%	↕ 2%	↕ 2%
Rainfall - winter	↕ 2%	↕ 2%	↕ 2%
Rainfall - spring	↓ 2-5%	↕ 2%	↓ 2-5%
Downward solar radiation - summer	↕ 1%	↕ 1%	↕ 1%
Downward solar radiation - autumn	↕ 1%	↕ 1%	↕ 1%
Downward solar radiation - winter	↕ 1%	↕ 1%	↕ 1%
Downward solar radiation - spring	↕ 1%	↕ 1%	↕ 1%

3.5 Delivery mechanisms for climate prediction

In this section, we describe how predictions of climate information at the range of time scales might be delivered to stakeholders. This initial treatment should serve as a starting point for a discussion on the potential delivery mechanisms for the predictions of climate variables favoured by industry. A glossary of terms is included in (Appendix 8.1).

The delivery mechanism depends on the nature of the information, in particular on the useful time scale of information, and the complexity, and the urgency with which the information is required. Forecast time-scales can range from short-term (hours to days) to long-term (years); the appropriate communication method varies between these time-scales (Table 3.7). For example, long-term forecasts would typically be relevant for a period of a year or more. Stakeholders will often refer to this information on more than one occasion during that period and as such, this type of information can be effectively communicated via mail out pamphlets or Internet sites. In comparison, short-term forecasts are suited to transient communication methods such as radio and television bulletins. Given the short-term nature of the forecast, repeated stakeholder access is unnecessary because the information is updated frequently. The urgency of the forecast is the second key information-type attribute. Seasonal climatologies are an example of non-urgent information, as once constructed there is little change. Such information could be disseminated via the Internet while if the information was for example, a flood warning, radio announcements would be the preferred channel for this critical short-term forecast.

Table 3.7. Communication channels and their appropriateness to the three forecasting timescales: long-term (decades), medium-term (years) and short-term (<months) for salmon stakeholders. Grey shading denotes a suggested communication channel appropriate to the forecasting timescale. Note that these recommendations are general as other factors may impact on suitability of the communication channel. Modified from Hobday and Alpine (2005).

	Forecasting timescale		
Communication channel	***Long-term***	***Medium-term***	***Short-term***
Internet webpage			
Television			
Newspaper			
Fax			
Radio			
Workshops / Meetings			
Posters			
Book/ Pamphlet/ Brochure			

The second factor that influences effective communication is the intended audience. Key audience attributes that effect delivery success include (i) language, (ii) education background, and (iii) access to communication technologies. Information should be conveyed in clear language or else information will not be received by the stakeholder community. Similar problems can arise due to the second attribute; education and exposure to the material. Differing levels of education with regard to interpretation can impact dissemination of forecasts and can also create information biases. The final attribute is stakeholder access to communication technologies. For example, whilst the Internet may be available, stakeholders may not have regular access to forecasts delivered via this medium. Before selecting any communication channel, consultation to determine stakeholder preferences should occur. Finally, other constraints may limit the choice of delivery methods. Attributes influencing this aspect of data communication include financial considerations, data volume, and available expertise. For example, whilst it may be ideal to distribute short-term forecasts via the Internet, television, marine radio and newspaper, financial restrictions may limit the options. Model simulations may only be possible via the internet.

3.6 Supplementary Information

A number of supplementary data sources, such as Internet sites and statistical prediction software tools, are available to enhance current meteorological and oceanographic forecasting abilities and act as a source of further information to stakeholders. Table 3.8 provides sources for accessing this information for a range of present environmental variables.

Table 3.8. **Examples of supplementary information sources for key meteorological and oceanographic variables together with their respective information timescale. Also noted is whether the user is required to interpret the information (Interpretive, I) or if information is immediately ready for dissemination to users (Direct, D). Modified from Hobday and Alpine (2005).**

Environmental variable	Forecast Timescale	D/I	Web Address
Meteorological			
Wind Speed	Short-term	D	http://www.bom.gov.au
Wind Direction	Short-term	I	http://www.bom.gov.au
Rainfall	Short-term	D	http://www.bom.gov.au
	Medium-term	D	http://www.bom.gov.au
Storm Warnings	Short-term (6 -12hr)	D	http://www.bom.gov.au
Air temperature	Medium-term	D	http://www.bom.gov.au
Oceanographic			
Wave Height (Swell)	Short-term	D	http://www.bom.gov.au
Tides	All	D	http://www.bom.gov.au/oceanography/tides/
Water Temperature	Short-term	I	http://www.cmar.csiro.au/remotesensing/oceancurrents/
ENSO Associated Events	Long-term	D	http://www.bom.gov.au/climate/enso/
Climate Change	Long-term	D	http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp_reports.shtml
Sea surface temperature, sea surface height and current speed	Short-term	I	US Naval Research Laboratory Global Nowcast/Forecast, provides images from numerical model output for SST, SSH and current speed at very high resolution (1/32 degrees) http://www7320.nrlssc.navy.mil/global_nlom32/pacific.html

4 Salmon performance at higher temperatures

Barbara Nowak and Christopher Carter

4.1 Effects of higher temperatures on salmon health

4.1.1 Effects of global warming on fish physiology

It has been shown that in wild fish populations, the main physiological effects of climate change will be due to thermal limitation of oxygen. Global warming will cause oxygen limitation through the forced rise in oxygen demand and through reduction of oxygen solubility in water at higher temperature (Figure 4.1) (Pörtner et al. 2006). This oxygen limitation will also apply to fish in sea cages unless additional sources of oxygen are used.

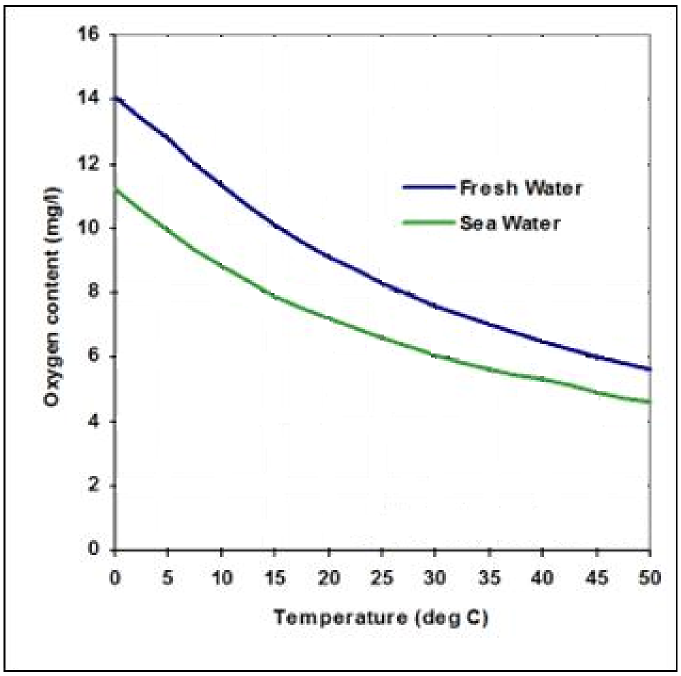

Figure 4.1 Decreased oxygen content of seawater and freshwater with increasing temperature. (source: toolbox.com)

4.1.2 Salmonid immune response and resistance to diseases

Elevated water temperatures within the optimum physiological range (5-10^{o}C above ambient temperature) generally enhance immune functions. However, this does not always translate into increased resistance to diseases. Furthermore, an increase of temperature above optimum physiological range causes immunosuppression, most likely due to thermal stress. This results in an increased susceptibility to infectious diseases.

4.1.3 Outbreak of diseases currently affecting salmon farming in Tasmania

Most infectious diseases in aquaculture require environmental conditions which adversely affect the host and / or are benefiting the pathogen. Infectious disease outbreaks usually occur either due to the immunosuppression of the host or environmental factors being particularly beneficial for the pathogen. Temperature is the most important environmental factor involved in most disease outbreaks. Disease outbreaks on salmon farms (both hatcheries and marine grow-out) are currently more prevalent in warmer years. Additionally, if there is a disease outbreak and the temperature is greater the resulting mortality is greater. Increased temperature is a risk factor for most diseases currently affecting salmon industry (such as Amoebic Gill Disease (AGD), Rickettsia-like Organism (RLO) infections, Marine Flexibacteriosis) and more disease outbreaks occur in summer, even more during unusually warm years. Reduced rainfall in summer will have a synergistic effect on the outbreaks of Amoebic Gill Disease. It may also adversely affect the availability of fresh water for bathing (see Table 3.6).

Increased water temperature will cause immunosuppression, which will make salmon more susceptible to infectious diseases. While some pathogens may disappear due to too high water temperatures, other pathogens will become more prevalent. For example, marine flexibacteriosis outbreaks are likely to become more frequent. Furthermore, yersiniosis infections in marine environment (from carriers) occur more often at higher temperatures and thus will be more common if the water temperature is greater.

4.1.4 Potential effect of temperature changes on vaccination

While all vaccinations are currently undertaken at hatcheries, which will be temperature controlled and operating at optimum temperature, if fish become stressed and immunosupressed by high water temperature after transfer to sea cages, the efficacy of vaccination could be adversely affected. Most research conducted overseas on the effects of elevated temperatures on vaccination has been done either at relatively low temperatures or on rainbow trout. Consequently the results may be misleading under Australian conditions.

4.1.5 Potential emerging pathogens and diseases due to climate change

Changes in environmental factors often lead to the emergence of new pathogens and diseases. Many disease outbreaks occur for the first time during unusually high temperatures. For example, AGD which has been a health issue in the Tasmanian salmon industry for many years is increasingly being recorded in many other countries with increasing water temperature. New AGD outbreaks have occurred for the first time during and after unusually warm summers. Given Atlantic salmon are farmed in Tasmania at higher temperatures than elsewhere in the world it is difficult to predict what the potential new challenges will be.

4.1.6 Other potential health problems

Some species of jellyfish can cause significant problems for salmon farms, including suffocation and toxicity. Warming ocean conditions and man’s activities have already resulted in increases in populations of some jellyfish. It has been predicted that global warming may lead to further increases in jellyfish blooms worldwide (Mills 2001). Higher temperature could also increase the effects of jellyfish due to the potential for low oxygen concentrations in water and an increased toxicity of jellyfish toxins at higher temperatures.

Harmful algal blooms (HAB) are driven by ocean climate changes. Increased ocean temperature will benefit many HAB-causing species. Increase in water temperature can result in establishment of non-native species, including plankton (for example, algae and jellyfish) and microorganisms. Increased plankton blooms could result in increased mortality events on salmon farms.

The oceans are becoming more acidic due to the absorption of increasing atmospheric carbon dioxide. Surface ocean pH has decreased by 0.1 pH unit since 1750, and is expected to decline by an additional 0.2 to 0.3 units by 2100 (Hobday et al. 2007). While this change may not have direct effect on salmon health it is possible that it can contribute to disease outbreaks.

4.1.7 Knowledge gaps

Little research has been done on the effects of higher temperature on Atlantic salmon health in Tasmania. Most of our knowledge of the effects of temperature on salmon health is based on information from the Northern Hemisphere, often investigating temperatures which are considered within the lower range in Tasmania. Furthermore, rainbow trout is more commonly used in research than Atlantic salmon. Some of the knowledge gaps identified by this review include: efficacy of existing vaccines at higher water temperature, effect of increased temperature on salmon immune response, effect of high temperature on pathogens currently affecting salmon farming, presence of organisms which could become pathogenic or affect salmon health in Tasmanian waters.

4.1.8 Conclusions

Rising water temperatures will increase thermal stress and as a result cause an increase in the potential of disease outbreaks. In the short term, outbreaks of most current diseases will most likely intensify. In particular, AGD could be an increasing problem, not only because of the immune suppression and environmental conditions favouring the disease, but also due to reduced fresh water availability. Therefore, development of a vaccine against AGD and selective breeding for AGD resistant stock should remain a high priority. There is a general lack of knowledge about effects of higher water temperatures and other environmental changes related to global warming on farmed Atlantic salmon. Increased research effort is required to address this knowledge gap. The obvious industry priorities should be on selective breeding for increased tolerance to higher water temperatures, research on performance of currently used vaccines at higher temperatures, development of vaccines which will support immunity at increased temperatures and research on optimisation of summer management of farmed salmon (diet and husbandry).

4.2 Influence of higher water temperatures on growth and nutrition of salmon

4.2.1 Introduction

Growth rate is the outcome of numerous factors and their interactions that are directly and indirectly influenced by water temperature. Understanding research on the impact that temperature has on growth in a nutritional context is the focus of this section. The literature can be divided into two inter-related groups: research that measures, and sometimes models, growth in relation to different temperatures and research that examines the effect of temperature on nutritional processes that influence growth. The former group includes consideration of conceptual approaches, assumptions, generalizations and types of models, it also requires the expression of growth to be considered. Nutritional processes are broadly defined to include those involved in acquisition, assimilation and metabolism of nutrients.

Feed intake is a critical factor that obviously influences growth. It is important to recognize that experiments have adopted different approaches to managing feed intake and therefore results have different meanings. Feeding to satiation means that fish will eat to meet their nutrient (probably energy) requirements and feed intake typically increases rapidly with increasing temperature until appetite is inhibited at higher temperatures. This experimental design will show an optimum temperature at which feed intake is highest. However, at satiation the nutritional response of fish at any temperature will be the combination of two effects: feed intake and temperature. Some studies used the same ration at all temperatures in an attempt to remove differing feed intake as a variable and show a more direct effect of temperature. A potential problem with controlling feed intake is that at higher temperatures energy expenditure is higher so the fish will receive a ration than meets less of their requirements than at a lower temperature. Since the purpose of this review is to relate information to commercial outcomes, it is noted that experiments using satiation feeding provide more relevant information. However, they do not as clearly demonstrate the underlying mechanisms and highlight the need for strategic research in this area.

Until recently the majority of research on nutritional requirements was conducted close to the optimum temperature for the particular fish species (Table 4.2). In order to understand changes in nutritional physiology due to temperature, research is now being conducted at more extreme temperatures (Roberts et al. 2001; Carter et al. 2005). For example, the digestible protein and energy requirements for seawater Atlantic salmon at 19°C are now available (Carter et al. 2008b). In being able to make definitive statements or model growth very precisely at elevated temperatures there are other significant factors that have rarely been investigated due the complexity of incorporating them into an experimental design. These include fluctuating temperature, recovery after exposure to extreme temperatures, acclimation and thermal history (Meeuwig et al. 2004). There is also a body of literature, mainly on wild fish, that considers genotype differences (see Appendix 8.3).

4.2.2 Growth and Growth Models

Arguably, current concepts and approaches to describing fish growth and using them to understand the effects of temperature (and other environmental factors) come from studies published in the late sixties and early seventies, particularly by J.R. Brett and J.M. Elliott who worked on sockeye salmon and brown trout, respectively. Of course these studies built on earlier work and several notable approaches to developing models for fish growth have been published since. Nevertheless, whilst considerable advances have been made in understanding biological mechanisms that underlie differences in growth the basic constructs / models have not advanced very far. This may be changing now (Bar et al. 2007).

Description of growth

The majority of experiments are conducted over relatively short time periods, in the order of weeks, and use change in mass (weight) or calculate a daily rate, usually Specific Growth Rate (SGR, %/day). If required for comparative purposes it should be noted that SGR assumes growth is exponential, it also scales with fish mass. Other indices are sometimes used, for example the Daily Growth Coefficient (DGC) which assumes growth is proportional to mass to the power of 2/3. Similarly, it has been suggested that protein and energy requirements should be expressed in terms of mass to the power of approximately 0.7 and 0.8, respectively (Bureau et al. 2002; Carter et al. 2008b). The Thermal Growth Coefficient (TGC) model of fish growth is based on "degree days" and was designed to use data at one temperature to predict growth at different temperatures (Jobling 2003). However, several assumptions of the model can easily be violated, especially at extreme temperatures. Jobling (2003) briefly identified critical aspects of the TGC model, the most significant is that while growth follows a "bell shaped" curve with changing temperature the TGC model assumes growth increases linearly with increasing temperature. Consequently, the TGC model will over-estimate growth at low temperatures and under-estimate growth at high temperatures. This argues against using TGC to express growth of Atlantic salmon at elevated temperatures. The TGC model provides an accurate predictor of growth when previous growth with similar stock under similar husbandry conditions is known (Bureau et al. 2002).

Feed intake and growth

The most straightforward approach has been to grow fish at different temperatures and measure the change in growth at different temperatures. Satiation feeding, growth and growth efficiency, sometimes efficiency of retaining energy and protein, are measured. The classic studies were done on sockeye salmon by Brett and colleagues (Brett et al. 1969; Brett and Groves 1979; Brett et al. 1982) and established the growth-ration (GR) curve approach, plotting ration versus growth rate. Growth rate was expressed as % body weight / day. Since temperature determines the metabolic rate and hence the requirement for food, it acts as a controlling factor on growth. Brett's studies showed that growth increases gradually with increasing temperature and falls dramatically beyond the optimum temperature, the temperature at which maximum growth rates occur. Several studies followed this approach to predict the optimum temperature for salmonids (Table 4.1). Foundation research on Atlantic salmon showed growth rates increased with temperature over the entire experimental ranges of 4-16°C and 2-14°C for freshwater and seawater Atlantic salmon, respectively (Austreng et al. 1987). Unfortunately, optimum values cannot be predicted because there was no decrease in growth at the temperatures studied. Currently the best data sets on ration and growth, and probably the most sophisticated models, are those owned by farms or feed companies.

Bioenergetic and factorial models
Elliott, working on brown trout, conducted very meticulous research to describe growth in terms of energy budgets following a bioenergetic approach (Elliott 1975a; Elliott 1976a; Elliott 1979). Temperature was a key variable and its influence on feed intake, growth, body composition, nutrient retention efficiency and metabolic losses was modelled over the temperature range 4 to 22°C. Extending from early studies on bioenergetics of fish growth, it is now increasingly recognised that factorial approaches describing the amount of nutrient required in a way that divides nutrient requirements into components, such as for maintenance and growth, provide a useful method for describing growth requirements in terms of digestible nutrient intake (and therefore the optimum composition of feeds for different conditions) (Carter et al. 2008b).

4.2.3 Temperature Effects on Nutritional Variables

Ingredients and diet formulation
Considering the importance of this topic relatively little research has been done on the relationships between elevated temperature and ingredient characteristics. Glucose tolerance was investigated in Atlantic salmon at 2 and 12.5°C after feeding on diets with low (1.6%), medium (5.6%) and high (13.9%) extruded maize starch (Hemre et al. 1995). Utilisation of starch increased with temperature so that Atlantic salmon were able to use 5.6 and 13.9% dietary starch at 12.5°C but not at 2°C (Hemre et al. 1995).

Lupin and soybean meals were used to replace 15% of fish meal in Atlantic salmon diets that were fed at 14 and 18°C, growth was higher at 14°C but there were no differences due to temperature (Carter et al. 2008a). Soybeans are noted for causing enteritis in Atlantic salmon, both lupins and soybean caused increased damage to the digestive tract but there was no further effect due to temperature (Carter et al. 2008a). Sectors of the Atlantic salmon industry in Tasmania have a strong preference for using high fish meal / low plant meal diets. Likely trends of increasing fish meal price and decreasing availability argue strongly for strategic research into fish meal replacement at elevated temperatures.

Nutrient requirements
As temperature increases the requirement for energy increases, consequently increasing the energy density of a feed has the potential to improve growth. Several early studies found improved growth of salmonids with increased dietary energy density (Brocksen and Bugge 1974; Hecht and McEwan 1992). At this time extrusion technology was developing and higher energy density feeds were being tested, commercial feeds were probably underspecified for energy. Currently commercial extruded salmonid feeds have high energy density. Extruded diets and other factors have resulted in increased growth of Atlantic salmon and there have been examples of nutrient requirement values not meeting the requirements for increased growth. It should be noted that nutrient deficiency was related to increased growth rate not directly to temperature. An advantage of using factorial modelling is that requirements are related to growth and not expressed as a (meaningless) proportion of the diet.

There does not appear to be any evidence for changes in nutrient requirements that cannot be explained by changes in growth. Commercially, there is now a focus on using high protein summer diets, these are effective partly because they ensure more effective provision of amino acids to meet increased requirements for increased growth.

At 21.8°C there were no differences for rainbow trout in protein (DP) or energy (DE) digestibility, heat increment or energy retention fed high (23.2 g DP / MJ DE) or low (17.5 g DP / MJ DE) protein diets, the higher protein diet had lower protein retention (Oliva-Teles and Rodrigues 1993). These data are surprising in that the low protein diet contained only 30% protein and 9% fish meal, wheat meal being the only protein source. The digestible protein (DP) digestible energy (DE) requirements for 400-500 g Atlantic salmon at 19°C were determined using a factorial approach to be 19.8 g DP / MJ DE (Carter et al. 2008b). This requirement value supports the use of higher protein diets at elevated temperature. Using a variety of methods it was concluded that an amino acid deficiency at 19°C was unlikely (Carter et al. 2008b). Furthermore the main effect of moderately low dissolved oxygen was to reduce feed intake and therefore growth whereas diet composition had relatively little direct effect on growth (Carter et al. 2008b).

Analysis of Atlantic salmon maintenance energy requirements suggested a threshold in requirement between 18 and 19°C, the requirement increased by a large amount at the higher temperature (Carter et al. 2008b). However, this was a tentative observation and further research is recommended.

There are a few good examples of other nutrients becoming deficient due to high growth rates at high temperature, the diets were then under specified. High incidence of jaw deformity, termed “screamer” condition, was reported in Atlantic salmon transferred to sea water at temperatures of 20°C (Roberts et al. 2001). This was thought to be due to dietary vitamin C and phosphate levels being below requirement levels during a critical period and the issue was addressed by changing feed formulations. Increased cataract formation has been linked to a combination of high and fluctuating temperature but possible nutritional deficiencies (histidine, riboflavin) were discounted (Bjerkas et al. 2001).

Digestion and absorption

Apparent digestibility (AD) is the practical measurement of digestive and absorptive efficiency and reflects complex inter-relationships between factors such as diet composition; feed intake; gastric and digestive tract evacuation; digestive enzyme synthesis and activity; and absorption across the digestive tract epithelium. These physiological factors are influenced by temperature. However, as noted above, feed intake increases with temperature and with increases in physiological processes involved in digestion often balance the increased amount of food material in the digestive tract so that digestive efficiency remains the same. Fish, therefore, have some capacity to maximise digestibility at any given temperature but this is probably reduced at extreme temperatures. For example, in Arctic charr at 0.6°C the AD for protein, carbohydrate and lipid was lower than at 10°C (Olsen and Ringo 1998).

Temperature increases feed intake and whilst it is generally assumed nutrient AD is independent of the amount ingested there are some exceptions (Hudon and de la Noue 1985; Guillaume et al. 1999). AD for starch is negatively correlated with intake for rainbow trout whereas it is higher at 18 than at 8°C (Guillaume et al. 1999). Fats have different melting points and temperature can influence AD for fats, particularly saturated fats at low water temperature.

Expression of AD as a percent / fraction per unit of intake indicates the efficiency of digestion whereas using absolute intake of digestible nutrients provides a more direct link to absolute growth.

Energy loss (respiration and metabolism)
As noted above there is a critical relationship between increasing temperature and metabolic rate that, theoretically, is exponential. In addition, temperature influences energy losses through a variety of other mechanisms that might include changes in metabolic substrates, swimming activity, ability to recover from swimming, anaerobic metabolism and ability to deal with changes in water quality such as low dissolved oxygen or elevated carbon dioxide.

Sockeye salmon acclimated to 15°C had reduced maximum swimming speed at higher and lower temperatures (Brett 1967). The scope of activity in rainbow trout tested between 5 and 25°C, was highest close to the optimum temperature (Dickson and Kramer 1971). It has been proposed that at temperatures above optimum, heart function decreases, cardiac output declines because it does not receive a high enough amount of oxygen in the venous blood due to the body musculature taking proportionally too great an amount (Farrell 2007). In Atlantic salmon acclimated to 12°C recovery from exhaustive exercise was faster at 18°C, warmer water appeared to enhance recovery (Galloway and Kieffer 2003). The situation maybe complicated when threshold lactate levels are reached and the ability of fish to under go a second test is included (Jain and Farrell 2003). At 19°C triploid brook trout were unable to recover from exhaustive exercise, they had poorer anaerobic metabolism than diploids and higher mortality (Hyndman et al. 2003). Rainbow trout hearts were less able to utilize a fatty acid (palmitate) at 15 than at 5°C, whereas glucose metabolism was unchanged (Bailey and Driedzic 1993).

Protein metabolism as a key biological process will obviously be strongly affected by temperature. Protein synthesis has been measured in relation to temperature in several species and maximum rates have been predicted to occur at the optimum temperature for growth. This has yet to be demonstrated and limited empirical evidence suggests it may not be the case (McCarthy et al. 1999). The significance of understanding protein metabolism and protein turnover in particular is that it is expensive energetically, responds to amino acid influx and can provide information on mechanisms that underlie nutrition changes due to factors such as temperature and so provide directions for nutritional based management of the effects of these factors (Carter and Houlihan 2001). One consequence of temperature is that RNA concentrations are higher at lower temperatures, more RNA is used to achieve higher protein synthesis because rates are physiologically limited by the temperature. At extreme temperatures amino acids may become limiting, potentially and partly explaining a mechanism for threshold temperatures. As noted elsewhere this was not apparent at 18°C in Atlantic salmon but would perhaps be at 19°C (Carter et al. 2008b). Investigation of various aspects of protein metabolism at temperatures above 18°C is recommended. These would be best achieved using on farm studies and currently available indices of nutritional status (Carter et al. 2008b).

Chemical composition

The gross chemical composition of salmonids is largely a consequence of the balance between energy expenditure and nutrient supply. Carcass lipid is more variable in relation to nutritional status than protein and reflects its more immediate use as an energy source when nutrient intake is low or for storage when nutrient intake is high. Thus, the relationship between nutrient intake and retention is steeper for lipid (and energy) than for protein. Under situations where energy expenditure increases the carcass fat will decrease more rapidly if not balanced by increased nutrient (feed) intake. At high temperatures the change in starved brown trout carcass chemical composition was rapid but decreased with feeding at maximum rations (Elliott 1976b).

Post-harvest characteristics

In Atlantic salmon, feeding fish oil or soy oil at temperatures of 5 and 12°C did not affect carcass or heart lipid but did cause limited differences in fatty acid composition (Grisdale-Helland et al. 2002). Atlantic salmon had significantly reduced long chain unsaturated / saturated fatty acid scores at 19°C than at 15°C and lower temperatures (Miller et al. 2006). Similarly, rainbow trout increased the proportion of saturates and decreased the proportion of desaturates when being acclimated to 20 from 5°C, the reverse occurred when acclimated to 5 from 20°C (Hagar and Hazel 1985). Interestingly the same trend of decreased unsaturated fatty acids occurred for pink salmon between 12.8 and 18.3°C but reversed at 21.1°C (Kepshier et al. 1983).

Arctic charr raised at 10 or 15°C had different colour and physical characteristics, colour was “better”, more orange, at 10°C and physical characteristics (hardness, gumminess, chewiness, fracture ability) had higher scores at 15°C (Gines et al. 2004). Chinook salmon acclimated to lower temperatures of 10.7 and 12.4°C were more sensitive to post-harvest storage temperature than those held at an elevated temperature of 18.8°C (Jerrett et al. 2000). The effect of water temperature on stress response of rainbow trout caught by anglers indicates an important consideration for future research, lactate was higher in fish from the higher temperature and could have implications for post-harvest muscle pH and rigor (Meka and McCormick 2005). During early development the number of white muscle fibres is inversely related to temperature due to the effects on numbers of undifferentiated myoblasts (Johnston 1999). Fillet gaping in Atlantic salmon is higher in warmer temperatures (Morkore and Rorvik 2001).

Table 4.1 Optimum temperatures for feed intake and growth of selected salmonids

Species, study	Conditions	Feed intake: range	Feed intake: optimum	Growth: optimum
Salmo sp.				
Atlantic salmon				
(Koskela et al. 1997)	11-23°C; "Baltic" salmon		17	15
(Elliott 1991)	5-27°C; Wild freshwater parr (England)	7.0 - 22.5		
(Forseth et al. 2001)	5-24°C; Wild freshwater parr (Norway)		19.5-19.8	18-19
(Jonsson et al. 2001)	Wild freshwater parr (Norway)		19-21	16-20
Peterson et al. 1989	First feeding			17.5-18.2
(Siemien and Carline 1991)	10-22°C; First feeding			18
Brown trout				
(Elliott 1975a)	Hatchery trout; 8-358 g;		13.4-18.4	
(Elliott and Hurley 2000)	5-18°C; 250-318 g; Fed insects Fed fish		13.9 16.6 - 17.4	
Sockeye salmon				
(Brett et al. 1969)	1-24°C; 1-20 g	1-20	15	

Table 4.2 Thermal tolerance levels for salmonids (Adapted from Elliot 1982; Grande and Andersen 1991). Critical thermal maxima is established at 50% mortality. Lower and critical thermal range is influenced by acclimation temperature and is the temperature range over which fish survive. Upper incipient lethal temperature is the temperature below which fish survive for considerable time. The thermal tolerance zone is defined by critical and acclimation temperature range.

	Lower critical range (°C)	Upper critical range (°C)	Upper incipient lethal temperature (°C)	Thermal tolerance (°C^2)
Salmo sp.				
Atlantic salmon		20-34	27.8	
			29.2	
Brown trout	0-4	19-30	24.7	583
Oncorhynchus sp.				
Rainbow trout	0-9	19-30	26.2	
Chum salmon	0-7	22-28	23.8	468
Sockeye salmon	0-7	22-28	24.4	505
Coho salmon	0-6	23-28	25	528
Chinook salmon	0-7	22-28	25.1	529
Salvelinus sp.				
Arctic charr	0	22-27		
American brook trout	0-7	20-29	25.3	625

4.2.4 Knowledge gaps

Feed intake, growth and growth efficiency show a skewed bell shaped curve with increasing temperature: these parameters have maximum values at an optimum temperature and tend to fall more sharply at temperatures above optimum compared to a gradual change at temperatures below. Growth is described as the net result of energy expenditure increasing exponentially and feed (nutrient) intake increasing to a maximum from where it decreases. This approach is adequate for providing a generalised view about the effect of temperature but doesn't provide resolution that may be necessary on farms or take account of multiple secondary factors. For example, the lack of data and the complexity of designing experiments that consider many secondary factors to precisely model changes with temperature make it difficult to determine whether there are critical threshold temperatures or changes are incremental.

The influence of temperature on digestive efficiency is relatively small: whilst increased temperature increases physiological rates such as enzyme activity, transit times and absorption; these are generally balanced by increased feed intake and the need to digest an increasing mass of feed. The effects of temperature are more likely at extreme temperatures and temperature may affect specific nutrients such as saturated fats or complex carbohydrates. This means research on the interaction between elevated temperature and ingredient characteristics is required. The consequence is that sustainable Australian agricultural based ingredients which are perhaps less vulnerable to world commodity markets may be ignored in favour of increasingly expensive fish meal and oil.

Many of these studies focus on juvenile life-history stages of salmonids. There appears to be very little information available about the impact of warmer waters on the nutrition of large production salmonids held in sea cages. Temperature can affect the final product and further research is required.

4.2.5 Conclusions

Increased water temperature impacts on salmonid growth and nutrition in a variety of ways. These can be broadly divided between the direct influence of temperature on growth and its indirect influence via specific nutritional and physiological processes that affect growth. Establishing relationships between temperature and feed intake, growth and growth efficiency has been broadly researched for several salmonid species: the majority of studies investigated feed intake and changes in wet weight, some included protein and energy retention. Growth during key life-history stages during freshwater, smoltification, seawater and maturation were treated separately from each other. Investigations on how temperature affects aspects of nutrition and physiology that may themselves impact on growth include digestion, chemical composition, tissue structure, nutrient requirements, oxygen consumption, swimming, and fatigue. Essentially their influence is through effects on nutrient intake / absorption, retention and loss.

Temperature can affect the final product. Fish grown in warmer water have better physical flesh quality, but poorer colour. Flesh lipid levels were more influenced by feed intake and little by rearing temperature. Although higher temperatures did not directly affect the deposition of lipids, high temperature affected the fatty acid composition, in relation to saturated fatty acids the amount of unsaturated fatty acids decreased with increasing temperature. There is a large body of academic literature on thermal acclimation and membrane fatty acid composition but it is difficult to integrate this into practical outcomes.

5 Alternate species and solutions

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This section focuses mostly on the opportunities and challenges facing the salmon industry if it tries to diversify into other fish species more suited to warmer temperatures. However, in adapting to climate change the salmon farming industry will have a number of other options beyond improving the current system of sea cage culture using established techniques. These include (in no particular order):

1. Relocation of existing grow-out facilities to possibly more suitable areas with cooler temperatures.
2. Removing the environmental challenges by evolving the industry into one using shore based grow-out facilities using recirculation technology.
3. Genetically engineering Atlantic salmon to tolerate higher temperatures either through selective breeding or transgenetic manipulation.
4. Possibly farming a salmonid species with a more suitable temperature and disease profile.

5.1 Relocation of activities and offshore cages

Two obvious possibilities present themselves: moving south to colder waters; or moving more offshore into deeper, cooler and more stable waters. Good sheltered cage culture sites in southern Tasmania with lower temperature profiles than current farming zones are not available. More exposed offshore sites are available in State Waters but would require new government zoning and the use of stronger cages, feeding systems, supply boats and infrastructure and may not offer any greater advantage with respect to lower water temperature profiles. Another possibility is for fish farming ships to be used but their development is still embryonic and operating them in the southern ocean would appear extremely difficult. True open ocean offshore sea cage technology is being developed overseas but is not currently used commercially in Australia. The countries experimenting with offshore caged aquaculture include Australia, Chile, China, France, Ireland, Italy, Japan, Korea, Mexico, Norway, Portugal, Russia and Spain. The engineering of offshore cages is improving rapidly and some have the capacity to submerge to take advantage of cooler waters. The costs of offshore operation are currently extremely high but the industry will still be moving in that direction even without climate change because it will allow expansion and reduce environmental sustainability concerns.

5.2 Recirculation technology

Intensive on-shore recirculation systems are now commercially in operation within Australia but on a scale that is not compatible with the volumes of salmon currently produced in sea cages. The favoured species for recirculation systems in Australia and increasingly on the world stage is barramundi (Asian sea bass). There has been some interest from Australian companies and consortiums in establishing commercial recirculation grow-out systems in Tasmania, the most recent a proposal for a snapper grow-out facility in the north of the state. While technically feasible, salmon culture in recirculation systems is not widely practised in other parts of the world. However, the industry does increasingly rely on the technology for the hatchery production of smolts. Basically, the economics do not currently justify production of large fish in recirculation systems.

5.3 Other salmonids

Farming other species of salmonids to combat climate change is unlikely because the temperature preferences of other species are similar or poorer in respect of high temperatures (Table 4.2). If the species do not occur in Australia then there is the added complication of importation and biosecurity.

5.4 Choices of new marine fish species

The development of marine fish farming in Australia has only occurred over the last two decades with total production estimated to be about 33,751 tonnes in 2006/7, valued at AUD$433 million (ABARE 2007). Three other species besides salmonids are commercially cultured in significant volumes: southern blue fin tuna *Thunnus maccoyii* in South Australia; yellowtail kingfish *Seriola lalandii* in South Australia, Western Australia and New South Wales and Barramundi *Lates calcarifer* (Bloch), in Queensland, South Australia, Northern Territory and New South Wales. All three species can technically be cultured in Tasmania.

A workshop study in 1994 identified five potential new candidates for sea cage culture in Tasmania from an initial screening of 40 species. In order of preference they were: striped trumpeter, greenback flounder, banded morwong, yellowtail kingfish and trevalla (Searle and Zacharin 1994). If you consider intensive shore-based culture then to this list must be added the over 30 marine fish species that have now been studied for farming or stock enhancement in Australia (Battaglene and Fielder 1997; Battaglene and Kolkovski 2005). New species have mostly been chosen following consideration of the market potential, industry value, technical feasibility, production economics and compatibility with existing aquaculture industries (Treadwell et al. 1991; Quartararo 1996). Research programs to determine the breeding and larval rearing requirements of newly selected marine species, are currently established in all states and territories of Australia, except the Australian Capital Territory and Victoria (Table 5.1).

The importation of exotic fish species is not considered a viable option for Australian aquaculture under the current environmental regulations. While the salmon farming industry is based on exotic species they were imported into Australia at least 50 years ago. The discussion on new species is therefore restricted to native Australian species. Three species have potential as new species candidates for Tasmanian sea cage culture under warmer temperatures. However, there is currently no direct evidence for commercial feasibility in Tasmania.

5.4.1 Striped trumpeter

Striped trumpeter was chosen as the best candidate for diversifying sea cage culture in Tasmania following a rigorous selection process (Searle and Zacharin 1994). They are highly prized as one of the best eating fishes in Australia. They are also greatly esteemed as sashimi in Japan and have firm white flesh, which is both tasty and fatty (Yearsley 1999). Recent market research into the flesh qualities of "farmed striped trumpeter" (wild-caught juveniles reared in captivity to adulthood) rank them alongside Australia's best white-fleshed fish in controlled taste tests. Another potential market advantage is the very high omega-3 polyunsaturated fatty acids (PUFA) concentrations in the flesh of "farmed fish" (Nichols et al. 2005). They also have a limited distribution in southern Australia from Sydney to Kangaroo Island and around Tasmania and New Zealand. Once plentiful in Tasmania the fishery for striped trumpeter has now declined from over 100 tonnes to >30 tonnes per annum. Striped trumpeter were selected not only for their marketing qualities, but also their docile nature, lack of cannibalism, ability to take formulated feeds and be held in captivity at high densities. However, they have a complex and extended larval phase with a 9 month "paper fish" stage and to date they have not proven easy to culture (Battaglene and Cobcroft 2007).

Recent research into striped trumpeter culture has been through the Aquafin CRC from 2001 to 2008. Excellent progress was made in understanding and controlling reproduction. Brood stock collected from the wild can be routinely spawned year-round through temperature and photoperiod control (Morehead 1997). An important breakthrough was the identification and control of myxozoan, (*Kudoa neurophilia*), infections (Grossel et al. 2003). The challenge for the development of striped trumpeter is now to scale up production and improve juvenile quality, particularly jaw malformations (Battaglene and Cobcroft 2007). Two parasitic copepods have been described (*Chondracanthus goldsmidi* n. sp. and *Caligus nuenonnae*) and control treatments investigated (Tang et al. 2007; Andrews et al. in press). Research towards the end of the Aquafin CRC has focused on grow-out of post-larvae, and optimal temperatures and feeding conditions have been established. Malformation rates were reduced from > 90% to <25%. The production of around 3000 high quality juveniles generated increased interest from industry and the first fish were stocked into sea cages in December 2006, followed by another two shipments in 2007.

Growth of striped trumpeter in sea cages has exceeded that in land based tanks and survival has been excellent. Details are industry protected through an agreement with Huon Aquaculture Company, the second largest salmon company in Australia. The success of the grow-out trials has led to a further successful FRDC application for research to produce greater quantities of juveniles to test the longer term growth and survival in sea cages. The cost of producing striped trumpeter juveniles is potentially higher than that of other farmed marine fish because they do not metamorphose till 50 g in weight. If a way can be found to stock post-larvae of 5 g into sea cages or to rear them more cost-effectively in land based systems it will greatly improve the economic potential of large-scale culture. The temperature tolerance of striped trumpeter to higher sea water temperatures is not known.

Table 5.1 Selected cultured Australian marine fin-fish produced, or which have been under investigation for, commercial farming or stock enhancement programs in Australia. With a list of research laboratories involved in research of selected species. (Modified from Battaglene 1995 and Battaglene and Fielder 1997).

COMMON NAME	SCIENTIFIC NAME	CLIMATE	STATE OR TERRITORY
Atlantic salmon[a]	*Salmo salar*	Coldwater	TAS
Ocean trout[a]	*Oncorhynchus mykiss*	Coldwater	TAS
Brook trout[a]	*Salvelinus fontinalus*	Coldwater	TAS
Greenback flounder[bei]	*Rhombosolea tapirina*	Coldwater	TAS
Long-snout flounder	*Ammotretis rostratus*	Coldwater	TAS
Striped trumpeter[ei]	*Latris lineata*	Coldwater	TAS
Banded morwong[e]	*Cheilodactylus spectabilis*	Coldwater	TAS
Yellowtail kingfish[e]	*Seriola lalandi*	Temp/Cold	SA,WA,NSW
Black bream[ij]	*Acanthopagrus butcheri*	Temp/Cold	TAS & WA
Yellowfin bream	*Acanthopagrus australis*	Temperate	QLD
Southern blue-fin tuna[a]	*Thunnus maccoyii*	Temperate	SA
Australian bass[acg]	*Macquaria novemaculeata*	Temperate	NSW & QLD
Snapper[bghj]	*Pagrus auratus*	Temperate	NSW, SA&WA
Mulloway[bg]	*Argyrosomus japonicus*	Temperate	NSW & SA
Sand whiting[cg]	*Sillago ciliata*	Temperate	NSW & QLD
Trumpeter whiting[g]	*Sillago maculeata*	Temperate	NSW & QLD
WA Dhufish[j]	*Glaucosoma hebraicum*	Temperate	WA
Dolphin fish	*Coryphaena hippurus*	Trop/Temp	WA
Pikey bream	*Acanthopagrus berda*	Tropical	QLD
Barramundi[adf]	*Lates calcarifer*	Tropical	QLD,SA&NSW
Coral trout	*Plectropomus spp.*	Tropical	QLD
Golden snapper[d]	*Lutjanus johnii*	Tropical	NT & QLD
Mangrove jack[f]	*Lutjanus argentimaculatus*	Tropical	QLD
Grouper[f]	*Epinephelus spp.*	Tropical	QLD & WA

[a] Produced commercially
[b] Experimental grow out
[c] Bribie Island Aquaculture Research Centre, PO Box 191, Bribie Island, Qld 4507
[d] Darwin Aquaculture Centre GPO Box 990 Darwin NT 0801
[e] TAFI, Nubeena Crescent, Taroona, Tasmania 7053
[f] Northern Fisheries Research Centre, PO Box 5396, Cairns, Qld 4870
[g] NSW Fisheries, Port Stephens Research Centre, Taylors Beach NSW 2316
[h] SA Aquatic Sciences Centre 2 Hamra Av West Beach, SA 5024
[i] University of Tasmania, Locked Bag 1370, Launceston, Tasmania 7250
[j] WA Fishing and Aquaculture Centre, 1 Fleet St Fremantle, WA 6160

5.4.2 Southern blue fin tuna

Southern Blue fin Tuna (SBT) is a long-lived, highly migratory species, forming a single, widely distributed population in the southern oceans including Tasmania. The fishery for SBT is an international one, pursued throughout the temperate waters of the Southern Hemisphere, with Japan, Australia, Korea, Taiwan, Indonesia and New Zealand accounting for nearly all of the current global catch of around 16,000t. The farming of SBT started in 1989. The industry adapted the technology developed by salmon farmers in Tasmania. However, in contrast to salmon farming, tuna farming relies on the supply of fish >10kg from the wild for fattening. Schooling fish caught in South Australian waters are towed to farms near Port Lincoln where they are grown out for a period of 3-7 months on a variety of frozen baitfish. The tuna are harvested for export, frozen or fresh. There is a limited number of wild fish available for on-growing and research is underway to breed tuna in captivity to allow increased production (www.cleanseastuna.com.au). Tuna farming is profitable because of the high price paid for premium grade sashimi in Japan. Australian production was estimated at 8,806 tonnes in 2006, valued at $156 million.

Quotas for SBT could theoretically be purchased by Tasmanian farmers but schools of smaller SBT are not common in Tasmanian waters and fattening operations are unlikely to be profitable. If successful breeding of cultured SBT becomes routine then cage culture would be possible in Tasmania. However, no hatchery production of SBT is currently available and water temperatures even with pronounced global warming are possibly suboptimal for growth. Considerable secrecy surrounds current farming operations and little growth data, particularly as it relates to temperature, is available for fattened fish and none for smaller juvenile fish cultured in sea cages.

5.4.3 Yellowtail kingfish

Yellowtail kingfish are distributed from southern Western Australia to southern Queensland and separate populations occur in NZ and Japan where they are farmed. They are an extremely fast growing fish reaching up to 70 kg and they, and similar species, have been cultured in Japan for decades using wild caught juveniles at similar temperatures to those found in Tasmania. A rapidly expanding industry is developing in Australia using hatchery produced seed stock with farms established in SA, WA and NSW. Production statistics for yellowtail kingfish are difficult to obtain but it is driving the increase in the ‘other’ category of aquaculture production in South Australia from ~1100 tonnes valued at ~$9 million in 2002-03 to 2000 tonnes and $17 million in 2004-05 (ABARE 2007). Clean Seas Aquaculture is the largest producer of yellowtail kingfish having produced over 600,000 cultured juveniles in 2006 and > 1 million juveniles in 2007. Cranial and skeletal malformations have been reported in cultured yellowtail kingfish in SA, NSW, WA, Japan and New Zealand (Cobcroft et al. 2004). Malformations add to the cost of farming by increasing grow-out time, reducing survival, adding infrastructure and labour costs, reducing marketability and fish quality. Yellowtail kingfish are susceptible to a range of parasites including gill flukes *Benedenia seriolae* and *Zeuxapta seriolae* (Monogenea) which require management by bathing fish in either hydrogen peroxide or fresh water (Hutson et al. 2007). Other potential diseases identified from wild fish include *Paradeontacylix* spp. (Digenea), *Kudoa* sp. and *Unicapsula seriolae* (Myxozoa).

Yellowtail kingfish was examined as a species for diversification of the salmonid sea cage industry in Tasmania in the 1990's. Young juveniles were caught in NSW and transferred to Tasmania, growth rate and survival was high when held at elevated water temperatures (5-10^{o}C above ambient) but poor when held under ambient conditions (Ritar et al. 1998). The study concluded that there was little opportunity for diversification within the existing salmonid industry in Tasmania. Increasing temperatures by 3^{o}C would probably allow them to be farmed in northern Tasmania were wild fish are occasionally caught.

5.5 New species possibly more suited to intensive land based culture

A number of other species have at different times been suggested as new species for culture in Tasmania. We list them here as candidates that for the most part may be better suited to intensive shore-based recirculation systems rather than sea cages.

5.5.1 Banded morwong

Banded morwong are part of the live fish trade out of Tasmania. Some research into the breeding of morwong has been conducted (Ritar et al. 2006). They are a very slow growing species as adults but recent studies suggest juvenile growth can be faster. There is considerable market potential within the live fish trade to Asia and some interest in farming from local processors. Like striped trumpeter, banded morwong have a long and protracted post-larval rearing stage and similar difficulties in juvenile seed stock production.

5.5.2 Barramundi

Barramundi occur throughout Asia and northern Australia. They were first bred in Australia in 1984 using intensive techniques developed in Asia. They are a tropical species not suitable for cage culture in Tasmania. Highly intensive shore-based grow out systems (freshwater or saltwater) combined with a year-round supply of hatchery produced fish is currently practiced in a number of states and could theoretically be an industry in Tasmania. Higher energy costs of rearing a tropical species would need to be considered. The strict rules on the importation of fish in Tasmania and the nodavirus disease they are prone to may make translocation of seed stock difficult (Mundy et al. 1992). Total Australian production was estimated at 2,075 t in 2006, valued at $ 17 million.

5.5.3 Greenback flounder

The culture of greenback flounder, *Rhombosolea tapirina* has been researched in some detail and they were routinely produced by the Tasmanian Department of Primary Industry and Fisheries and the University of Tasmania for a number of years (Hart 1994). While hatchery technology is well developed and seed stock supply assured, the slow growth of fish could be a drawback. As a flatfish they are not ideally suited for sea cage culture and their farming prospects are no longer considered as good as they were in the 1990's. There is also a belief that cheap sources of flatfish from NZ make farming greenback flounder currently uneconomic.

5.5.4 Mulloway

Mulloway, *Argyrosomus japonicus* is widely distributed in temperate waters in Australia and has been farmed since the 1990's in both NSW and SA (Battaglene and Talbot 1994). A moderately fast growing species it has been phased out in preference to kingfish in many farms. A nocturnal feeder it may grow too slowly in Tasmanian waters and is not a native species and therefore may be restricted from cage culture.

5.5.5 Snapper

Snapper, *Pagrus auratus*, are found throughout temperate Australian and NZ waters and a closely related species red sea bream *Pagrus major* is extensively farmed in Japan. Snapper have been farmed in NSW, SA and WA since the mid 1990's but slow growth rates and high production costs have not lead to significant commercial production, despite the firm technical basis for the development of the industry (Quartararo1996). There has been some interest in farming snapper using a large recirculation system in northern Tasmania where a small native population exists.

5.5.6 Other species

Beyond the species listed above there are other candidate new species which have prospects based on overseas experiences in NZ or which have some current industry interest. They include trevalla (*Hyperoglyphe antartica*), hapuka (*Polyprion oxyeneios*), silver trevally (*Pseudocaranx dentex*) and various puffer fish. However, there is little published information on which to base further discussion.

5.6 Challenges to new species development

5.6.1 Supply of seed stock

Atlantic salmon smolts are produced in freshwater hatcheries and there is currently no commercial marine fish hatchery in Tasmania. One of the biggest impediments to the development of new marine fish aquaculture industries has been the reliable cost-effective supply of high quality seed stock (Battaglene and Fielder 1997). Development of new species in Australia has in general proven more difficult and taken considerably longer than first envisaged. The development of commercial marine fish hatcheries in mainland states has been, with the exception of barramundi hatcheries, particularly slow and in many instances they have been poorly sited. Commercial marine fish hatcheries are expensive and a hatchery capable of producing the many millions of seed stock required for the salmon industry in Tasmania may be prohibitively expensive. All but the biggest companies would find such expenditure difficult and a similar model to that developed with the introduction of Atlantic salmon and the establishment of a state-backed 'Saltas model' marine hatchery may be required.

5.6.2 *Expansion into new sites*

It is likely that new zoning areas will need to be developed for sea cage culture of new species. Current salmon leases are in many instances located in areas with significant freshwater runoff, remain brackish for extended periods, and / or have freshwater surface stratification. These are all excellent conditions for salmonid culture but less well suited to marine species, particularly the oceanic species, like striped trumpeter and yellowtail kingfish, which are not euryhaline. Expansion into new areas may increase distances to shore bases and increase operational costs.

5.6.3 *Development of new markets and value added products*

Most of the discussion has been focused on biological attributes and issues relating to new species development. Alongside the development of suitable farming techniques are the economic considerations of marketing new species. Salmon are sold to a well established market and are a very versatile product well suited to value adding e.g., smoking. While the demand for high quality white-fleshed fish is increasing the markets may be different and in some cases more aligned with exporting. The larger salmon companies are vertically integrated and have their own processing factories which in most cases could be adapted to process alternative species.

5.6.4 *Health issues*

All new marine fish species are going to require health management. New species are particularly venerable to parasites, bacterial and viral diseases. The known parasites and diseases of particular relevance are mentioned under each species discussed above and are often species specific. The salmonid industry has controlled health through vaccination, husbandry, and in-feed medication including antibiotics and treatment baths. As discussed under chapter 4.1 disease outbreaks may become more common and difficult to control in salmon due to climate change. The use of freshwater to control AGD is particularly expensive but it may also be required in other species, stretching the resource base. The possibility for cross contamination of diseases between salmonids and new species also exists and there have been related outbreaks overseas. Separation of farming zones for new species is one possible control mechanism but would come at a cost.

5.6.5 *Interaction with wild fish*

All sea cage farming operations result in escaped farmed fish. Escapes of salmon in Tasmania are not uncommon and are usually due to human error, storm events, or seal attacks. Escaped salmon create problems for wild fish stocks because it encourages recreational gill netting which indiscriminately catches wild fish. In other parts of the world where salmon are farmed within their natural range there are other potentially more serious issues with salmonid escapees, including genetic fitness reductions and increased parasitic loading. If native Tasmanian fish are farmed then monitoring may be required to determine potential negative effects on local stocks.

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Tang, D., Andrews, M., Cobcroft, J.M., 2007. The first Chondracanthid (Copepoda: Cyclopoida) reported from cultured finfish, with a revised key to the species of *Chondracanthus*. Journal of Parasitology 93, 788-795.

Taylor, S.G., 2008. Climate warming causes phenologicla shift in pink salmon, Oncorhynchus gorbuscha, behavior at Auke Creek, Alaska. Global Change Biology 14, 229-235.

Thuvander, A., Wichard, U.P., Reitan, L.J., 1993. Humoral antibody response of brown trout *Salmo trutta* vaccinated against furunculosis. Diseases of Aquatic Organisms 17, 17-23.

Tobback, E., Decostere, A., Hermans, K., Haesebrouck, F., Chiers, K., 2007. *Yersinia ruckeri* infections in salmonid fish. Journal of Fish Diseases 30, 257-268.

Tops, S., Lockwood, W., Okamura, B., 2006. Temperature-driven proliferation of *Tetracapsuloides bryosalmonae* in bryozoan hosts portends salmonid declines. Diseases of Aquatic Organisms 70, 227-236.

Treadwell, R., McKelvie, L., Maguire, G.B., 1991. Profitability of selected aquacultural species. Australian Bureau of Agricultural and Resource Economics, Research Report 92.2, Canberra, ACT, 85.

Yearsley, G., 1999. Australian Seafood Handbook. Domestic Species. Editors Yearsley, G.K., Last, P.R., Ward, R.D., 461, Courtney Colour Graphics, Melbourne.

Young, N.D., Crosbie, P.B.B., Adams, M.B., Nowak, B.F., Morrison, R.N., 2007. *Neoparamoeba perurans* n. sp., an agent of amoebic gill disease of Atlantic salmon (*Salmo salar*). International Journal for Parasitology 37, 1469-1481.

Young, N.D., Dykova, I., Snekvik, K., Nowak, B.F., Morrison, R.N., 2008. *Neoparamoeba perurans* is a cosmopolitan aetiological agent of amoebic gill disease. Diseases of Aquatic Organisms 78, 217-223.

Wallaert, C., Babin, P.J., 1994. Effects of temperature variations on dietary lipid absorption and plasma lipoprotein concentrations in trout (*Oncorhynchus mykiss*). Comparative Biochemistry and Physiology. Part B: Biochemistry & Molecular Biology 109b(2-3), 473-487.

Webster, S.J., Dill, L.M., 2007. Estimating the energetic cost of abiotic conditions using foraging behaviour. Evolutionary Ecology Research 9(1), 123-143.

Windell, J.T., Kitchell, J.F., Norris, D.O., Norris, J.S., Foltz, J.W., 1976. Temperature and rate of gastric evacuation by rainbow trout. Transactions of the American Fisheries Society 105, 712-717.

Wilby, R.L., Charles, S.P., Zorita, E., Timbal, B., Whetton, P., Mearns, L.O., 2004. Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods. Part of Supporting Material of the Intergovernmental Panel on Climate Change prepared at the request of the Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA). Web link: www.ipcc-data.org/guidelines/dgm_no2_v1_09_2004.pdf.

Wilkie, M.P., Brobbel, M.A., Davidson, K., Forsyth, L., Tufts, B.L., 1997. Influences of temperature upon the post exercise physiology of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Science 54, 503-511.

8 Appendices

8.1 Glossary

This glossary provides definitions and explanations of technical terms.

Amoebic Gill Disease: Important disease in sea-caged salmonids; manifested by lethargy, flared opercula, rapid death; encouraged by high temperatures: current treatment freshwater bathing.

Apparent Digestibility: The practical measurement of digestive and absorptive efficiency, reflecting the inter-relationships between factors such as diet composition; feed intake; gastric and digestive tract evacuation; digestive enzyme synthesis and activity and absorption across digestive tract epithelium.

Climatology: Average conditions based on historical data e.g. a water temperature seasonal climatology would represent average water temperature conditions for each month of a year (Jan - Dec).

Climate change: Climate change is the change in average weather over time and over a region. Climate change includes changes in temperature, wind patterns and precipitation.

Climate regime: Climate is commonly defined as the weather averaged over a long period of time (say 30 years). A climate regime is a period of time with the same climatic conditions. It may be long and worldwide, such as an ice age, or short and regional, such as a 10 year period of cooler conditions in eastern Australia.

Daily growth co-efficient: Measure of growth, assumes that growth is proportional to the mass to the power 2/3.

Degree days: The product of time and temperature required to reach a particular stage of development or size.

Dynamical downscaling: Modelling technique which involves the nesting of high a resolution circulation model within a larger model, such as a regional model.

Ensemble analysis: Analysis technique involving simultaneously considering a range of models or the same model with a range of conditions in order to derive a prediction.

Geopotential: The potential energy of a unit mass relative to sea level, numerically equal to the work that would be done in lifting the unit mass from sea level to the height at which the mass is located, against the force of gravity.

Growth Ration (GR) curve: Curve plotting feed ration versus growth rate (usually expressed as % body weight per day or mg per g body weight per day).

Interannual: Refers to a climatic process that re-occurs every three to ten years.

Long-term forecast: Meteorological and oceanographic predictions given for forthcoming periods ranging from years to decades.

Marine Flexibacteriosis: skin disease of salmonids caused by *Tenacibaculum maritimum.*

Medium-term forecast: Meteorological and oceanographic predictions given for forthcoming periods ranging from months to years.

Quasi-decadal cycle: a cycle that appears to have a period of approximately 10 years, but not always.

Rickettsia-like Organism: Intracellular bacterium (undescribed species) causing systemic infection in salmonids farmed in marine environment, similar to piscirickettsiosis (caused by *Piscirickettsia salmonis* - bacterial pathogen exotic to Australia).

Short-term forecast: Meteorological and oceanographic predictions given for forthcoming periods ranging from hours to days.

Specific growth rate (SGR): Measure of growth that assumes exponential growth between two times and is most applicable to fast growing juvenile fish,(expressed as %/day).

Statistical modelling: Field of modelling broadly based on calculating a relationship between two variables (predictor and response variable) and then using this relationship to translate values of the known variable into values of the unknown response variable.

Turbidity: Cloudiness caused by particles suspended in water.

Thermal Growth Co-efficient: A measure of fish growth that takes account of water temperature and is based on 'degree days'. It can be used to predict growth at different temperatures using data from other temperatures although caution is required if extrapolating to extreme temperatures.

Yersinosis: Systemic disease caused by bacterium *Yersinia ruckeri,* while the fish usually get infected during the freshwater stage outbreaks can still occur in sea cages due to carrier status of some fish

8.2 Summary of published literature - section 4.1

8.2.1 Effects of high temperatures on immune response of fish

Various spp.

Bly, J.E., Quiniou, S.M., Clem, L.W., 1997. Environmental effects on fish immune mechanisms. In: Gudding, R., Lillehaug, A., Midtlyng, P.j., Brown, F. (Eds), Fish Vaccinology. Dev Biol Stand. Basel, Karger, 90, 33-43.

- Elevated water temperatures within the physiological range (5-10°C above ambient temp) generally enhance immune functions. Could be due to induction of Heat shock proteins (HSP) which protect protein folding and trafficking from adverse effects of high temperatures.

Bowden, T.J., Thompson, K.D., Morgan, A.L., Gratacap, R.M.L., Nikoskelainen, S., 2007. Seasonal variation and the immune response: A fish perspective. Fish & Shellfish Immunology 22, 695-706.

- As explained by Bly 1997 and Alcorn 2002.

O. tshawytscha

Harrahy, L. N. M., Schreck, C.B., Maule, A.G., 2001. Antibody-producing cells correlated to body weight in juvenile chinook salmon (*Oncorhynchus tshawytscha*) acclimated to optimal and elevated temperatures. Fish & Shellfish Immunology 11, 653-659.

- Fish of same weight acclimated to high temperatures (21°C v/s 13°C) show higher numbers of antibody producing cells (APC).

O. nerka

Alcorn, S.W., Murray, A. L., Pascho, R.J., 2002. Effects of rearing temperature on immune functions in sockeye salmon (*Oncorhynchus nerka*). Fish & Shellfish Immunology 12, 303-334.

- Fish reared at 8ºC relied more on the non-specific immune response, while the specific immune response was used to a greater extent in fish reared at 12°C.
- Increased lymphocyte numbers in fish reared at 12°C.
- Higher proportion of phagocytic cells were observed in fish reared at 8°C, but could mean that mature phagocytes have a tendency to emigrate from the haematopoietic tissues in fish reared at 12°C.
- Production of an antigen specific antibody response is enhanced with higher temps. The specific serum antibody response was higher for fish reared at 12°C, as well as the serum immunoglobin concentration and natural antibody titre.
- At higher temperature, the percentage of leucocytes that were lymphocytes and the ability to mount an antibody response to a T-cell dependant antigen was greater.
- Changes in rearing temps affect disease resistance by acting on both humoral and cellular immune functions.
- Environmental temp may also affect factors pathogens use to overcome the fish's immune response.

Salmo salar

Pettersen, E.F., Bjørløw, I., Hagland, T.J., Wergeland, H.I., 2005. Effect of seawater temperature on leucocyte populations in Atlantic salmon post-smolts. Veterinary Immunology and Immunopathology 106, 65-76.

- In Post-smolt period (0-14 weeks after SW transfer) the distribution of immunoglobulin positive (Ig+) cells and neutrophils in isolated peripheral blood leucocytes (PBL) and head kidney leucocytes (HKL) were studied at 18°C, 14°C, 10°C and 6°C.

- At 6°C higher percentages of Ig+ cells were found in PBL compared to the other temperatures. At 18°C higher proportions of neutrophils and lower proportions of Ig+ cells in PBL were found compared to the other groups.
- The proportions of HKL populations do not seem to be dependent on temperature. No clear differences in the percentages of Ig+ cells and neutrophils in HKL were observed in any groups. The results could indicate that the post-smolts reared at a temperature of 18 °C experienced thermal stress or a non-optimal environment.

O. mykiss

Nikoskelainen, S., Bylund, G., Lilius, E.M., 2004. Effect of environmental temperature on rainbow trout (*Oncorhynchus mykiss*) nnate immunity. Developmental and comparative immunology 28, 581-592.

- Fish were acclimatized at 5, 10, 15 and 25°C. For each temp group, RB activity, phagocytosis, complement lytic activity and opsonisation capacity of plasma were measured at 5, 10, 15 and 20°C during the in vitro assays.
- Respiratory burst (RB) activity was higher and the peak time was earlier in groups acclimatized at 15 and 20°C.
- Higher acclimation temperatures increased the lytic activity of both the alternative and the total complement pathways.
- The opsonisation activity was higher with higher acclimation temps. The titres of natural immunoglobulin were higher at the highest acclimation temp.
- The higher the temperature the assays were carried out the higher the RB activity for all the acclimation groups.
- Therefore environmental temperatures must affect innate immunity at least in the same order as they affect adaptive immunity.

8.2.2 Effects of high temperatures on vaccine efficacy

V. salmonicida , A. salmonicida

Eggset, G., Mikkelsen, H., Killie., J.E. A., 1997. Immunocompetence and duration of immunity against *Vibrio salmonicida* and *Aeromonas salmonicida* after vaccination of Atlantic salmon (*Salmo salar* L.) at low and high temperatures. Fish & Shellfish Immunology 7, 247-260.

- *Salmo salar*: Comparison of fish vaccinated with a water-based and an oil-emulsified vaccine. When fish were vaccinated and challenged at 10°C (high temperature) the protection was improved against both pathogens (low mortalities) indicating that rearing temps has an impact on the rate by which protection develops.

Kollner, B., Kotterba, G., 2002. Temperature dependent activation of leucocyte populations of rainbow trout, *Oncorhynchus mykiss*, after intraperitoneal immunisation with *Aeromonas salmonicida*. Fish & Shellfish Immunology 12, 35-48.

- *O. mykiss*: When comparing trouts kept at <12°C v/s >15°C, animals kept at higher temperatures developed a higher leukocyte response.
- At >15°C, the amount of monocytes, granulocytes and B cells in blood and of monocytes and B-cells in spleen prepared for *A. salmonicida* increased much more than other leukocyte populations (T-cells and thrombocytes).
- Fish kept at <12°C developed a stronger antibody response than those kept at 15°C.
- Environmental temp of 10-12°C is near the physiological optimum for trout.

Lillehaug, A., Ramstad, A., Baekken, K., Reitan, L.J., 1993. Protective immunity in Atlantic samon (*Salmo salar* L.) vaccinated at different temperatures. Fish & Shellfish Immunology 3, 143- 136.

- *S. salar*: Fish vaccinated by injection and immersion showed lower protection when vaccinated at 8°C or 10°C than at lower temps (2, 4 and 6°C).
- However, antibody titres against *V. salmonicida* were higher in fish vaccinated by injection at 8°C or 10°C.

Steine, N.O., Melingen, G.O., Wergeland, H.I., 2001. Antibodies against *Vibrio salmonicida* lipopolysaccharide (LPS) and whole bacteria in sera from Atlantic salmon (*Salmo salar* L.) vaccinated during the smolting and early post-smolt period. Fish & Shellfish Immunology 11, 39-52.

- *S. salar*: Fish vaccinated during smolting period at higher temps than others (but only 9.5°C) were the only ones with high antibody values after 4 and 8 weeks post-primary vaccination.
- Other groups were vaccinated at lower temps (3.5, 3.6 and 6°C).

Y. ruckeri

Raida, M.K., Buchmann, K., 2007. Temperature-dependent expression of immune-relevant genes in rainbow trout following *Yersinia ruckeri* vaccination. Diseases of Aquatic Organisms 77, 41-52.

- *O. mykiss*: Fish were acclimatised at 5, 15 and 25°C and inoculated with a bacterin and immune-relevant gene expression measured. The bacterin induced cytokine gene expression, expression of cellular receptor genes and immunoglobulin production, which were higher at higher temps.
- The production of pro-inflammatory cytokine IL-1β occurred faster and at higher rates at higher temps.
- IFN-γ was up regulated in immunised fish, especially at higher temps. Naive fish showed higher levels of antibodies when kept at 25°C, showing a temperature-dependant production of natural immunoglobulin.
- No depression of gene expression could be detected even at temperatures close to the lethal limit for *O. mykiss* (25°C).

Raida, M.K., Buchmann, K., 2008. Bath vaccination of rainbow trout (*Oncorhynchus mykiss* Walbaum) against *Yersinia ruckeri*: Effects of temperature on protection and gene expression. Vaccine 26, 1050-1062.

- Protection of rainbow trout fry following bath vaccination with a bacterin of *Y. ruckeri* 01, the bacterial pathogen causing enteric red mouth disease (ERM), was investigated at 5, 15 and 25 degrees C.
- Rainbow trout fry were acclimatised for 8 weeks at the three temperatures before vaccination. They were subsequently challenged with *Y. ruckeri* 4 and 8 weeks post-vaccination, which demonstrated a significant protection of vaccinated fish kept at 15 degrees C. No protective effect of vaccination in rainbow trout reared at 5 and 25 degrees C could be recorded.
- Spleen tissue was sampled from vaccinated and control fish at 0, 8, 24 and 72 h post-vaccination in order to analyse gene transcript profiles using quantitative real-time RT-PCR (q-PCR). Gene expression in fish vaccinated at 15 degrees C (the protected fish) was up-regulated with regard to the pro-inflammatory cytokines IFN-gamma, TNF-alpha, IL-6 and the anti-inflammatory cytokines IL-10 and TGF-beta, the cell receptors TcR, CD8 alpha, CD4, C5aR and the teleost specific immunoglobulin IgT.
- Passive immunisation using transfer of plasma from vaccinated fish to naive fish conferred no protection. This indicates that humoral factors such as Ig and complement are less important in the protection induced by bath vaccination. Expression of cellular factors such as CD8 alpha was significantly increased in the protected trout and this suggests that cellular factors including cytotoxic T-cells could play a role in immunity against *Y. ruckeri*.

Vibrio anguillarum

Acosta, F., Lockhart, K., Gahlawat, S.K., Real, F., Ellis, A.E., 2004. Mx expression in Atlantic salmon (*Salmo salar* L.) parr in response to *Listonella anguillarum* bacterin, lipopolysaccharide and chromosomal DNA. Fish and Shellfish Immunology 17, 255-263.

- In *S. salar*: By injecting either a bacterin, purified DNA or purified LPS of the pathogen; the expression of Mx genes (for Mx proteins) occurred faster (from day 1) in fish injected at 10ºC compared to those injected at 6ºC (where response occurred after 3 days and peaked later as well).

8.2.3 Effects of high temperatures on pathogens

V. salmonicida

Colquhoun, D.J., Sørum, H., 2001. Temperature dependent siderophore production in *Vibrio salmonicida*. Microbial Pathogenesis 31, 213-219.

- Causative agent of cold water vibriosis, in Atlantic salmon. Occurs only at low water temperatures and not normally above 10°C.
- Siderophore production occurs in vitro only at 10°C or below, but in iron-limited media optimal cell growth was identified at 12°C.
- Growth without significant siderophore production was also observed in iron-limited media at temperatures above and below 10°C. Temperature sensitive iron sequestration may constitute a significant virulence.

A. salmonicida

Thuvander, A., Wichard, U.P., Reitan, L.J., 1993. Humoral antibody response of brown trout *Salmo trutta* vaccinated against furunculosis. Diseases of Aquatic Organisms 17, 17-23.

- *S. trutta*: Due to low temperatures, outbreaks of furunculosis do not appear (6.5 to 9°C). In order to recreate acute mortalities due to a furunculosis outbreak, water temperatures must reach values of 18°C.

Y. ruckeri

Tobback, E., Decostere, A., Hermans, K., Haesebrouck, F., Chiers, K., 2007. *Yersinia ruckeri* infections in salmonid fish. Journal of Fish Diseases 30, 257-268.

- Infection through carrier fish is especially important under stress conditions. Carriers can transmit it to healthy fish when temperature was raised to 25°C.
- Expression of the operon for Yrp1 protease and siderophore (virulence factors) was found to be high at 18°C but repressed at 28°C and may be an adaptation to the optimal temp for efficient infection and colonization.

Tenacibaculum maritimum

Handlinger, J., Soltani, M., Percival, S., 1997. The pathology *of Flexibacter maritimus* in aquaculture species in Tasmania, Australia. Journal of Fish Diseases 20, 159-168.

- In *S. salar* and *O. mykiss*: 1st severe outbreak in Tasmania was in all southern east area during summer 1988-1989 (Nov to Jan). Fish developed ulcerated skin lesion during a period (months) of cloud-free sunny days, when water temps went up to 21°C. Most severe outbreaks related to warm water conditions and extended period of sunny days.
- Some of histopathological changes were similar to those observed as a result of UV irradiation.
- In experimental infections conducted at water temps of 18°C and with controlled lights, fish develop the disease but no lesions on eyes or dorsal region were observed, supporting the theory that UV radiation could be a precursor factor for the development of the lesions.

V. anguillarum

Powell, J.L., Loutit, M.W., 1994. The detection of fish pathogen *Vibrio anguillarum* in water and fish using a species-specific DNA probe combined with membrane filtration. Microb Ecol 28, 375-383.

- In water samples: The numbers of bacteria present in the water were assessed (cultivable colonies). Samples from a land-based site and marine sites were collected.
- In the land based site, where the fresh water was drawn from a stream (lower NaCl concentrations) the numbers of the bacteria increased as the water temp increased.
- In the water from the marine samples there were fewer cultivable cells and they did not correlate with water temps.

Neoparamoeba perurans

Douglas-Helders, M., Saksida, S., Raverty, S., Nowak, B.F., 2001. Temperature as a risk factor for outbreaks of Amoebic Gill Disease in farmed Atlantic salmon (*Salmo salar*). Bulletin of European Association of Fish Pathologists 21(3), 114-117.

Adams, M.B., Nowak, B.F., 2004. Sequential pathology after initial freshwater bath treatment for amoebic gill disease in cultured Atlantic salmon, *Salmo salar* L. Journal of Fish Diseases 27, 163-173.

Douglas-Helders, M., Nowak, B.F., Butler, R., 2005. The effect of environmental factors on the distribution of *Neoparamoeba pemaquidensis* in Tasmania. Journal of Fish Diseases 28, 583-592.

- Clinical AGD in *Salmo salar* has been documented between 15°C and 20°C in Tasmania.
- Experimental infection has shown that temps above 16°C increase mortalities. Outbreaks are reported to occur at higher water temps, with temperature being the most important factor affecting AGD presentation and progression (after salinity).
- High temperatures may facilitate a faster reinfection rate. Higher water temps correlate with higher number of trophozoites in the water column and severity is associated with higher numbers of the pathogen.

8.2.4 Effects of global warming in populations and emerging diseases

Pathogen: Lactococcus garvieae, Streptococcus iniae.

Ghittino, C., Prearo, M., Ghittino, M., Eldar, A., 1998. Recent knowledge on warm water "Streptococcoses" in rainbow trout (Recenti acquisizioni sulle "Streptococcosi" d'acqua calda nella trota iridea). Boll. Soc. Ital. Patol. Ittica 10, 43-50.

- In O. *mykiss*: warm water "Streptococcoses" are emerging problems in various Mediterranean Countries.
- Clinical and external signs appear at water temperature above 15°C.
- Prevention can be achieved with IP vaccination.

Proliferative kidney disease

Tops, S., Lockwood, W., Okamura, B., 2006. Temperature-driven proliferation of *Tetracapsuloides bryosalmonae* in bryozoan hosts portends salmonid declines. Diseases of Aquatic Organisms 70, 227-236.

- In various salmonid spp: PKD is an emerging disease causing around 25% mortalities in brown trout in freshwater environments.
- The parasite multiplies in fishes primarily in the kidney and spleen, and fish hosts mount a massive cell-mediated immune response. Outbreaks are seasonal occurring when water temps reach 15°C.
- Increased temperatures can provoke, accelerate and prolong the proliferation of infective stages of *Tetracapsuloides bryosalmonae*. Latency decreased with increasing temperature.
- PKD outbreaks could be exacerbated by increased temperatures promoting parasite proliferation in fishes and prolonged stimulation of the fish immune response thereby increasing disease.
- There is no treatment and is expected to heavily attack salmonids from aquaculture industry.

8.2.5 General on climate change

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S., Samuel, M.D., 2002. Climate Warming and Disease Risks for Terrestrial and Marine Biota. Science 296, 2158-2162.

- Climate warming can increase pathogen development and survival rates, disease transmission, and host susceptibility.
- The direct components of predicted climate change affecting marine organisms over the next century are (i) temperature increase, (ii) sea level increase and subsequent changes in ocean circulation, and (iii) decrease in salinity.

- The numerous mechanisms linking climate warming and disease spread support the hypothesis that climate warming is contributing to ongoing range expansions.
- Pathogens have preferred temps, and will expand or contract ranges depending on their tolerances. Range changes may affect biodiversity either by introducing a new pathogen or parasite to a population, or by releasing hosts from a major source of population regulation.

Roessig, J.M., Woodley, C.M., Cech, J.J., Hansen, L.J., 2004. Effects of global climate change on marine and estuarine fishes and fisheries. Reviews in Fish Biology and Fisheries 14, 251-275.

- Because algal blooms (fish poisoning) have been correlated with excessive rain (wash of fertiliser and sewage into coastal waters), their frequency and severity are likely to increase with the predicted increasing climatic variability.

Hari, R.E., Livingstone, R.S., Burkhardt-Holm, P., Gűttinger, H., 2006. Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. Global Change Biology 12, 10-26.

- Populations of brown trout have been decreasing on Swiss lakes during the last quarter of the 20^{th} century, in association with increases in water temperatures. This has lead to an increase in the presentation of PKD.
- It indicates that maximum growth rates for brown trout occur at 13.1-13.9°C, while growth ceases above 18.7-19.5°C. It also mentions that the incipient lethal temp for this species (survival for 7 days) is at 24.7±0.5°C and that the ultimate lethal temp (survival for 10 mins) is 29.7±0.36°C.

Climate change on parasites

Marcogliese, D.J., 2001. Implications of climate change for parasitism of animals in the aquatic environment. Canadian Journal of Zoology 79, 1331-1351.

- Models predict that changes in temp will be conducive to alterations in water level, degree of eutrophication, ice cover, stratification, acidification, currents, UV radiation.
- General effects of increased temps on parasites are rapid growth and maturation, earlier maturation in spring, increased number of generations per year, earlier transmission and potential transmission year-round.
- With increasing temps, biomass and density of the benthos could decline and parasites with direct life cycles such as monogeanans could proliferate because they grow and mature faster.
- With high temps and reduced O2 concentrations, gill parasites may proliferate and cause respiratory problems.

General on global warming

Crozier, L.G., Zabel, R.W., Hamlet, A.F., 2008. Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon. Global Change Biology 14, 236-249.

- Previously observed that juvenile survival in Snake River spring/summer Chinook salmon is strongly correlated with summer temperature in some populations and with fall streamflow in others.
- Explored potential differential responses of the viability of four of these populations to changes in streamflow and temperature that might result from climate change.
    - **i.** linked predicted changes in air temperature and precipitation from several General Circulation Models to a local hydrological model to project streamflow and air temperature under two climate-change scenarios.
    - **ii.** developed a stochastic, density-dependent life-cycle model with independent environmental effects in juvenile and ocean stages, and parameterized the model for each population.
- Found that mean abundance decreased 20-50% and the probability of quasi-extinction increased dramatically (from 0.1-0.4 to 0.3-0.9) for all populations in both scenarios. Differences between populations were greater in the more moderate climate scenario than in the more extreme, hot/dry scenario. Model results were relatively robust to realistic uncertainty in freshwater survival parameters in all scenarios.
- Results demonstrate that detailed population models can usefully incorporate climate-change predictions, and that global warming poses a direct threat to freshwater stages in these fish,

increasing their risk of extinction, infer that maintaining habitat diversity will help buffer some species from the impacts of climate change.

Taylor, S.G., 2008. Climate warming causes phenologicla shift in pink salmon, *Oncorhynchus gorbuscha*, behavior at Auke Creek, Alaska. Global Change Biology 14, 229-235.

- Thirty-four years (1972-2005) of water temperature data and extensive biological observations at Auke Creek, Alaska, indicate a general warming trend that affected the native pink salmon (*Oncorhynchus gorbuscha*) population. Serial environmental records at nearby Auke Bay, Alaska over 46 years show trends of increasing air and sea surface temperatures. Trends of increased total precipitation and earlier date of ice out on nearby Auke Lake also occurred, but not at significant rates.
- Average water temperatures during the incubation of pink salmon in Auke Creek increased at a rate of 0.03 degrees C yr(-1) over the 34-year period. For the 1972-2005 broods, midpoints of fry migrations from Auke Creek ranged between April 2 and May 7, and there was a trend of earlier migration of pink salmon fry at a rate of -0.5 days yr(-1).
- The migration timing of adult salmon into Auke Creek also showed a trend toward earlier timing. The earlier adult migration combined with warmer incubation temperatures are related to earlier migration of pink salmon fry.
- If the observed warming trend continues, Auke Creek may become unsuitable habitat for pink salmon. Given the trend for salmon fry to migrate earlier, a larger portion of the population may become mismatched with optimum environmental conditions during their early marine life history. If salmon adults continue to migrate into the creek earlier when water temperatures are commonly high, it will result in increased prespawning mortality.

8.3 Summary of published literature - section 4.2

8.3.1 Growth and Growth Models

Feed intake and growth

Brett, J.R., Shelbourn, J.E., Shoop, C.T., 1969. Growth rate and body composition of fingerling Sockeye salmon, *Oncorhynchus nerka*, in relation to temperature and ration size. Journal of the Fisheries Research Board of Canada 26, 2363-2394.

- Compared the effects of temperature (1, 5, 10, 15, 20, 24°C) and ration (0. 1.5, 3, 4.5, 6% and excess) on sockeye salmon.
- No growth occurred at >23°C regardless of ration size.
- Maintenance rations increased rapidly above 12°C. Maintenance ration for 20°C was seven times that level for 1°C.
- The optimum ration for 20°C was five times that level for 1°C, the maximum ration for 20°C was three times that level for 1°C.
- Fish held at higher water temperatures had higher moisture content in their bodies than fish held in cooler temperatures.
- It was noted that many physiological processes are influenced by temperature and time and that the huge difference in degree days (83-1700) may have had an effect on the results.

Jonsson, B., Forseth, T., Jensen, A.J., and Næsje, T.F., 2001. Thermal performance of juvenile Atlantic salmon, *Salmo salar* L. Functional Ecology 15, 701-711.

- Measured growth and feed consumption of wild Atlantic salmon parr from various streams of different temperatures.
- Although results were different between populations, they appeared unrelated to temperature.
- Estimated optimum growth temperatures were estimated between 16-20°C, while the optimum temperature for food consumption was between 19-21°C.

Koskella, J., Pirhonen, J., and Jobling, M., 1997. Feed intake, growth rate and body composition of juvenile Baltic salmon exposed to different constant temperatures. Aquaculture International, 5, 351-360.

- Investigated the effects of temperature (11, 15, 17, 19 and 23°C) on the feed intake, growth rate and body composition of Atlantic salmon.

- Feed intake was greatest at 17°C. SGR was highest at 15°C.
- The upper thermal limits for feed intake was 29°C and 24.1°C for growth.

Mørkøre, T., Rørvik, K., 2001. Seasonal variations in growth, feed utilisation and product quality of farmed Atlantic salmon (*Salmo salar*) transferred to seawater as 0+ smolts or 1+ smolts. Aquaculture 199, 145-157.

- Assessed seasonal variations in various parameters including growth for Atlantic salmon (held in freshwater, aged either 9 months or 16 months at the start of the trial) over a 12 month period in Norway.
- Seasonal differences were greatest in the older fish for growth rates, although these differences were not significant.

Meeuwig, M.H., Dunham, J.B., Hayes, J.P., Vinyard, G.L., 2004. Effects of constant and cyclical thermal regimes on growth and feeding of juvenile cutthroat trout of variable sizes. Ecology of Freshwater Fish 13, 208-216.

- Investigated the effect of temperature (steady 12, 18 or 24°C or cyclical 15-21, 12-24°C) on the growth and feeding behaviour of cutthroat salmon.
- The growth rates of fish held in cyclical regimes and at 24°C were adversely affected by temperature, but feed intake was only affected by the constant high temperature in the 24°C conditions. In addition, the larger the fish the greater the effects of the high temperatures.
- The results indicated that even brief exposure to high temperatures (24°C) had adverse effects for the fish.

Myrick, C.A., Cech Jr., J.J., 2005. Effects of temperature on the growth, food consumption, and thermal tolerance of age-0 Nimbus-strain Steelhead. North American Journal of Aquaculture 67, 324-330.

- Compared feed consumption, growth and temperature tolerance for steelhead at temperatures of 11, 15 and 19°C.
- No difference in feed consumption among three temperatures, higher growth rate at 19°C, and trout adjusted their upper thermal tolerance when held in warmer water (from 27.5°C for 11°C fish to 29.6°C for 19°C fish).

Peterson, R.H., Martin-Robichaud, D.J., 1989. First feeding of Atlantic salmon (*Salmo salar* L.) fry as influenced by temperature regime. Aquaculture 78, 35-53.

- Investigated the effect of rearing and incubation temperature on first feeding and subsequent survival.
- Found that incubation temperature had little effect, but that rearing temperature at time of first feed did.
- Found that the larvae did best in temperatures ranging from 16-20°C, with the projected optimum temperature at 17.5-18.2°C. Fish did not do well at 23°C, and this was thought to be due to heat stress.

Bioenergetic and factorial models

Bailey, J., Alanärä, A., 2006. Digestible energy need (DEN) of selected farmed fish species. Aquaculture 251, 438-455.

- Investigated the effect of body weight and temperature on the digestible energy needs of farmed fish species including salmonids.
- Found that temperature did not affect the DE requirements of salmonids.

Brocksen, R.W., Bugge, J.P., 1974. Preliminary investigations on the influence of temperature on food assimilation by rainbow trout *Salmo gairdneri* Richardson. Journal of Fish Biology 6, 93-97.

- Tested the energy assimilation by juvenile rainbow trout at a range of temperatures (5, 17 and 20°C).
- The lowest assimilation level was at 5°C and the highest was at 20°C.
- Energy assimilation increased as temperature increased. This was thought to be due to a doubling of metabolic rate caused by increased activity and temperature, which in turn increased the energy demands of the fish.
- It was also suggested that increased temperatures increased the enzyme activity and so more energy was able to be digested and absorbed.

Elliott, J.M., 1975b. Weight of food and time required to satiate brown trout, *Salmo trutta* L. Freshwater Biology 5, 51-64.

- Investigated the effect of body weight (8-358g) and water temperature (3.8-21.6°C) on the feed consumption of young hatchery reared brown trout.
- Found that appetite was greatest between 13.3-18.4°C and decreased rapidly above 18.4°C. At 19.5°C appetite was half the maximum amount reached.
- Also found that maintenance requirements were greater than the energy provided by the food above 18.4°C as metabolic rate increased with increasing water temperature. Hence fish rapidly lost weight.
- All fish regardless of size responded in a similar manner to increasing water temperature, except that the overall feed intake was bigger for bigger fish (as to be expected).
- Found that feeding behaviour was erratic at temperatures above 19°C and hence it impossible to calculate satiation times.

Elliott, J.M., 1975c. Number of meals in a day, maximum weight of food consumed in a day and maximum rate of feeding for brown trout, *Salmo trutta* L. Freshwater Biology 5, 287-303.

- Investigated the effects of water temperature (3.8-18.1°C) and fish size (9-302g) on feed consumption and time between feeds and feeds per day when fed to satiation.
- Found that time between feeds was much shorter when water temperature was higher. Also found that the amount eaten per day increased as water temperature increased.
- Feeding rate decreased dramatically at temperatures above 19.3°C.

Elliott, J.M., 1976. The energetics of feeding, metabolism and growth of brown trout (*Salmo trutta* L.) in relation to body weight, water temperature and ration size. Journal of Animal Ecology 45, 923-948.

- Investigated the energy budgets of brown trout (5-281g) using various ration sizes at temperatures ranging from 3.8-21.7°C.
- Temperature affected the daily energy intake (C), energy lost in faeces (F) and excretory products (U), metabolism (R) and the change on the energy content of the fish (ΔB).
- Decreasing energy intake caused the optimum temperature for ΔB also decreased.
- Efficiency of energy utilization decreased as temperatures increased above 11°C.

Elliott, J.M., 1982. The effects of temperature and ration size on the growth and energetics of salmonids in captivity. Comparative Biochemistry and Physiology B 73B, 81-91.

- There are thermal limits not only for survival but also for feeding (also influenced by acclimation i.e., if a fish is acclimated to a higher temperature then it will continue to feed to a higher temperature.
- Daily energy intake is affected by both fish size and water temperature.
- Absorption efficiency for energy in food increases with increasing temperature.
- Energy loss in faeces and excretory products is dependent on water temperature.
- Energy available for growth and metabolism decreases at higher temperatures.
- Survival time in starving fish is directly influenced by water temperature.
- Optimum temperature for growth does not correspond with the most efficient temperature for growth due to effects of increasing metabolism etc.

Hecht, T., McEwan, A.G., 1992. Changes in gross protein and lipid requirements of rainbow trout, *Oncorhynchus mykiss*, (Walbaum), at elevated temperatures. Aquaculture and Fisheries Management 23, 133-148.

- Assessed the protein and lipid requirements of two size cohorts (<4.5g, >25g) of juvenile rainbow trout at temperatures of 18-25°C in recirculation systems in South Africa where trout spend up to a third of the year in thermal stress conditions.
- Assessed results based on the growth rate, FCR (low), protein efficiency ratio (PER) (high), and carcass lipid levels (low).
- Found that for trout <4.5g, the optimum protein to lipid ratios in the diet were - 35% dietary protein with either 20 or 23% dietary lipids.
- Found that increasing water temperature, decreased the protein requirements (50% in optimal temperatures) and increased the lipid requirements (15-18% in optimal temperatures) - possibly as a result of increased energy demand caused by increased metabolic rate.

- Protein levels could not be reduced below 35% as this is the protein threshold. Below this level growth is impossible.
- The introduction of specially formulated summer diets has caused a 24.1% decrease in the cost of production per 1kg of fish when compared to a normal commercial diet.

Smith, R.R., Rumsey, G.L., Scott, M.L., 1978. Net energy maintenance requirements of salmonids as measured by direct calorimetry: Effect of body size and environmental temperature. The Journal of Nutrition 108, 1017-1024.

- Investigated the effect of body size and temperature on the metabolic rate of several fish species including Atlantic salmon (1-4 g) using temperatures of 3-18°C.
- Found that the metabolic rate increased linearly as water temperature increased. However they recommended further investigation for temperatures outside those tested because extrapolated values were unexpected.

Physiological predictors of thermal optima and maxima

Grande, M., Andersen, S., 1991. Critical thermal maxima for young salmonids. Journal of Freshwater Ecology 6, 275-279.

- Determined the thermal maxima for lake trout (*Salvelinus namaycush*, 25.9°C), Atlantic salmon (*Salmo salar*, 29.2°C), and - together - brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*), and rainbow trout (*Oncorhynchus mykiss*), 26.2-27.9°C.

Johansson, D., Ruohonen, K., Kiessling, A., Oppedal, F., Stiansen, J., Kelly, M., Juell, J., 2006. Effect of environmental factors on swimming depth preferences of Atlantic salmon (*Salmo salar* L.) and temporal and spatial variations in oxygen levels in sea cages at a fjord site. Aquaculture, 254 594-605.

- Investigated the preferred swimming depth of caged Atlantic salmon in response to temperature, light, oxygen levels, salinity, feeding and water currents in a stratified fjord site using a high and low stocking density.
- Found that the preferred temperature was 16-18°C, and that oxygen levels were low where fish congregated.

Rodnick, K.J., Gamperl, A.K., Lizars, K.R., Bennett, M.T., Rausch, R.N., Keeley, E.R., 2004. Thermal tolerance and metabolic physiology among redband trout populations in south-eastern Oregon. Journal of Fish Biology 64, 310-335.

- Investigated the thermal maxima, metabolic rate (routine and maximum) and swimming performance of three wild strains of rainbow trout (different size cohorts) in different water temperatures.
- At temperatures of 24-28°C larger fish had higher metabolic costs than smaller fish and were more affected by temperature.
- Results also suggested that metabolic energy stores had a positive correlation with the swimming behaviour of rainbow trout at higher temperatures.

Selong, J.H., McMahon, T.E., Zale, A.V., Barrows, F.T., 2001. Effect of temperature on growth and survival of bull trout, with application of an improved method for determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130, 1026-1037.

- Bull trout thermal requirements have not been previously defined.
- Tested temperatures at 2°C intervals ranging from 8-28°C. Found 98% survival for 8-18°C, but 0% for 22-38°C. Therefore determined that lethal temperature was 20.9°C.
- Found that peak growth occurred at 13.2°C, with a decrease in feed consumption above 16°C eventuating in no feeding above 22°C.
- Found that feed/lipid/protein efficiencies were similar for 8-18°C, but decreased above 20°C.

Webster, S.J., Dill, L.M., 2007. Estimating the energetic cost of abiotic conditions using foraging behaviour. Evolutionary Ecology Research 9(1), 123-143.

- Investigated the energetic costs associated with different temperatures (8.9, 12.6 or 15.7°C) and salinities.
- Salmon showed a preference for foraging in the 8.9°C water compared to the 15.7°C water, but did not a preference for the 8.9°C over the 12.6°C.

- Energetic costs of different temperatures were the same when water temperature differed by only 4°C, but was 1.72 greater when there was a 7°C difference.

Growth: Maturation and Reproduction

Adams, C.E., Thorpe, J.E., 1989. Photoperiod and temperature effects on early development and reproductive investment in Atlantic salmon (*Salmo salar* L.). Aquaculture 79, 403-409.

- Investigated effects of photoperiod and temperature on Atlantic salmon maturation rates.
- Temperatures used were 5°C above ambient temperature to a maximum of 20°C and ambient water temperature.
- Found that increased temperature increased the number of males that underwent early maturation and increased ovary investment in female fish.

Baum, D., Laughton, R., Armstrong, J.D., Metcalfe, N.B., 2005. The effect of temperature on growth and early maturation in a wild population of Atlantic salmon parr. Journal of Fish Biology 67, 1370-1380.

- Investigated the effect of water temperature on the maturation rates and size of wild Atlantic salmon parr.
- Distillery effluent raised water temperatures downstream by 1.2-6.3°C (2.7°C±0.2°C, mean ± SE) above the ambient water temperature.
- Found that the densities of salmon were higher in the cooler water.
- Found that mature parr in the cooler water were smaller than mature parr in the warmer water and that this suggests that warmer water fish have a higher size limit before maturation can occur.

Berglund, I., Hansen, L.P., Lundqvist, H., Jonsson, B., Eriksson, T., Thorpe, J.E., Eriksson, L.O., 1991. Effects of elevated winter temperature on seawater adaptability, sexual rematuration, and downstream migratory behaviour in mature male Atlantic salmon parr (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 48, 1041-1047.

- Assessed the effects of different temperature regimes (9°C above ambient for two month periods with three different starting times, constant 9°C for five months, and a control group held at ambient temperature through out the experiment, ambient temperature was <0.06°C at the beginning of the trial and increased to 11°C by the end of the trial) on the rematuration of Atlantic salmon.
- Also used two groups of male fish - immature and previously mature fish.
- There was no significant difference in rematuration rates between the groups of fish held in warmer temperatures for two months, regardless of the starting time. However the rematuration rates for these groups (28.9%) were lower than for the other groups, although not significantly different from the five group (84.1% for the control, 38.7% for the five month group).
- Assessed the effects of different temperature regimes on the rematuration of Atlantic salmon (9°C above ambient for two month periods with three different starting times, constant 9°C for five months, and a control group held at ambient temperature through out the experiment, ambient temperature was <0.06°C at the beginning of the trial and increased to 11°C by the end of the trial).
- Also used two groups of male fish - immature and previously mature fish.
- Fish grown at 9°C for five months grew significantly faster (reaching 55.7g) than any other temperature regime and the control group (reaching 35.5g) had the slowest growth rate.

Duston, J., Saunders, R.L., 1999. Effect of winter food deprivation on growth and sexual maturity on Atlantic salmon (*Salmo salar*) in seawater. Canadian Journal of Fisheries and Aquatic Sciences 56, 201-207.

- Assessed the effect of feed ration and feed intake on the maturation rate of Atlantic salmon.
- There were temperature differences between sites and although the aim of the experiment was not to test this it was concluded that winter temperature has an important influence on sea age at maturity. Higher maturation rates occurred in fish that had been held in relatively warmer water (4, 7°C) when compared to fish held in the cold water (1°C).

Dziewulska, K., Domagala, J., 2003. Precocious males of cultured Atlantic salmon, *Salmo salar* L. in the second spawning season. Acta Ichthyologica et Piscatoria 33(2), 153-160.

- Low growth male Atlantic salmon that had been cultured in 0.1-10°C water were assessed during the first spawning season to determine the gonadal development stage and the level of precocious male maturation within the population.
- It was determined that precocious males were present within the population and that they were capable of fertilisation.

Friedland, K.D., 1998. Ocean climate influences on critical Atlantic salmon (*Salmo salar*) life history events. Canadian Journal of Fisheries and Aquatic Sciences 55, 119-130.

- Maturation rates of wild salmonids are dependent on environmental factors including water temperature.
- Growth rates of wild salmonids are dependent on environmental factors including water temperature.

Herbinger, C.M., Friars, G.W., 1992. Effects of winter temperature and feeding regime on the rate of early maturation in Atlantic salmon (*Salmo salar*) male parr. Aquaculture 101(1-2), 147-162.

- Assessed the effects of two temperature regimes (3-7°C, 7-14°C) and feed rations (satiation and restricted) on the growth and maturation rates of salmon parr.
- The effect of temperature on maturation rate was not statistically significant despite its association with increased growth.
- Maturation was more affected by feed ration than by temperature, although there was a slightly higher maturation rate in the fish held in the cooler water (at odds with increased growth rates at higher temperature).
- Male and female parr growth was similar in the cooler water. However there was a significant effect when the effects of temperature were considered in association with feed ration. Fish did better when fed to satiation and also responded well to the warmer water temperature.

Hutchings, J.A., Jones, M.E.B., 1998. Life history variation and growth rate thresholds for maturity in Atlantic salmon, *Salmo salar*. Canadian Journal of Fisheries and Aquatic Sciences 55, 22-47.

- Reviewed data (published and unpublished) to describe the patterns in Atlantic salmon life history and its relation to maturity.
- Early maturity is affected by an individual fish's growth rate at sea, which is in turn affected by temperature and photoperiod. The faster they grow, the sooner they reach the minimal size for maturation.

McClure, C.A., Hammell, K.L., Moore, M., Dohoo, I.R., Burnley, H., 2007. Risk factors for early sexual maturation in Atlantic salmon in seawater farms in New Brunswick and Nova Scotia, Canada. Aquaculture 272, 370-379.

- Investigated the risk factors associated with grilsing at marine Atlantic salmon farms.
- Risk factors included differences in water temperature between late winter and early autumn.
- Water temperature is also a risk factor when it is colder than average in the cooler months and warmer than average in the warmer months i.e. it more of a risk when the water temperature is at the more extreme ends of the temperature tolerance scale.
- In addition, the greater the temperature differences between seasons, the greater the risk of grilse.
- Average body weight per farm did not correlate with the average monthly water temperature.

Saunders, R.L., Henderson, E, B., Glebe, B.D., 1982. Precocious sexual maturation and smoltification in male Atlantic salmon, (*Salmo salar*). Aquaculture 28, 211-229.

- One year old male parr were grown under two temperature (a constant 10°C, and 3.4-5.7°C) - photoperiod regimes to assess the effect of the regimes on the lipid and condition factor of mature and immature males during smolting.
- Gonadosomatic indexes decreased as water temperature decreased.
- Salinity tolerance occurred sooner in fish that were held in higher temperatures.
- The mature males had a slower growth rate than immature males.

8.3.2 Nutritional variables

Digestibility

Brett, J.R., Higgs, D.A., 1970. Effect of temperature on the rate of gastric digestion in fingerling sockeye salmon, *Oncorhynchus nerka*. J. Fish. Res. Bd. Can., 27, 1767-1779.

- Compared the rate of gastric digestion rates for yearling sockeye salmon at a range of temperatures (3, 5, 10, 15, 20, and 23°C) when fed artificial pellets to satiation.
- The rate of digestion was proportional to the amount of food found in the stomach at any given temperature.
- Gastric digestion rate increased as temperature increased (147 h at 3°C to 18 h at 23°C).

Fauconneau, B., Choubert, G., Blanc, D., Breque, J., Luquet, 1983. Influence of environmental temperature on flow rate of foodstuffs through the gastrointestinal tract of rainbow trout. Aquaculture 34, 27-39.

- Investigated the digestion rates of rainbow trout when temperature fluctuated from 9-10°C to 18°C in one day.
- Digestion rate was affected, decreasing after just one day of exposure. Results were independent of feed intake and thus were a result of the temperature change.

Nicieza, A.G., Reiriz, L., Braña, F., 1994. Variation in digestive performance between geographically disjunct populations of Atlantic salmon: countergradient in passage time and digestion rate. Oecologia 99, 243-251.

- Investigated the digestion rates of two strains (Scottish and Spanish) of Atlantic salmon at three different temperatures (5, 12 and 20°C).
- Dry matter digestion increased as water temperature increased (no difference between strains).
- Evacuation rates were longer for the Spanish (adapted to warmer water) strain than the Scottish strain (adapted to cooler water) at 5 and 20°C.
- Results show evidence of a counter-gradient variation in digestion rates that may be in response to growing opportunities.

Windell, J.T., Kitchell, J.F., Norris, D.O., Norris, J.S., Foltz, J.W., 1976. Temperature and rate of gastric evacuation by rainbow trout. Transactions of the American Fisheries Society 105, 712-717.

- Compared effects of temperature (5, 10, 15 and 20°C) on gastric evacuation for two different diets using rainbow trout.
- Found that evacuation rates increased as temperature increased (58.5-72.4 h at 5°C compared to 16.4 h at 20°C).
- Noted that digestion rates rarely show an optimum, but do reach a maximum rate as the threshold for thermo tolerance is reached.
- Noted various difficulties that arise when comparing temperature effects and digestion between literature (temperature variations, thermal history and size of experimental animals, weight, volume, and feed quality, fullness of the fish stomach).

Chemical composition

Elliott, J.M., 1976. Body composition of Brown trout (*Salmo trutta* L.) in relation to temperature and ration size. Journal of Animal Ecology 45, 273-289.

- Investigated the effect that feed ration, body weight and water temperature (3.8-19.5°C) had on the growth rates and body composition of brown trout.
- Found that ash content was not affected by temperature. Temperature affected the body composition in a secondary fashion, by influencing the amount of feed consumed and the time spent feeding.
- At high temperatures the rate of change of body composition of starved fish was high, but decreased for fish that were fed maximum amounts.

Koskella, J., Pirhonen, J., Jobling, M., 1997. Feed intake, growth rate and body composition of juvenile Baltic salmon exposed to different constant temperatures. Aquaculture International, 5, 351-360.

- Lipid deposition was not affected by rearing temperature.

Gines, R., Valdimarsdottir, T., Sveinsdottir, K., Thorarensen, H., 2004. Effects of rearing temperature and strain on sensory characteristics, texture, colour, and fat of Arctic Charr (*Salvelinus alpinus*). Food Quality and Preference 15, 177-185.

- Arctic charr were reared at 10 and 15°C were slaughtered and the fillets were analysed using a variety of methods to determine the differences in quality.
- The fish reared in 10°C had a higher measure of red, yellow, orange and chroma than the 15°C fish.
- Raw fillets of the 15°C had higher values for hardness, gumminess, chewiness and fracture ability then the fillets of 10°C fish.
- Fat content did not appear too affected by temperature.
- All of these are commercially important attributes and are relevant to the marketability of the product.

Jerret, A.R., Law, R.A., Holland, A.J., Cleaver, S.E., Ford, S.C., 2000. Optimum postmortem chilled storage temperature for summer and winter acclimated, rested, Chinook salmon (*Oncorhynchus tshawytscha*) white muscle. Journal of Food Science 65 (5), 750-755.

- Chinook salmon that had previously been acclimated to 10.7, 12.4 and 18.8°C were killed with anaesthetic and stored in 35% (typo in the abstract?) at a variety of temperatures (2-19°C) to assess the effects of post mortem storage temperature on the metabolic rate of white muscle.
- Fish acclimated to 10.7 and 12.4°C were 2.2 times more sensitive to the storage temperature than 18.8°C acclimated fish.

Meka, J.M., McCormick, S.D., 2005. Physiological response of wild rainbow trout to angling: impact of angling duration, fish size, body condition, and temperature. Fisheries Research 72, 311-322.

- Assessed the immediate physiological response of wild rainbow trout to catch and release stress.
- Plasma cortisol, glucose, ions (sodium, potassium and chloride), and lactate were used to assess the effects of various parameters including water temperature.
- Fish caught when water temperature was higher (13°C compared to 10°C) had significantly higher lactate and plasma cortisol levels.

Miller, M.R., Nichols, P.D., Barnes, J., Davies, N.W., Peacock, E.J., Carter, C.G., 2006. Regiospecificity profiles of storage and membrane lipids from the gill and muscle tissue of Atlantic salmon (*Salmo salar* L.) grown at elevated temperature. Lipids 41, 865-876.

- Investigated the effects of high water temperature (19°C) on storage and lipid membranes profiles in the gill and muscle tissues.
- Found that red and white muscles of the 19°C fish had lower levels of total n-3 PUFA, PUFA, and increased saturated fatty acids (SFA) in the lipid profiles compared to the 15°C fish.
- Found that temperature particularly affected the phospholipid (cell membrane) fraction. There were higher levels of SFA in PL and less PUFA (particularly n-3/n-6) in the gills and white muscle.
- The ratios of FA that formed part of the PL were different to the normal ratios for salmon reared in cooler temperatures.
- Temperature increases caused the fish lipids to adapt to the warmer water by decreased unsaturation and chain length of FA.

Mørkøre, T., Rørvik, K., 2001. Seasonal variations in growth, feed utilisation and product quality of farmed Atlantic salmon (*Salmo salar*) transferred to seawater as 0+ smolts or 1+ smolts. Aquaculture 199, 145-157.

- Assessed seasonal variations in various parameters including product quality for Atlantic salmon (held in freshwater, aged either 9 months or 16 months at the start of the trial) over a 12 month period in Norway.
- Tissue fat content was higher in the autumn.
- There was a positive correlation between high growth rates and increased tissue softness. Fillet gaping was highest in the warmer months.

Olsen, S.H., Sorensen, N.K., Stormo, S.K., Elvevoll, E.O., 2006. Effect of slaughter methods on blood spotting and residual blood in fillets of Atlantic salmon (*Salmo salar*). Aquaculture 258, 462-469.

- Assessed the effects of slaughter method on the residual blood of fillets. This was measured by the number of blood spots and haemoglobin left in the fillet.

- The time that it took blood to coagulate was strongly correlated with temperature. When carcasses were stored in cooler temperatures (0.5±0.5°C compared to 4.0±0.5°C) the blood took longer to clot and so blood spotting was less of an issue as bleeding time was increased.
- Live chilling (holding tanks with water at 1.0±0.5°C) also decreased the incidence of blood spots by increasing the time it took for blood to coagulate.

Wallaert, C., Babin, P.J., 1994. Effects of temperature variations on dietary lipid absorption and plasma lipoprotein concentrations in trout (*Oncorhynchus mykiss*). Comparative Biochemistry and Physiology. Part B: Biochemistry & Molecular Biology 109b(2-3), 473-487.

- Assessed the rate of lipid absorption in juvenile rainbow trout at different temperatures.
- Rapid temperature (not seasonal) changes affected the plasma concentrations of glucose, lipids and lipoproteins, but not free glycerol.
- The plasma concentration of very low density lipoproteins increased by two or three times after two days of warm water acclimation. This in turn caused an increase in low density lipoproteins.

Tissue structure

Johnston, IA., 1999. Muscle development and growth: potential implications for flesh quality in fish. Aquaculture 177 (1-4), 99-115.

- Reviewed the effects of environmental parameters on the muscle development for various fish species including Atlantic salmon and various trout. Also reviewed effects on Atlantic herring, common carp and the largemouth bass (see below).
- Myogenesis at the 30-somite stage was not affected by temperature in Atlantic salmon or brown trout.
- Water temperature during early development affected the number and size distribution of white muscle fibres in Atlantic salmon. Water temperature of 10°C yielded 33% less white muscle fibres than cooler temperatures. Atlantic salmon reared at 5°C had twice as many white muscle fibres than fish reared at 11°C, while Atlantic salmon reared at 8°C had 16.6% fewer embryonic white muscle fibres than fish reared at 4.3°C.
- Exposing Atlantic salmon to different incubation temperatures during the egg stage can influence to number of undifferentiated myoblasts and hence influence the muscle recruitment in later developmental stages.

Energy loss (respiration and metabolism)

Brett, J.R., 1967. Swimming performance of sockeye salmon (*Oncorhynchus nerka*) in relation to fatigue and temperature. Journal of the Fisheries Research Board of Canada 24, 1731-1741.

- Investigated the relationship between swimming performance and fatigue using fingerling sockeye salmon and the effects that increasing temperature had on that relationship.
- When acclimated to 15°C salmon had a 4% reduction in swimming speed when exposed to 10 and 20°C.
- Temperatures above the lethal limit had a rapid decline in swimming performance.

Dickson, I.W., Kramer, R.H., 1971. Factors influencing scope for activity and active and standard metabolism of rainbow trout (*Salmo gairdneri*) J. Fish. Res. Bd. Can., 28, 587-596.

- Compared the metabolic activity of hatchery reared and wild rainbow trout at a variety of temperatures (5, 10, 15, 20, 25°C).
- Scope for activity is considered as a means to assess the environmental stress on fish.
- Scope for activity at all temperatures was similar for both fish groups, except for 25°C, where the wild trout were significantly higher.
- For hatchery trout the scope was highest at 15°C. It was also highest 6 days after starvation.

Elliot, J.M., 1976c. Energy losses in the waste products of brown trout (*Salmo trutta* L.). Journal of Animal Ecology 45, 561-580.

- Assessed the excreted energy losses at a variety of temperatures (up to 24°C).
- As temperature increased the amount of energy lost in the faeces decreased.
- Absorption efficiency increased as temperature increased.
- As the temperature increased the amount of energy lost in excretory products increased.

- Available energy increased as temperature increased at the cooler temperatures but decreased as temperature continued to rise above the optimum.

Farrell, A.P., 2002. Cardiorespiratory performance in salmonids during exercise at high temperature: insights into cardiovascular design limitations in fishes. Comparative Biochemistry and Physiology Part A 132, 797-810.

- Assessed salmonids in lab and in the field to determine if critical swimming performance had an optimum temperature and if this was associated with the maximum cardiac scope and the maximum aerobic scope.
- Determined that when temperature was above the optimum (dependent on acclimation but generally around 18°C) the overall performance of the fish declines. For example when the acclimated optimum temperature is 11°C (rainbow trout) then the maximum cardiac output is 40% lower at 18°C compared to 11°C. Also suggested that aerobic capacity is greater at 11°C than at 4 or 18°C.
- Suggested that this could be due to a decline in the heart performance where the body is using more oxygen than is supplied and so the heart does not receive its oxygen requirement in the returning venous blood.
- This effect is enhanced at warmer temperatures because warmer water temperatures increase the ability of skeletal muscle to take up oxygen from the blood.

Farrell, A.P., 2007. Cardiorespiratory performance during prolonged swimming tests with salmonids: a perspective on temperature effects and potential analytical pitfalls. Philosophical Transactions of the Royal Society B-Biological Sciences 362, 1487, 2017-2030.

- Measured the changes in steady state oxygen consumption, cardiac output and tissue oxygen in relation to swimming speed using prolonged swimming trials of rainbow trout.
- Determined that oxygen uptake has an optimum temperature (not given in abstract).
- Determined that steady state swimming was interrupted as fish approached fatigue and their movements became irregular.

Galloway, B.J., Kieffer, J.D., 2003. The effects of an acute temperature change on the metabolic recovery from exhaustive exercise in juvenile Atlantic salmon (Salmo *salar*). Physiological and Biochemical Zoology 76 (5), 652-662.

- Influence of water temperature on recovery from exhaustive exercise using juvenile Atlantic salmon. Tested the responses of white muscle phosphocreatine, ATP, lactate, glycogen, glucose, pyruvate, plasma lactate and plasma osmolality, during rest and at 0, 1, 2 and 4 h post exercised. Fish were exercised at 12°C and then recovered in either 6°C or 18°C.
- The 6°C exposure reduced the metabolic recovery of the fish, while phosphocreatine, ATP and plasma lactate recovered well (within 2-4 h) in fish exposed to 18°C during recovery.
- Warmer conditions enhance recovery after exhaustive exercise.

Hammer, C., 1995. Fatigue and exercise tests with fish. Comparative Biochemistry and Physiology, Part A 112, 1-20.

- Reviews past experiments relating to fatigue and exercise in fish.
- Notes that the critical swimming speed is dependent on a variety of factors including water temperature and that it is difficult to compare tests relating to critical swimming speed because of its variability resulting from the interaction of many factors.

Hyndman, C.A., Kieffer, J.D., Benfey, T.J., 2003. Physiology and survival of triploid brook trout following exhaustive exercise in warm water. Aquaculture 221, 629-643.

- Assessed the effects of high temperature (19°C) on the post exercise recovery of diploid and triploid brook trout.
- Triploids used phosphocreatine and more glycogen than diploids during recovery. Triploids had difficulty using anaerobic metabolic pathways and took longer to recover. They also had a higher mortality rate (90% after 4 h).

Jain, K.E., Farrell, A.P., 2003. Influence of seasonal temperature on the repeat swimming performance of rainbow trout *Oncorhynchus mykiss*. Journal of Experimental Biology 206, 3569-3579.

- Investigated the recovery of rainbow trout after exhaustive exercise at a variety of temperatures (5-17°C), to explore the relationship between performance and preceding metabolic rate.

- Increasing water temperature increased the ability of the trout to perform a critical swimming test, but there was no correlation between increasing temperature and the ability to repeat the test.
- Swimming performance in the test at the higher temperatures was lower in the second test than the first (possibly due to a bigger anaerobic swimming effort), but both tests were equal for fish acclimated to cooler temperatures.
- Decreased performance in the second test was correlated with threshold lactate levels - if the threshold was reached in the first swim, then performance in the second test was less than in the first.
- Fish acclimated to colder water had less metabolic disruption.

Lee, C.G., Farrell, A.P., Lotto, A., MacNutt, M.J., Hinch, S.G., Healey, M.C., 2003. The effect of temperature on swimming performance and oxygen consumption in adult sockeye (*Oncorhynchus nerka*) and coho (*O. kisutch*) salmon stocks. Journal of Experimental Biology 206, 3239-3251.

- Assessed the effect of water temperature on swimming performance and metabolic rates of wild salmon from locations. Temperatures varied between locations (5-20°C).
- Differences in metabolic rates between stocks were consistent with differences between water temperatures, as was the maximum oxygen consumption.

Poppe, T.T., Taksdal, T., Bergtun, P.H., 2007. Suspected myocardial necrosis in farmed Atlantic salmon, *Salmo salar* L.: a field case. Journal of Fish Disease 30, 615-620.

- Suggest that high water temperature is one of the factors that contribute to increased cardiac workload, which in turn leads cardiac lesions that further affects that cardiac function including causing heart failure.

Reid, S.D., Dockray, J.J., Linton, T.K., McDonald, D.G., Wood, C.M., 1995. Effects of a summer temperature regime representative of a global warming scenario on growth and protein synthesis in hardwater- and softwater-acclimated juvenile rainbow trout (*Oncorhynchus mykiss*). Journal of Thermal Biology 20 (1-2), 231-244.

- Assessed the effect of increased summer temperatures on the growth, appetite, conversion efficiency and protein turnover rate in the liver, gills and white muscle of wild rainbow trout.
- Used hard and soft water at ambient (13-24°C) and ambient +2°C conditions.
- At the beginning of the experiment (when temperatures were still relatively cool) growth, appetite and conversion efficiency increased by an average of 16%. Further high temperature exposure then led to a 20% decrease in these parameters.
- At the beginning of the experiment (when temperatures were still relatively cool) protein turnover increased by an average of 16%. Further high temperature exposure then led to a 20% decrease in protein turnover.

Wilkie, M.P., Brobbel, M.A., Davidson, K., Forsyth, L., Tufts, B.L., 1997. Influences of temperature upon the post exercise physiology of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Science 54, 503-511.

- Assessed the post exercise disturbances when Atlantic salmon were exhaustively exercised at 12, 18 or 23°C that they had previously been acclimated to.
- Phosphocreatine and ATP decreased in the white muscle for all temperatures.
- Phosphocreatine was rapidly restored within an hour for all three temperatures, but ATP took longer at 12°C.
- Decreased glycogen was correlated with increased lactate levels in the white muscle and this took longer to return to normal levels at 12°C than it did at 18 or 23°C.
- Plasma osmolality was also increased post exercise and again this was slower to recover at 12°C than at either 18 or 23°C.
- Mortality levels were significant (30%) at 23°C.

Wild populations

Kaeding, L.R., Kaya, C.M., 1978. Growth and diets of trout from contrasting environments in a geothermally heated stream: the Firehole River of Yellowstone National Park. Transactions of the American Fisheries Society 107, 432-438.

- Sampled wild brown and rainbow trout in Firehole River, Yellowstone National Park.
- River affected by geothermal energy and therefore water temperature is high in some areas (up to 28°C in some areas). River also contains increased mineral levels as a result of geological activity.
- Found that rainbow trout were only present in warmer water but showed similar characteristics to the warmer water brown trout.
- Found that brown trout in warmer water ate larger prey and in greater quantities, had faster growth rates, were bigger and two growing seasons in a year compared to the cooler water brown trout.

Morrison, B.R.S., 1989. The growth of juvenile Atlantic salmon, *Salmo salar* L. and brown trout, *Salmo trutta* L., in a Scottish river system subject to cooling-water discharge. Journal of Fish Biology 35, 539-556.

- Distillery effluent raised downstream water temperatures 1-3°C above ambient throughout the year.
- Found that salmon and trout grew faster in the warmer waters than they did in the cooler waters, regardless of age.