Mitigating impacts of climate change on stream food webs

Final Report

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MITIGATING IMPACTS OF CLIMATE CHANGE ON STREAM FOOD WEBS

Impacts of Elevated Temperature and Carbon Dioxide on the Critical Processes Underpinning Resilience of Aquatic Ecosystems

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

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Disclaimer

Cover image: Darren Giling

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ABSTRACT

Understanding the effects of changing climates on the processes which support aquatic biodiversity is of critical importance for managing aquatic ecosystems. This research used an experimental approach to determine whether there are potential ecological surprises in terms of threshold relationships between climate and critical aquatic processes. These results were then placed in the context of the potential for riparian replanting to mitigate against these impacts. A review was carried out of climate change experiments in freshwaters, and revealed that the vast majority of studies have failed to take into account predicted increases in the frequency of extreme events (such as heatwaves) on biota. In order to include these components of changes in climate, a methodology was developed for downscaling global circulation models of climate change to generate realistic temperature data to use as an experimental treatment. Stream communities from the field were brought into experimental flumes and warmed according to the predictions of the down-scaled climate change models. Experiments were run for six weeks and responses were measured for basal processes (algal productivity and carbon dynamics) and aquatic invertebrate communities. Basal processes showed relatively small responses to the changed temperature regime, and appear to be relatively resistant for warming on the scale predicted under climate change scenarios for the next century. Aquatic invertebrate communities did show some responses, but these tended to be in terms of changes in size structure withion particular taxa rather than major impacts on patterns of biodiversity. The largest effects were seen for emerging adults of aquatic insects, were all species in the community responded in some way to our 2100 climate change treatment. Responses were species- and sex-specific. Males of all mayfly species emerged faster under 2100 temperatures compared to 1990-2000 temperatures. For the mayfly *Ulmerophlebia pipinna* (Leptophlebiidae), this implied a change in the sex ratio that could potentially compromise populations and, ultimately, lead to local extinctions. Furthermore, our results show a decrease in the overall community body size (average across taxa) due to a shift from bigger to smaller species. These results are in accord with the ecological rules dealing with the temperature-size relationships (in particular, Bergmann’s rule). Studies of streams in the field revealed that riparian vegetation did cool stream temperatures, and that the presence of riparian vegetation, ideally with extensive vegetation cover across the catchment, did appear to maintain higher diversity and abundance in stream invertebrate communities. Therefore it seems that restoring riparian vegetation does represent an effective means of adaptation to changing climates for temperate south eastern Australian freshwaters.

EXECUTIVE SUMMARY

In freshwater systems, a number of recent reviews have discussed the potential impacts of climate change at scales from regional to global. Freshwater systems are particularly vulnerable to changing climates as they are often highly range-restricted, and are subject to competition for water resources with human uses.

Direct effects of increased stream temperatures are predicted to have major implications for the distribution of cold-water fish, particularly salmonids. Ecosystem consequences of altered climate are predicted to include changes in palatability of food resources and size spectra of animals resulting in altered food web structure.

In Objective 1 we reviewed the studies which have assessed effects of warming on aquatic communities. We found that these studies by-and-large have been based on field studies or are conceptual in nature, although in recent years there has been a small number of experimental studies. A review of those experimental studies found that the vast majority had either used a fixed mean warming treatment or an increment imposed on background conditions. The former of these remove variability from temperature. The latter retains existing variability in temperature. However climate change projections suggest dramatic increases in temperature variability as well as increases in mean temperature.

In order to experimentally assess the effects of realistic weather conditions arising from future climates we developed an approach for generating realistic temperature, CO_2 and sunlight series from global circulation models. We generated a daily weather time series that had the statistical features (e.g. wet/dry and hot/cool spells) of the Historical climate for Melbourne (1990-2009) and then superimposed the Miroc High resolution GCM projections for the A1B scenario. A series of weather was generated for a period of 20 years and the Jan/Feb period for the 10th year was extracted for use in driving the experimental treatments.

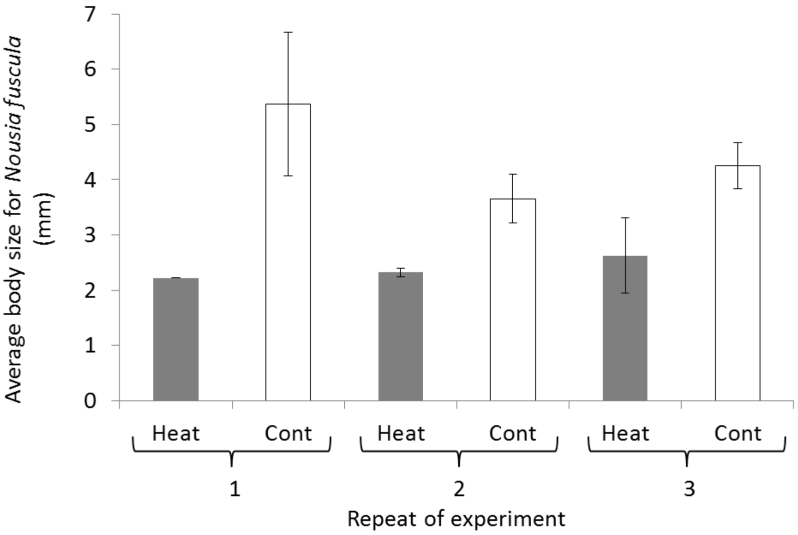
The generated weather series was then applied to experimental stream flumes which contained natural communities of algae and macroinvertebrates, and a range of ecological responses were measured, including algal productivity, organic matter processing and aquatic invertebrate food webs.

Algal productivity was higher in the climate change treatments, particularly in the mid part of the experiment. However it seems that a number of factors other than temperature act to limit algal productivity, and that responses to temperature change on the scales predicted under climate change scenarios are likely to be relatively small.

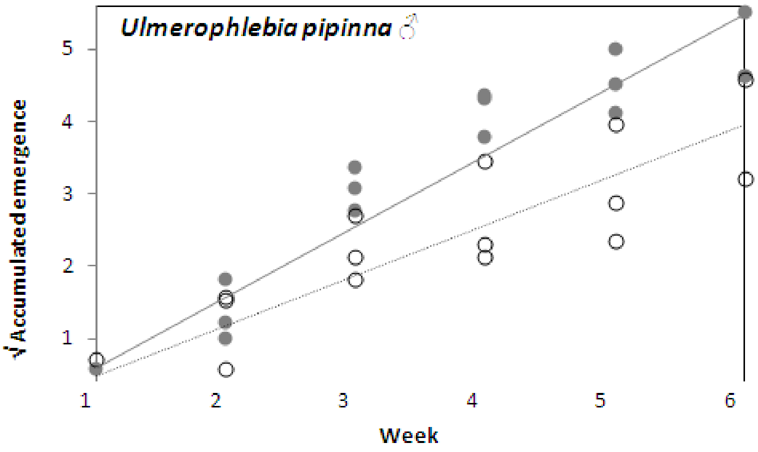
Dissolved organic carbon results suggested that terrestrially derived carbon was more quickly being consumed in the climate change treatment. This led to lower molecular weight organic matter being available, with a higher proportion of low aromaticity, microbially-derived fulvic acids in the climate change treatment. Effects were weak however, and not statistically significant, potentially due to the low replication in this study. These results confirm earlier studies which have suggested carbon processing may be relatively resistant to the relatively small changes in temperature consistent with those expected under climate change.

Aquatic invertebrate communities showed differing responses to altered temperatures. There was no clear effect on the number of taxa, and there was only a relatively minor increase in abundance in the warmed treatment. However for some taxa there were dramatic effects on size structure, with smaller individuals predominating (compare

average body size for the mayfly *Nousia* in warmed treatments (grey bars on figure below) to unwarmed treatments (white bars).



For the emerging adult stage of aquatic insects our results showed that all species in the community responded in some way when exposed to climate change treatment conditions, but that responses were species- and sex-specific. Total emergence across all taxa was higher in the climate change treatment as result of increased numbers emerging in the mayfly and Trichoptera groups. One of the most abundant mayfly species in Australian freshwater systems, *Ulmerophlebia pipinna*, responded to warmer temperatures by emerging in higher abundances, at smaller sizes and with a different sex ratio (figure below, compare warming treatment [grey symbols] with control [white symbols]).



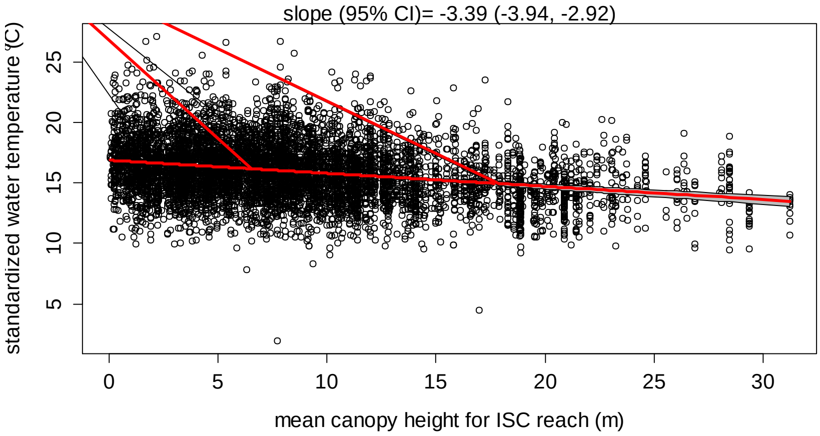
There was a change in the emerging insect community from one dominated by larger taxa (*U. pipinna*) to one dominated by smaller taxa (*Nousia fuscula*, *Nousia* spp., and *Agapetus* sp.) suggesting that temperature plays a major role in driving changes in the size structure of aquatic insect communities.

Responses to warming by different taxa were highly variable. The aquatic insect of south-eastern Australia has components of taxa which have evolved under cooler conditions (Gondwanan relicts, particularly stoneflies and mayflies) but also includes taxa which have diversified in the time since the Australian climate has become hotter and drier. The differing evolutionary history of these taxa is likely to have a major role in determining potential to respond to changing climate.

There was evidence that the climate change treatment caused changes in timing of emergence, with potential impacts on reproduction. Reproductive asynchrony, the occurrence of reproductively active individuals at different times within the reproductive period of the larger population, has been reportedly associated with unstable or unpredictable environmental conditions, including global warming. Males of all mayfly species (*U. pipinna, N. fuscula*, and *Nousia* spp.) emerged faster under climate change treatment conditions. In *U. pipinna*, there was a clear shift in the sex ratio from female biased under control treatment temperatures to significantly less female biased under climate change treatment temperatures.

Detailed temperature studies of five streams flowing from unvegetated areas into revegetated patches show that riparian vegetation can cool stream water on a scale (1-5 deg C) which is sufficient to offset the increases expected under climate change.

LiDAR analysis was used to test for broader-scale relationships between water temperature and riparian vegetation across Victoria. These results confirmed the detailed reach-level studies, and show that local-scale riparian vegetation cools streams by approximately 3 degrees Celsius, which is of a scale sufficient to mitigate against the predicted effects of climate change.



Riparian vegetation appears to have the potential to increase the resilience of aquatic communities to the impacts of climate change. Riparian restoration may be particularly beneficial in warmer catchments and may help to reduce negative effects of anthropogenic global warming in many regions.

1. OBJECTIVES OF THE RESEARCH

Adapting to the impacts of climate change requires an understanding of the complex ecological processes which underpin the relationships between climate and biodiversity (Lavergne *et al.* 2010). The impacts of changing climates in the field have been described in great detail and include range shifts (including invasions), altered patterns of timing of ecological phenomena (such as flowering), changes in body size distributions, and altered rates of ecosystem functions (e.g. Parmesan 2006; Traill *et al.* 2010; Sheridan and Bickford 2011). While we have an increasingly complete view of the effects of climate change on populations and individual physiology, it remains a challenge to understand the effects on biotic interactions and ecological feedbacks (Traill *et al.* 2010; Walther 2010). Such an understanding is critical if we are to apply our predictions of climate change effects to core issues such as conservation planning (McCarty 2001).

1.1 Objective 1 – To review community-level climate change experiments that have been carried out to date and describe the approaches taken.

There is an increasing awareness of the need for experimental approaches to studying climate change (Dawson *et al.* 2011). Climate change across much of the planet will include underlying increases in mean conditions (e.g., temperature, precipitation, solar radiation, and wind) but also climate variability (Jentsch *et al.* 2007). Increasing variability will cause changes in the frequency, duration, and intensity of extreme weather events such as heatwaves and dry spells (Katz and Brown 1992; Easterling *et al.* 2000; IPCC 2012). Experiments have been increasingly used over the last few decades to understand climate change impacts, and in particular, the mechanisms that underlie them (e.g. Henry and Molau 1997; Melillo *et al.* 2002; Crous *et al.* 2012). However generally these studies have investigated the effects of mean warming rather than any change in variability.

We assess the ways in which conditions resulting from climate change predictions have been applied as treatments in experiments on freshwater, marine and terrestrial systems. We assess the approaches taken in the different ecosystem types and the basis for those differences.

1.2 Objective 2 – To develop a methodology for down-scaling global circulation models to generate realistic treatments for climate change experiments.

Understanding the effects of changing climates on the processes which support aquatic biodiversity is of critical importance for managing aquatic ecosystems, and can be informed by carrying out community-level experiments. However, the majority of experimental studies of the effects of climate change have relied on very simple treatments of either warming to a stable temperature (therefore removing natural variability) or warming imposed on ambient conditions (thereby creating a set increase in temperature across all conditions, i.e. minimum temperatures are increased and maximum temperatures are increased) (e.g. Ledger *et al.* 2011). Actual changes in climate are likely to be different to either of these scenarios – climate change models in south-eastern Australia predict increases in maximum temperatures and in the length of hot spells, and much small changes in minimum temperatures (CSIRO-BoM 2007). In addition there will be changes in solar irradiance and increases in atmospheric CO_2. The effects of these variables have not been considered in experiments seeking to understand the effects of climate change on freshwater ecosystems. In order for climate change experiments to be realistic there is a need to generate experimental treatments that truly reflect conditions expected under future climates. This requires downscaling global circulation models to generate weather scenarios that include changes in mean conditions and changes in patterns of variability.

We describe an approach to using regional or global climate change models as the basis for generating experimental treatments which reflect the complex features of predicted future weather conditions.

1.3 Objective 3 – Using realistic climate change treatments in an experimental context to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions.

Predicting the ecological impacts of climate change is a crucial challenge that requires an understanding of the complex physiological, ecological, and evolutionary processes underpinning the relationships between climate and biodiversity (Lavergne *et al.* 2010; Bellard *et al.* 2012). Long-term observational records have been critical at revealing ecological patterns in response to climate change, including alterations in species' phenologies (e.g. Parmesan 2006; Pau *et al.* 2011), changes in body size distributions (e.g. Daufresne *et al.* 2009; Sheridan and Bickford 2011; Goodman *et al.* 2012), and alterations in rates of ecosystem function (e.g. Traill *et al.* 2010). Observational data have also been used to forecast the effect of climate change on biota by modelling changes in distributions under climate change scenarios (Walther *et al.* 2002). For example, 'climate envelope modelling' forecasts species distributions in accordance with their physiological thresholds. Although long-term ecological data and computational modelling provide important context for the study of climate change, they do not elaborate specific underlying ecological mechanisms. Understanding these mechanisms is critical to better evaluate the consequences of climate change on biota, and to apply our predictions to core issues in conservation planning and management (McCarty 2001).

Experiments have been increasingly used over the last few decades to understand climate change impacts and elucidate underlying mechanisms (e.g. Hogg and Williams 1996; Henry and Molau 1997; Melillo *et al.* 2002; Crous *et al.* 2012; Grieg *et al.* 2012). Most experimental studies have investigated the likely impacts of increases in mean climatic conditions ("trend effects" *sensu* Jentsch *et al.* 2007). However, it is now evident that trend effects will be complemented by changes in the timing, duration and intensity of extreme weather events such as heatwaves and dry spells ("event effects" *sensu* Jentsch *et al.* 2007). In south eastern Australia, climate models predict increases in the frequency of summer high rainfall events (where winter rainfall has historically been more common) and increases in extreme summer temperatures (Hobday and Lough 2011). Extreme weather events are important drivers of local patterns of diversity as well as of population and community dynamics (Parmesan *et al.* 2000; Parmesan 2006; Jentsch *et al.* 2007).

In freshwater systems, increased temperatures are predicted to have a broad range of impacts on; palatability of food resources (Van de Waal *et al.* 2010; Sardans *et al.* 2012), size spectra of animals (Daufresne *et al.* 2009; Yvon-Durocher *et al.* 2011), and phenology (Winder and Schindler 2004) resulting in altered food web structure (Woodward *et al.* 2010a). These predictions have largely been based on long-term field data or based on hypothesised relationships, although in the last decade there has been a number of experimental studies which have concentrated on increases in mean temperatures (McKee *et al.* 2003; Feuchtmayr *et al.* 2010; Yvon-Durocher *et al.* 2011; Dossena *et al.* 2012). While these experiments have been highly informative, they have failed to incorporate meaningful patterns of climatic variability as predicted by climate models. These studies have also emphasised impacts on biodiversity. Effects of temperature on ecosystem functions such as algal productivity, nutrient cycling and carbon dynamics are much less well understood, although the need for detailed study of these processes has been identified for over a decade (Palmer 1997; Lake *et al.* 2000).

Algal productivity has been shown in laboratory studies to be strongly affected by temperature (see DeNicola 1996 for a review). Impacts of increased temperature on algae in freshwater systems include changes in community composition (in particular from diatoms to green algae and blue-green algae dominated communities) and increases in algal productivity up to 30 degree Celsius, with declines thereafter. However DeNicola (1996) also notes that in most natural freshwater systems temperature is not the primary limiting factor on algal production, but instead interacts in complex ways with disturbance regime, light availability and nutrient dynamics. For example in Californian rivers disturbance drove primary production through depletion of populations of grazing insects after flows (Power 1995). Direct effects of temperature on algal productivity are difficult to predict, particularly in the context of other community and ecosystem interactions (De Nicola 1996).

Effects of temperature on carbon dynamics are similarly complex. Regional warming will alter riparian plant species composition and litter nutrient content, with consequences for the quality and quantity of detrital inputs (Meyer and Pulliam 1992). Predicted increases in carbon:nitrogen ratios in terrestrially derived plant litter will reduce decomposition rates and the quality of resources for in-stream consumers of detritus (Ineson and Cotrufo 1997, Ostrofsky 1997, Palmer 2000, Woodward *et al.* 2010). Altered hydrology as a result of changing climates may also alter retention times for litter (Arnell *et al.* 1996). These impacts are likely to interact with direct effects of warming on fungal and microbial communities. It has been suggested based on experimental warming studies that fungal and bacterial communities may be better able to up regulate in response to warming, whereas algal communities respond to warming less effectively (Yvon-Durocher *et al.* 2010). This could generate a scenario where fungi and bacteria out-compete algal communities for nutrients, resulting in a feedback where photosynthesis to respiration ratios reduce, and CO_2 production from freshwater ecosystems increases as warming increases (Gorham 1991, Yvon-Durocher *et al.* 2010).

The majority of studies of effects of climate on on aquatic systems as ‘closed’ environments and lack consideration of the linkages to adjacent terrestrial environments. Terrestrial and freshwater ecosystems are intimately connected via physical processes and fluxes of energy and nutrients across the riparian ecotone (Gregory *et al.* 1991). In particular, emerging insects connect terrestrial and aquatic environments by moving energy from streams, lakes, and ponds to the adjacent riparian communities. Emergent insects are an important subsidy to terrestrial predators, such as birds, lizards, insects, and spiders (e.g. Nakano *et al.* 1999; Sabo and Power 2002). In some instances, emerging insects can make up to 80% of a predator’s diet (Kato *et al.* 2003). Therefore, the timing of aquatic emergence can be crucial for both aquatic and terrestrial food web dynamics, and can affect resource flows between the two environments.

We measured the effects of a changed temperature regime on a range of ecological patterns and processes present in temperature streams. Specifically, we were interested in how current versus predicted stream temperatures impacts on; algal productivity, processing of dissolved organic matter, aquatic invertebrate community composition and emerging adult insect body size, community composition and sex ratios.

1.4 *Objective 4 – Using existing field data and experimental results, assess the potential for adaptive management of riparian vegetation to mitigate against the effects of changing climate.*

Riparian vegetation can act to mitigate against the effects of changing climate through a) acting as a carbon sink and b) moderating local temperatures through the creation of thermal refugia (Davies-Colley and Quinn 1998). There has been considerable discussion of the potential for riparian revegetation to moderate stream temperatures in North America, largely in the context of provision of habitat for salmonid fish (Beschta and Taylor 1988). Studies have shown that water temperatures can be reduced by up to 4 degrees Celsius on a 30 degree Celsius day by the presence of riparian shading (Sugimoto *et al.* 1997), which is of the same magnitude as predicted increases in temperature as a result of changing climate (CSIRO 2001). While there is still considerable debate over the magnitude of effects and interactions with flow, type of vegetation and stream form (see Moore *et al.* 2005 for a review), there is potential for riparian vegetation to mitigate against the effects of changing climate on stream biodiversity and ecosystem processes. Long term field studies of Australian streams have shown changes in community composition in stream invertebrates in response to periods of drought (Chessman 2009; Thomson *et al.* 2012), consistent with broader international reviews (Woodward *et al.* 2010a).

Thomson *et al.* (2012) used a large macroinvertebrate dataset collected from 1990 to 2009 to investigate trends in community composition and identify factors contributing to those trends. Data was used from 7372 samples from 2165 sites (100–250 m length, depending on stream size), which were sampled 1–30 times (median = 2) over the 20 years. A range of water quality and habitat variables, including water temperature, dissolved oxygen, pH, turbidity and substrate characteristics, were measured concurrently with macroinvertebrate samples according to Environmental Protection Authority (EPA) Victoria protocols (EPA 2003). Three standard macroinvertebrate condition indices were calculated for every sample: (1) the total number of taxa (total richness); (2) the number of Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) families detected (EPT richness, (Barbour *et al.* 1999)) and (3) the stream invertebrate grade number average level (SIGNAL; (Chessman 2003)). They found that macroinvertebrate indices were related to vegetation, flow and climate variables measured at stream reach and larger spatial scales. There was a positive response to local riparian tree cover, with the magnitude of that response being higher in catchments with higher tree cover (Figure 1). Invertebrate community health indices all increased when riparian trees were present, but that increase was largest when catchment tree cover was in excess of approximately 60%.

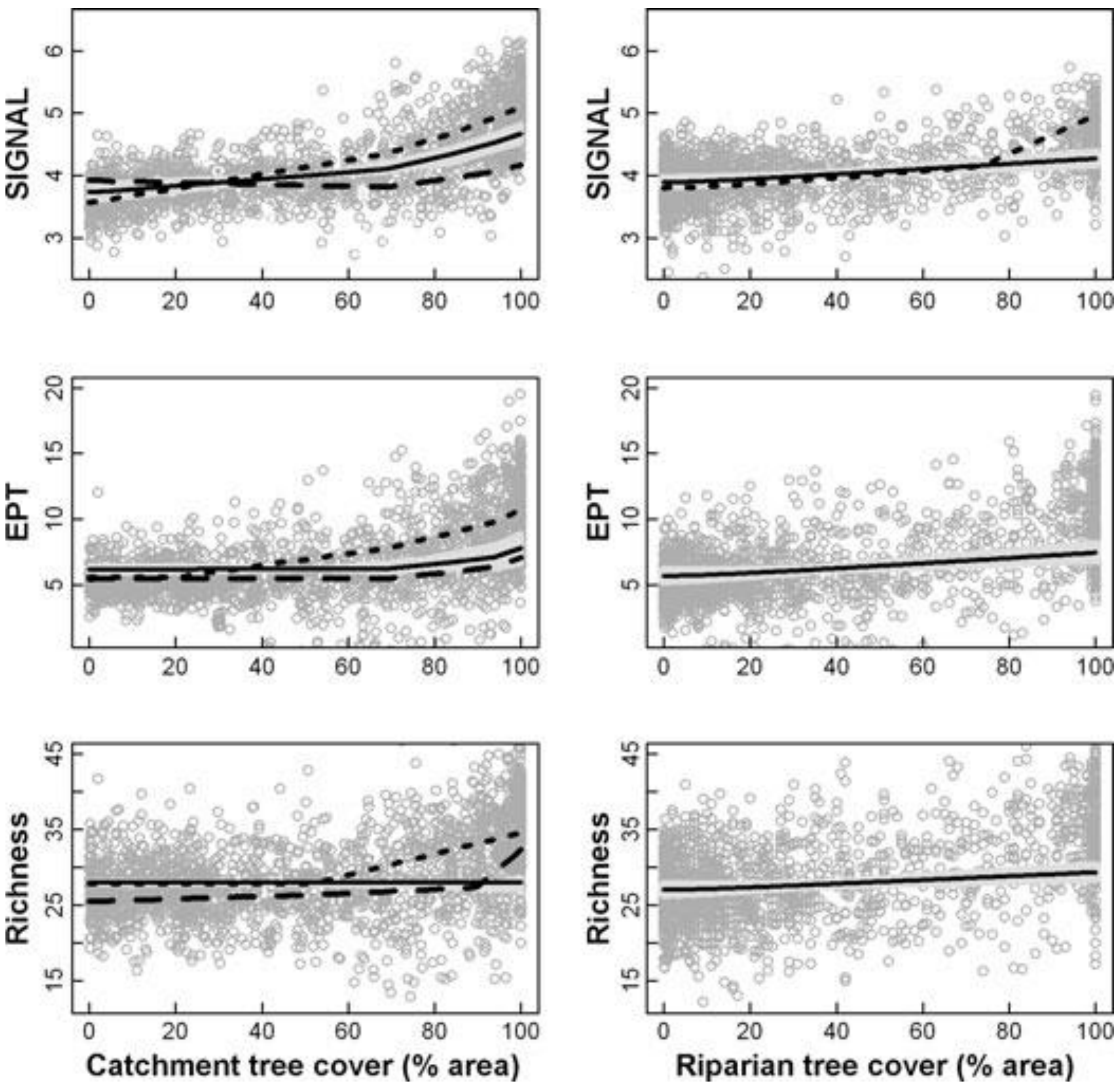


Figure 1. Relationships between mean SIGNAL (top), EPT (middle) and total richness scores at the reach scale and catchment (LHS) and riparian (RHS) tree cover.

Solid black lines are posterior means for conditional mean responses (assuming all other covariates constant at their means). Grey bands represent 95% credible intervals for mean responses (taken from Thomson et al. 2012).

Attributing better ecological condition to any cooling effect as a result of riparian vegetation was difficult in the Thomson *et al.* (2012) study because a) stream temperature data was limited to spot measurements which may not reflect diel impacts and b) the nature of information on riparian vegetation was relatively poor in terms of spatial resolution and detail with respect to local patterns of shading from riparian trees.

This research uses a detailed temperature dataset from five streams is used to determine the magnitude of any cooling effect from riparian trees at the spatial scale which is most frequently used for riparian replantings (500m-1km of stream linear length).

Detailed information on the nature of riparian vegetation collected using LiDAR is used with the information from Thomson *et al.* 2012 in order to determine the potential for riparian forest to cool streams at a landscape scale.

2. RESEARCH ACTIVITIES AND METHODS

2.1 Overview

Our approach couples detailed laboratory based experiments with field data in order to make realistic predictions about the effects of climate change, and the potential for riparian plantings to be used as an adaptive management tool to mitigate against those effects. We use highly controlled experimental stream flumes with highly realistic temperature treatments to assess the impacts on a range of critical aquatic processes. The research consists of four major phases (see below and Figure 2).

Phase One

Literature review and generation of realistic climate treatments from existing data (Objective 1 and 2). This work has been published and the manuscript is presented in Appendix 1. Detailed technical information on developing the climate change treatments is presented in Appendix 2.

Phase Two

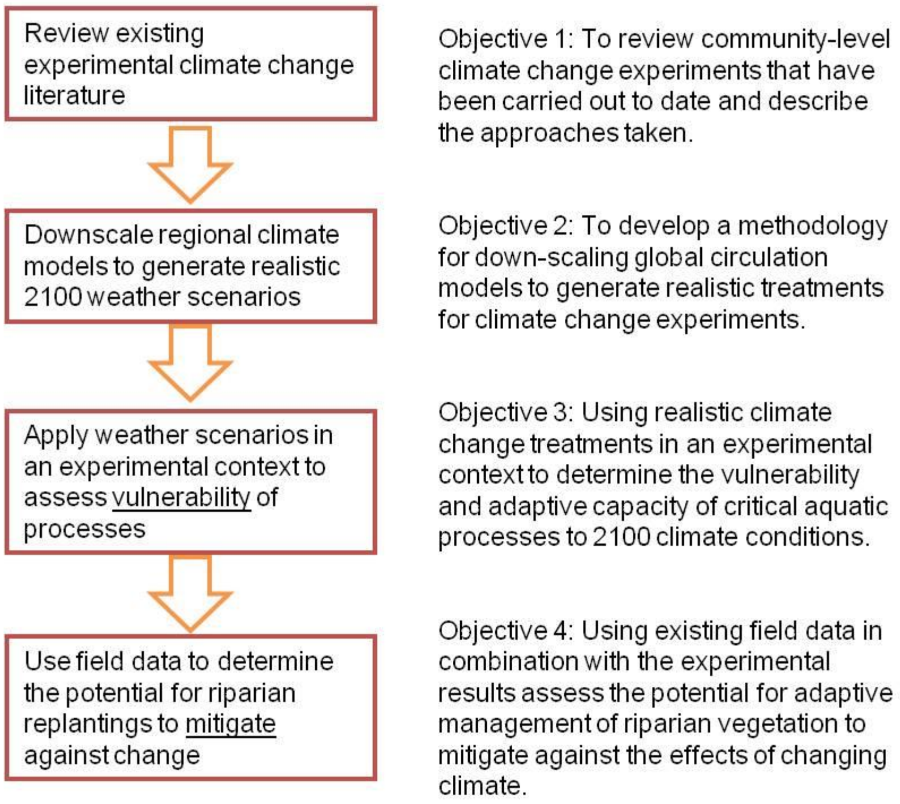
Experimentally manipulating conditions in stream flumes in order to assess effects on critical aquatic processes (Objective 3).

Phase Three

Integration of results from Phase Two with information on thermal mitigation using riparian plantings (Objective 4).

Phase Four

Interpretation, reporting and outreach. Critically assessing the potential for riparian plantings to mitigate against the effects of warming.



Review existing experimental climate change literature

Objective 1: To review community-level climate change experiments that have been carried out to date and describe the approaches taken.

Downscale regional climate models to generate realistic 2100 weather scenarios

Objective 2: To develop a methodology for down-scaling global circulation models to generate realistic treatments for climate change experiments.

Apply weather scenarios in an experimental context to assess vulnerability of processes

Objective 3: Using realistic climate change treatments in an experimental context to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions.

Use field data to determine the potential for riparian replantings to mitigate against change

Objective 4: Using existing field data in combination with the experimental results assess the potential for adaptive management of riparian vegetation to mitigate against the effects of changing climate.

Figure 2. Major phases of research and the objectives addressed by each phase

2.2 Review of community-level climate change experiments

Studies which have experimentally applied climate change treatments to ecological communities were reviewed using Web of Science (accessed 1/7/2012 to 1/11/2012, using the keywords climate change with; experiment or experimental or manipulation or warming). Studies which used natural gradients such as altitude and latitude were deliberately excluded, as they do not directly manipulate environmental conditions. We also excluded studies of single species, which includes a large body of literature from studies of adaptive capacity to evolutionary genetics. Those studies were classified into *a priori* defined ‘generations’ of experiments, each of which treats temperature in different ways (see Table 3).

2.3 Methodology for down-scaling global circulation models to generate realistic treatments for climate change experiments

Two types of approaches (dynamical and statistical) are normally used to take information from global climate models (GCMs) (~100km resolution) to be applied at higher resolutions that are more meaningful to local ecological scales (see Wilby and Wigley 1997, for a review). These approaches have been widely used in hydrology, but not directly in ecological experiments (Wilby and Dawson, 2012). Global climate models typically have coarse temporal (monthly) and spatial resolution and are most useful at these scales. Experimental treatments for ecological studies need predictions at relatively fine spatial and temporal scales. These need to incorporate increases in mean temperatures, but also increased variability and increased frequency of extreme events, such as heatwaves and extreme rainfall events, and more subtle impacts such as changes in cloud cover.

In our example, we sought to generate a climate change treatment to apply to indoor experimental stream flumes in order to assess climate change impacts on stream benthic communities. We wanted to compare responses to conditions representative of mid-summer over the last decade, to mid-summer conditions predicted to occur under a climate change scenario for 2100. The controllable variables in the flumes were temperature, rainfall (as flow velocity) and light intensity. We carried out the down-scaling process for one future time (2100) and one time of year (60 days in summer), using a single model and one emissions scenario (A1B scenario, predicting a year 2100 carbon dioxide concentration of 700ppm) (IPCC 2000). However, more complex experiments could generate treatments for other years, times of year or emissions scenarios. In addition, multimodel ensembles could be used to capture the uncertainty in climate predictions resulting from structural differences in the global climate models as well as uncertainty due to variations in initial conditions or model parameterisations (Semenov and Stratonovitch 2010). It is important that these weather time series are not averaged in a multiple ensemble as the resultant time series will lose its statistical variation. Rather the key here is to ultimately generate multiple weather time series treatments (ensembles) that are applied experimentally so that the ecological results are robustly replicated.

Our strategy was to use the information contained in a GCM output which projects how climate may evolve under future scenarios over the following centuries and apply that to the local scale. We then merged this data with statistical information from real historical observations and applied that to the changed climate from the GCM to a time series at daily resolution using a ‘weather generator’ (see below). Specifically in our case, we used the MIROC global climate model outputs available from the Center for Climate System Research (CCSR), University of Tokyo (http://www.ccsr.u-tokyo.ac.jp/) as the basis for our generation of the temperature treatment data. The model has a spatial resolution of 1.4 degree in longitude, 0.5-1.4 degree in latitude, and 43 vertical levels in the medium-resolution version. We chose this model because it has performed well for the Australian climate (Pitman and Perkins 2008). Data were extracted from the CMIP3 (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) archive which is a repository for climate models that were used in preparing the IPCC Fourth Assessment Report (http://www.ipcc.ch/). We extracted the air temperature variable (TASA1) from the run “sresb1atmmotasmiroc3_2medres” to demonstrate the method. This file was for the A1B scenario with a carbon dioxide concentration in the year 2100 of 700ppm. Further information on climate change scenarios can be found at www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf. We extracted data for the grid cell closest to Melbourne Airport, Australia (37.67 °S 144.83 °E) for the 21st century.

To generate weather data we entered the GCM data into the LARS-WG stochastic weather generator (http://www.rothamsted.ac.uk/mas-models/larswg.php) (Semenov *et al.* 1998). LARS-WG is a model simulating hourly time-series of daily weather at a single site, which can generate long time-series of weather conditions for a particular site, and includes extreme weather events, such as extreme daily precipitation and long dry spells or heat waves (Semenov *et al.* 1998). LARS-WG has been well validated in diverse climates around the world (Semenov *et al.* 1998). It utilises semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation. The seasonal cycles of means and standard deviations are modelled by finite Fourier series of order 3 and the residuals are approximated by a normal distribution (http://www.rothamsted.ac.uk/mas-models/download/LARS-WG-Manual.pdf).

We used the following methodology as per Semenov and Stratonovitch (2010).

1. Model Calibration – Observed weather data from Melbourne airport (Australian Bureau of Meteorology site number**:** 086282, elevation: 113 m, period: 1990 – 2009) were analysed to determine the local statistical characteristics of air temperature. This information is stored in two parameter files.
2. Model Validation - the statistical characteristics of the observed and synthetic weather data were analysed to determine if there are any statistically-significant differences (none found).
3. Generation of Synthetic Weather Data - the parameter files derived from observed weather data during the model calibration process were used to generate synthetic weather data having the same statistical characteristics as the original observed data, but differing on a day-to-day basis. We applied our global climate model-derived changes in temperature to the LARS-WG parameter files to generate daily weather for 2090-2100.
4. Experimental series – A series of weather (20 years long) is generated based on the changes in global climate (2090-2100) and the Jan/Feb period for the 10th year was extracted for use in driving the experimental treatments. Data were similarly generated for the control period (1990-2010). Probability distribution functions for distributions of minimum and maximum temperatures were generated for 2100 (generated by the simulation) and based on combined data for real weather data from the same region 1990-2000. Because we needed to generate water temperature data (rather than the air temperature data generated by the model), a long-run series of historical water temperatures for the study site were used with historical air temperature data from the Melbourne airport weather station to generate a relationship between air and water temperature. It is important to note that these kind of relationships are highly non-linear (Mohseni *et al.* 1998) and may be relatively site specific depending on local riparian vegetation and interactions with groundwater, amongst other factors. As such, experiments which seek to assess impacts on particular freshwater sites will require detailed historical water temperature data.

It should be noted that a stochastic weather generator is not a predictive tool that can be used in weather forecasting, but is simply a means of generating time-series of synthetic weather statistically ‘identical’ to the observations. The resulting scenarios can be used as experimental treatments to be compared to controls resulting from ambient conditions or to treatments based on historical weather conditions. We used the variance of the ‘real’ historical data and applied that to the climate scenario to generate a weather series. Here we generated a single run, as generating repeated simulations then averaging results will remove extreme events from the data.

Detailed technical information on the approach used here is presented in Appendix Two.

2.4 Using realistic climate change treatments in an experimental context to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions

2.4.1 Experimental set up

Experiments were run between December 2011 and June 2012. Prior to the experiments, six colonization trays (95 cm length x 57 cm width x 38 cm depth) were dug into the substrate in the Little Yarra River, Victoria, Australia, and half filled with natural substrate (cobbles, pebbles, and gravel). Trays were then left to colonise with natural biofilm and stream invertebrates. After four weeks, trays were collected and transported in river water to Monash University flume facility to be placed into 3000L recirculating flumes (7m long x 0.7m wide x 0.5m deep). Flumes were fitted with a motor-powered paddle to create a mid-channel flow velocity of 1.0 ms-1. Three light banks, each consisting of a set of six full spectrum fluorescent tubes (Sylvania© 36W 172 Activa) were suspended over each of the flumes. The lights were set for a 16: 8 day: night cycle and generated photosynthetically active radiation (PAR) at 10cm depth of 25-35 µmol m-2 sec-1, sufficient for algal growth (Naiman and Décamps 1997). Two experimental flumes were filled with river water from the colonisation site and allowed to circulate for at least 48 hours before adding the trays. Three colonised trays were placed into each flume, one under each light bank. For one week both flumes were exposed to a temperature regime mimicking the natural conditions from the source river, to allow the communities to acclimatize to flume conditions. We then randomly assigned the Control treatment to one flume and Climate Change treatment to the other.

Experiments were run for six weeks. During the experiment the flumes were topped up weekly with water from the source stream to compensate for evaporation. Nutrient conditions in the source stream were measured in February 2012, and 100 µg l–1 of nitrogen (as ammonium chloride) and 11 µg l–1 of phosphorus (as monopotassium phosphate) were continuously added to the flumes to mimic natural levels in the source stream. After six weeks, the flumes were emptied and cleaned completely. The experiment was carried out three times, providing replicates through time of each temperature treatment with three trays per replicate.

2.4.2 Temperature treatments

Each flume was equipped with a temperature-control system that allowed application of realistic daily temperature treatments which altered on an hourly basis. Temperature treatments were generated based on down-scaled regional climate models as described in Chapter One. We wanted to compare responses to conditions representative of mid-summer over the last decade, to mid-summer conditions predicted to occur under a climate change scenario for the year 2100. Because we needed water temperature data (rather than the air temperature data generated by the model), a long-run series of historical water temperatures for the study site (2005-2010; Thompson, unpublished data) were used with historical air temperature data from the Melbourne airport weather station to generate a relationship between air and water temperature. The resulting treatments were hourly water temperature predictions for a 60 day period in summer for conditions under the GCM for 1990-2000 (‘Control’) and 2090-2100 (‘Climate Change’). This generated a temperature regime for the Treatment that was warmer on average by approximately 1 degree Celsius, was typified by higher maximum temperatures (32.7 as compared to 27.5) and was characterised by long runs of >25 degree temperatures (Table 1, Figure 3).

Table 1. Summary of temperature treatments (in degrees Celsius) applied to the flumes for six weeks

Replicates are pairs of treatments run at the same time. For detailed information on the temperature treatment see Appendix One.

Replicate	1 Treatment	2 Treatment	3 Treatment	1 Control	2 Control	3 Control
Average	20.5	20.9	20.2	19.8	19.1	19.4
Standard deviation	2.0	2.7	2.7	1.9	1.9	1.9
Median	19.9	19.9	19.8	19.2	19.4	18.8
Minimum	17.4	17.8	17.4	17.0	17.0	17.0
Maximum	32.7	32.7	32.7	27.5	27.5	27.5
% readings >25 deg C	7.8	10.9	11.1	2.0	3.8	2.8
% readings >30 deg C	0.6	0.6	0.6	0.0	0.0	0.0

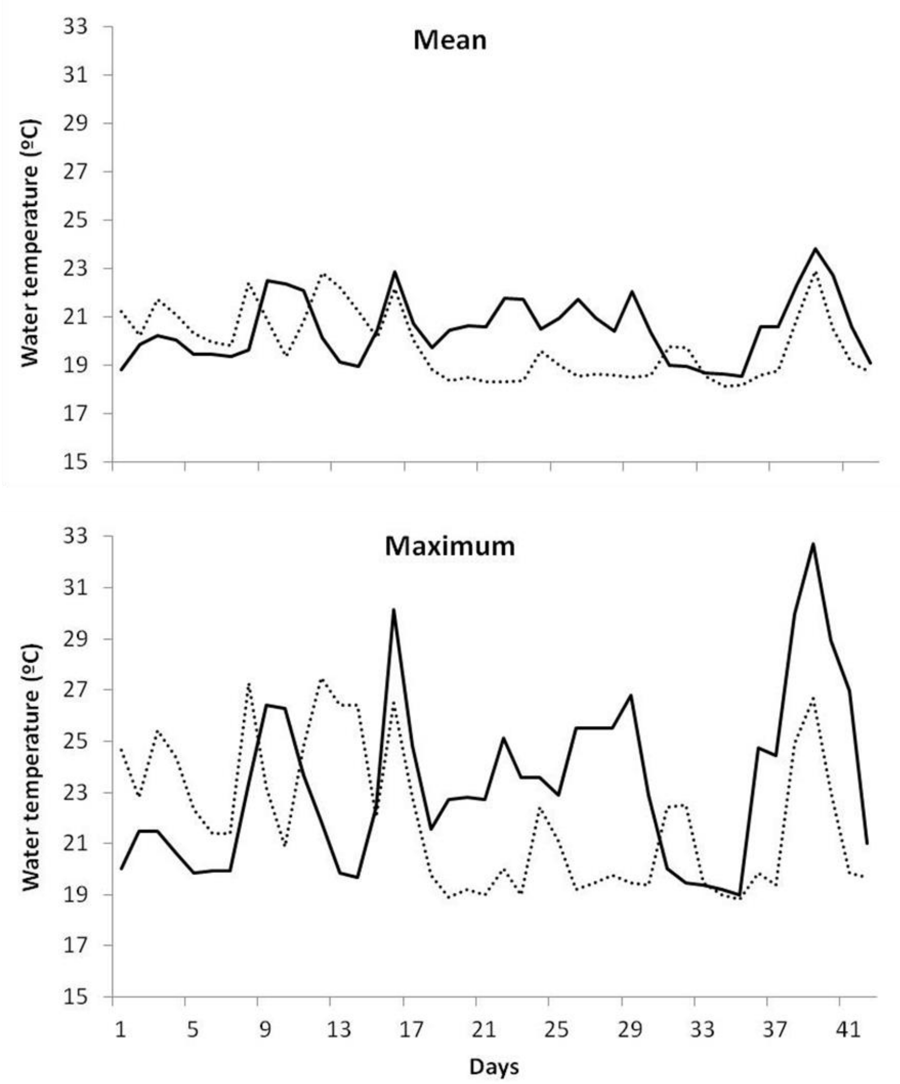


Figure 3. Mean and maximum water temperatures for the experimental treatments applied to the flumes on each occasion.

Solid lines indicate the climate change treatment and dotted lines the control treatment.

2.4.3 Benthic algae analyses

In order to assess rates of photosynthesis in response to the treatments, chlorophyll fluorescence was measured using a PAM (Pulse Amplitude Modulated) fluorescence meter for the first replicate of the experiment only. The PAM fluorescence technique is a useful tool to investigate the photosynthetic properties of intact benthic communities and their response to environmental factors, such as temperature or UV radiation (Stojkovic 2005). We measured Photosynthesis-Irradiance (P-I) curves to evaluate the photosynthetic performance of freshwater biofilms, as a whole community, to the temperature treatments (Stojkovic 2005).

Frosted glass slides (30 x 30 mm) were used as artificial substrates for growing biofilms. Slides were placed in Perspex plates (180 x 300 mm), each holding 20 slides. This set-up enabled the collection of random samples without disrupting other slides in the set. One plate (= 20 slides) was placed in each of the three colonization trays in a flume (= 3 plates / flume). Plates were left for two weeks prior to the first sampling. The first week of sampling was thus the second week of the experiment. After that, slides were collected on a fortnightly basis.

One slide from each colonization tray in a flume was randomly chosen from the plates and Photosynthesis-Irradiance (P-I) curves measurements were carried out. Measurements were performed immediately after the slides were retrieved from the trays. An Underwater Diving PAM (Walz, Germany) was used for measurements of Photosynthesis-Irradiance (P-I) curves. Each slide was placed in a small Perspex chamber that would hold the slide in an appropriate amount of flume water, which prevented the slide from drying-out during the measurements. The Diving PAM fibre-optic was placed in a special holder that fitted above the chamber, with the distance between the fibre-optic and the slide surface being approximately 2 cm. Actinic light was provided by the internal source of the Underwater Diving PAM. The P-I curves were used to calculate relative electron transport (rETR) (equivalent to gross photosynthetic rates as µmol electrons m^{-2} s^{-1}) and alpha (equivalent to the efficiency of light harvesting)

2.4.4 Dissolved organic carbon (DOC) analyses

We used fluorescence spectrophotometry (excitation-emission matrices (EEMs)) to characterise DOC compounds and identify DOC sources. Duplicate DOC samples were collected from each flume every two weeks. The DOC samples were collected from each of the ten stream sites and filtered (Whatman GF/C) into pre-combusted amber glass jars and acidified to pH<2. The samples were refrigerated immediately and analysed within 48 hrs. The whole water sample and MilliQ water blank EEMs were performed on a Varian Cary Eclipse fluorescence spectrophotometer with a xenon lamp. Fluorescence intensity was measured between excitation wavelengths 250nm to 400nm at 10nm increments and emission wavelengths 400nm to 550nm at 2nm increments, following McKnight *et al.* (2001). The EEMs were then corrected according to the methods of McKnight *et al.* (2001) and Stedmon and Bro (2008). Specifically, fluorescence intensity values for each whole water sample and blanks were multiplied by correction factors to account for lamp spectral properties calculated according to manufacturer guidelines using a concentrated solution of rhodamine. Next, inner filter effects for both the absorbed and emitted wavelengths were accounted for by collecting specific absorbance for each whole water sample and blank on a Unicam UV-visible spectrophotometer at 2nm increments over the range of 220nm to 600nm. The specific absorbance for each emission (Aemit) and excitation (Aexcit) were then multiplied by 0.5cm for the light pathlength and by the DOC concentration of the sample. These values were then summed (Atotal), and each fluorescence intensity values was divided by 10-A(total) (McKnight *et al.* 2001). Spectra were then Raman normalised to the area under the Raman scatter peak (ex 350), converting to Raman units (following Stedmon *et al.* 2003). The Raman and instrument corrected MilliQ blank EEMs were then deducted from the whole water samples and any negative values set to zero. Blank correction removes most of the Raman scattering effects (Stedmon and Bro 2008) and the region affected by second order Rayleigh scattering (occurring approximately where emission wavelength is twice the excitation wavelength) was set to zero (following Rinnan and Andersen 2005). Finally, the whole water sample EEMs were normalised to their maximum intensity (following McKnight *et al.* 2001).

We used the fluorescence index (FI) to as an indicator of the source of DOC. End members described by McKnight *et al.* (2001) show FI ratios of DOC from terrestrial higher vegetation sources range from 1.3-1.5, and autochthonous microbial sources 1.7-1.9. FI was calculated as the ratio of emission intensity at 470nm to 520nm at an excitation wavelength of 370nm (following McKnight *et al.* 2001).

2.4.5 Specific UV absorbance (SUVA)

Triplicate filtered (Whatman GF/C) water samples from each flume were collected in pre-combusted amber glass jars, on the same date as the EEM sampling. These were refrigerated immediately for return to the laboratory, where they were frozen in 15mL polypropylene tubes (falcon tubes) until analysis. The samples were defrosted slowly in a refrigerator prior to analysis. The UV visible absorbance of each sample was then measured at 280nm on a Unicam UV-visible spectrophotometer using a quartz cuvette with a pathlength of 1cm. SUVA280nm is then calculated following Chin *et al.* (1994) as:

$$\text{SUVA280nm} = \text{Abs280nm} / \text{DOC (moles L}^{-1}\text{)}.$$

The following equations were then used to calculate the weight-averaged molecular weight and percentage aromaticity of the DOC compounds in the sample (Chin *et al.* 1994):

$$\text{MW (g mol-1)} = 3.99\ (\text{SUVA280}) + 490$$

$$\text{Aromaticity (\%)} = 0.05\ (\text{SUVA280}) + 6.74$$

2.4.6 Aquatic invertebrates and emerging aquatic insects

Each tray was covered with an emergence net (500 µm mesh) and all emerging adult aquatic insects and exuviae in each net were collected daily over the course of the six-week experiments. At the end of each experiment a 20cmx20cm Surber sampler (0.25mm mesh) was used to sample a random location within each tray to a depth of 5cm in the substrate. Invertebrates were preserved in ethanol for later identification and measurement for length.

2.4.7 Statistical analysis

Statistical analysis of all of the response variables was carried out using R version 2.14.2 (R Development Core Team 2012), and utilising a repeated measures analysis with temperature treatment as the main factor. Because of the relatively low power of the repeated measures analysis, an additional one factor analysis of variance was also carried out for an effect of temperature treatment on each of the variables on the last sampling occasion.

We tested the effects of the temperature treatment on the aquatic communities using univariate two factor nested analysis of variance, that nested temperature treatment within each of the repeat trials, using the trays as independent replicates. Effects of temperature and repeat were tested for total taxa richness, total abundance, and mean body length across the community and for the most abundant taxa. The abundance by taxa matrix was log(X=1) transformed and a similarity matrix was generated using Bray-Curtis similarities. This matrix was graphed as a non-metric multi-dimensional scaling ordination. Differences between repeat trials and temperature treatments were analysed using a nested analysis of similarities that nested temperature treatment in each repeat. Differences in communities between temperature treatments were determined using similarity percentages.

For emerging adults of aquatic invertebrates we tested the effects of the temperature treatments on five response variables: mean total accumulated insect emergence, rates of accumulated emergence, mean body size (mm) for the whole insect community (=mean community body size) and for individual taxa, and sex ratio of the two numerically dominant species. Mean community body size was calculated as the mean of all taxa in the community. Responses in each flume were calculated as the mean value across the three trays. Responses for each temperature treatment were then calculated as the mean across the three repeats.

Analysis of covariance (ANCOVA) (comparison of slopes) following square root or log transformations of the accumulated emergence data were used to test for block effect (months) within each treatment, with time (weeks) as the covariate. There were no block effects for either treatment, so statistical analyses were performed for a one-factor design averaging treatment over blocks (see below). ANCOVAs were then performed to test for differences in accumulated emergence between the two treatments averaging over blocks. Since 10 separate ANCOVAs were performed, sequential Bonferroni's adjustment was applied to obtain an experiment-wise error rate of = 0.05 across all dependent variables. The temperature treatment as the main effect and the interaction between treatment and week (slopes of the curves) were considered. We were not interested in testing differences between weeks and so week was not included as the second main factor. Individual taxa body size and mean community body size were analysed from the second week of the experiments to allow one week for the temperature treatment to have an effect. Differences in individual taxa body size and mean community body size between treatments were tested using ANCOVAs and t-tests on untransformed data after verifying for block effect within each treatment. T-tests were performed to compare individual taxa sizes at the end of the experiment between treatments. Bonferroni's adjustments were applied to obtain an experiment-wise error rate of = 0.05 across all dependent variables (n=10).

2.5 Using existing field data in combination with the experimental results, assess the potential for adaptive management of riparian vegetation to mitigate against the effects of changing climate

2.5.1 Patch-scale analysis

To assess the local effects of riparian vegetation on stream water temperature, temperature loggers were placed in five streams in central Victoria (Table 2) from the 1st November 2011 to the 1st of March 2012. In four streams a logger was placed in an area of revegetated stream between 12 and 21 years old, and in an adjacent (1-5km upstream) area where there was no riparian vegetation. Revegetated reaches ranged between 250 and 500m in linear length along the stream and were sampled at the mid point of the revegetated section. In the fifth site the loggers were placed in two unvegetated reaches approximately 2km apart. Water temperatures were taken hourly and a daily mean calculated for each site within each stream for each day. Differences in the daily means between the upstream and downstream reaches were calculated for a total of 166 days.

Table 2. Sites sampled for water temperature at five central Victoria streams over summer 2011/2012

Stream	Site	Age of canopy vegetation
Castle	Upstream	0
	Downstream	14
Moonee	Upstream	0
	Downstream	21
Warrenbayne	Upstream	0
	Downstream	17
Sevens	Upstream	0
	Downstream	12
Faithfuls	Upstream	0
	Downstream	0

2.5.2 Landscape-scale analysis

To assess the relationship between riparian vegetation and stream temperature at a landscape scale, data from a fixed-wing aircraft LiDAR (Light Detection and Ranging) survey of Victorian waterways (Department of Sustainability and Environment, 2013). The LiDar system used was a Leica ALS50-II and ALS60 flown at 634 – 1590m with a scanner field of view of 30 degrees (+/- 15degrees) and a nominal swathe width of 992m. The pulse rate used was 140400Hz with a average point density of 4pt/m2 yielding a laser footprint diameter of 0.36m and vertical accuracy of +/-0.2m. LiDAR acquisition started on 2nd November 2009 and was completed in April 2011, and covered a total of 64 066km^2 (see Figure 4).

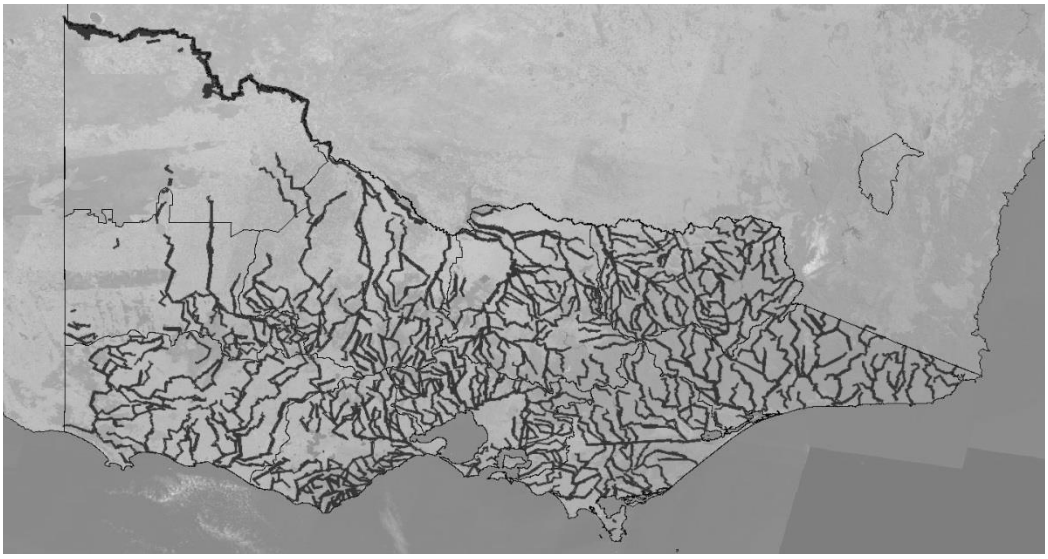


Figure 4. LiDAR coverage of waterways in Victoria during surveys flown 2009-2011 (figure provided by Department of Sustainability and Environment, Victoria (from Thomson et al., 2012))

We related water temperature data collected as part of EPA Victoria stream condition monitoring program from 1990 through 2010 to the LiDAR data. We used water temperature data from 1600 EPA monitoring sites located within Index of Stream Condition (ISC) reaches (EPA 2003). EPA sites whose nominal geographic coordinates were > 50m from mapped ISC stream lines or whose site location description did not correspond to the nearest mapped ISC reach were omitted from analyses). Many sites were sampled multiple times throughout the survey period, yielding 3500 temperature records for analysis. We calculated the mean canopy height within 15m of the mapped stream line (i.e. 30 m total buffer width) for all ISC reaches (reach-scale mean canopy height), and the mean canopy height within a 30m radius of EPA site locations (site-scale mean canopy height). EPA point locations were moved to the nearest location intersecting a mapped stream line prior to calculating site-scale means. We also derived values for elevation, stream order, and the proportion of the total upstream catchment with native vegetation cover (catchment-scale vegetation extent), for all EPA sites. Catchment-scale vegetation extent values were obtained from the geofabric database (Stein 2006). All spatial data extraction and calculations were performed with ArcGIS 10.1 software.

We used a hierarchical Bayesian model with spatial random effects to relate water temperature to riparian and catchment vegetation values. The model included time-of-day, day-of-year, and year as covariates to account for temporal variation, and elevation, Strahler order number (stream size) and geographic coordinates (longitude, latitude) to account for expected spatial gradients unrelated to vegetation effects. In addition, the model included nested random effects corresponding to river basin, river, reach, and site to account for spatial variation, and correlations, not accounted for by included covariates. We used sine and cosine transformations of the Julian day of year (see Thomson *et al.* 2012) to accommodate seasonal effects. There was no substantive evidence of non-linear relationships between temperature and any other covariate (assessed using spline functions and Bayes model selection, as in Thomson *et al.*, 2012). Therefore we present results from linear models only.

3. RESULTS AND OUTPUTS

3.1 Review of community-level climate change experiments

There were 109 studies published between 2000 and 2012 (Table 3, Appendix 1). In total 65 studies were found from terrestrial environments, 23 from marine settings and 21 from freshwaters. Those studies were classified into *a priori* defined 'generations' of experiments, each of which treats temperature in different ways (Table 3).

Table 3. Review and classification into generations of community climate change experiments 2000 – 2012 (terrestrial and marine) and 1995-2012 (freshwater) which involved temperature manipulations (excluding other physical and chemical manipulations)

For definitions of the 'generations' of studies see the main text. Number of studies (with percentages of the total in brackets following) are shown. Individual papers are shown in Appendix 1, Supplementary Table S1.

Generation	Effects on mean	Effects on variability	Incorporates extreme events?	Number of studies found		
				Terrestrial	Marine	Freshwater
Fixed mean	Increase	Large reduction	No	3 (4.6%)	15 (65.2%)	5 (23.8%)
Fixed minima	Increase	Small reduction	No	7 (10.7%)	0 (0%)	0 (0%)
Fixed increment	Increase	No effect	Some	51 (78.5%)	8 (34.8%)	15 (71.4%)
Extreme event	Increase	Increase	Yes	4 (6.2%)	0 (0%)	1 (4.8%)

3.1.1 Approaches taken

Generation One: Fixed mean experiments

Fixed mean experiments represent the simplest treatment possible and apply temperature treatments at a stable level over the length of the experiment. Most often these take the mean temperature of current conditions and add an increment to it to generate a new mean temperature, which is then applied as the treatment (compare Figure 5A to Figure 5B). Some of the studies listed in Table 3 (e.g. Beisner *et al.* 1996; Mitchell and Lampert 2000) compared fixed temperature treatments, others (e.g. Petchey *et al.* 1999; Fox and Morin, 2001) compared a constant to a warming treatment. These types of experiments underestimate the effects of climate change as they do not include the 'event effect' component in the treatment. The warming treatments in these experiments are also associated with a reduction in temperature variability, potentially confounding any results.

Generation Two: Fixed minima experiments

Fixed minima or maxima experiments have commonly been applied in warming experiments in the field. Experiments using substrate warmers inserted into the forest floor are an example of this type of approach (Melillo *et al.* 2002), as are experiments which re-radiate heat during the night to reduce night time minimum temperatures (e.g. Lloret *et al.* 2005). While able to prevent the coolest temperatures occurring, and have some warming effects on cool to moderate temperature days, they cannot affect the warmest days or generate high temperature extremes. Effectively, these treatments generate fixed minimum temperatures. The effect is to increase mean temperatures but to reduce variability, although not to the extent of fixed mean experiments (Figure 5C). It does not appear that this approach has been applied in freshwater systems to date, although addition of fixed amounts of warm water to a stream would have this effect.

Generation Three: Increment studies

Although more challenging to apply than traditional warming studies, increment studies apply a temperature treatment while retaining natural variability in temperature. Most often, these treatments are applied as a fixed increment (for example +3.5 degree Celsius) over natural conditions. These experiments have the advantage that they incorporate many of the natural features of weather, for example, one warmer than average day is more likely to follow another than it is to follow a colder than average day. Overall, these studies increase mean temperatures while retaining the variability which is typical of current climates (Figure 5D). For example, Yvon-Durocher *et al.* (2010) used twenty mesocosms in southern England and warmed ten of these by 3-5 degrees Celsius above ambient conditions. These types of experiments cannot incorporate features such as predicted climates where, for example, winter becomes warmer but spring becomes cooler. Nor do these kinds of experiments take into account changes in the climate variability. As such, they may underestimate the effects of climate change in some systems.

Generation Four: Extreme event studies

The most recent examples of climate change studies explicitly include extreme events in some fashion. In terrestrial studies, experimental enclosures have been exposed to drought, night heat waves, and extreme rainfall scenarios in order to assess effects on primary productivity (e.g. Fay *et al.* 2000; Beier *et al.* 2004). These approaches do not seem to have been applied in freshwater studies of the effects of temperature. Dang *et al.* (2009) applied an increased diel temperature variation to stream mesocosms and assessed impacts on detrital decomposition, but this experiment exposed the system to a cyclic series of extreme events rather than periodic events. A number of freshwater studies have assessed the effects of drying as an extreme event, (Leberfinger *et al.* 2010; Ledger *et al.* 2011) but none to date have considered extreme temperature events such as heatwaves explicitly, as shown in Figure 5E. Extreme event studies increase means and variability in temperatures, but do not replicate changes in the timing or duration of extreme events.

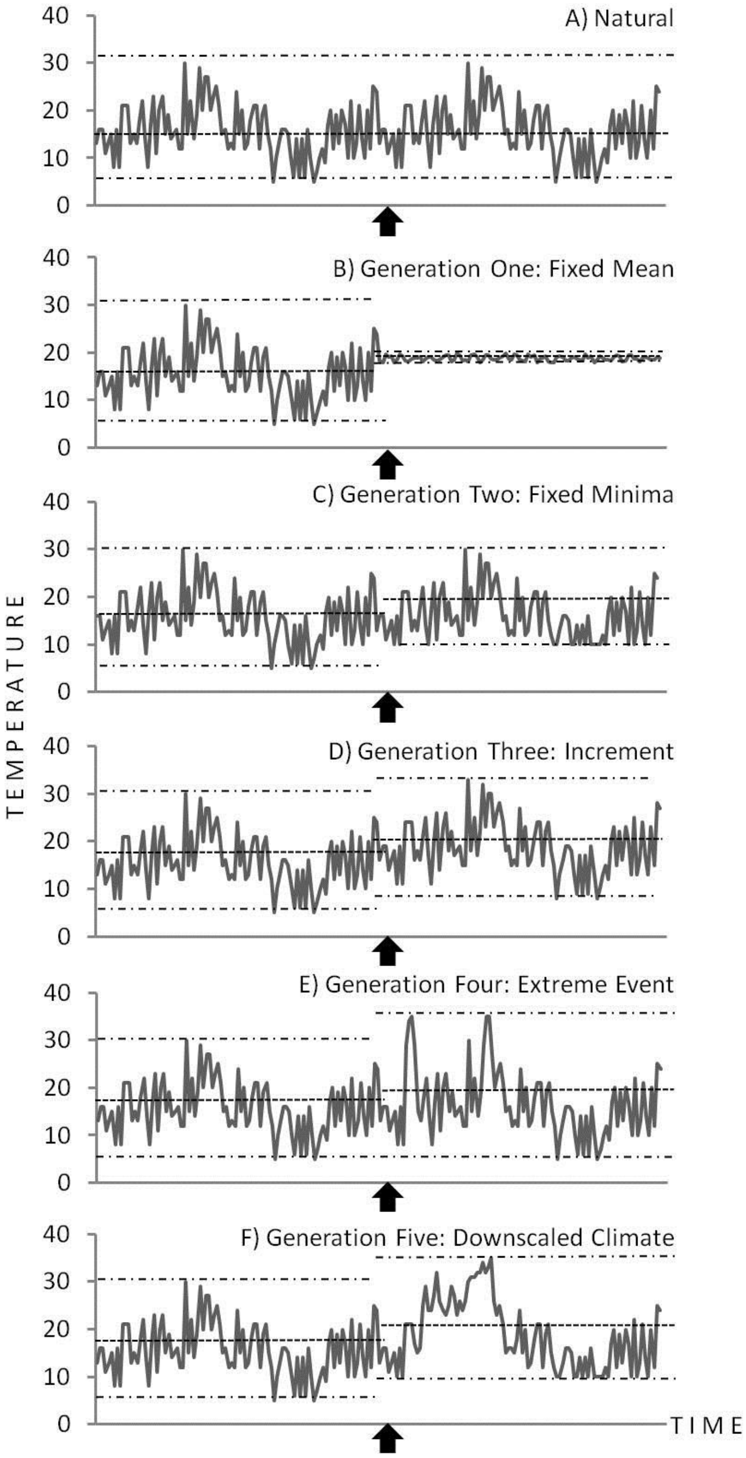


Figure 5. Conceptual diagram of generations of temperature treatments used in climate change experiments

A) baseline temperature (natural or current scenario), B) fixed mean (temperature set to a fixed value), C) fixed minima (temperature has a fixed minimum), D) increment (fixed increment is applied to natural variability), E) extreme event (extreme event is superimposed on natural variability), F) downscaled climate model (temperature is determined by weather scenarios generated from down-scaled climate model). Dashed lines indicate maximum, mean, and minimum temperatures. The black arrow indicates when experimental treatments are applied.

3.1.2 Comparing approaches across ecosystems

Terrestrial studies are by far the most common in the literature, with 60% of reviewed studies being terrestrial, despite the shorter time period which was considered for the literature review. Climate change experiments in terrestrial settings have tended to consider the effects of not only temperature but also rainfall and increased atmospheric CO_2 concentrations. Smaller scale experiments in terrestrial settings have utilised chambers and have applied temperature treatments as both fixed means and fixed increments. Larger scale terrestrial experiments utilising substrate warmers, in particular, were a feature of early high-profile climate change research (Melillo *et al.* 2002). These approaches logistically lend themselves to fixed increment treatments, and these predominate in the published terrestrial climate change literature (Table 3). While there has been recognition for some years of the need to incorporate extreme events into studies of climate change impacts on terrestrial ecosystems (Jentsch *et al.* 2007), these continue to be the exception in studies of the effects of temperature (Table 3). That said, a number of recent studies have explored the impacts of extreme heat events either alone, or combined with other stressors (Bjerke *et al.* 2011; Van Peer *et al.* 2004). Combined treatments are particularly relevant to terrestrial systems, where high temperatures are strongly associated with reduced rainfall, and for plant communities, where high rainfall can mitigate impacts of high temperatures (Van Peer *et al.* 2004).

Studies of the effects of climate change-induced changes in temperature on marine communities remain relatively rare, in part because of the logistic difficulties of applying treatments at large scales. Marine climate change studies have included an emphasis on the effects of CO_2 and acidification, as key impacts on coral reefs (Hoegh-Guldberg *et al.* 2011) and pelagic primary producers (Beardall *et al.* 2009). The majority of experimental studies of the impacts of increased temperatures have either been fixed mean studies or fixed increment studies (Table 3). For the majority of marine systems this may make sense, as the high thermal mass of the oceans means that warming will tend to occur relatively slowly (days to weeks), making oceanic systems more tolerant of short term (days) spikes in atmospheric temperatures. While extreme events may be proportionally less important in terms of temperature impacts in marine settings, there are clearly described impacts of relatively short term (weeks) warming episodes on coral reefs (Baker *et al.* 2008). It may be that the emphasis on field studies of climate change impacts, and the difficulties of carrying out scalable experiments on these systems has led to the relative paucity of experimental warming studies on marine communities.

In freshwater systems, a number of recent reviews have discussed the potential impacts of climate change at scales from regional (e.g. Heino *et al.* 2009; Johnson *et al.* 2009; Fenoglio *et al.* 2010; Morrongiello *et al.* 2011) to global (e.g. Ficke *et al.* 2007; Perkins *et al.* 2010; Woodward *et al.* 2010b). Freshwater systems are particularly vulnerable to changing climates as they are often highly range-restricted, and are subject to competition for water resources with human uses (Hobday and Lough 2011). Effects of extreme events in freshwater occur in two main areas. The first is via extreme heat events, which in aquatic systems also have consequences for the availability of oxygen and concentrations of toxicants (Ficke *et al.* 2007). Secondly, extreme rainfall events can have major effects on disturbance regimes via changed hydrology (Ficke *et al.* 2007). These effects become more complex in areas where seasonality of rainfall is predicted to change under climate change scenarios, or where changes in human water demands further impact water availability (Kundzewicz *et al.* 2008).

3.2 Methodology for down-scaling global circulation models to generate realistic treatments for climate change experiments

Probability distribution functions for distributions of minimum and maximum temperatures were generated for 2100 (generated by the simulation) and based on combined data for real weather data from the same region 1990-2000 (Figure 6). The temperature data only was used for the experimental treatments (see Section 2.4 above).Other data generated by the simulations is presented in Appendix 2.

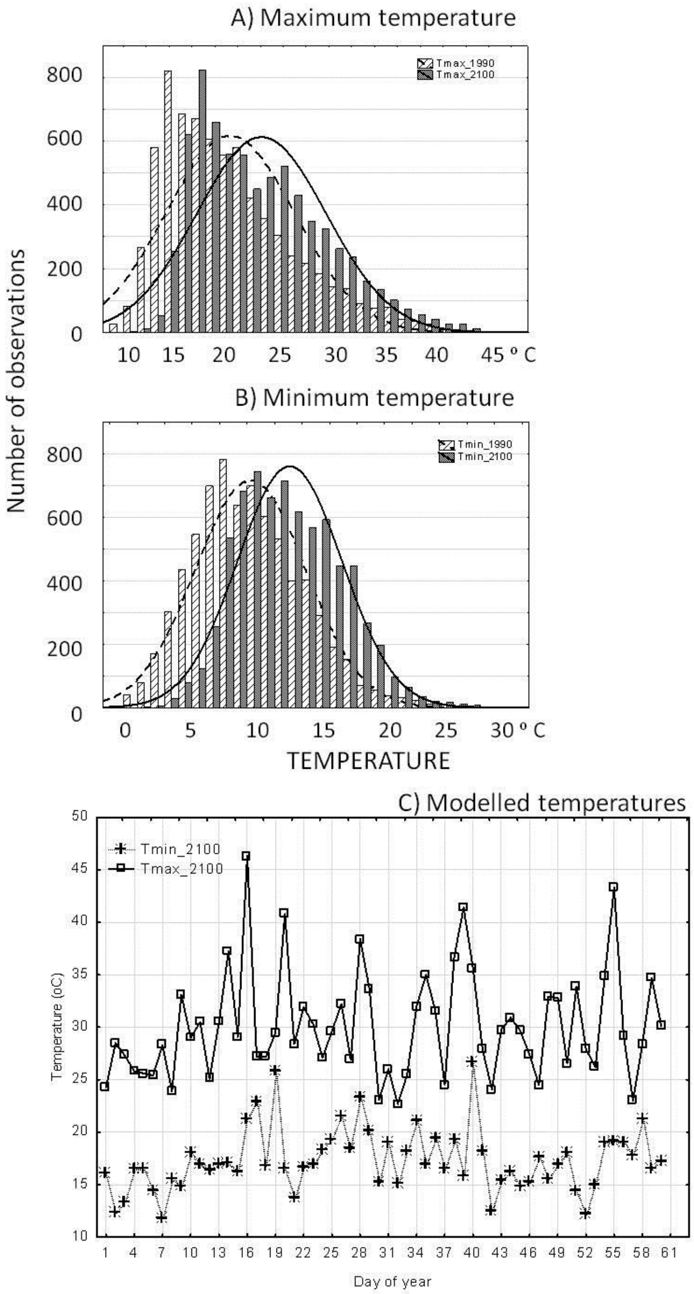


Figure 6. Probability distribution functions illustrating the shifts in the actual and expected distributions of A) maximum and B) minimum temperatures for the decade 1990-2000 (based on real data, white striped bars) and 2100 (based on weather simulations from the climate model; grey bars). C) Modelled temperature series for the first 60 Julian days of 2100.

3.3 Using realistic climate change treatments in an experimental context to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions

3.3.1 Benthic algae analyses

Relative electron transport (equivalent to gross photosynthetic rates as µmol electrons m^{-2} s^{-1}) was higher in the climate change treatment than the control on the last two sampling occasions (Figure 7), with extremely high productivity values measured in the treatment flume on the second sampling occasion. However there was no statistically significant effect of treatment either across all sampling intervals ($F_{1,2}$ = 1.744, p=0.213) or for the final sampling interval alone ($F_{1,4}$=1.898, p=0.240). There was some evidence of greater efficiency of light harvesting in the climate change treatment (Figure 7), and while this was not statistically significant across all sampling intervals ($F_{1,2}$ = 2.069, p=0.181) it was for the final sampling interval alone ($F_{1,4}$=196.065, p<0.001).

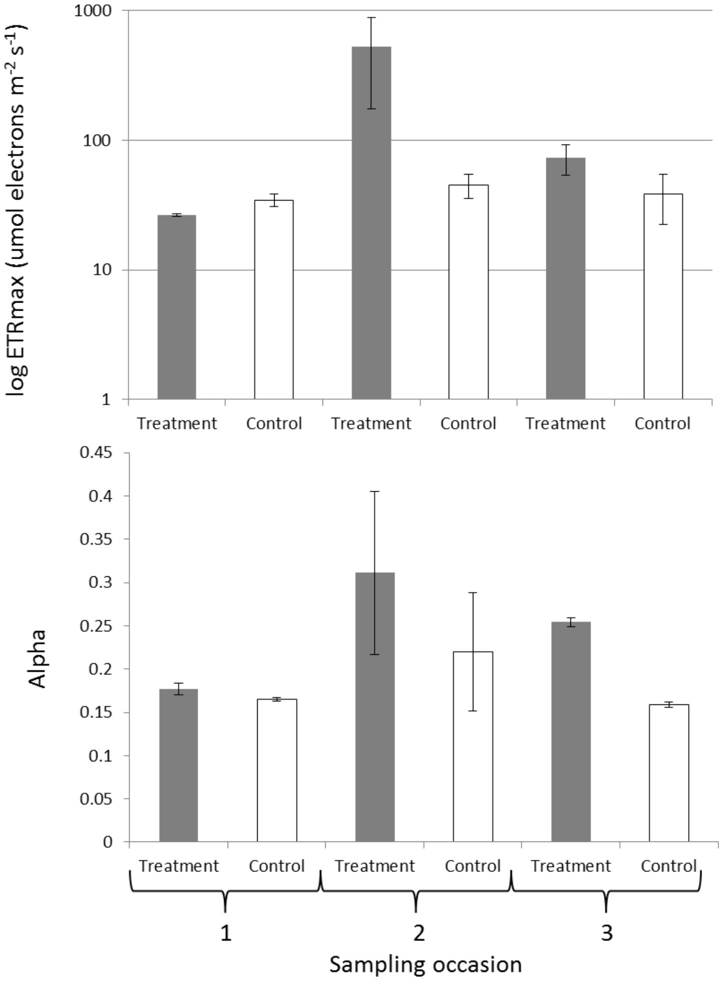


Figure 7. Effects of temperature (grey bars = climate change treatment, white bars = control) on algal productivity measured as relative electron transport (ETRmax) and efficiency of light harvesting (alpha) sampled at two weekly intervals through the first replicate of the experiment

Results are means of three samples from each flume on each sampling occasion, with standard errors.

3.3.2 Dissolved organic carbon (DOC) analyses

Characterisation of the organic dissolved carbon found no statistically significant difference between temperature treatments for fluorescence index ($F_{1,2}$=0.347, p=0.580), molecular weight ($F_{1,2}$=0.666, p=0.421) or aromaticity ($F_{1,2}$=0.666, p=0.421) (Figure 8). There was a trend suggesting that terrestrially derived carbon was more quickly being consumed in the climate change treatment, leading to lower molecular weight organic matter being available, with more, low aromaticity microbially-derived fulvic acids in the climate change treatment.

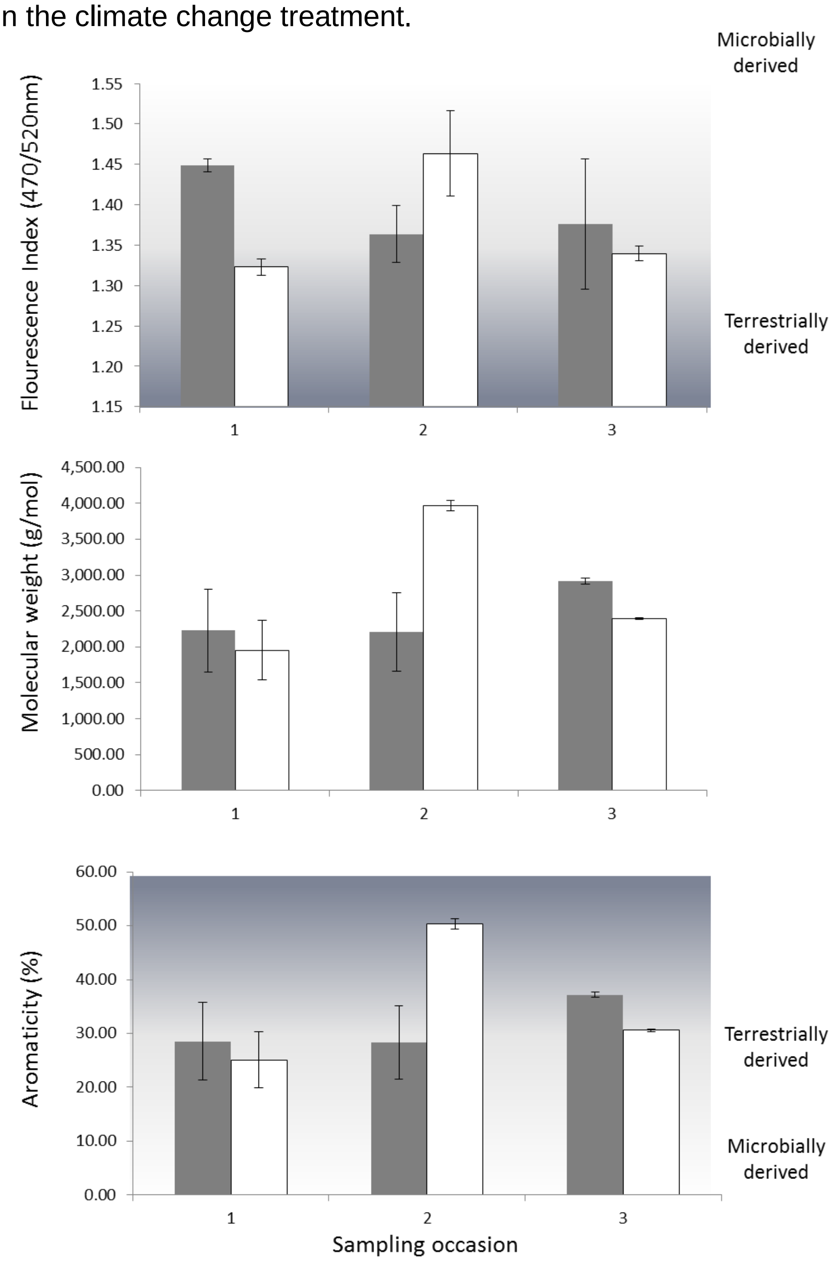


Figure 8. Effects of temperature (grey bars = climate change treatment, white bars = control) dissolved organic carbon measured as fluorescence index, molecular weight and aromaticity sampled at two weekly intervals through the three replicates. Background shading indicates the likely origin of the carbon, with grey indicating terrestrial origin and white indicating microbial origin (after McKnight *et al.* 2001).

Results are means of the three flumes on each sampling occasion, with standard errors.

3.3.3 Aquatic community structure and abundance

Invertebrate communities were maintained over the entire term of the experiment, as evidenced by ongoing emergence of a range of taxa through the experiment. Communities were dominated in terms of abundance by two mayfly taxa, *Nousia* spp. and *Ulmerophlebia pipinna*, together with an elmid beetle *Austrolimnius* and several chironomid families; Chironominae, Tanypodinae and Orthocladiinae (Appendix 3). Copepod crustaceans were also abundant. Patterns of taxa richness did not differ across the repeats of the experiment or by temperature treatment (Table 4, Figure 9). However there were statistically significantly differences in the number of individuals between repeats, and between temperature treatments, driven by larger numbers of individuals in the warming treatment for two of the three repeats of the experiment (Table 4, Figure 9).

Table 4. ANOVA results of differences in taxa richness, total abundance for aquatic stages of biota in Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) temperature treatments for the three repeats of the experiment

Bold indicates significant at p=0.05 level.

	Repeat	Treatment	Repeat x Treatment
	F2,11	F1,11	F2,11
	[p]	[p]	[p]
Taxa richness	3.580	0.586	2.136
	[0.063]	[0.460]	[0.164]
Abundance	4.577	9.064	3.721
	[0.036]	[0.012]	[0.058]

Communities were much less variable when subjected to the Climate Change treatment (Index of Multivariate Dispersion; Control = 1.187, Climate Change = 0.855) (Figure 10). Multivariate analysis found differences in community composition between repeats of the experiment (Global rho = 0.553, p=0.004), but also between temperature treatments taking into account differences between repeats (Global rho =0.124, p=0.05). Differences between treatments were driven by lower abundances of the elmid beetle *Austrolimnius,* copepods, chironomids and the two mayfly species in the controls. Elmid species other than Austrolimnius were more abundant in the Climate Change treatments.

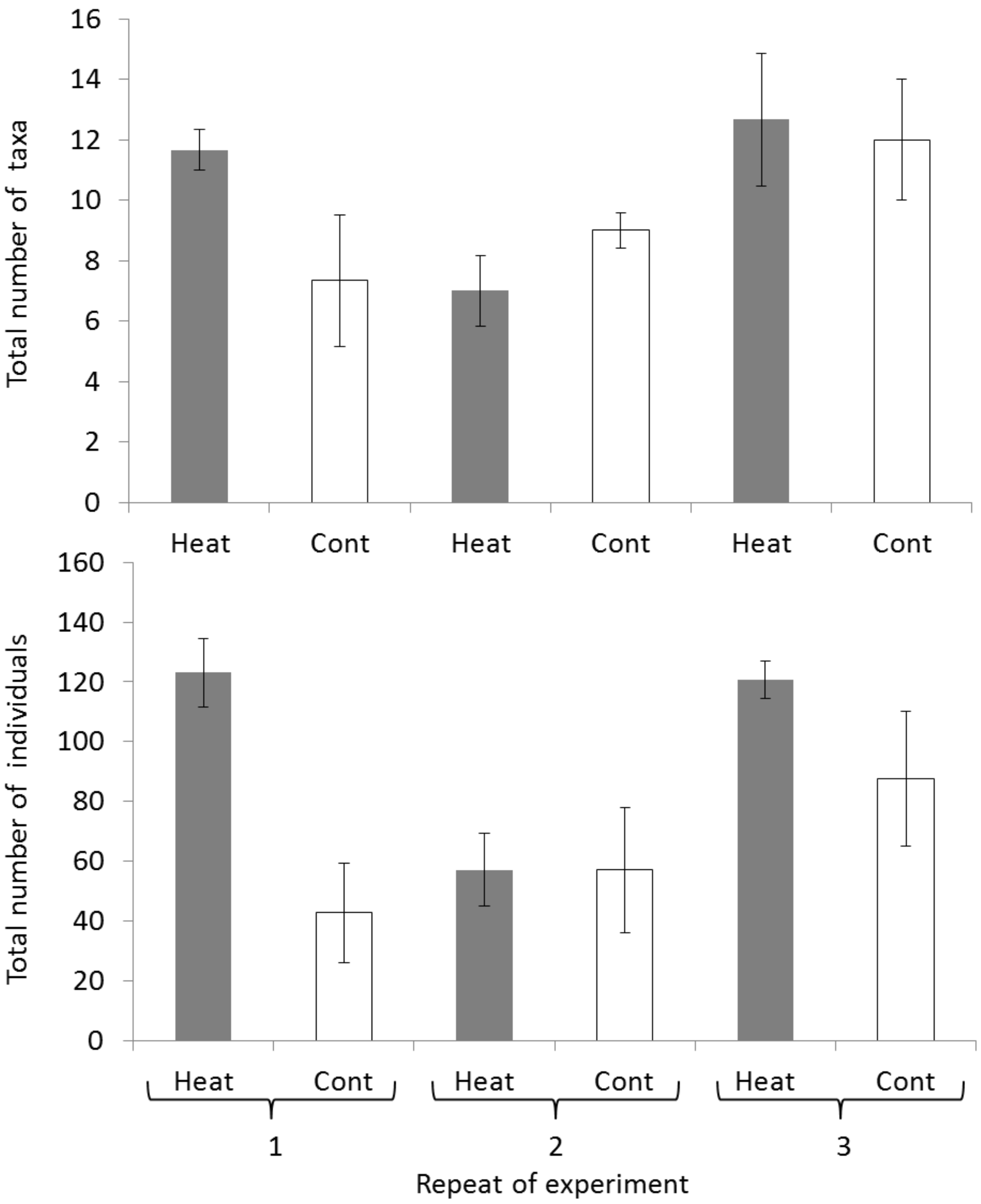


Figure 9. Total number of taxa and number of individuals in the aquatic community for each repeat of the experiment for the Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) treatments.

Values are means of the three trays with standard errors.

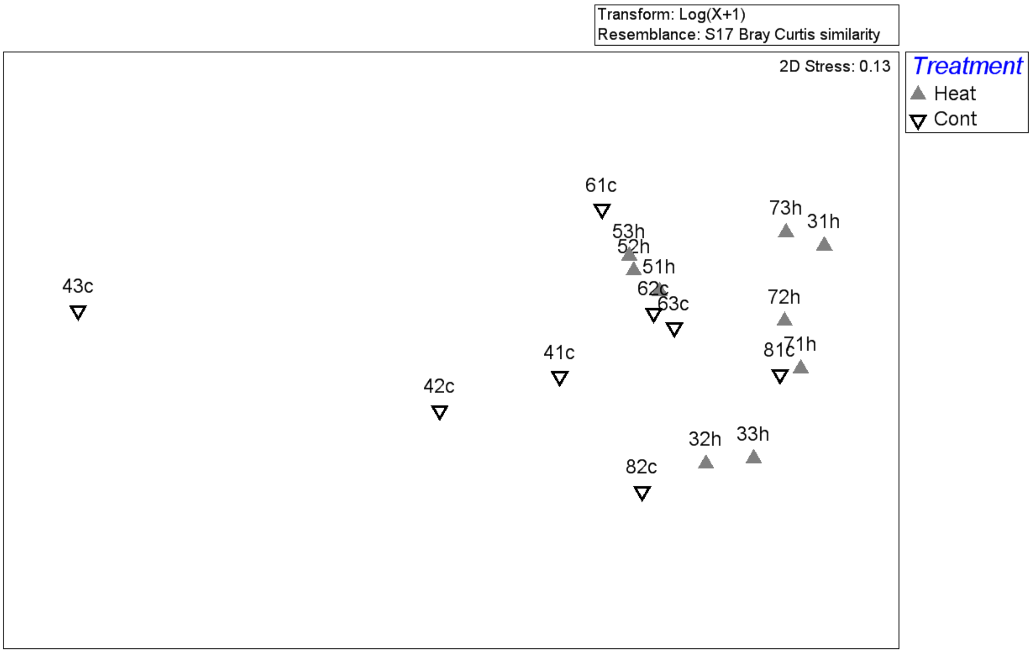


Figure 10. Non-metric multi-dimensional scaling ordination of Bray-Curtis similarities of log X+1 transformed abundance across taxa groups for the Control (mean 1990-2000 summer conditions; white triangles) and Climate Change (predicted 2100 summer conditions; grey triangles) treatments. Each symbol indicates the community from a replicate tray and is labelled x,y,z where x = flume number, y=tray number and z indicates control (c) or climate change (h) treatment.

3.3.4 Aquatic community body size

There was no overall effect of the experimental treatments on community body size, but there was a dramatic and highly significant reduction in the average size of one of the most abundant taxa, *Nousia* spp. (Figure 11, Table 5). No other taxa showed any effect of either repeat or temperature treatment on body size (data not shown).

Table 5. ANOVA results of differences in average length across the community and for *Nousia* spp. for aquatic stages of biota in Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) temperature treatments for the three repeats of the experiment.

	Repeat	Treatment	Repeat x Treatment
	F2,11, [p]	(F1,11, [p]	F2,11, [p]
Community average length	9.080	0.060	0.880
	[0.005]	[0.810]	[0.442]
Average length of *Nousia* spp.	0.681	18.413	0.979
	[0.526]	[<0.001]	[0.406]

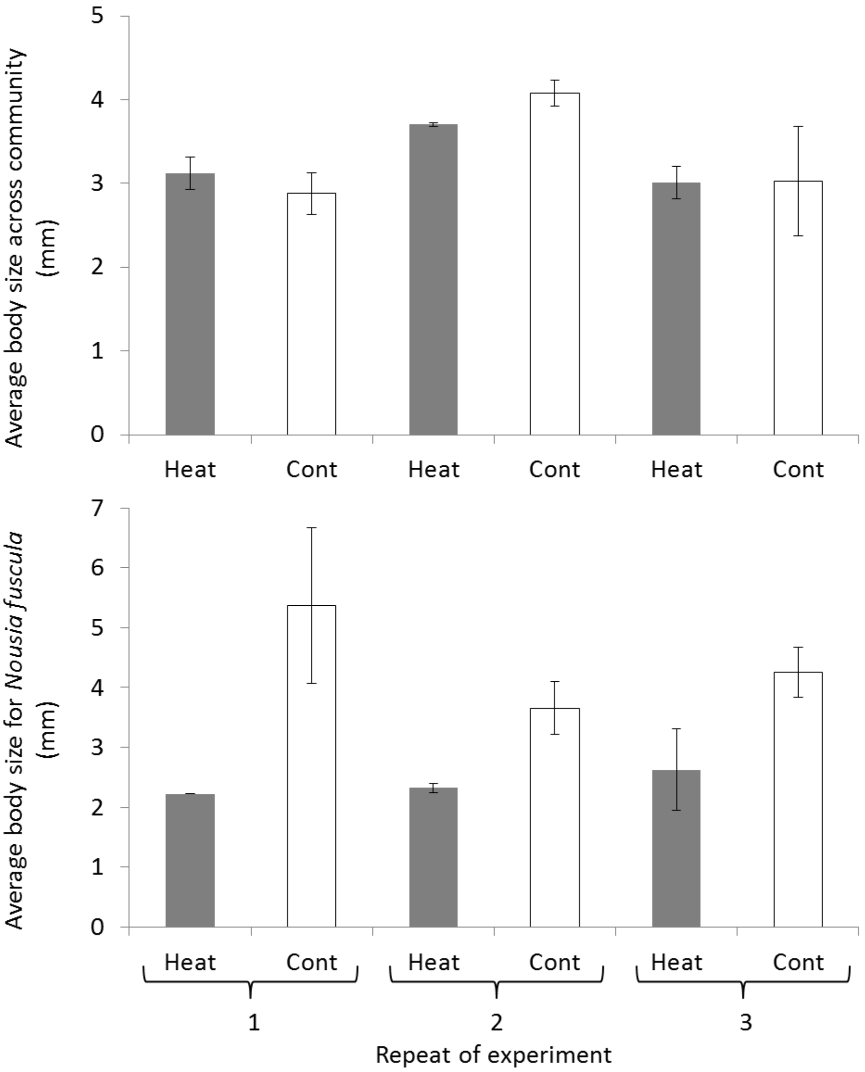


Figure 11. Average body size across the whole community and for *Nousia fuscula* alone for each repeat of the experiment for the Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) treatments. Values are means of the three trays with standard errors.

3.3.5 Emerging insects: rates of emergence

Mean total accumulated emergence was significantly higher in the Climate Change treatment than in the Control treatment for all taxa combined, for the mayfly *U. pipinna*, and for Trichoptera (Table 6, Figure 12). Rates of emergence were higher for males U. *pipinna* and N. *fuscula* from the Climate Change treatment compared to the Control treatment (ANCOVAs, slopes significantly different at p<0.01, Table 6, Figure 12). Accumulated emergence of *U. pipinna* was significantly higher in the Climate Change treatment than in the Control treatment for both males and females, but rates of emergence differed (Figure 13). At the end of the experiment, *U. pipinna* females in the Climate Change treatment were ~30% more abundant than in the Control treatment, while *U. pipinna* males were almost twice as much as abundant in the Climate Change treatment. As a result, female to male ratio was significantly lower in the Climate Change treatment compared to that in the Control treatment (1.4:1 in the Climate Change treatment compared to 2.5:1 in the Control treatment, t-test, p=0.01) (Figure 14).

Table 6. ANCOVA results of differences in mean accumulated emergence of adult aquatic insects between Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) temperature treatments. Temperature treatment main effects, and interaction of treatment and week (slopes of the curves) were considered. Post-hoc tests are presented when ANCOVA results indicated differences between treatments before Bonferroni's adjustment of p-values ($p<0.05$). * = statistically significant differences after Bonferroni's adjustment ($p=0.005$).

	$F_{1,33}$	P	Post-hoc tests
All taxa combined			
Temperature	56.66	<0.001*	Climate Change > Control
Temperature x week	0.38	0.54	
Ulmerophlebia pipinna total			
Temperature	14.94	<0.001*	Climate Change > Control
Temperature x week	5.20	0.03	Climate Change > Control
U. *pipinna* females			
Temperature	10.24	0.003*	Climate Change > Control
Temperature x week	2.27	0.14	
U. pipinna males			
Temperature	18.87	<0.001*	Climate Change > Control
Temperature x week	8.16	0.005*	Climate Change > Control
Nousia spp. total			
Temperature	0.05	0.81	
Temperature x week	4.58	0.04	Climate Change > Control
Nousia spp. females			
Temperature	0.20	0.65	
Temperature x week	3.45	0.07	
Nousia spp. males			
Temperature	0.78	0.38	
Temperature x week	4.54	0.04	Climate Change > Control

Table 6 cont. ANCOVA results of differences in mean accumulated emergence of adult aquatic insects between Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) temperature treatments. Temperature treatment main effects, and interaction of treatment and week (slopes of the curves) were considered. Post-hoc tests are presented when ANCOVA results indicated differences between treatments before Bonferroni's adjustment of p-values (p<0.05). * = statistically significant differences after Bonferroni's adjustment (p=0.005).

N. *fuscula* males			
Temperature	0.74	0.39	
Temperature x week	7.66	0.005*	Climate Change > Control
Trichoptera total (excluding *Agapetus* sp.)			
Temperature	4.11	<0.001*	Climate Change > Control
Temperature x week	1.06	0.31	
Agapetus sp. total			
Temperature	2.02	0.16	
Temperature x week	1.09	0.30	

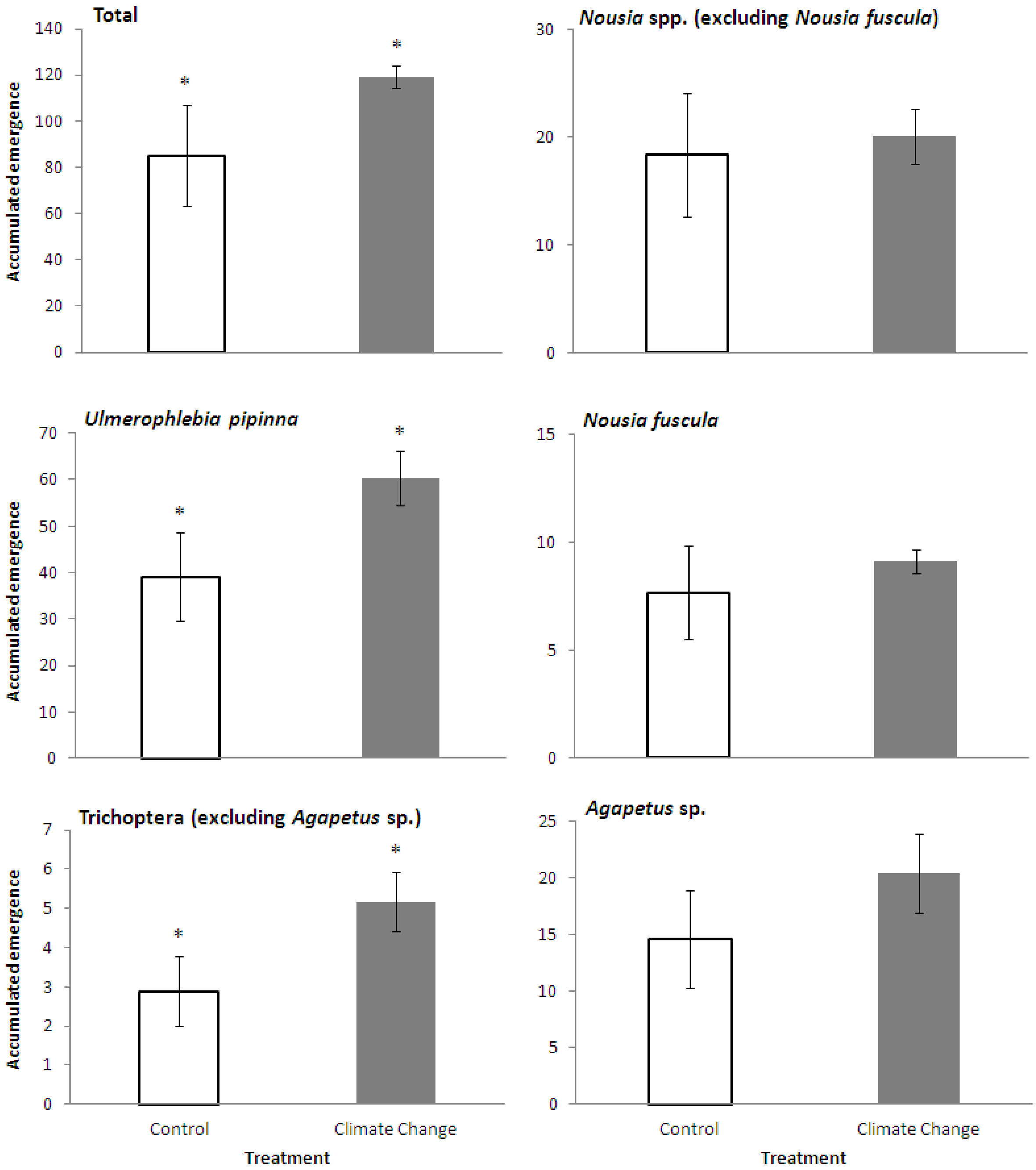


Figure 12. Mean accumulated emergence (number of individuals) for the total community and the individual taxa for the Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) treatments. Error bars represent SE. * = statistically significant differences between treatments after Bonferroni's adjustment (p=0.005).

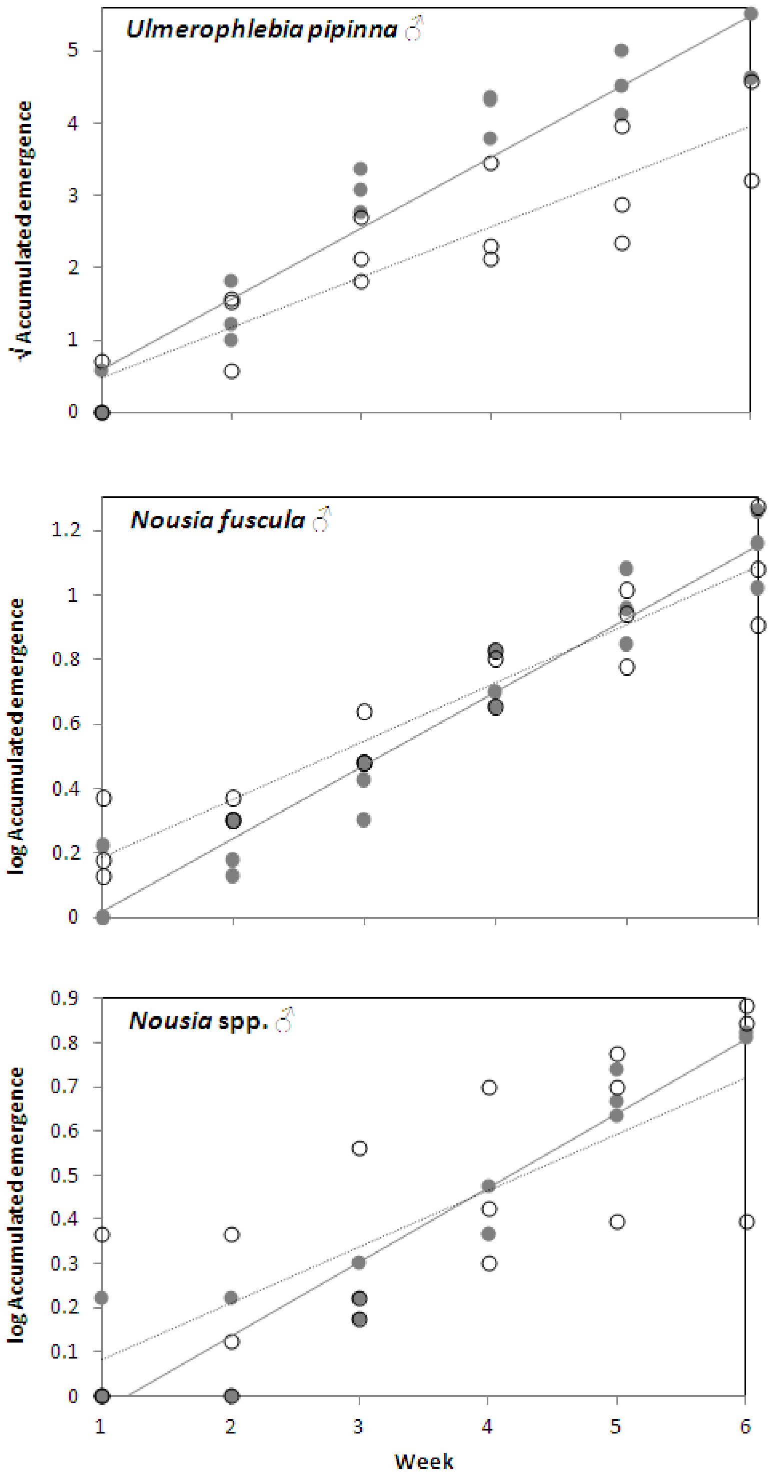


Figure 13. Rates of accumulated emergence (number of individuals) of mayflies *Ulmerophlebia pipinna*, *Nousia fuscula*, and *Nousia* spp. males for the Control (mean 1990-2000 summer conditions, open circles and dashed line) and Climate Change (predicted 2100 summer conditions, closed circles and line) treatments. Note different y-axis scales. Slopes for the first two species were significantly higher in the Climate Change treatment than in the Control treatment after Bonferroni's adjustment (p=0.005). Rates for females did not differ between treatments for any of the three species (p>0.005).

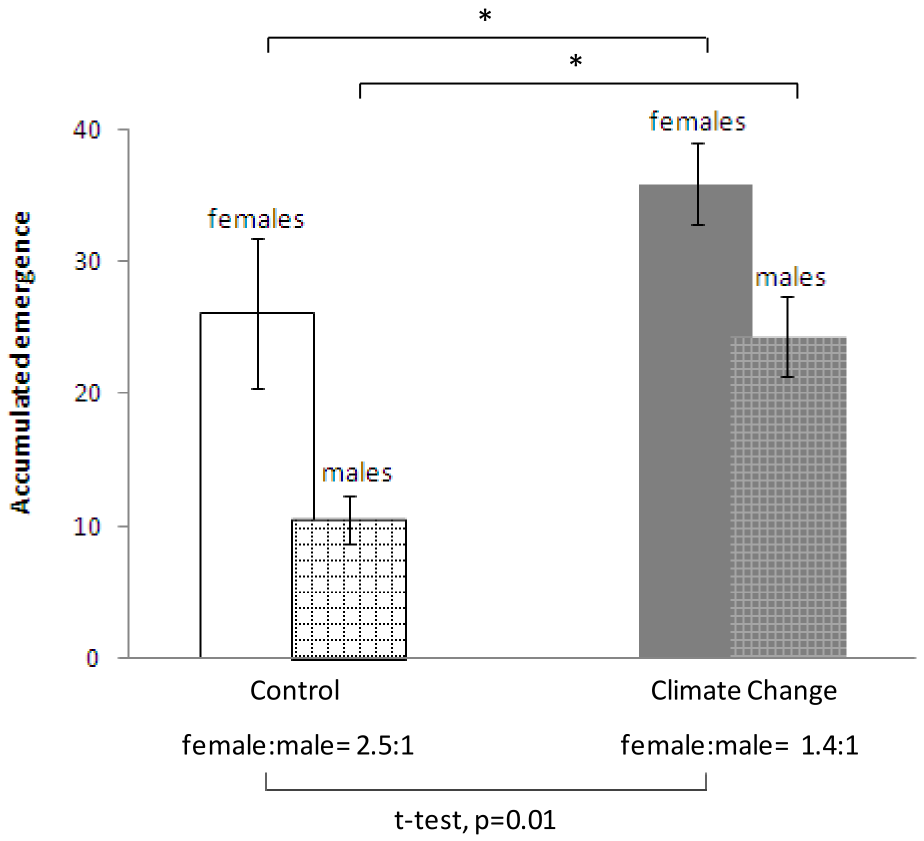


Figure 14. Mean total accumulated emergence of mayfly *Ulmerophlebia pipinna* females and males (number of individuals) for the Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) treatments. Error bars represent SE. * = statistically significant differences between treatments after Bonferroni's adjustment (p=0.005).

3.3.6 Emerging insect size structure

Individual taxa

No significant trend in mean body size was observed for any taxa in either Climate Change or Control treatment (all slopes non significant at p>0.05). At the end of the experiment, there were no significant differences in mean body size between treatments for any species (t-tests, p>0.05) (Table 7).

Emerging insect mean community body size (average across taxa)

Mean body size for emerging insects significantly decreased over the course of the experiment in communities subjected to Climate Change temperatures (significant slope, p<0.01) but not in the Control treatment (non-significant slope, p=0.64) (Figure 15). This pattern was driven by a shift in species composition from large species (*U. pipinna*) to small species (*N. fuscula*, *Nousia* spp., and *Agapetus* sp.) in the Climate Change treatment. The proportion (in terms of abundance) of *U. pipinna* significantly decreased (p<0.01) and that of *N. fuscula*, *Nousia* spp., and *Agapetus* sp. significantly increased (p<0.01) in the Climate Change treatment (Figure 16). In the Control treatment, the proportion of N. *fuscula* significantly decreased (p=0.02) and there was no shift in proportion of abundances for the rest of the species (p>40, Figure 16).

Table 7. Differences in mean body size ± SE at the end of the experiment (with t-tests results) between Control (mean 1990-2000 summer conditions) and Climate Change (predicted 2100 summer conditions) treatments.

	Control	Climate Change	t-test
Ulmerophlebia pipinna			
Total	8.40 ± 0.32	8.51 ± 0.14	0.77
Female	8.10 ± 0.19	8.32 ± 0.23	0.49
Male	8.86 ± 0.31	8.81 ± 0.18	0.90
Ulmerophlebia pipinna exuviae			
Total	7.83 ± 0.04	7.68 ± 0.09	0.22
Female	7.25 ± 0.25	7.82 ± 0.32	0.24
Male	7.75 ± 0.25	7.92 ± 0.34	0.45
Nousia spp.			
Total	6.66 ± 0.16	6.09 ± 0.16	0.06
Female	6.70 ± 0.16	6.05 ± 0.17	0.06
Male	6.29 ± 0.21	5.51 ± 0.10	na*
N. fuscula	5.72 ± 0.07	5.93 ± 0.19	0.38
Agapetus spp.	3.02 ± 0.05	3.01 ± 0.14	0.42

*Only two replicates available for each treatment

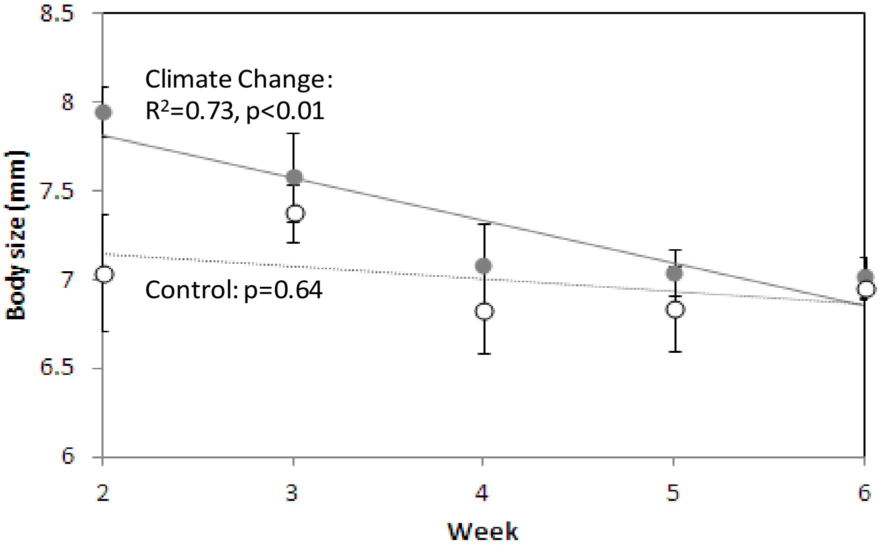


Figure 15 Overall community body size (average across taxa) over time for the for the Control (mean 1990-2000 summer conditions, open circles and dashed line) and Climate Change (predicted 2100 summer conditions, closed circles and line) treatments. The regression was significant only in the Climate Change treatment.

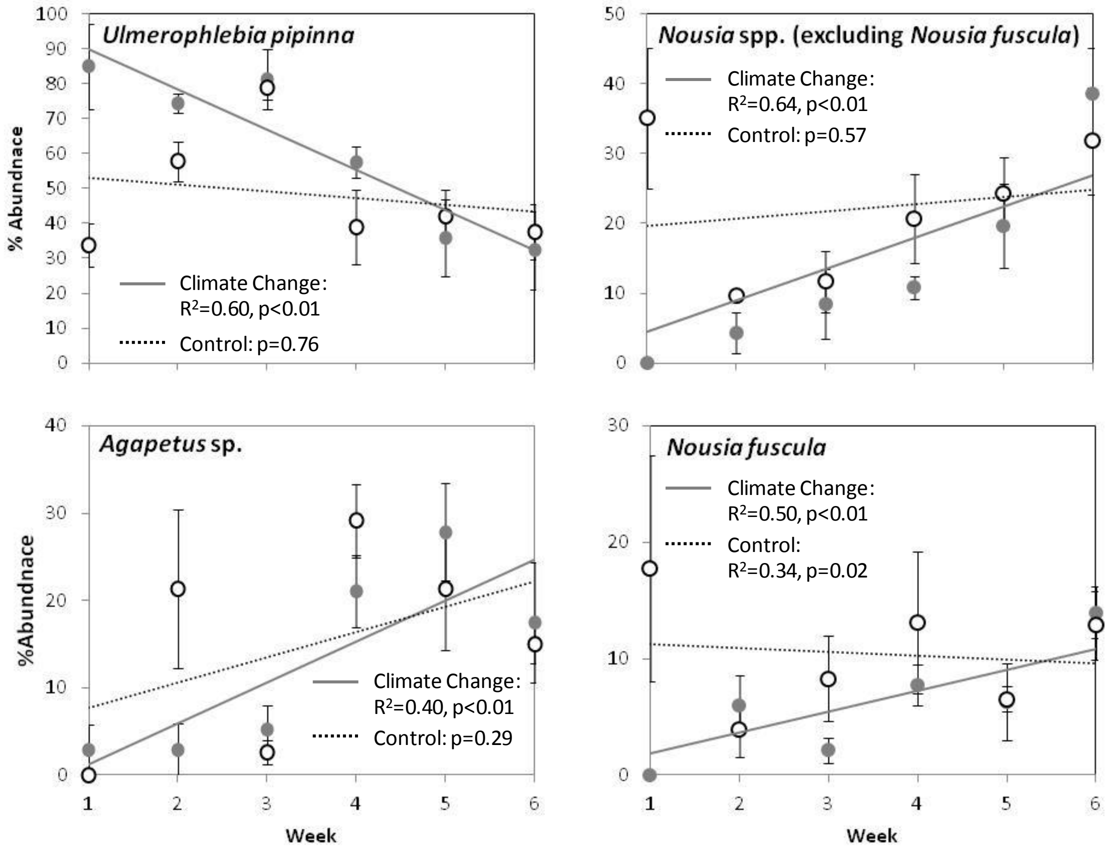


Figure 16. Percentage abundance over time for mayflies *Ulmerophlebia pipinna*, *Nousia fuscula*, and *Nousia* spp., and caddisfly *Agapetus* sp. for the Control (mean 1990-2000 summer conditions, open circles and dashed line) and Climate Change (predicted 2100 summer conditions, closed circles and line) treatments. Slopes were significant only for the Climate Change treatment.

3.4 Using existing field data in combination with the experimental results to assess the potential for adaptive management of riparian vegetation to mitigate against the effects of changing climate

3.4.1 Patch-scale analysis

Temperature data for paired sites through time was only available for five streams; four with unvegetated upstream reaches and vegetated downstream reaches and a fifth where both reaches were unvegetated. There was strong evidence for a cooling effect of riparian vegetation, with the four streams with vegetated riparian zones all having lower mean water temperatures over summer than the unvegetated sites. The magnitude of this cooling varied between approximately 1 degree Celsius and 5 degrees Celsius (Figure 17).

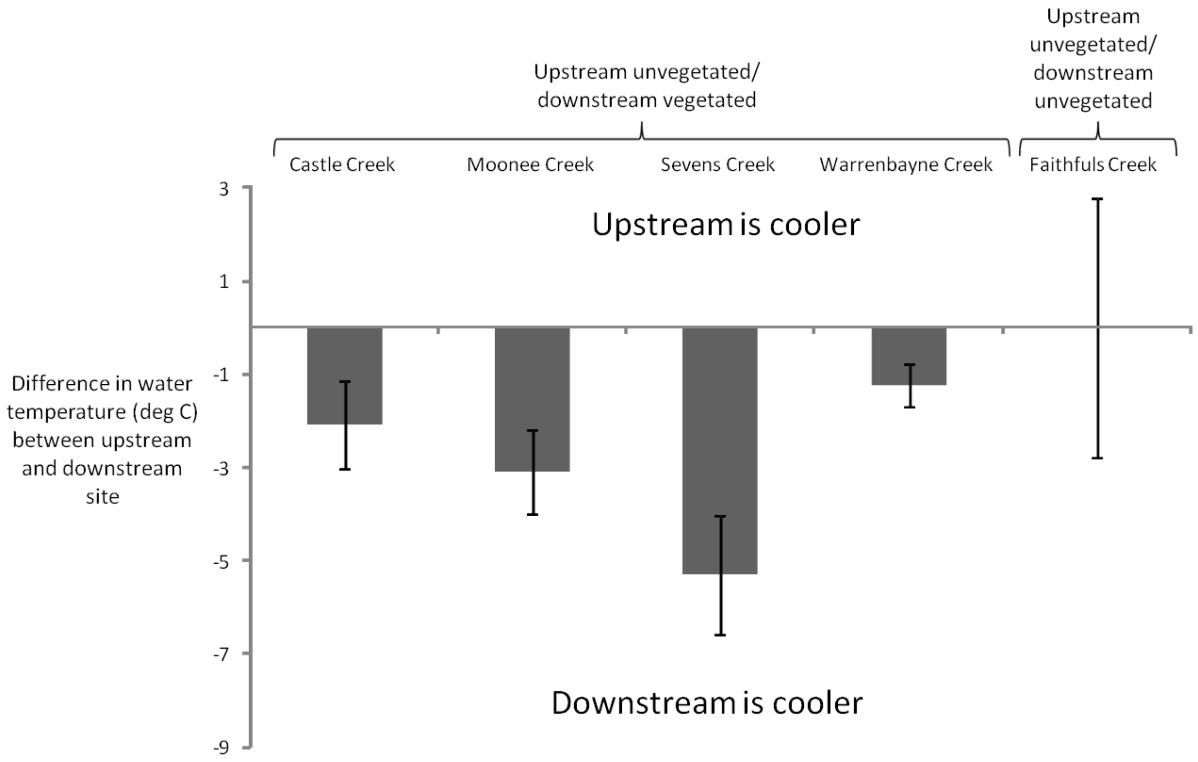


Figure 17. Difference in stream water temperature between an upstream site and a downstream site in five streams over summer (November 2011-April 2012). Four streams have unvegetated upstream sites and downstream sites with riparian zones which are between 12 and 21 years old. The final stream (Faithfuls) was unvegetated at both sites.

3.4.2 Landscape-scale analysis

There was strongly negative relationship between water temperature and reach-scale mean canopy height (Figure 18). Water temperature also had a negative association with catchment-scale native vegetation extent, even after the reach-scale riparian effect was accounted for (Figure 18). As expected, water temperatures showed strong seasonal patterns (warmer closer to summer solstice), increased with time-of-day, and with elevation, latitude and longitude. Water temperatures also tended be higher in larger streams. Note that the estimated riparian and catchment vegetation effects are conditional on all other temporal and spatial effects (including random effects) in the model, and the results are controlled for these other sources of variation.

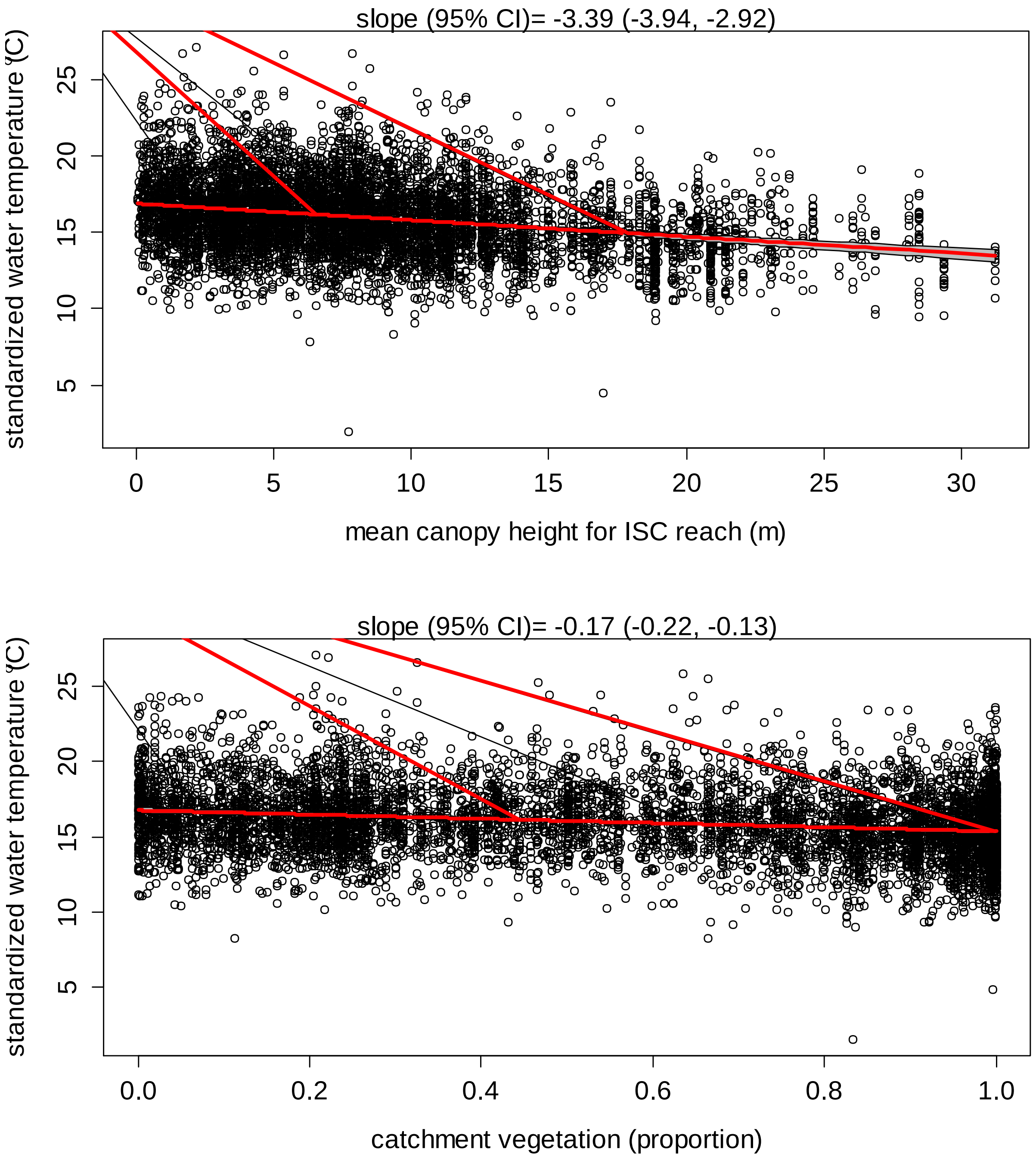


Figure 18. Relationship between stream temperature and riparian vegetation immediately adjacent to a reach (top panel) and over the catchment as a whole (bottom panel). The magnitude of the cooling effect of local vegetation is approximately 3 degrees, but is greatest in catchments where catchment vegetation is already moderating temperatures (data from Thomson et al., 2012).

4. DISCUSSION

4.1 Review of community-level climate change experiments

Direct effects of increased stream temperatures are predicted to have major implications for the distribution of cold water fish, particularly salmonids (Meisner 1990; Bryant 2009). Ecosystem consequences of altered climate are predicted to include changes in palatability of food resources (van de Waal *et al.* 2010; Sardans *et al.* 2012) and size spectra of animals (Yvon-Durocher *et al.* 2011) resulting in altered food web structure (Woodward *et al.* 2010a). These studies by-and-large have been based on field studies or are conceptual in nature, although in recent years there has been a small number of experimental studies (e.g. Yvon-Durocher *et al.* 2011; Dossena *et al.* 2012). The studies have predominantly considered temperature effects as either increases to a fixed mean or fixed increment studies (Table 1). In larger water bodies, the high thermal mass of aquatic systems may make them less vulnerable to short-term heat extremes, but in many shallow waterbodies, short term heat waves may have profound effects (Dokulil *et al.* 2010). The most recent climate change experiments in freshwaters have included extreme events as one-off or recurring events (Leberfinger *et al.* 2010; Ledger *et al.* 2011). These studies have shown that extreme events can greatly alter ecosystem functioning and food web structure in freshwaters. While the existing experiments have been highly informative, they have failed to incorporate meaningful patterns of climatic variability as predicted by climate models. Applying meaningful experimental treatments is a core part of this enterprise, and this review clearly shows that we need to move to a next generation of climate-change experiments in community ecology.

4.2 Methodology for down-scaling global circulation models to generate realistic treatments for climate change experiments

We have illustrated here a means to use large-scale climate models to generate realistic climate change treatments for experiments. The kind of experimental data generated by our new methods allows the application of highly realistic treatments in experiments that include not only changes in mean conditions, but also increased frequency, intensity and duration of extreme events. None-the-less, they are challenging to apply outside of highly controlled laboratory conditions. In outdoor conditions increment studies can superimpose a warming treatment on the background conditions (e.g. Yvon-Durocher *et al.* 2010; Dossena *et al.* 2012). With simulated weather, there is the potential that a temperature treatment for a particular day may be cooler than ambient conditions, or may be considerably higher than ambient conditions. Both situations require highly energy intensive equipment to apply the treatments. While it is possible to apply simulated weather as a treatment in an outside experiment, the approach described in the current paper is most amenable to highly controlled laboratory settings. This has the additional advantage that it is possible to carry out factorial designs which incorporate other stressors, which has been identified as an important new challenge in climate change experiments (Wernberg *et al.* 2012). These experiments will require stringent attention to issues of experimental design (Jentsch *et al.* 2007; Wernberg *et al.* 2012) but have the potential to generate a much greater understanding of the interactive impacts of changing climate with other stressors.

Understanding complex community and ecosystem-level responses to climate is essential (Van der Putten *et al.* 2010) and is only feasible through the use of manipulative experiments. These must be considered in a framework that includes information on evolutionary potential, spatial processes, and long term feedbacks (Dawson *et al.* 2011), but experiments are none-the-less an essential part of understanding the mechanistic basis for responses to climate.

4.3 Using realistic climate change treatments in an experimental context to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions

4.3.1 Effects on basal processes

Impacts of climate change on basal processes such as primary productivity and organic matter dynamics are of critical importance, because these processes underpin patterns of diversity and abundance of higher consumers (Mulholland *et al.* 2001). The vast majority of climate change studies have concentrated on biodiversity directly, despite there being an identified need for a stronger emphasis on studies of ecosystem function (Lake *et al.* 2000, Poiani *et al.* 2000). In the area of ecosystem function a number of studies have addressed likely impacts of warming. Barlocher *et al.* (2008) found that warming a temperate stream by 4.3 degrees C increased rates of leaf litter decomposition. Fribeg *et al.* (2009) in a study of streams along a 20 degree thermal gradient found that algal productivity and leaf litter decomposition increased with temperature, but there was considerable variability in response over relatively small temperature gradients (2-4 degrees C). Most recently, Yvon-Durocher *et al.* (2010) described an increase in both algal productivity and microbial/fungal respiration with temperature, but also found that the increase in rates of respiration was much larger, suggesting that this may increase CO_2 emissions from freshwater ecosystems under climate change scenarios.

We found some evidence to suggest that algal productivity may increase slightly when systems are subjected to a thermal regime based on a downscaled climate change scenario for 2100. These results were not statistically significant in most cases, although the warmed treatment had signficantly higher values for light harvesting efficiency on the final sampling ocassion. This may be due to the relatively low power of the experimental design used here, which although comparable to those used in other studies (Yvon-Durocher *et al.* 2010) is limited by the difficulty in establishing and replicating these kind of studies. Similarly, the limited time over which the study was carried out may mean that longer term effects were not detectable. It seems most likely however that algal productivity is constrained by a range of factors, of which temperature is only one (DeNicola 1996). Nutrient levels in these experiments were low based on those observed in the field, and may have limited potential responses to increases in temperature. The magnitude of the increase in temperature was also much smaller than that used in the earlier studies by Barlocher (2009), Friberg *et al.* (2010) and Yvon-Durocher *et al.* (2010). This study also differed from those studies in that temperature varied, which may prevent primary producers from increasing productivity at rates seen in other studies. We suggest that for this region, with the relatively modest increases in temperature predicted, that the impact of warming alone on algal productivity will be small. This does not take into consideration other impacts which may occur due to changes in algal consumers or altered nutrient loads due to climate change impacts on patterns of runoff.

In interpreting the effects of the temperature treatments on carbon dynamics, we followed the approach of McKnight *et al.* (2001), who describe threshold values for interpreting the origins of carbon based on fluorescence index and aromaticity. It has been predicted that warmer conditions will favour bacteria and fungal communities, increasing decomposition rates and increasing respiration (Yvon-Durocher *et al.* 2010). Higher rates of decomposition under warmer conditions have been described both in laboratory experiments and in field studies along thermal gradients (Barlocher *et al.* 2008, Fribeg *et al.* 2009). Overall, the fluorescence and aromaticity values were indicative of a terrestrial origin for the dissolved organic carbon in both temperature treatments (McKnight *et al.*, 2001). However there were consistent differences in patterns through time depending on the temperature treatment. Whereas the fluorescence index in the warmed treatment tended to be relatively consistent through time, in the middle sampling occasion in the control treatment, the index suggested a higher proportion of microbially derived organic carbon, although aromaticity values show that terrestrially derived carbon still predominated. In general, temperature effects were small, and again it is not possible to separate an effect of low power from the absence of a temperature effect. That said, it is clear that there is no large effect of temperature differences of this relatively small magnitude between treatments (compared to the Barlocher *et al.* (2008) and Friberg *et al.* (2009) studies). These experiments did not incorporate some of the proposed second-order effects of climate change on organic matter dynamics in streams, including changes in quality and quantity of detrital inputs (Myer and Pulliam 1992), specifically increases in carbon:nitrogen ratios (Ineson and Cotrufo 1997, Ostrofsky 1997, Palmer *et al.* 2000, Woodward *et al.* 2010). It is also possible that altered hydrology as a result of changing climates will alter retention times for litter and thus bioavailability to consumers (Arnell *et al.* 1996).

4.3.2 Effects on macroinvertebrates

Our results showed that all species in the community responded in some way when exposed to Climate Change treatment conditions, but that responses were species- and gender-specific. In the aquatic community a number of taxa increased in abundance in the Climate Change treatment. These were predominantly grazers, and their increased abundance may in part explain the lack of a strong algal response to warming. Changes in body size did occur in some taxa, but this was highly variable, and there was no mean change in body size across the community. Total emergence for aquatic insects across all taxa was higher in the Climate Change treatment as result of increased numbers emerging in the mayfly and Trichopteran groups. One of the most abundant mayfly species in Australian freshwater systems, *U. pipinna*, responded to warmer temperatures by emerging in greater abundances, more quickly, and with an altered sex ratio. Under climate change conditions, *U. pipinna* emerged in high numbers at the beginning of the experiments, and then significantly decreased throughout the experiment. The opposite trend was observed for N. *fuscula*, *Nousia* spp., and *Agapetus* sp., which were present in increasing numbers in the emerging insect community in the Climate Change treatment as the experiment progressed.

The change in the insect community from one dominated by larger taxa (*U. pipinna*) to one dominated by smaller taxa (*N. fuscula*, *Nousia* spp., and *Agapetus* sp.) provides evidence that temperature plays a major role in driving changes in the size structure of aquatic insect communities. This effect was clear at a community level (particularly in emerging insects) but also at a population level, with body size significantly decreasing in the aquatic stages of *Nousia* spp.. These results are consistent with some of the general hypotheses describing temperature-size relationships. Bergmann’s rule (Bergmann 1847) states that warm regions tend to be inhabited by small-sized species. The species-shift hypothesis (Daufresne *et al.* 2009) predicts an increase in the proportion of small-sized species, in terms of abundances of individuals and/or number of species, in communities subjected to warming climates. Long-term observational and experimental reports have documented species-shifts in fish, zoo- and phytoplankton, and bacteria communities (Daufresne *et al.* 2009; Yvon-Durocher *et al.* 2011). Our results provide evidence that, at least for organisms with rapid generation times such as aquatic insects, these changes can occur over an extremely short time period.

While there was an overall shift in community composition favouring smaller-bodied taxa in the emerging insect community, patterns within populations were more variable.

The temperature–size rule proposes that the individual body size of ectotherms tends to decrease with increasing temperature (Atkinson 1994), and this has been supported by long-term observational data and experimental studies (Hogg and Williams 1996; Daufresne *et al.* 2009; Li *et al.* 2011). Within populations in the current study there was no consistent trend towards reduced body size. A number of other studies have shown no shift or increases in body size for caddisflies, stoneflies, and moths in streams subjected to warming (Perry *et al.* 1987; Hogg and Williams 1996; Gregory *et al.* 2000; Shama and Robinson 2006; Brown *et al.* 2010; Li *et al.* 2011). In an experimental long-term study, average size within zooplankton species was also unaffected by warming (Yvon-Durocher *et al.* 2011). Therefore, morphological responses of specific taxa to increasing temperatures appear to be variable and potentially difficult to predict. Physiological compensation may prevent some taxa emerging at smaller sizes under warming conditions (Huey and Kingsolver 1993). There is also a possible role for phylogeographic and evolutionary history to influence the potential for certain taxa to respond to climate. The aquatic insect fauna of south-eastern Australia has components which have evolved under cooler conditions (Gondwanan relicts, particularly stoneflies and mayflies) but it also includes taxa which have diversified in the time since the Australian climate has become hotter and drier (Byrne *et al.* 2008). The differing evolutionary history of these taxa is likely to have a major role in determining potential to respond to changing climate.

Food-web effects can also contribute to changes in body size. For instance, top-down constraints and resource availability can influence size structures of populations. We did not include predatory effects in this experiment (such as predation by fish), although this will ultimately affect size structure (e.g. Daufresne *et al.* 2009). Increased nutrient availability can also alter size structure, favouring larger body sizes (Yvon-Durocher *et al.* 2011; Marañón *et al.* 2012). Warmer conditions may increase rates of nutrient turnover and primary productivity (Yvon-Durocher *et al.* 2011). The small number of studies carried out on the effects of climate change on basal productivity in freshwater ecosystems have suggested that increased primary productivity could be a result of warming (Yvon-Durocher *et al.* 2011). We have insufficient data on algal and microbial productivity to test that mechanism here, but the fact that body sizes of aquatic larvae overall in the Climate Change treatment did not differ from those in the Control suggests that availability of nutrients was at least comparable between both temperature treatments.

Reproductive asynchrony occurs when reproductively active individuals of the two genders occur at different times within the reproductive period (Calabrese and Fagan 2004). Reproductive asynchrony has been associated with unstable or unpredictable environmental conditions, including global warming (Li *et al.* 2011). Asynchrony reduces overlap between sexes and thus reduces reproductive potential for the population (Calabrese and Fagan 2004). Males of mayfly species *U. pipinna* and *N. fuscula* emerged faster in the Climate Change treatment. In *U. pipinna*, there was a clear shift in the sex ratio from highly female biased (2.5:1) in the Control to a more even sex ratio (1.4:1) in the Climate Change treatment. Temperature-dependent sex determination has been described for a number of vertebrate taxa (Bull 1980; Conover and Kynard 1981; Janzen 1994; Parmesan *et al.* 2000). There are fewer studies examining climate change effects on insect sex ratios (Hogg and Williams 1996). That study also found a shift from female biased (3:2) to not sex bias (1:1) for *Lepidostoma vernale* (Trichoptera) under warmer conditions. In this study we cannot know whether longer periods of warming for *U. pipinna* would alter sex ratios further, or whether population processes may result in ratios moving back towards the initial values. We were not able to assess the demographic and fitness consequences of these changes in sex ratios, but they could be substantial. While equilibrium population sex ratios can be achieved in well-dispersed insects by microclimatic differences among habitats, this mechanism would be less effective for short-lived species and species with poor dispersal abilities, such as *U. pipinna* and many other mayfly species (Winterbourn *et al.* 2007).

One of the most frequently described ecological responses to climate change is the disruption of interactions between species. Decoupling of animal interactions - generally referred as the match–mismatch hypothesis - can affect different levels in the community and may have critical consequences for ecosystems (Winder and Schindler 2004). In the context of our results, the interaction between emerging insects and riparian predators can be disrupted if prey and predators respond differently to warming, for example, if there is a mismatch between food requirement from consumers such as riparian spiders and birds, and the availability of prey such as mayflies. Changes in insect emergence patterns can have direct and indirect effects on the food–web interactions between the riparian community and stream insects (Kato *et al.* 2003; Greig *et al.* 2012). In an outdoor mesocosm experiment Greig *et al.* (2012) found that warming advanced the phenology of insect emergence, ultimately affecting the recipient communities and altering the carbon balance between aquatic and terrestrial ecosystems. Species responses may become increasingly divergent as the magnitude of climate change increases, causing species-specific environmental thresholds to be reached (Pucko *et al.* 2011).

4.3.3 Study limitations

Our experiment is subject to a number of limitations. The benthic communities were sourced from a river which had been exposed to natural variation in climate, and were then exposed to a future climate scenario in a relatively short time (after one week of acclimatization). In reality, warming will occur over decades, superimposed by a relatively slow increase in the frequency of extreme events. This may allow taxa with sufficient variability to evolve in response to altering climates. This is particularly true of organisms with rapid generation times such as bacteria and aquatic insects. Although it has been widely discussed in the context of terrestrial organisms (Parmesan 2006; Sgro *et al.* 2011), there remains a challenge to incorporate evolutionary processes into freshwater studies of the effects of climate change.

We deliberately created a very simple environment to carry out these experiments. In natural situations a variety of mechanisms may allow species to cope with extreme climatic conditions. These include moving into areas of thermal refugia in the substrate below streams and seeking out areas of high aeration to avoid oxygen stress. For some animals, however, moving in response to changing temperature may be limited due to behavioural or life-history constraints. For example, the direction and magnitude of dispersal behaviour in aquatic insects plays a central role in reproduction and population dynamics, and for some adult mayflies it has been shown that they do not fly or move far from their emergence sites (Winterbourn *et al.* 2007).

There is a need to consider the degree to which these kind of highly-controlled experiments can be scaled to large-scale real-world conditions. Previous small-scale studies have also tended to concentrate on single species, so when experimental results have not scaled to field outcomes, it is difficult to determine which of these two factors is responsible (Wernberg *et al.* 2012, Wolkovich *et al.* 2012). In plant studies, it appears that small scale experiments may not scale up to large scales because they fail to incorporate complex community-level interactions and therefore underestimate warming impacts (Wolkovich *et al.* 2012). It is important to recognise the limitations of such small-scale experiments (Carpenter 1996; Underwood *et al.* 2005). The spatial scale of experiments has been shown to affect the magnitude of responses to treatments in a number of different systems (see Englund and Cooper 2003 for a review). In particular, open systems that are strongly reliant on landscape-scale processes such as metapopulation dynamics may respond differently to changing climate than do systems where local processes predominate (Underwood *et al.* 2005). Manipulations at relatively small scales are likely to be the only way to explore impacts of climate change in a way which incorporates all of the features of predicated future climates (Englund and Cooper 2003). We propose that a suite of approaches including laboratory experiments, use of extreme events within traditional experimental increment studies and field studies of extreme events will be needed to gain a thorough understanding of the likely effects of future climates. Increasingly, frameworks are being suggested for how best to integrate across this suite of data (Denny and Benedetti-Cecchi, 2012).

4.3.4 Summary

The majority of climate change studies published to date have concentrated on increases in mean temperatures, but the need to include extreme events in studies of climate change has been well recognised over the last decade (e.g. Easterling *et al.* 2000; Jentsch *et al.* 2007; Lloret *et al.* 2012). One of the distinctive features of this study is the use of a realistic climate change treatment which includes extreme events (in this case relatively prolonged ‘heat waves’) as a part of the treatment. Individualistic traits, such as physiological tolerances and life-history strategies, likely underlie the variability in strength of response of not only species, but also sexes within species, even when they were subjected to the same climatic conditions (Parmesan and Yohe 2003; Parmesan 2006).

Overall, realistic changes in stream temperature regimes, consistent with those predicted by climate change models, do not appear to have a dramatic effect on algal productivity and carbon dynamics, at least over relatively short time periods. Additional experiments on effects of carbon dioxide and temperature changes in combination on algae are currently underway, but pilot results suggest that changes are minimal in terms of altered species composition and carbon:nitrogen ratios. There is a need for additional work on the effects of altered carbon:nitrogen ratios in leaf litter on streams, and these experiments are feasible through use of leaves with experimentally altered stoichiometry.

Our experiment provides evidence that increases in mean and extreme temperatures will alter community and size structure of aquatic insect communities, and patterns of emergence of the adult stages of aquatic insects. It also shows that warming effects are species- and sex-specific. For the most important mayfly species in our system, this may potentially lead to local population extinctions, which will likely result in direct and indirect cascading effects on the aquatic and terrestrial food–webs.

4.4 Using existing field data in combination with the experimental results to assess the potential for adaptive management of riparian vegetation to mitigate against the effects of changing climate

Riparian vegetation is known to have important effects, including bank stabilization, provision of coarse wood and leaf litter, filtration, and moderation of temperatures (e.g. Davies and Nelson 1994; Naiman and Latterell 2005; Reid *et al.* 2008). Our results have shown impacts on aquatic invertebrate populations under realistic climate change scenarios. Further, there is evidence from our published work across Victoria, that warming conditions are implicated in declining aquatic ecosystem health (Thomson *et al.* 2012). The work by Thomson *et al.* (2012) at a landscape scale shows that the extent of native vegetation across a catchment appears to have a stronger overall influence on reach scale condition than local riparian vegetation, but there are detectable effects of local scale replantings. Stream water temperature appears to be one of the important drivers underlying this result. Our paired reach results and landscape scale LiDAR-based anaylsis show that riparian vegetation can cool stream water on a scale which is consistent with the increases expected under climate change. As a result, riparian vegetation appears to have the potential to mitigate against the climate change impacts on aquatic communities. Our results from field studies indicate that the benefits of local riparian vegetation increase with increasing air temperature, and in the warmest basins, the riparian tree effect on SIGNAL scores was of similar magnitude to the catchment tree cover effect (Thomson *et al.* 2012). Thus, riparian restoration may be particularly beneficial in warmer catchments and may help to reduce negative effects of anthropogenic global warming in many regions.

4.5 Synthesis and management implications

4.5.1 Effects of temperature on stream biota and processes

A review of international literature, in combination with an experimental study was used to determine the effects of warming associated with climate change on stream ecosystems. The majority of experimental studies to date have failed to take into account the increased variability in climatic conditions which is predicted to occur under climate change scenarios. However incorporating changes in temperature variability into a climate change experiment did not produce dramatically different responses to those already published.

Algal productivity and carbon dynamics did not show major responses to a warming treatment. Algal productivity increased slightly, but is likely to be limited by numerous other factors in stream systems. Respiration and carbon dynamics did not alter significantly. These ecosystem processes appear to be relatively resistant to impacts of altered temperatures of the magnitude predicted under climate change scenarios.

Aquatic macro-invertebrate communities did respond to the warming treatment. While there were no clear impacts on biodiversity, the size-structure of communities both in-stream and as emerging adults was altered. This is consistent with overseas studies. There are grounds for concern over the impacts of altered size structure on population processes for several invertebrate taxa, with the potential for local extinctions and longer-term impacts on biodiversity. These impacts would be consistent with the effects of drought which have been observed in longer-term field surveys of aquatic macro-invertebrates.

Altered timing of emergence of adult insects and changes in size-structure may have impacts on terrestrial biota which rely on these insects as a food resource. These include groups such as frogs, birds and bats.

4.5.2 Potential mitigation using riparian vegetation

Analysis of existing large-scale datasets of macro-invertebrate relationships with riparian vegetation, and analysis of effects of riparian vegetation on stream temperatures was used to assess the potential for riparian replantings to be used to mitigate against the effects of changing climate.

There is strong evidence that declines in aquatic biodiversity associated with drought conditions were less severe in areas which retain native forest cover, even when other covarying factors are taken into account. Temperature emerges as an important predictor of stream macro-invertebrate community condition in analyses of long-term surveys.

Local-scale measurements and landscape-scale analysis using LiDar of the relationship between riparian vegetation and stream temperatures suggests that cooling effects of approximately 3 degrees Celsius are realistic in response to riparian vegetation, even when the patch size of the vegetation is relatively small (approximately 500 linear stream metres). The cooling effect is largest in 2-3 order streams. Catchment vegetation in total interacts with the amount of local vegetation to predict temperatures of larger streams.

5. GAPS AND FUTURE RESEARCH DIRECTIONS

Our research has identified a number of gaps that require future research.

1. A need to extend the current results over longer time periods to understand the potential for taxa to adapt to climatic changes occurring over several seasons. This would require experimental treatments maintained over very long periods and would be logistically challenging.

2. We sought to include an increase in CO2 concentrations as a part of our experimental treatments, but reaeration by the flumes prevented this. There has been considerable research in marine systems on the effects of acidification due to increased CO2 concentration, but this has not yet occurred in freshwater systems.

3. As indicated in Section 4.3.4, one important mechanism for climate change effects on streams is likely to be changes in riparian vegetation, either in terms of species composition, or in the chemical composition of litter. There is considerable potential for research in this area.

4. There is a need to understand interactions between phylogeographic history and vulnerability to climate change. Our communities were dominated by temperate adapted fauna which may lack the evolutionary history to adapt to changing climates. Fauna from inland Australia with a long history of exposure to aridification may be more capable of adapting to change.

5. An understanding of the genetic and physiological basis for adaptation to changing climate. There is currently considerable attention being paid to understanding the mechanisms that underpin adaptation to changing climate, utilising genetic and genomic tools. These have considerable potential to be applied in stream ecosystems, because many of the tools have been developed for working on insects.

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APPENDIX 1: MEANS AND EXTREMES: BUILDING VARIABILITY INTO COMMUNITY-LEVEL CLIMATE CHANGE EXPERIMENTS

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ABSTRACT

Understanding the likely effects of climate change can be achieved using an experimental approach. However, studies assessing climatic effects on ecological communities have typically applied static warming treatments to measure changes in community composition and ecosystem function. While these studies have been highly informative, the way in which they have been applied has some weaknesses. These include applying temperature treatments which fail to incorporate either current, or predicted future, patterns of variability. Future climates are likely to include extreme events which have greater impacts on ecological systems than changes in means alone. Here we review the studies which have used experiments to assess impacts of climate on marine, freshwater and terrestrial communities. These studies are classified into a set of ‘generations’ based on how they incorporate variability. The majority of studies have taken relatively simple approaches to climate change experiments, often failing to incorporate extreme events. In terrestrial ecosystems in particular, many experiments have reduced climatic variability in climate change experiments, when most models predict increased variability. Marine studies have tended to not concentrate on changes in variability, likely in part because the thermal mass of oceans will moderate variation. In freshwaters, climate change experiments have a much shorter history than in the other ecosystems, and have tended to take a relatively simple approach. We propose a new ‘generation’ of climate change experiments using down-scaled climate models which incorporate predicted changes in climatic variability, and describe a process for generating data which can be applied as experimental climate change treatments.

INTRODUCTION

Predicting the consequences of climate change requires an understanding of the complex physiological, ecological, and evolutionary processes which underpin the relationships between climate and biodiversity (Lavergne *et al.* 2010; Bellard *et al.* 2012). Our understanding of the effects of changing climate on ecosystems has been greatly informed by field studies showing range shifts (including invasions) (e.g. Parmesan 2006; Thomas 2010; Dietl and Flessa 2011), altered patterns of phenology (e.g. Walther 2004; Parmesan 2006; Pau *et al.* 2011), changes in body size distributions (e.g. Sheridan and Bickford 2011; Goodman *et al.* 2012), and altered rates of ecosystem functions (e.g. Traill *et al.* 2010). Palaeoecological and long term ecological data also provide important context for the study of changing climates (e.g. Dietl and Flessa 2011; Willis and MacDonald 2011). While we have an increasingly complete view of the effects of climate change on populations and individual physiology, it remains a challenge to understand the effects on biotic interactions and ecological feedbacks (Traill *et al.* 2010; Van der Putten *et al.* 2010; Walther 2010). Such an understanding is critical if we are to apply our predictions of climate change effects to core issues such as conservation planning (McCarty 2001).

There is an increasing awareness of the need for experimental approaches to studying climate change, ideally embedded in a framework which also incorporates palaeoecological and evolutionary data, field studies, and computational modelling (Dawson *et al.* 2011). While the use of latitudinal and altitudinal gradients as surrogates for experimental climate change treatments is highly informative (e.g. Umina *et al.* 2005) variation in conditions along those gradients may not accurately reflect predicted changes in climate. Climate change across much of the planet will include underlying increases in mean meteorological quantities (e.g. temperature, precipitation, solar radiation, and wind) ('trend effects'; Jentsch *et al.* 2007), but also the variability of these quantities. Increasing the variability will cause changes in the frequency, duration, and intensity of extreme weather events such as heatwaves and dry spells ('event effects'; Jentsch *et al.* 2007) (Katz and Brown 1992; Easterling *et al.* 2000; IPCC 2012). In other words, climate change includes both a trend and variability component.

Experimentally applying climate change treatments is one way to understand the effects of variability and extreme weather events on ecological systems. Experiments have been increasingly used over the last few decades to understand climate change impacts, and in particular, the mechanisms that underlie them. These have included experiments where CO_2 and temperature have been manipulated at the scale of whole trees (Crous *et al.* 2012), warming of sections of Arctic tundra (Henry and Molau 1997), and using heating cables to warm forest soils (Melillo *et al.* 2002). Generally these studies have investigated the effects of mean warming rather than any change in underlying variability.

While most experimental studies have focussed on trend effects of changes in climate, variability and subsequent extreme event effects are often biologically more significant. These include heavy rainfall and associated flooding, extreme heat or cold events at a variety of temporal scales, and extreme weather events such as hurricanes and fires (IPCC, 2012). Predicted increases in mean temperatures due to climate change are likely to impact species over relatively long time periods (years to decades), resulting in range shifts and alterations in ecological interactions (Parmesan 2006). Extreme disturbances of various types are associated with dramatic biological effects at different levels of ecological organization, from the individual (e.g. physiological stress) (Parmesan *et al.* 2000) to the ecosystem (shifts between states) (Allen and Breshears 1998; Scheffer and Carpenter 2003). While mean trend effects may be moderated by evolutionary change (Sgro *et al.* 2011), event effects are likely to have immediate consequences which may result in extinction even when there is potential for evolutionary change (Gutschick and BassiriRad 2003).

It is becoming clear both from climate modelling and from trends in climate, that future climate will be characterised in many regions by increases in the frequency of extreme events (Jentsch *et al.* 2007). We have used the IPCC (2012) definition of extreme events which is essentially statistical (i.e. events which fall outside the 90th percentile under current climatic conditions). Extreme high temperature events include increases in intensity (higher maximum temperatures), frequency and duration of high temperature events which are rare under current climatic conditions (IPCC, 2012). We know that in many ecological systems extremes are the most important events for determining community dynamics (Gutschick and BassiriRad 2003). The probability and consequences of extreme events have been increasingly discussed in the scientific literature, particularly in the context of climate change (Jentsch *et al.* 2007). However biological responses to temperature can be highly non-linear and are typified by thresholds, interactions with other climatic conditions, such as rainfall, and the potential for organisms to adapt to changed conditions (Benedetti-Cecchi *et al.* 2006, Gutschick and BassiriRad 2003).

In the following review we assess the ways in which conditions resulting from climate change predictions have been applied as treatments in experiments on freshwater, marine and terrestrial systems. We assess the approaches taken in the different ecosystem types and the basis for those differences. Finally we describe an approach to using regional or global climate change models as the basis for generating experimental treatments which reflect the complex features of predicted future weather conditions.

DISCUSSION

Part One: Trends and insights from climate change experiments

Studies which have experimentally applied climate change treatments to ecological communities were reviewed using Web of Science (accessed 1/7/2012 to 1/11/2012, using the keywords climate change with; experiment or experimental or manipulation or warming). Studies which used natural gradients such as altitude and latitude were deliberately excluded, as they do not directly manipulate environmental conditions. We also excluded studies of single species, which includes a large body of literature from studies of adaptive capacity to evolutionary genetics. This resulted in 109 studies published between 2000 and 2012 (Supplementary Materials S1). Because there were relatively few freshwater studies, the literature review was extended for freshwaters only to include the time period 1995-2000. In total 65 studies were found from terrestrial environments, 23 from marine settings and 21 from freshwaters. Those studies were classified into a priori defined 'generations' of experiments, each of which treats temperature in different ways (Table A1.1).

Table A1.1. Review and classification into generations of community climate change experiments 2000 – 2012 (terrestrial and marine) and 1995-2012 (freshwater) which involved temperature manipulations (excluding other physical and chemical manipulations). For definitions of the 'generations' of studies see the main text. Number of studies (with percentages of the total in brackets following) are shown. Individual papers are shown in Supplementary Table S1.1.

Generation	Effects on mean	Effects on variability	Incorporates extreme events?	Number of studies found		
				Terrestrial	Marine	Freshwater
Fixed mean	Increase	Large reduction	No	3 (4.6%)	15 (65.2%)	5 (23.8%)
Fixed minima	Increase	Small reduction	No	7 (10.7%)	0 (0%)	0 (0%)
Fixed increment	Increase	No effect	Some	51 (78.5%)	8 (34.8%)	15 (71.4%)
Extreme event	Increase	Increase	Yes	4 (6.2%)	0 (0%)	1 (4.8%)

Generation One: Fixed mean experiments

Fixed mean experiments represent the simplest treatment possible and apply temperature treatments at a stable level over the length of the experiment. Most often these take the mean temperature of current conditions and add an increment to it to generate a new mean temperature, which is then applied as the treatment (compare Figure A1.1A to Figure A1.1B). Some of the studies listed in Table A1.1 (e.g. Beisner *et al.* 1996; Mitchell and Lampert 2000) compared fixed temperature treatments, others (e.g. Petchey *et al.* 1999; Fox and Morin, 2001) compared a constant to a warming treatment. These types of experiments underestimate the effects of climate change as they do not include the ‘event effect’ component in the treatment. The warming treatments in these experiments are also associated with a reduction in temperature variability, potentially confounding any results.

Generation Two: Fixed minima experiments

Fixed minima or maxima experiments have commonly been applied in warming experiments in the field. Experiments using substrate warmers inserted into the forest floor are an example of this type of approach (Melillo *et al.* 2002), as are experiments which re-radiate heat during the night to reduce night time minimum temperatures (e.g. Lloret *et al.* 2005). While able to prevent the coolest temperatures occurring, and have some warming effects on cool to moderate temperature days, they cannot affect the warmest days or generate high temperature extremes. Effectively, these treatments generate fixed minimum temperatures. The effect is to increase mean temperatures but to reduce variability, although not to the extent of fixed mean experiments (Figure A1.1C). It does not appear that this approach has been applied in freshwater systems to date, although addition of fixed amounts of warm water to a stream would have this effect.

Generation Three: Increment studies

Although more challenging to apply than traditional warming studies, increment studies apply a temperature treatment while retaining natural variability in temperature. Most often, these treatments are applied as a fixed increment (for example +3.5 degree Celsius) over natural conditions. These experiments have the advantage that they incorporate many of the natural features of weather, for example, one warmer than average day is more likely to follow another than it is to follow a colder than average day. Overall, these studies increase mean temperatures while retaining the variability which is typical of current climates (Figure A1.1D). For example, Yvon-Durocher *et al.* (2010) used twenty mesocosms in southern England and warmed ten of these by 3-5 degrees Celsius above ambient conditions. These types of experiments cannot incorporate features such as predicted climates where, for example, winter becomes warmer but spring becomes cooler. Nor do these kinds of experiments take into account changes in the climate variability. As such, they may underestimate the effects of climate change in some systems.

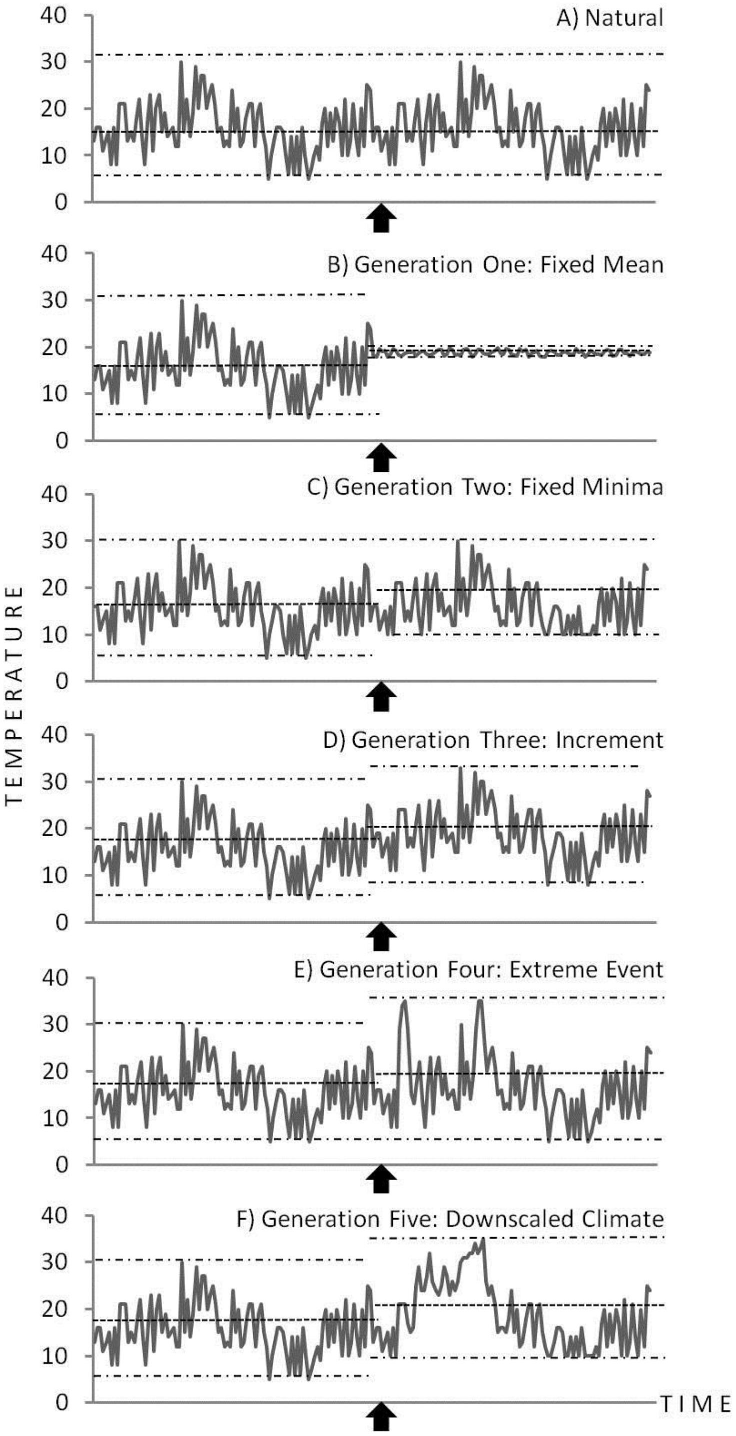

Figure A1.1. Conceptual diagram of generations of temperature treatments used in climate change experiments. A) baseline temperature (natural or current scenario), B) fixed mean (temperature set to a fixed value), C) fixed minima (temperature has a fixed minimum), D) increment (fixed increment is applied to natural variability), E) extreme event (extreme event is superimposed on natural variability), F) downscaled climate model (temperature is determined by weather scenarios generated from down-scaled climate model). Dashed lines indicate maximum, mean, and minimum temperatures. The black arrow indicates when experimental treatments are applied.

Generation Four: Extreme event studies

The most recent examples of climate change studies explicitly include extreme events in some fashion. In terrestrial studies, experimental enclosures have been exposed to drought, night heat waves, and extreme rainfall scenarios in order to assess effects on primary productivity (e.g. Fay *et al.* 2000; Beier *et al.* 2004). These approaches do not seem to have been applied in freshwater studies of the effects of temperature. Dang *et al.* (2009) applied an increased diel temperature variation to stream mesocosms and assessed impacts on detrital decomposition, but this experiment exposed the system to a cyclic series of extreme events rather than periodic events. A number of freshwater studies have assessed the effects of drying as an extreme event, (Leberfinger *et al.* 2010; Ledger *et al.* 2011) but none to date have considered extreme temperature events such as heatwaves explicitly, as shown in Figure A1.1E. Extreme event studies increase means and variability in temperatures, but do not replicate changes in the timing or duration of extreme events.

Part Two: Comparing approaches across ecosystems

Terrestrial ecosystems

Terrestrial studies are by far the most common in the literature, with 60% of reviewed studies being terrestrial, despite the shorter time period which was considered for the literature review. Climate change experiments in terrestrial settings have tended to consider the effects of not only temperature but also rainfall and increased atmospheric CO_2 concentrations (the latter two are not considered in this review). Smaller scale experiments in terrestrial settings have utilised chambers and have applied temperature treatments as both fixed means and fixed increments. Larger scale terrestrial experiments utilising substrate warmers, in particular, were a feature of early high-profile climate change research (Melillo *et al.* 2002). These approaches logistically lend themselves to fixed increment treatments, and these predominate in the published terrestrial climate change literature (Table A1.1). While there has been recognition for some years of the need to incorporate extreme events into studies of climate change impacts on terrestrial ecosystems (Jentsch *et al.* 2007), these continue to be the exception in studies of the effects of temperature (Table A1.1). That said, a number of recent studies have explored the impacts of extreme heat events either in isolation, or in combination with other stressors (Bjerke *et al.* 2011; Van Peer *et al.* 2004). Combined treatments are particularly relevant to terrestrial systems, where high temperatures are strongly associated with reduced rainfall, and for plant communities, where high rainfall can mitigate impacts of high temperatures (Van Peer *et al.* 2004).

Marine ecosystems

Studies of the effects of climate change-induced changes in temperature on marine communities remain relatively rare, in part because of the logistic difficulties of applying treatments at large scales. Marine climate change studies have included an emphasis on the effects of CO_2 and acidification, as key impacts on coral reefs (Hoegh-Guldberg *et al.* 2011) and pelagic primary producers (Beardall *et al.* 2009). The majority of experimental studies of the impacts of increased temperatures have either been fixed mean studies or fixed increment studies (Table A1.1). For the majority of marine systems this may make sense, as the high thermal mass of the oceans means that warming will tend to occur relatively slowly (days to weeks), making oceanic systems more tolerant of short term (days) spikes in atmospheric temperatures. While extreme events may be proportionally less important in terms of temperature impacts in marine settings, there are clearly described impacts of relatively short term (weeks) warming episodes on coral reefs (Baker *et al.* 2008). It may be that the emphasis on field studies of climate change impacts, and the difficulties of carrying out scalable experiments on these systems has led to the relative paucity of experimental warming studies on marine communities.

Freshwater ecosystems

In freshwater systems, a number of recent reviews have discussed the potential impacts of climate change at scales from regional (e.g. Heino *et al.* 2009; Johnson *et al.* 2009; Fenoglio *et al.* 2010; Morrongiello *et al.* 2011) to global (e.g. Ficke *et al.* 2007; Perkins *et al.* 2010; Woodward *et al.* 2010a). Freshwater systems are particularly vulnerable to changing climates as they are often highly range-restricted, and are subject to competition for water resources with human uses (Hobday and Lough 2011). Effects of extreme events in freshwater occur in two main areas. The first is via extreme heat events, which in aquatic systems also have consequences for the availability of oxygen and concentrations of toxicants (Ficke *et al.* 2007). Secondly, extreme rainfall events can have major effects on disturbance regimes via changed hydrology (Ficke *et al.* 2007). These effects become more complex in areas where seasonality of rainfall is predicted to change under climate change scenarios, or where changes in human water demands further impact water availability (Kundzewicz *et al.* 2008).

Direct effects of increased stream temperatures are predicted to have major implications for the distribution of cold water fish, particularly salmonids (Meisner 1990; Bryant 2009). Ecosystem consequences of altered climate are predicted to include changes in palatability of food resources (van de Waal *et al.* 2010; Sardans *et al.* 2012) and size spectra of animals (Yvon-Durocher *et al.* 2011) resulting in altered food web structure (Woodward *et al.* 2010a). These studies by-and-large have been based on field studies or are conceptual in nature, although in recent years there has been a small number of experimental studies (e.g. Yvon-Durocher *et al.* 2011; Dossena *et al.* 2012). The studies have predominantly considered temperature effects as either increases to a fixed mean or fixed increment studies (Table A1.1). In larger water bodies, the high thermal mass of aquatic systems may make them less vulnerable to short-term heat extremes, but in many shallow waterbodies, short term heat waves may have profound effects (Dokulil *et al.* 2010). The most recent climate change experiments in freshwaters have included extreme events as one-off or recurring events (Leberfinger *et al.* 2010; Ledger *et al.* 2011). These studies have shown that extreme events can greatly alter ecosystem functioning and food web structure in freshwaters.

Part Three: Using down-scaled climate models to generate experimental climate change treatments

It is now possible to generate experimental treatments which are based on the predictions of global climate change models for large scale climate phenomena, but down-scaled to generate hourly weather scenarios. Two types of approaches (dynamical and statistical) are normally used to take information from global climate models (GCMs) (~100km resolution) to be applied at higher resolutions that are more meaningful to local ecological scales (see Wilby and Wigley 1997, for a review). These approaches have been widely used in hydrology, but not directly in ecological experiments (Wilby and Dawson, 2012). Global climate models typically have coarse temporal (monthly) and spatial resolution and are most useful at these scales. Experimental treatments for ecological studies need predictions at relatively fine spatial and temporal scales. These need to incorporate increases in mean temperatures, but also increased variability and increased frequency of extreme events, such as heatwaves and extreme rainfall events, and more subtle impacts such as changes in cloud cover. For example in Figure A1.1F, prolonged extreme high temperature events ('heatwaves') appear in the treatment based on predictions from a GCM.

In our example, we sought to generate a climate change treatment to apply to indoor experimental stream flumes in order to assess climate change impacts on stream benthic communities. We wanted to compare responses to conditions representative of mid-summer over the last decade, to mid-summer conditions predicted to occur under a climate change scenario for 2100. The controllable variables in the flumes were temperature, rainfall (as flow velocity) and light intensity. We carried out the down-scaling process for one future time (2100) and one time of year (60 days in summer), using a single model and one emissions scenario (A1B scenario, predicting a year 2100 carbon dioxide concentration of 700ppm) (IPCC 2000). However, more complex experiments could generate treatments for other years, times of year or emissions scenarios. In addition, multimodel ensembles could be used to capture the uncertainty in climate predictions resulting from structural differences in the global climate models as well as uncertainty due to variations in initial conditions or model parameterisations (Semenov and Stratonovitch 2010). It is important that these weather time series are not averaged in a multiple ensemble as the resultant time series will lose its statistical variation. Rather the key here is to ultimately generate multiple weather time series treatments (ensembles) that are applied experimentally so that the ecological results are robustly replicated.

Our strategy was to use the information contained in a GCM output which projects how climate may evolve under future scenarios over the following centuries and apply that to the local scale. We then merged this data with statistical information from real historical observations and applied that to the changed climate from the GCM to a time series at daily resolution using a 'weather generator' (see below). Specifically in our case, we used the MIROC global climate model outputs available from the Center for Climate System Research (CCSR), University of Tokyo (http://www.ccsr.u-tokyo.ac.jp/) as the basis for our generation of the temperature treatment data. The model has a spatial resolution of 1.4 degree in longitude, 0.5-1.4 degree in latitude, and 43 vertical levels in the medium-resolution version. We chose this model because it has performed well for the Australian climate (Pitman and Perkins 2008). Data were extracted from the CMIP3 (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) archive which is a repository for climate models that were used in preparing the IPCC Fourth Assessment Report (http://www.ipcc.ch/). We extracted the air temperature variable (TASA1) from the run "sresb1atmmotasmiroc3_2medres" to demonstrate the method. This file was for the A1B scenario with a carbon dioxide concentration in the year 2100 of 700ppm. Further information on climate change scenarios can be found at www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf. We extracted data for the grid cell closest to Melbourne Airport, Australia (37.67 °S 144.83 °E) for the 21st century.

To generate weather data we entered the GCM data into the LARS-WG stochastic weather generator (http://www.rothamsted.ac.uk/mas-models/larswg.php) (Semenov *et al.* 1998). LARS-WG is a model simulating hourly time-series of daily weather at a single site, which can generate long time-series of weather conditions for a particular site, and includes extreme weather events, such as extreme daily precipitation and long dry spells or heat waves (Semenov *et al.* 1998). LARS-WG has been well validated in diverse climates around the world (Semenov *et al.* 1998). It utilises semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation. The seasonal cycles of means and standard deviations are modelled by finite Fourier series of order 3 and the residuals are approximated by a normal distribution (http://www.rothamsted.ac.uk/mas-models/download/LARS-WG-Manual.pdf).

We used the following methodology as per Semenov and Stratonovitch (2010).

1. Model Calibration – Observed weather data from Melbourne airport (Australian Bureau of Meteorology s**ite number:** 086282, e**levation:** 113 m, period: 1990 – 2009) were analysed to determine the local statistical characteristics of air temperature. This information is stored in two parameter files.

2. Model Validation - the statistical characteristics of the observed and synthetic weather data were analysed to determine if there are any statistically-significant differences (none found).

3. Generation of Synthetic Weather Data - the parameter files derived from observed weather data during the model calibration process were used to generate synthetic weather data having the same statistical characteristics as the original observed data, but differing on a day-to-day basis. We applied our global climate model-derived changes in temperature to the LARS-WG parameter files to generate daily weather for 2090-2100.

4. Experimental series – A series of weather (20 years long) is generated based on the changes in global climate (2090-2100) and the Jan/Feb period for the 10th year was extracted for use in driving the experimental treatments (Figure 1.2). Data were similarly generated for the control period (1990-2010). Probability distribution functions for distributions of minimum and maximum temperatures were generated for 2100 (generated by the simulation) and based on combined data for real weather data from the same region 1990-2000 (Figure A1.2). Because we needed to generate water temperature data (rather than the air temperature data generated by the model), a long-run series of historical water temperatures for the study site were used with historical air temperature data from the Melbourne airport weather station to generate a relationship between air and water temperature. It is important to note that these kind of relationships are highly non-linear (Mohseni *et al.* 1998) and may be relatively site specific depending on local riparian vegetation and interactions with groundwater, amongst other factors. As such, experiments which seek to assess impacts on particular freshwater sites will require detailed historical water temperature data.

It should be noted that a stochastic weather generator is not a predictive tool that can be used in weather forecasting, but is simply a means of generating time-series of synthetic weather statistically ‘identical’ to the observations. The resulting scenarios can be used as experimental treatments to be compared to controls resulting from ambient conditions or to treatments based on historical weather conditions. We used the variance of the ‘real’ historical data and applied that to the climate scenario to generate a weather series. Here we generated a single run, as generating repeated simulations then averaging results will remove extreme events from the data.

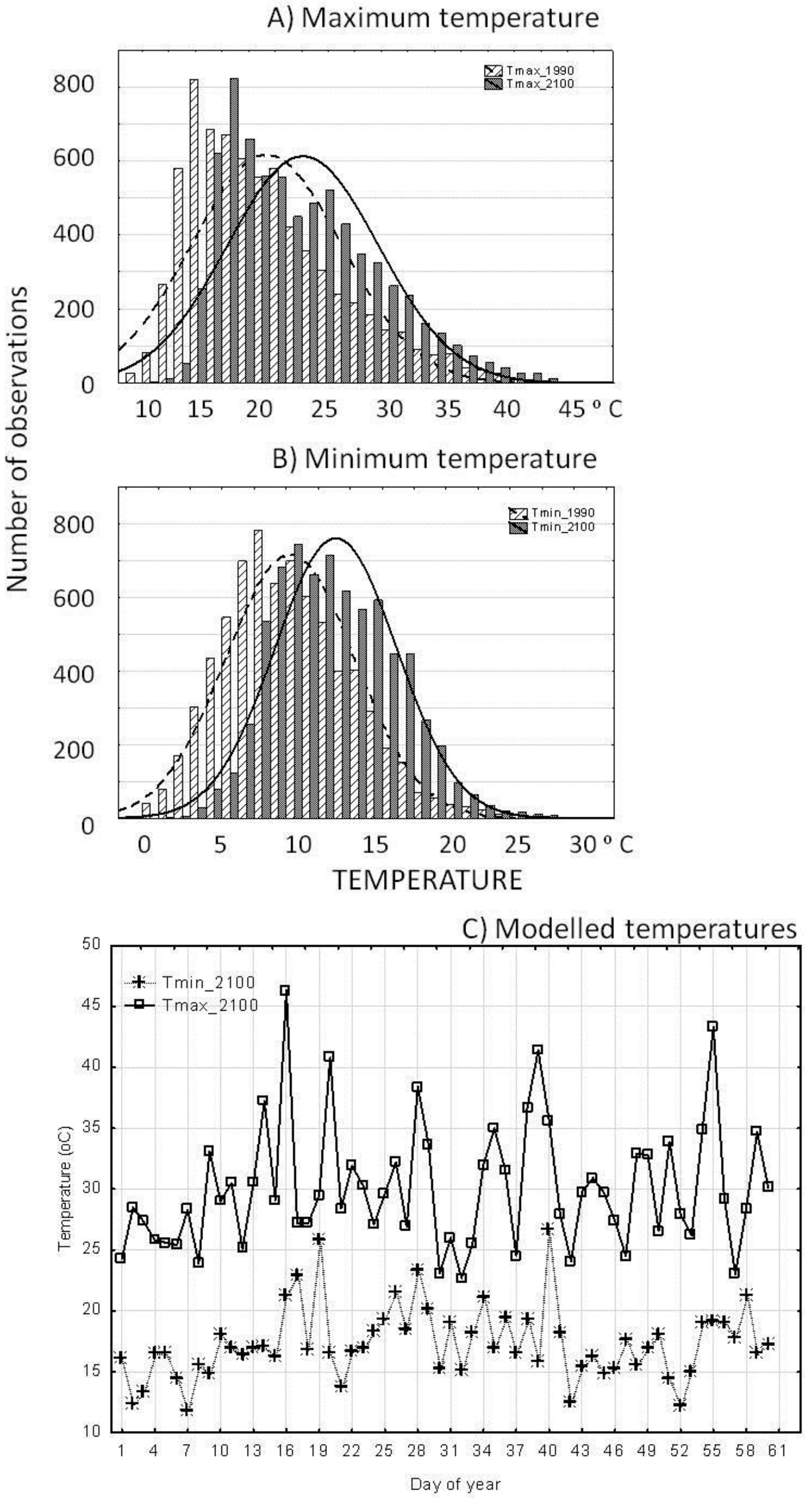

Figure A1.2: Example of the potential to downscale climate models to generate climate change treatments. Probability distribution functions illustrate the shifts in the actual and expected distributions of A) maximum and B) minimum temperatures for the decade 1990-2000 (based on real data, white striped bars) and 2100 (based on weather simulations from the climate model; grey bars). C) Modelled temperature series for the first 60 Julian days of 2100.

This kind of experimental data allows the application of highly realistic treatments in experiments that include not only changes in mean conditions, but also increased frequency, intensity and duration of extreme events. None-the-less, they are challenging to apply outside of highly controlled laboratory conditions. In outdoor conditions increment studies can superimpose a warming treatment on the background conditions (e.g. Yvon-Durocher *et al.* 2010; Dossena *et al.* 2012). With simulated weather, there is the potential that a temperature treatment for a particular day may be cooler than ambient conditions, or may be considerably higher than ambient conditions. Both situations require highly energy intensive equipment to apply the treatments. While it is possible to apply simulated weather as a treatment in an outside experiment, the approach described in the current paper is most amenable to highly controlled laboratory settings. This has the additional advantage that it is possible to carry out factorial designs which incorporate other stressors, which has been identified as an important new challenge in climate change experiments (Wernberg *et al.* 2012). These experiments will require stringent attention to issues of experimental design (Jentsch *et al.* 2007; Wernberg *et al.* 2012) but have the potential to generate a much greater understanding of the interactive impacts of changing climate with other stressors.

There is a need to consider the degree to which these kind of highly-controlled experiments can be scaled to large-scale real-world conditions. Previous small-scale studies have also tended to concentrate on single species, so when experimental results have not scaled to field outcomes, it is difficult to determine which of these two factors is responsible (Wernberg *et al.* 2012, Wolkovich *et al.* 2012). In plant studies, it appears that small scale experiments may not scale up to large scales because they fail to incorporate complex community-level interactions and therefore underestimate warming impacts (Wolkovich *et al.* 2012). It is important to recognise the limitations of such small-scale experiments (Carpenter 1996; Underwood *et al.* 2005). The spatial scale of experiments has been shown to affect the magnitude of responses to treatments in a number of different systems (see Englund and Cooper 2003 for a review). In particular, open systems that are strongly reliant on landscape-scale processes such as metapopulation dynamics may respond differently to changing climate than do systems where local processes predominate (Underwood *et al.* 2005). Manipulations at relatively small scales are likely to be the only way to explore impacts of climate change in a way which incorporates all of the features of predicated future climates (Englund and Cooper 2003). We propose that a suite of approaches including laboratory experiments, use of extreme events within traditional experimental increment studies and field studies of extreme events will be needed to gain a thorough understanding of the likely effects of future climates. Increasingly, frameworks are being suggested for how best to integrate across this suite of data (Denny and Benedetti-Cecchi, 2012).

CONCLUSION

The majority of studies have concentrated on increases in mean temperatures, but there is an increasing awareness that extreme climatic events are likely to be the dominant force structuring ecological communities (Lloret *et al.* 2012). The need to include extreme events in climate change experiments has been well recognised over the last decade (e.g. Easterling *et al.* 2000; Jentsch *et al.* 2007). However, in climate change experiments in community ecology, the vast majority of studies have applied set increments to ambient conditions as experimental treatments in warming studies, which can be viewed as an early generation approach. This may effectively mimic effects of climate change on mean temperatures, but does not incorporate predicted changes in the frequency, intensity, and duration of extreme events.

We have concentrated here on the effects of warming, however, some of the insights we present will also apply to studies which manipulate other factors such as precipitation. Modelling for rainfall is much more difficult, but increased extreme rainfall events are projected for many regions, including south eastern Australia (Hobday and Lough 2011). Interactions between different types of climate responses (e.g., temperature and precipitation) are particularly problematic, as many climate change scenarios predict changes in the synchronicity of these events. In south eastern Australia for instance, models predict increases in the frequency of summer high rainfall events (where winter rainfall has historically been more common) and increases in extreme summer temperatures (Hobday and Lough 2011). Incorporating these interactions into climate change experiments will require the kind of down-scaling and weather scenario generation illustrated in Part Three.

It remains a challenge to incorporate the uncertainties involved with climate model projections into experimental biological impacts research. Uncertainties in projections arise due to model processes (e.g., radiation and carbon cycle effects), differences between models (each climate group has their own model), and lack of certainty around projected emissions pathways/scenarios (Reichler and Kim 2008). These uncertainties should be taken into account by considering the distribution of possible outcomes (Semenov and Stratonovitch 2010) and ideally an experimental design that uses an ensemble of ecological treatments rather than a single realisation as demonstrated here. This is particularly important given the emerging understanding of the complexities of responses to climatic extremes and how they interact with changes in mean conditions and past history of exposure to extremes (Benedetti-Cecchi *et al.* 2006; Pincebourde *et al.* 2012).

We have illustrated here a means to use large-scale climate models to generate realistic climate change treatments for experiments. Understanding complex community and ecosystem-level responses to climate is essential (Van der Putten *et al.* 2010) and is only feasible through the use of manipulative experiments. These must be considered in a framework that includes information on evolutionary potential, spatial processes, and long term feedbacks (Dawson *et al.* 2011), but experiments are none-the-less an essential part of understanding the mechanistic basis for responses to climate. While the existing experiments have been highly informative, they have failed to incorporate meaningful patterns of climatic variability as predicted by climate models. Applying meaningful experimental treatments is a core part of this enterprise, and this review clearly shows that we need to move to a next generation of climate-change experiments in community ecology.

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S1.1 Supplementary Materials. Experimental climate change studies carried out for terrestrial (2000-2012, n=64), freshwater (1995-2012, n= 21) and marine (2000-2012, n=23) communities. Study systems and durations of experiments are shown. Studies are divided into 'generations' based on their approach to applying climate change treatments (see text for details and Table 1.1 for a summary).

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
Terrestial	Fixed mean	(Breeuwer *et al.* 2008)	Sphagnum species	154
Terrestial	Fixed mean	(Eisenhauer *et al.* 2012)	Earthworms	36
Terrestial	Fixed mean	(Biddanda *et al.* 2001; Hofstetter *et al.* 2007)	Fungi, mites, and pine beetle community	35
Terrestial	Fixed minima	(Lloret *et al.* 2009)	Mediterranean shrubland	2555
Terrestial	Fixed minima	(Bakonyi *et al.* 2007)	Soil nematode community	1095
Terrestial	Fixed minima	(Lloret *et al.* 2005)	Mediterranean shrubland	1460
Terrestial	Fixed minima	(Lloret *et al.* 2004)	Mediterranean shrubland	1460
Terrestial	Fixed minima	(Peñuelas *et al.* 2004)	North and South European plants	730
Terrestial	Fixed minima	(Wessel *et al.* 2004)	Shrublands	730
Terrestrial	Fixed minima	(Melillo *et al.* 2002)	Hardwood forest	3650
Terrestial	Fixed increment	(Cavieres and Sierra-Almeida 2012)	Alpine grass	730
Terrestial	Fixed increment	(Büscher *et al.* 2012)	Grassland	730

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
Terrestial	Fixed increment	(Grau *et al.* 2012)	Sub-Arctic forest-tundra ecotone	1095
Terrestial	Fixed increment	(Hoeppner and Dukes 2012)	Old-field herbaceous community	730
Terrestial	Fixed increment	(Natali *et al.* 2012)	Tundra plant communities	730
Terrestial	Fixed increment	(Dawes *et al.* 2011)	Alpine dwarf shrubs	1095
Terrestial	Fixed increment	(Xinwei *et al.* 2011)	Alpine meadow	90
Terrestial	Fixed increment	(Keuper *et al.* 2011)	Northern peatland	2920
Terrestial	Fixed increment	(Morgan *et al.* 2011)	Semi-arid grasslands	1095
Terrestial	Fixed increment	(Bai *et al.* 2010)	Semi-arid temperate steppe	730
Terrestial	Fixed increment	(Bloor *et al.* 2010)	Upland grassland ecosystem	730
Terrestial	Fixed increment	(Kardol *et al.* 2010)	Old-field ecosystem	730
Terrestial	Fixed increment	(Morin *et al.* 2010)	Oak species	1095
Terrestial	Fixed increment	(Barton and Schmitz 2009)	Grassland food-web	75
Terrestial	Fixed increment	(Barton *et al.* 2009)	Old-field food web	100
Terrestial	Fixed increment	(Briones *et al.* 2009)	Temperate grassland communities	730
Terrestial	Fixed increment	(Day *et al.* 2009)	Vascular-plant dominated Antarctic tundra	730
Terrestial	Fixed increment	(Engel *et al.* 2009)	Old-field community	1095

Ecosystem	Generation classifying study type	Reference/s	System studied	Length of experiment (days)
Terrestial	Fixed increment	(Rinnan *et al.* 2009)	Subartic heath	3650-4745
Terrestial	Fixed increment	(Villalpando *et al.* 2009)	Old-field insect community	730
Terrestial	Fixed increment	(Biasi *et al.* 2008)	Lichen-rich dwarf shrub tundra	730
Terrestial	Fixed increment	(Day *et al.* 2008)	Vascular-plant dominated Antarctic tundra	1460
Terrestial	Fixed increment	(De Boeck *et al.* 2008)	Grassland communities	1095
Terrestial	Fixed increment	(Grime *et al.* 2008)	Limestone grasslands	4745
Terrestial	Fixed increment	(Sherry *et al.* 2008)	Old-field tallgrass prairie	1460
Terrestial	Fixed increment	(De Boeck *et al.* 2007)	Grassland communities	365
Terrestial	Fixed increment	(Peñuelas *et al.* 2007)	Shrublands	2555
Terrestial	Fixed increment	(Williams *et al.* 2007)	Grassland	1095
Terrestial	Fixed increment	(Aerts *et al.* 2006)	Sub-arctic bog species	1095
Terrestial	Fixed increment	(De Dato *et al.* 2008)	Mediterranean shrublands	1095
Terrestial	Fixed increment	(Walker *et al.*, 2006)	Arctic tundra	2190
Terrestial	Fixed increment	(Bates *et al.* 2005)	Limestone grasslands	2555
Terrestial	Fixed increment	(Dukes *et al.* 2005)	California grassland	1825
Terrestial	Fixed increment	(Hollister *et al.* 2005)	Arctic tundra	1825-2555
Terrestial	Fixed	(Klanderud and Ørjan	Alpine plants	1460

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
	increment	2005)		
Terrestial	Fixed increment	(Aerts *et al.* 2004)	Sub-arctic bog species	730
Terrestial	Fixed increment	(Gunnarsson *et al.* 2004)	Boreal mire	1460
Terrestial	Fixed increment	(Klein *et al.* 2004)	Meadows and shrublands	1460
Terrestial	Fixed increment	(Boelman *et al.* 2003)	Tundra	4745
Terrestial	Fixed increment	(Dunne *et al.* 2003)	Subalpine meadow	1095
Terrestial	Fixed increment	(Kudo and Suzuki 2003)	Alpine shrubs	1825
Terrestial	Fixed increment	(Van Wijk *et al.* 2003)	Arctic and subarctic ecosystems	at least 1095
Terrestial	Fixed increment	(Zavaleta *et al.* 2003)	Grassland	1095
Terrestial	Fixed increment	(Richardson *et al.* 2002)	Sub-Arctic dwarf shrub heath community	3285
Terrestial	Fixed increment	(Shaw *et al.* 2002)	Grassland	1095
Terrestial	Fixed increment	(De Valpine and Harte 2001)	Montane meadow	2555
Terrestial	Fixed increment	(Graglia *et al.* 2001)	Sub-Arctic, alpine dwarf shrub heaths	1095-3650
Terrestial	Fixed increment	(Rustad *et al.* 2001)	High and low tundra, grassland, and forest	730-3285
Terrestial	Fixed increment	(Bakonyi and Nagy 2000)	Nematode community	120
Terrestial	Fixed increment	(Grime 2000)	Limestone grasslands	1825

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
Terrestial	Fixed increment	(Weltzin *et al.* 2000)	Wetlands	1460
Terrestrial	Extreme event	(Beier *et al.* 2004)	Grasslands	90-150
Terrestial	Extreme event	(Bjerke *et al.* 2011)	Sub-Arctic heathland bryophytes and lichens	1095
Terrestial	Extreme event	(Van Peer *et al.* 2004)	Grasslands	14
Terrestial	Extreme event	(Dodds *et al.* 2000)	Grasslands	0.3
Marine	Fixed mean	(Aberle *et al.* 2007)	Ciliate communities	120
Marine	Fixed mean	(Connell and Russell 2010)	Kelp forests and non-calcareous algae	98
Marine	Fixed mean	(Fu *et al.* 2007)	cyanobacteria	14
Marine	Fixed mean	(Gaedke *et al.* 2010)	Phytoplankton	120
Marine	Fixed mean	(Höffle *et al.* 2012)	Seagrasss, drift algae, and snails	28
Marine	Fixed mean	(Holmer *et al.* 2010)	Seagrass and drift algae	35
Marine	Fixed mean	(Hoppe *et al.* 2008)	Phytoplankton and bacteria	90
Marine	Fixed mean	(Kjellerup *et al.* 2012)	Copepod	14
Marine	Fixed mean	(Lewandowska and Sommer 2010)	Phytoplankton and mesozooplankton	120
Marine	Fixed mean	(Lionard *et al.* 2012)	Phytoplanton	9
Marine	Fixed mean	(Sommer and Lengfellner 2008)	Baltic sea phyto- and zooplankton	120
Marine	Fixed mean	(Sommer and Lewandowska 2011)	Phytoplankton and zooplankton	38

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
Marine	Fixed mean	(Sommer *et al.* 2007)	Baltic sea phyto- and zooplankton	120
Marine	Fixed mean	(Thyssen *et al.* 2011)	Phytoplankton	8
Marine	Fixed mean	(Veiga *et al.* 2011)	Crabs and mussels	2
Marine	Fixed increment	(Eklof *et al.* 2012)	Seagrass mesocosms	35
Marine	Fixed increment	(Eriksson Wiklund *et al.* 2009)	Pelagic food web	60
Marine	Fixed increment	(Hare *et al.* 2007)	Bering Sea phytoplankton	9-10
Marine	Fixed increment	(Klauschies *et al.* 2012)	Baltic Sea phytoplankton	35-84
Marine	Fixed increment	(O'Connor 2009)	Marine macroalga-amphipod	11, 14, and 17
Marine	Fixed increment	(O'Connor *et al.* 2009)	Phytoplankton and zooplankton	8
Marine	Fixed increment	(Smale and Wernberg 2012)	Sessile assemblage	>21
Marine	Fixed increment	(Morelissen and Harley 2007)	Intertidal community	150
Freshwater	Fixed mean	(Beisner *et al.* 1996, 1997)	Temperate lakes	150
Freshwater	Fixed mean	(Petchey *et al.* 1999)	Laboratory culture bottles	49
Freshwater	Fixed mean	(Fox and Morin 2001)	Pond protists	40
Freshwater	Fixed mean	(Heide *et al.* 2006)	Duckweed-moth system	2
Freshwater	Fixed mean	(Domis *et al.* 2007)	Temperate lakes	61

Ecosystem	**Generation classifying study type**	**Reference/s**	**System studied**	**Length of experiment (days)**
Freshwater	Fixed increment	(Hogg *et al.* 1995)	First-order streams	730
Freshwater	Fixed increment	(Hogg and Williams 1996)	First-order streams	730
Freshwater	Fixed increment	(McKee *et al.* 2002a; McKee *et al.* 2002b; McKee *et al.* 2003)	Shallow lakes	730
Freshwater	Fixed increment	(Moss *et al.* 2003)	Shallow lakes	730
Freshwater	Fixed increment	(Strecker *et al.* 2004)	Alpine ponds	50
Freshwater	Fixed increment	(Baulch *et al.* 2005)	Boreal lake	56
Freshwater	Fixed increment	(Christoffersen *et al.* 2006)	Shallow lakes	480
Freshwater	Fixed increment	(Feuchtmayr *et al.* 2007)	Shallow lakes	730
Freshwater	Fixed increment	(Barlocher *et al.* 2008)	First-order streams	425
Freshwater	Fixed increment	(Feuchtmayr *et al.* 2009)	Shallow lakes	240
Freshwater	Fixed increment	(Feuchtmayr *et al.* 2010)	Shallow lakes	150
Freshwater	Fixed increment	(Liboriussen *et al.* 2011)	Shallow lakes	365
Freshwater	Fixed increment	(Yvon-Durocher *et al.* 2011)	Mesocosms	850
Freshwater	Fixed increment	(Dossena *et al.* 2012)	Shallow lakes	180
Freshwater	Fixed increment	(Berger *et al.* 2007)	Temperate lakes	70
Freshwater	Extreme event	(Dang *et al.* 2009)	Streams	62-486

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APPENDIX 2: PRODUCTION AND ANALYSIS OF WEATHER FORCING FOR EXPERIMENTS

Summary

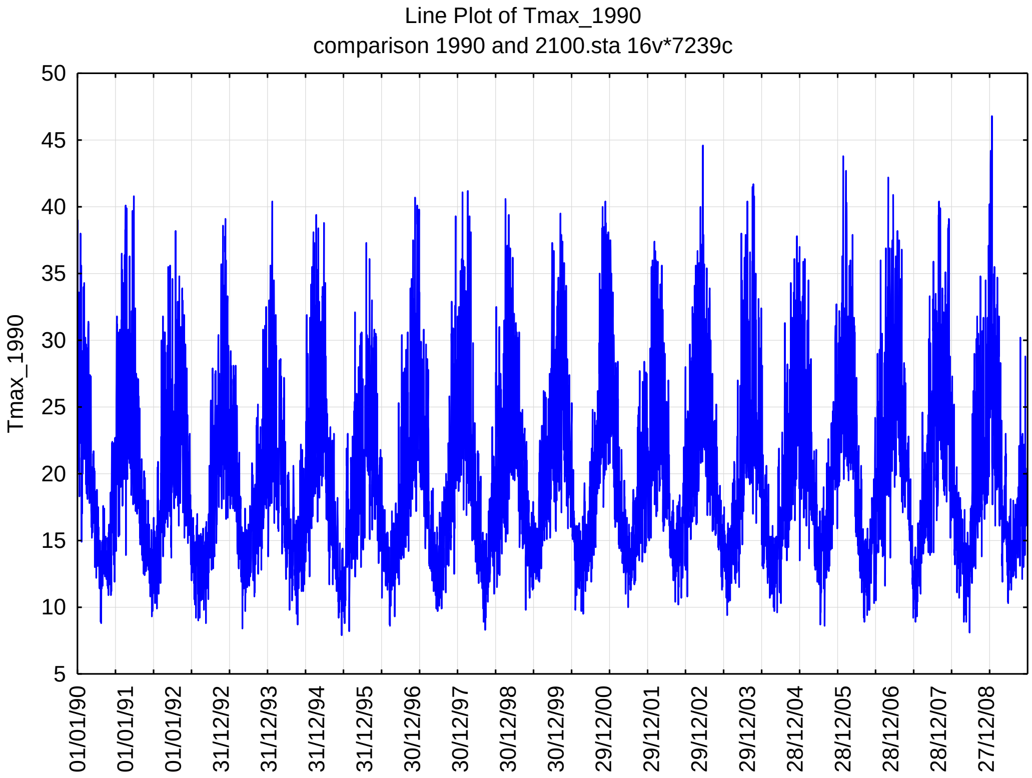
The aim of this work is to produce a time series of realistic temperature, CO_2 and sunlight ‘weather conditions’ for treatments to determine the vulnerability and adaptive capacity of critical aquatic processes to 2100 climate conditions. The majority of previous experimental studies of the effects of climate change have relied on very simple treatments of either warming to a stable temperature (therefore removing natural variability) or warming imposed on ambient conditions (thereby creating a set increase in temperature across all conditions, i.e. minimum temperatures are increased and maximum temperatures are increased; e.g. Ledger *et al.* 2011). Actual changes in weather (which drives ecosystems on a daily basis) will be a combination of background climate, climate changes trends and statistical variation in climate (such as increases in maximum temperatures and in the length of hot spells, and much small changes in minimum temperatures (CSIRO 2007)). These are not accounted for in most ecosystem studies. Here we generate a daily weather time series that has the statistical features (e.g. wet/dry and hot/cool spells) of the Historical climate for Melbourne (1990-2009) and has then applied the Miroc High resolution GCM projections for the A1B scenario superimposed. A series of weather is generated for a period of 20 years and the Jan/Feb period for the 10th year was extracted for use in driving the experimental treatments.

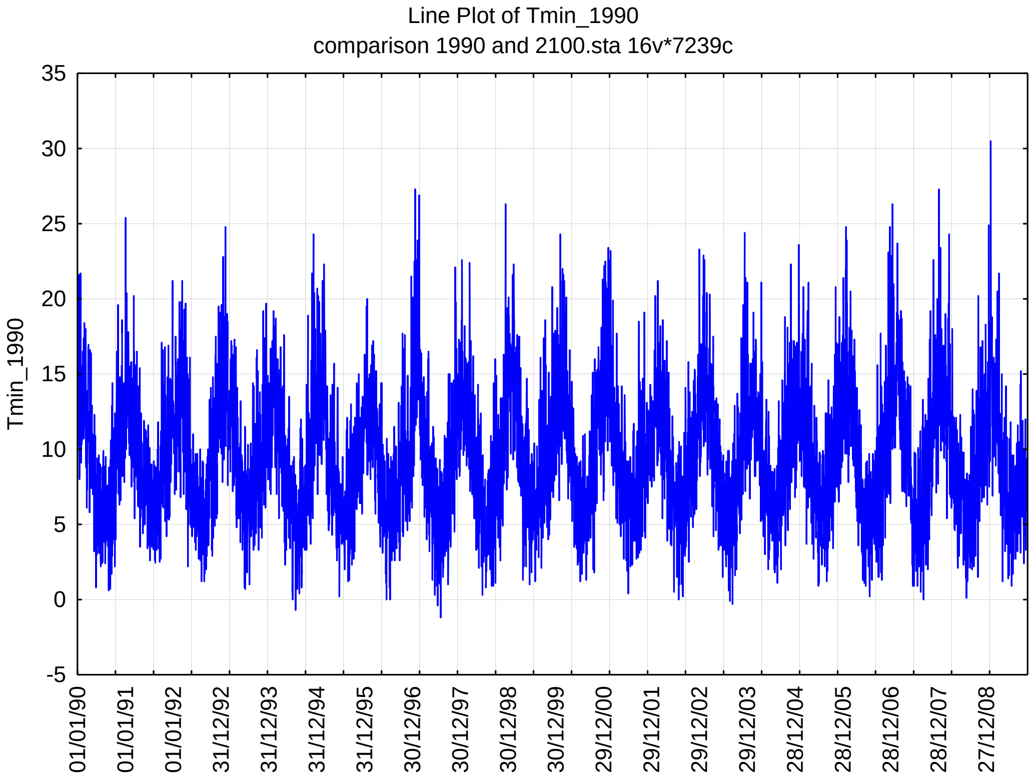
Meteorological data

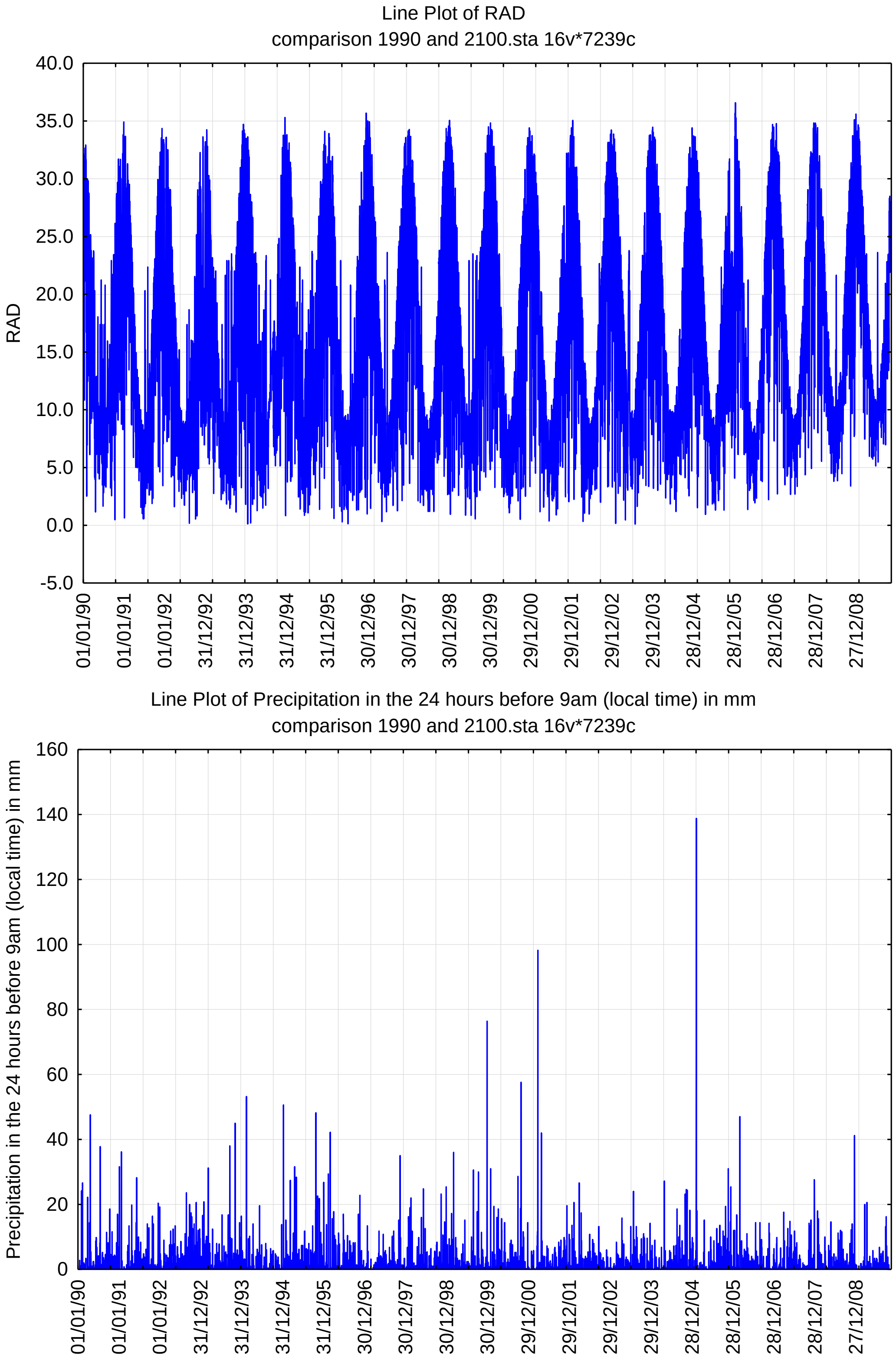
Historical meteorological data was extracted from the Bureau of meteorology archives for the Melbourne airport weather station 1990-2009 (Figure A2.1).

Time series of meteorological parameters from 1990 to 2009 are given below.

The statistical features of the climate from this data were calculated using the following (http://www.rothamsted.ac.uk/mas-models/larswg.php) and are given in Supplementary Materials S2.1.


Line Plot of Tmax_1990
comparison 1990 and 2100.sta 16v*7239c


Line Plot of Tmin_1990
comparison 1990 and 2100.sta 16v*7239c


Line Plot of RAD
comparison 1990 and 2100.sta 16v*7239c

Line Plot of Precipitation in the 24 hours before 9am (local time) in mm
comparison 1990 and 2100.sta 16v*7239c

Figure A2.1. Time series of historical data from Melbourne Airport 1990-2009

Climate change projections

We used the MIROC global climate model outputs from the Center for Climate System Research (CCSR), University of Tokyo (http://www.ccsr.u-tokyo.ac.jp/). From the technical manual “The Model for Interdisciplinary Research on Climate (MIROC), which is the coupled general circulation model used in the K-1 project, consists of five component models: atmosphere, land, river, sea ice, and ocean. The atmospheric component interacts with the land and sea ice components. The air-sea exchange is realized exclusively between the atmosphere and sea ice components, not directly between the atmosphere and ocean components, and the ocean component interacts only with the sea ice component. That is, air-sea flux at ice-free grids is consequently passed to the ocean component without modification, but it is first passed to the sea ice component. The river component receives ground runoff water from the land component and drains riverine runoff water into the sea ice component. Lakes are dealt with by the sea ice and ocean components.” (http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC/tech-repo.pdf).

We chose this model because it has performed well for the Australian climate (Pitman *et al.*)

Data was extracted from the CMIP3 (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) archive which is a repository for climate models that were used in preparing the IPCC fourth assessment report (http://www.ipcc.ch/). Data from CMIP4 was not yet available at the time of analysis.

We chose the A1B scenario to generate the weather time series for our experimental treatments. This scenario is a subset of the A1 storyline where “A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).” (http://www.ipcc.ch/ipccreports/tar/wg1/029.htm). Further information on climate change scenarios can be found at the IPC C Webb sought in a special report (www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

Carbon dioxide concentrations at 2100 under the A1B scenario are 700 ppm (Figure A2.2).

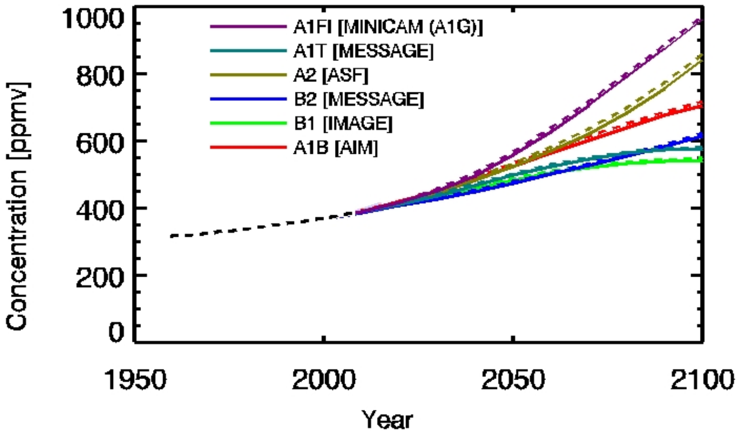


Figure A2.2: Atmospheric CO_2 concentrations as observed at Mauna Loa from 1958 to 2008 (black dashed line) and projected under the 6 SRES marker and illustrative scenarios. Two carbon cycle models (see Box 3.7 in IPCC, 2001) are used for each scenario: BERN (solid lines) and ISAM (dashed). http://www.ipcc-data.org/ddc_co2.html.

To generate weather data we utilised the excellent LARS-WG stochastic weather generator (http://www.rothamsted.ac.uk/mas-models/larswg.php). LARS-WG is a model simulating time-series of daily weather at a single site. It can be used to generate long time-series suitable for the assessment of agricultural and hydrological risk; to provide the means of extending the simulation of weather to unobserved locations; to serve as a computationally inexpensive tool to produce daily site-specific climate scenarios for impact assessments of climate change. It simulates extreme weather events, such as extreme daily precipitation and long dry spells or heat waves. LARS-WG has been well validated in diverse climates around the world (See references in Appendix 2). LARS-WG is based on the series weather generator described in Racsko *et al.* (1991). It utilises semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation. The seasonal cycles of means and standard deviations are modelled by finite Fourier series of order 3 and the residuals are approximated by a normal distribution. (http://www.rothamsted.ac.uk/mas-models/download/LARS-WG-Manual.pdf).

It should be noted that a stochastic weather generator is not a predictive tool that can be used in weather forecasting, but is simply a means of generating time-series of synthetic weather statistically ‘identical’ to the observations.

The following process was used to generate synthetic weather data (as per LARS-WG):

1. Model Calibration - SITE ANALYSIS - observed weather data are analysed to determine their statistical characteristics. This information is stored in two parameter files.
2. Model Validation - QTEST - the statistical characteristics of the observed and synthetic weather data are analysed to determine if there are any statistically-significant differences.
3. Generation of Synthetic Weather Data - GENERATOR - the parameter files derived from observed weather data during the model calibration process are

used to generate synthetic weather data having the same statistical characteristics as the original observed data, but differing on a day-to-day basis. Synthetic data corresponding to a particular climate change scenario may also be generated by applying global climate model-derived changes in precipitation, temperature and solar radiation to the LARS-WG parameter files.

Characteristics of the generated weather series are shown in Table A2.1. Probability distribution functions were generated to illustrate the shifts in the actual and expected distributions of min and max temperatures (Figure A2.3).

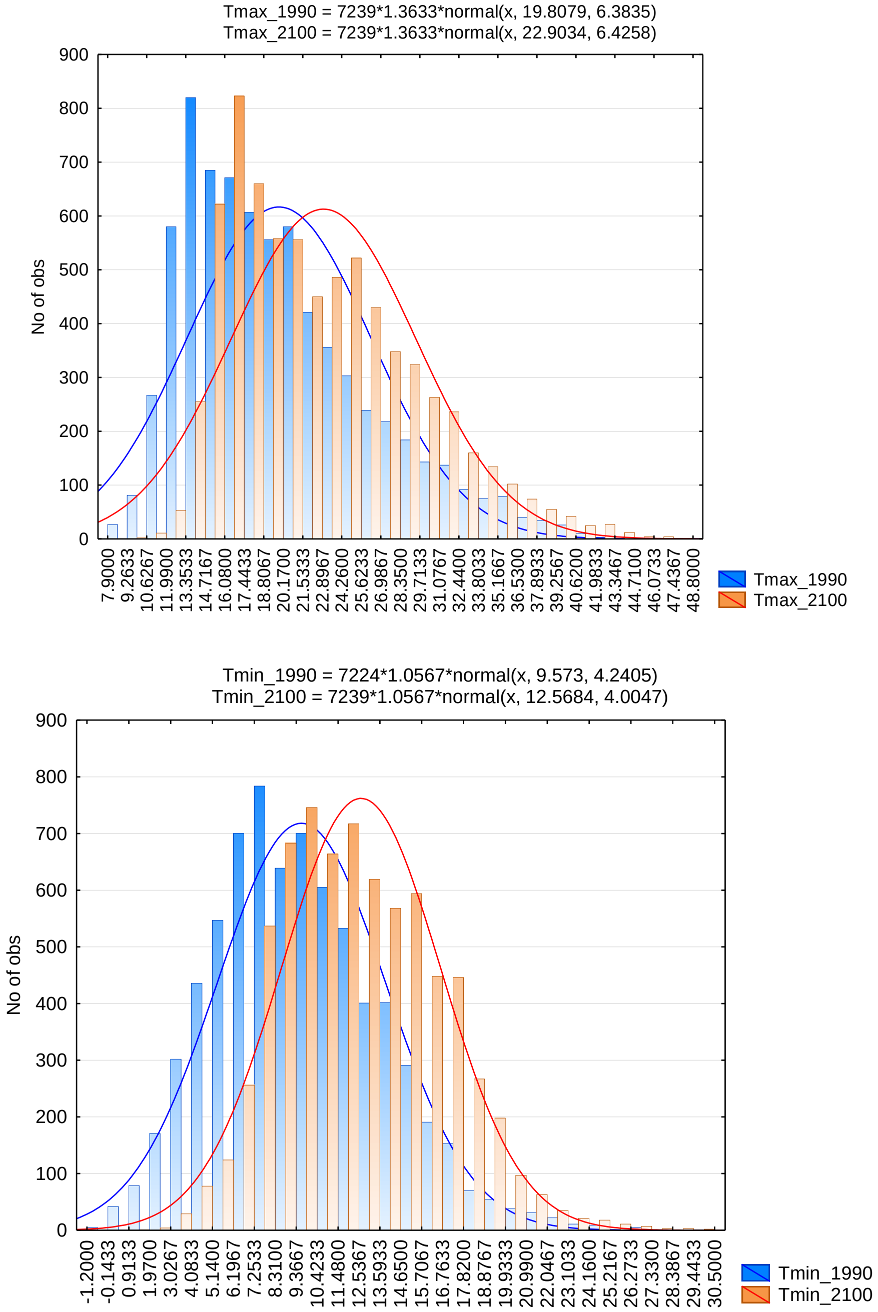


Figure A2.3: Probability distribution functions were generated to illustrate the shifts in the actual and expected distributions of min and max temperatures

Table A2.1: Statistics of the climate for historical (1990-2009) and generated weather statistics (2089-2100 under A1B).

Month	Tmin_2100 - Means	Tmin_2100 - Variance	Tmin_2100 – Minimum	Tmin_2100 - Maximum	Tmin_2100 - Q25	Tmin_2100 - Median	Tmin_2100 - Q75	Percentile - 5.000000	Percentile - 95.00000
1	17.11613	7.34410	11.20000	29.20000	15.30000	16.90000	18.80000	12.90000	21.50000
2	17.43186	7.70054	10.10000	29.70000	15.70000	17.20000	18.90000	13.20000	22.20000
3	15.68419	7.69590	7.70000	26.00000	14.00000	15.60000	17.35000	11.25000	20.70000
4	13.19567	6.60088	4.00000	22.00000	11.65000	13.20000	14.70000	9.00000	17.60000
5	11.05274	5.08062	3.80000	17.50000	9.70000	11.10000	12.50000	7.30000	14.85000
6	9.34233	4.83497	3.20000	16.30000	7.90000	9.50000	10.80000	5.45000	12.90000
7	8.48323	3.90805	1.30000	14.70000	7.40000	8.50000	9.70000	5.00000	11.70000
8	8.98903	3.97526	3.00000	15.10000	7.80000	8.90000	10.10000	5.40000	12.45000
9	10.10283	6.90528	2.50000	20.70000	8.30000	10.00000	11.50000	6.20000	14.90000
10	11.20602	8.67102	4.00000	22.20000	9.20000	11.10000	13.00000	6.60000	16.50000
11	13.14579	6.99630	6.30000	22.70000	11.60000	12.80000	14.70000	9.00000	17.80000
12	15.52190	9.51375	8.10000	29.90000	13.60000	15.20000	16.90000	11.40000	21.20000
All Grps	12.56837	16.03769	1.30000	29.90000	9.50000	12.20000	15.40000	6.80000	19.30000

Month	Tmin_1990 - Means	Tmin_1990 - Variance	Tmin_1990 - Minimum	Tmin_1990 - Maximum	Tmin_1990 - Q25	Tmin_1990 - Median	Tmin_1990 - Q75	Percentile - 5.000000	Percentile - 95.00000
1	13.94226	13.24687	6.30000	30.50000	11.40000	13.70000	15.90000	8.650000	20.70000
2	14.20602	11.43982	6.80000	26.90000	11.70000	14.00000	16.00000	9.400000	20.50000
3	12.48930	9.41414	3.70000	24.30000	10.40000	12.30000	14.50000	7.900000	17.90000
4	9.93050	10.51217	1.20000	21.70000	7.60000	9.70000	11.90000	5.100000	15.75000
5	8.28532	8.15586	0.80000	16.50000	6.30000	8.20000	10.10000	3.600000	13.25000
6	6.56833	7.13018	0.00000	14.10000	4.80000	6.75000	8.35000	2.000000	10.90000
7	5.71964	5.21287	-0.70000	11.50000	4.20000	5.80000	7.40000	1.800000	9.30000
8	5.98784	6.57467	-1.20000	13.30000	4.30000	5.90000	7.70000	1.800000	10.40000
9	7.17846	9.76842	-0.30000	18.50000	5.00000	7.00000	9.00000	2.600000	13.00000
10	8.62333	11.08303	1.30000	20.20000	6.20000	8.20000	10.70000	3.500000	14.40000
11	10.27825	11.20279	2.60000	22.60000	7.90000	9.85000	12.30000	5.400000	16.50000
12	12.06218	11.67707	5.20000	26.30000	9.70000	11.50000	13.80000	7.300000	18.60000
All Grps	9.57303	17.98178	-1.20000	30.50000	6.50000	9.20000	12.30000	3.300000	17.00000

Month	Tmax_2100 - Means	Tmax_2100 - Variance	Tmax_2100 - Minimum	Tmax_2100 - Maximum	Tmax_2100 - Q25	Tmax_2100 - Median	Tmax_2100 - Q75	Percentile - 5.000000	Percentile - 95.00000
1	30.16145	25.24434	21.20000	48.80000	26.30000	29.30000	33.05000	23.65000	40.30000
2	30.20566	27.54525	19.30000	45.40000	25.90000	29.60000	33.90000	23.20000	40.40000
3	27.49048	22.22752	18.30000	44.20000	24.00000	26.50000	30.50000	21.15000	36.20000
4	23.35233	13.78757	15.90000	35.60000	20.40000	22.60000	26.00000	18.50000	30.20000
5	19.00565	6.38561	13.90000	29.40000	17.30000	18.50000	20.50000	15.50000	23.80000
6	16.40783	3.43298	10.30000	24.20000	15.30000	16.25000	17.40000	13.65000	19.60000
7	15.79935	2.92724	10.90000	24.10000	14.70000	15.70000	16.85000	13.20000	18.75000
8	17.44323	4.61926	10.40000	27.30000	15.90000	17.20000	18.70000	14.50000	21.20000
9	19.51967	10.45314	13.10000	35.70000	17.00000	19.00000	21.40000	15.45000	25.40000
10	22.45561	17.26143	14.30000	38.00000	19.50000	21.70000	24.70000	17.00000	30.50000
11	25.02228	22.50079	15.70000	44.20000	21.50000	24.30000	27.90000	18.80000	33.70000
12	28.78183	25.46343	18.90000	46.80000	24.90000	27.60000	31.90000	22.40000	38.20000
All Grps	22.90338	41.29110	10.30000	48.80000	17.50000	21.80000	27.00000	14.90000	34.90000

Month	Tmax_1990 - Means	Tmax_1990 - Variance	Tmax_1990 - Minimum	Tmax_1990 - Maximum	Tmax_1990 - Q25	Tmax_1990 - Median	Tmax_1990 - Q75	Percentile - 5.000000	Percentile - 95.00000
1	26.49258	36.59070	13.90000	44.60000	21.80000	25.15000	30.30000	18.85000	37.95000
2	26.37257	35.98707	13.50000	46.80000	21.40000	25.40000	31.10000	18.40000	36.60000
3	24.05290	27.69897	14.20000	40.80000	19.95000	22.75000	27.70000	17.15000	33.75000
4	20.29467	17.39870	11.70000	34.50000	17.10000	19.60000	23.55000	14.60000	27.90000
5	16.61935	8.39497	9.80000	27.00000	14.50000	16.20000	18.40000	12.85000	22.15000
6	13.93983	4.38230	8.40000	21.80000	12.50000	13.80000	15.25000	10.80000	17.45000
7	13.27274	3.83879	7.90000	20.60000	12.00000	13.20000	14.50000	9.80000	16.60000
8	14.68177	6.70501	8.10000	24.60000	12.80000	14.40000	16.10000	11.05000	19.65000
9	16.84383	11.90290	8.20000	30.20000	14.30000	16.50000	18.85000	11.95000	23.05000
10	19.46732	21.16217	11.50000	36.00000	15.70000	18.60000	22.30000	13.60000	29.20000
11	21.98070	27.76504	11.60000	39.30000	17.90000	20.80000	25.30000	14.80000	31.60000
12	24.39168	35.10706	13.00000	43.80000	19.90000	23.10000	28.20000	16.60000	35.80000
All Grps	19.80793	40.74864	7.90000	46.80000	14.80000	18.60000	23.40000	11.90000	32.50000

A series of weather was generated for 20 years and the Jan/Feb period for the 10th year was extracted for use in driving the experimental treatments (Figure A2.4).

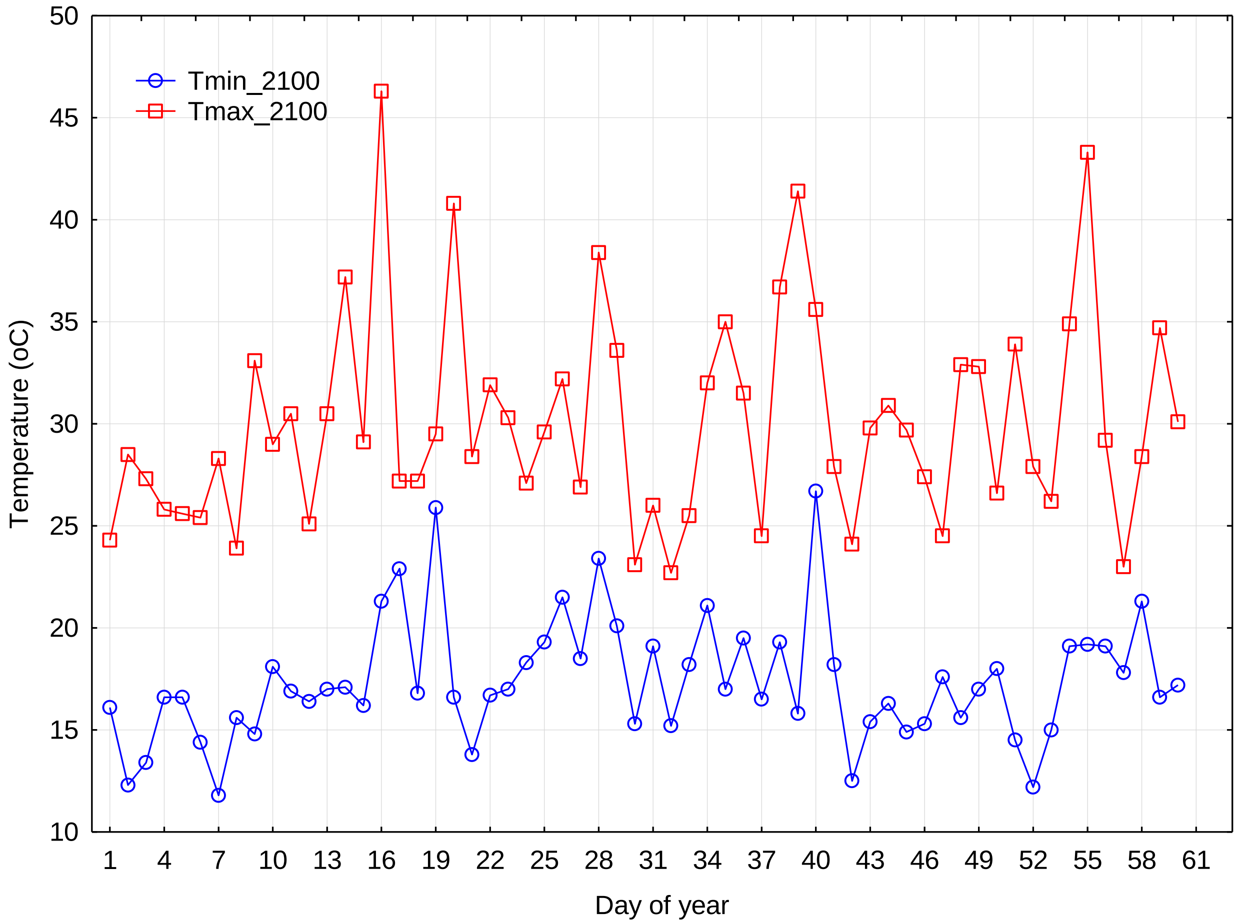


Figure A2.4: Time series of 'generated weather' for experimental treatments

SUPPLEMENTARY MATERIALS S2.1 – Statistical properties of Melbourne climate

Definitions of statistics and parameters are provided beneath

[NAME]

Melbourne

[LAT, LON and ALT]

-37.69 144.84 128.00

[YEARS]

1970 2009

[SERIES seasonal distributions: WET and DRY]

```
[DJF]

        518     23      1.90    1.30    2.27    1.17

        0.000   0.521   0.774   0.784   0.794   0.803   0.813   0.823   0.832   0.842   0.852
        0.861   0.871   0.881   0.891   0.900   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        3.00    3.00    3.00    3.00    3.00    4.00    4.00    5.00    6.00    7.00    8.00
        9.00    9.00

        517     23      4.98    4.32    5.02    4.12

        0.000   0.190   0.315   0.358   0.400   0.443   0.485   0.528   0.570   0.613   0.655
        0.698   0.740   0.783   0.825   0.868   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    1.00    3.00    3.00    3.00    3.00    4.00    4.00    4.00    5.00    5.00
        6.00    6.00    7.00    8.00    9.00    11.00   12.00   15.00   18.00   21.00   24.00
        30.00   30.00

[MAM]

        614     23      2.09    1.49    1.94    1.54

        0.000   0.477   0.721   0.735   0.748   0.762   0.775   0.789   0.802   0.816   0.829
        0.843   0.856   0.870   0.883   0.897   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        3.00    4.00    4.00    4.00    4.00    4.00    5.00    5.00    6.00    8.00    9.00
        11.00   11.00

        613     23      3.67    3.23    3.75    3.02

        0.000   0.282   0.478   0.509   0.540   0.571   0.601   0.632   0.663   0.694   0.725
        0.756   0.787   0.817   0.848   0.879   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    2.00    3.00    3.00    3.00    3.00    3.00    4.00    4.00    5.00
        5.00    5.00    6.00    6.00    7.00    8.00    9.00    12.00   14.00   16.00   18.00
        19.00   19.00
```

```
[JJA]

        731     23      2.50    1.83    2.87    1.70

        0.000   0.380   0.643   0.662   0.681   0.700   0.719   0.738   0.757   0.776   0.796
        0.815   0.834   0.853   0.872   0.891   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    4.00    4.00
        4.00    4.00    4.00    5.00    5.00    5.00    6.00    7.00    8.00    9.00    11.00
        13.00   13.00

        723     23      2.51    2.11    2.76    1.81

        0.000   0.411   0.636   0.656   0.675   0.695   0.714   0.734   0.754   0.773   0.793
        0.812   0.832   0.851   0.871   0.890   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    4.00
        4.00    4.00    4.00    4.00    5.00    5.00    6.00    7.00    10.00   11.00   14.00
        17.00   17.00

[SON]

        653     23      2.37    1.73    2.70    1.61

        0.000   0.401   0.665   0.682   0.700   0.717   0.735   0.752   0.770   0.787   0.805
        0.822   0.840   0.857   0.875   0.892   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        4.00    4.00    4.00    4.00    4.00    5.00    5.00    7.00    8.00    9.00    10.00
        13.00   13.00

        662     23      3.12    2.80    3.41    3.04

        0.000   0.363   0.556   0.581   0.606   0.632   0.657   0.682   0.708   0.733   0.758
        0.784   0.809   0.834   0.859   0.885   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    2.00    3.00    3.00    3.00    3.00    4.00    4.00    4.00    4.00
        4.00    5.00    5.00    5.00    6.00    7.00    8.00    10.00   12.00   14.00   15.00
        25.00   25.00
```

```
[SERIES statistics: max, N of observations, mean and sd for WET and DRY]

 8.00   7.00   6.00   8.00  11.00  10.00  11.00  13.00  10.00  13.00   8.00   9.00

  174    150    195    197    228    246    239    243    228    233    190    193

 1.89   1.77   1.85   2.06   2.32   2.41   2.44   2.62   2.50   2.31   2.34   2.00

 1.21   1.16   1.13   1.47   1.71   1.79   1.66   2.02   1.76   1.82   1.58   1.51

30.00  22.00  19.00  18.00  17.00  17.00  16.00  13.00  15.00  16.00  15.00  25.00

  173    153    190    188    228    245    241    241    235    234    190    197

 5.22   5.29   4.22   3.96   2.98   2.43   2.62   2.50   2.71   2.94   3.76   4.58

 4.85   4.29   3.79   3.45   2.30   2.06   2.24   2.04   2.40   2.62   2.93   3.99

[RAIN distributions]

        335     23      4.84    7.73    5.07    8.35

        0.000   0.239   0.418   0.453   0.488   0.523   0.559   0.594   0.629   0.664   0.699
        0.734   0.769   0.805   0.840   0.875   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        0.20    0.50    1.00    1.20    1.40    1.67    2.00    2.39    2.80    3.34    3.60
        5.10    6.35    7.71    9.66    12.43   15.57   19.50   26.51   31.18   36.46   50.40
        50.60   50.60

        270     23      6.09    12.78   6.42    15.36

        0.000   0.230   0.393   0.430   0.467   0.503   0.540   0.577   0.614   0.651   0.688
        0.725   0.762   0.799   0.836   0.873   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        0.20    0.50    1.00    1.30    1.60    1.80    2.20    2.80    3.60    4.00    4.60
        5.60    6.84    8.71    9.55    12.14   16.65   21.86   30.94   45.08   64.66
        135.01 138.80 138.80

        355     23      3.97    7.67    4.06    6.87

        0.000   0.237   0.411   0.447   0.483   0.518   0.554   0.589   0.625   0.661   0.696
        0.732   0.768   0.803   0.839   0.874   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        0.20    0.40    1.00    1.20    1.40    1.60    1.80    2.20    2.58    2.80    3.22
        3.80    4.60    5.21    6.00    8.48    10.63   15.28   20.35   27.32   34.81   72.08
        98.20   98.20

        398     23      4.33    9.48    4.26    8.82

        0.000   0.281   0.417   0.452   0.488   0.523   0.558   0.593   0.628   0.664   0.699
        0.734   0.769   0.804   0.840   0.875   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000
```

```
0.10   0.50   1.00   1.20   1.40   1.60   1.80   2.20   2.60   3.00   3.42
4.00   5.00   5.80   7.40   8.82   12.07  15.02  20.63  29.26  42.11  94.52
132.40 132.40

526    23     2.98   5.13   2.98   5.53

0.000  0.317  0.498  0.528  0.557  0.586  0.616  0.645  0.675  0.704  0.733
0.763  0.792  0.822  0.851  0.881  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.10   0.50   1.00   1.20   1.60   1.60   2.00   2.20   2.59   3.00   3.60
4.00   4.55   5.00   5.80   6.60   8.00   10.09  13.40  16.39  25.85  48.77
52.40  52.40

580    23     2.51   3.75   2.74   4.07

0.000  0.343  0.498  0.528  0.557  0.587  0.616  0.645  0.675  0.704  0.734
0.763  0.792  0.822  0.851  0.881  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.10   0.50   1.00   1.20   1.40   1.40   1.60   2.00   2.20   2.60   2.80
3.20   3.60   4.20   5.00   5.80   7.16   9.12   12.60  15.36  19.44  25.07
28.20  28.20

603    23     2.41   3.93   2.35   3.74

0.000  0.323  0.502  0.532  0.561  0.590  0.619  0.648  0.677  0.706  0.735
0.764  0.794  0.823  0.852  0.881  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.10   0.50   1.00   1.20   1.40   1.60   1.80   1.80   2.00   2.39   2.80
3.00   3.50   4.01   4.73   5.40   6.35   8.36   9.58   12.94  18.37  35.08
44.60  44.60

631    23     2.89   4.02   3.10   4.31

0.000  0.247  0.428  0.462  0.497  0.531  0.566  0.600  0.635  0.669  0.703
0.738  0.772  0.807  0.841  0.876  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.10   0.50   1.00   1.20   1.40   1.60   1.80   2.20   2.40   2.80   3.20
3.60   3.80   4.40   5.20   6.20   7.60   9.80   12.38  15.15  20.26  30.29
37.00  37.00

577    23     3.23   4.45   3.55   5.01

0.000  0.217  0.412  0.448  0.484  0.519  0.555  0.590  0.626  0.661  0.697
0.732  0.768  0.803  0.839  0.874  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.20   0.50   1.00   1.40   1.40   1.60   2.00   2.20   2.60   3.00   3.41
4.00   4.41   5.20   5.81   6.96   8.80   11.20  13.20  16.98  20.60  34.23
38.00  38.00

536    23     3.91   6.52   3.94   6.97
```

```
0.000  0.239  0.399  0.436  0.472  0.509  0.545  0.582  0.618  0.655  0.691
0.728  0.764  0.801  0.837  0.874  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.20   0.50   1.00   1.30   1.40   1.60   1.80   2.00   2.60   2.99   3.40
4.00   4.80   5.40   7.00   9.00   11.15  15.17  18.65  20.50  28.56  56.25
70.80  70.80

454    23     5.10   8.44   4.91   8.09

0.000  0.200  0.379  0.417  0.455  0.493  0.531  0.569  0.606  0.644  0.682
0.720  0.758  0.796  0.834  0.872  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.10   0.50   1.00   1.40   1.54   1.80   2.20   2.60   3.00   3.71   4.80
5.80   6.40   7.69   9.00   11.38  14.00  18.81  22.62  30.82  44.78  65.05
80.80  80.80

377    23     5.05   8.36   5.20   8.89

0.000  0.247  0.411  0.447  0.482  0.518  0.554  0.589  0.625  0.661  0.696
0.732  0.767  0.803  0.839  0.874  0.910  0.940  0.965  0.980  0.990  0.996
0.999  1.000

0.20   0.50   1.00   1.40   1.60   1.80   2.20   2.80   3.36   4.00   4.40
5.39   6.20   8.15   9.80   11.89  16.21  18.83  25.17  30.03  40.89  68.48
76.40  76.40
```

[RAIN monthly statistics: monthly total max and min, N of observations, monthly mean and sd]

```
101.6  200.6  142.2  141.6  155.5  105.4  94.4   97.1   127.0  143.8  157.8
139.0

1.6    1.0    4.4    4.8    8.0    10.4   7.0    16.4   8.2    5.6    18.2
1.6

39     39     39     39     39     39     40     40     40     40     39
39

41.615        42.169        36.092        44.151        40.203
37.362        36.412        45.520        46.605        52.422
59.374        48.836

23.907        46.541        25.161        32.041        27.713
20.902        19.359        20.407        25.941        32.550
34.230        33.714
```

[RAIN daily maxima: median, 95 percentile and maximum]

15.40	11.40	14.20	13.60	8.80	10.00	8.60	11.40	11.80	16.00	15.20	16.40
50.00	91.40	36.00	68.40	38.20	25.20	24.00	30.00	29.80	48.20	61.50	60.80
50.60	138.80	98.20	132.40	52.40	28.20	44.60	37.00	38.00	70.80	80.80	76.40

```
[MAX distributions]

        1209    23      26.24   6.01    25.79   5.82

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        13.90   17.40   17.80   18.80   19.70   20.30   21.00   21.60   22.20   22.80   23.60
        24.40   25.40   26.30   27.40   28.50   29.90   31.50   33.50   35.27   37.60   39.90
        40.79   44.60

        1092    23      26.49   5.85    26.36   5.93

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        13.50   16.58   17.57   18.75   19.80   20.50   21.20   22.00   22.60   23.20   24.10
        25.00   26.00   26.90   28.17   29.62   30.60   31.90   33.20   34.70   36.75   39.22
        40.25   46.80

        1208    23      24.05   5.24    24.24   5.29

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        12.70   15.21   15.92   17.10   18.30   19.00   19.60   20.20   20.70   21.21   21.70
        22.50   23.20   24.30   25.50   26.50   27.50   28.60   30.00   31.50   33.54   36.10
        37.68   40.80

        1170    23      20.23   4.11    20.06   4.18

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        11.70   13.40   13.90   14.70   15.50   16.10   16.70   17.20   17.65   18.20   18.70
        19.20   19.80   20.54   21.10   21.80   22.70   24.00   24.90   26.00   27.70   29.46
        30.13   34.50

        1209    23      16.63   2.99    16.59   3.04

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        8.00    11.40   12.00   12.70   13.30   13.80   14.30   14.60   14.90   15.20   15.50
        16.00   16.50   16.80   17.10   17.70   18.30   18.90   19.70   20.80   22.40   23.68
        24.80   27.00

        1170    23      13.63   2.10    13.56   2.17
```

```
0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

6.20   9.07   9.44   10.50  11.12  11.60  11.90  12.20  12.50  12.80  13.20
13.40  13.70  14.00  14.30  14.50  14.80  15.30  15.70  16.30  17.24  18.30
19.13  21.80

1239   23     13.02  2.02   12.90  2.04

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

5.70   8.60   9.00   9.72   10.60  11.20  11.50  11.80  12.10  12.30  12.60
12.80  13.00  13.40  13.60  14.00  14.20  14.50  14.80  15.40  16.20  17.40
18.00  22.70

1240   23     14.39  2.54   14.36  2.48

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

6.50   9.50   10.10  10.90  11.60  12.00  12.30  12.70  13.00  13.30  13.60
14.00  14.30  14.60  14.90  15.24  15.60  16.20  16.80  17.70  18.90  21.02
21.96  25.60

1200   23     16.55  3.38   16.47  3.26

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

8.20   10.50  11.00  11.80  12.73  13.30  13.80  14.20  14.60  15.01  15.50
15.90  16.40  16.90  17.30  17.80  18.40  19.00  19.70  20.97  22.60  24.80
26.50  30.20

1235   23     19.13  4.37   19.27  4.53

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

10.40  12.24  12.70  13.50  14.30  14.90  15.40  15.80  16.50  17.00  17.50
18.00  18.60  19.20  20.00  20.80  21.60  22.50  23.60  25.10  27.30  30.50
31.73  36.00

1170   23     21.74  5.27   21.65  5.37

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000
```

```
    11.60  13.60  14.00  14.96  15.90  16.60  17.20  17.80  18.50  19.01  19.70
    20.20  20.90  21.70  22.80  24.00  24.71  25.80  27.53  29.28  31.70  34.80
    35.90  39.60

    1219   23     24.38  5.71   24.60  5.74

    0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
    0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
    0.990  1.000

    13.00  14.92  15.84  16.95  18.20  18.90  19.50  20.00  20.70  21.31  21.90
    22.70  23.60  24.50  25.40  26.61  27.80  29.40  30.80  32.47  35.00  37.96
    39.32  43.80
```

[MAX monthly statistics: monthly mean max and min, N of observations, monthly mean and sd]

```
    29.7   30.3   27.1   23.4   18.7   15.4   15.1   17.4   18.8   21.6   26.2
    27.5

    21.9   23.3   20.9   17.3   15.2   12.4   11.7   12.8   13.7   16.2   19.4
    20.2

    39     39     39     39     39     39     40     40     40     40     39
    39

    26.242        26.492        24.054        20.229        16.630
    13.633        13.016        14.386        16.548        19.124
    21.738        24.381

    1.813  1.656  1.405  1.463  0.884  0.787  0.777  1.020  1.315  1.327  1.404
    1.746
```

[MAX daily maxima: median, 95 percentile and maximum]

```
39.00  38.20  33.90  28.30  22.70  17.70  16.70  18.80  23.20  28.10  32.80  36.10


44.20  43.30  39.30  34.40  26.90  19.80  18.50  23.00  29.00  33.30  39.30  42.20


44.60  46.80  40.80  34.50  27.00  21.80  22.70  25.60  30.20  36.00  39.60  43.80
```

[MAX daily minima: median, 5 percentile and minimum]

```
18.10  18.30  16.70  14.40  12.10  9.80   9.40   10.40  11.40  13.00  14.10  16.50


15.20  15.10  13.50  11.90  9.60   7.50   6.50   8.50   8.60   11.50  11.70  13.70


13.90  13.50  12.70  11.70  8.00   6.20   5.70   6.50   8.20   10.40  11.60  13.00
```

```
[MIN distributions]

        1209    23      13.61   3.54    13.37   3.48

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        6.00    7.00    7.80    8.80    9.60    10.10   10.70   11.30   11.60   12.20   12.60
        13.00   13.50   14.00   14.50   14.90   15.50   16.00   16.61   17.70   20.20   22.90
        24.58   30.50

        1092    23      14.05   3.33    14.05   3.40

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        4.80    7.79    8.38    9.35    10.09   10.70   11.30   11.84   12.40   12.80   13.20
        13.60   14.00   14.40   14.80   15.30   15.70   16.40   17.20   18.40   20.35   22.60
        23.51   26.90

        1205    23      12.60   3.21    12.57   3.18

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        3.70    6.11    6.81    7.90    8.70    9.40    9.97    10.40   10.85   11.30   11.74
        12.20   12.60   13.10   13.51   14.00   14.60   15.10   15.80   16.80   18.10   19.89
        20.90   24.30

        1170    23      10.14   3.14    10.30   3.24

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        1.20    3.90    4.30    5.30    6.30    7.00    7.50    8.00    8.40    9.00    9.40
        9.80    10.20   10.60   11.10   11.50   12.00   12.50   13.20   14.20   15.40   17.40
        18.70   21.70

        1209    23      8.32    2.81    8.42    2.90

        0.000   0.010   0.020   0.053   0.105   0.158   0.211   0.263   0.316   0.368   0.421
        0.474   0.526   0.579   0.632   0.684   0.737   0.789   0.842   0.895   0.947   0.980
        0.990   1.000

        0.60    2.41    3.00    3.60    4.60    5.50    5.95    6.50    7.00    7.30    7.70
        8.20    8.50    8.80    9.36    9.70    10.10   10.60   11.10   11.97   13.00   14.30
        14.98   16.50

        1170    23      6.18    2.65    6.11    2.70
```

```
0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

-0.90  0.27   0.60   1.60   2.60   3.40   4.00   4.60   5.00   5.40   5.76
6.20   6.50   6.90   7.20   7.60   7.91   8.30   8.80   9.30   10.34  11.56
12.10  14.10

1235   23     5.35   2.43   5.38   2.48

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

-2.50  -0.66  0.17   1.00   2.10   2.80   3.40   3.80   4.30   4.70   5.10
5.50   5.70   6.00   6.30   6.60   7.00   7.30   7.80   8.30   9.10   9.80
10.37  12.70

1237   23     5.87   2.46   5.74   2.39

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

-2.50  0.54   1.00   1.81   2.80   3.50   4.00   4.40   4.70   5.00   5.30
5.60   6.00   6.30   6.60   7.00   7.30   7.80   8.30   8.88   10.10  11.40
12.00  13.30

1199   23     7.01   3.01   6.90   2.92

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

-1.10  1.00   1.50   2.60   3.50   3.90   4.50   4.90   5.40   5.87   6.30
6.70   7.10   7.50   7.80   8.20   8.60   9.30   9.97   10.88  12.30  14.30
15.20  18.50

1232   23     8.42   3.30   8.40   3.53

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000

1.30   2.20   2.80   3.50   4.50   5.10   5.60   6.10   6.60   7.10   7.60
7.90   8.30   8.70   9.20   9.70   10.30  11.00  11.70  12.70  14.30  16.37
17.67  21.80

1169   23     10.22  3.34   10.31  3.38

0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
0.990  1.000
```

```
        0.90   3.87   4.40   5.40   6.30   7.00   7.50   8.00   8.40   8.80   9.20
        9.60   10.20  10.60  11.00  11.50  12.10  12.70  13.40  14.60  16.25  18.00
        19.63  23.60

        1217   23     11.92  3.34   11.89  3.33

        0.000  0.010  0.020  0.053  0.105  0.158  0.211  0.263  0.316  0.368  0.421
        0.474  0.526  0.579  0.632  0.684  0.737  0.789  0.842  0.895  0.947  0.980
        0.990  1.000

        4.10   5.73   6.60   7.31   8.20   8.80   9.22   9.63   10.10  10.50  10.90
        11.20  11.60  12.10  12.56  13.00  13.60  14.30  15.00  16.10  18.10  20.66
        22.83  26.30
```

[MIN monthly statistics: monthly mean max and min, N of observations, monthly mean and sd]

```
        16.1   16.8   15.6   11.6   10.9   8.4    6.7    7.4    8.4    9.7    13.1
        13.8

        11.0   11.8   10.8   8.2    6.5    3.9    3.1    4.7    4.9    7.2    8.4
        9.7

        39     39     39     39     39     39     40     40     40     40     39
        39

        13.613        14.050        12.600        10.137        8.321  6.182  5.359
        5.870  7.009  8.419  10.219        11.916

        1.451  1.380  1.128  0.923  0.832  0.947  0.864  0.694  0.813  0.702  0.918
        1.104
```

[MIN daily minima: median, 5 percentile and minima]

```
8.00   8.90   7.00   4.40   3.20   0.90   0.70   1.20   2.10   2.90   4.50   6.80


6.20   6.20   4.20   1.30   0.80   -0.60  -2.30  -0.70  0.00   1.70   2.00   5.20


6.00   4.80   3.70   1.20   0.60   -0.90  -2.50  -2.50  -1.10  1.30   0.90   4.10
```

[MIN daily maxima: median, 95 percentile and maximum]

```
21.70  20.50  19.00  16.60  13.80  10.90  9.70   10.90  13.60  15.80  17.20  19.90


27.30  24.80  24.00  21.10  16.10  13.60  11.50  13.20  16.60  19.50  22.60  25.20


30.50  26.90  24.30  21.70  16.50  14.10  12.70  13.30  18.50  21.80  23.60  26.30
```

[SPELLS of FROST and HEAT WAVES (>30 C)]

```
[DJF]

        2       23      1.00    0.00    1.00    0.00

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000

        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
        1.00    1.00

        478     23      1.83    1.19    2.20    1.06

        0.000   0.521   0.814   0.821   0.828   0.834   0.841   0.848   0.855   0.862   0.869
        0.876   0.883   0.889   0.896   0.903   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        3.00    3.00    3.00    3.00    3.00    4.00    4.00    5.00    6.00    6.00    7.00
        8.00    8.00

[MAM]

        3       23      1.33    0.47    1.34    0.47

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000

        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
        1.00    1.00    1.00    1.00    1.00    2.00    2.00    2.00    2.00    2.00    2.00
        2.00    2.00

        118     23      1.60    1.08    1.49    0.97

        0.000   0.653   0.864   0.868   0.871   0.874   0.877   0.881   0.884   0.887   0.890
        0.894   0.897   0.900   0.903   0.907   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        3.00    3.00    3.00    3.00    3.00    3.00    3.00    4.00    5.00    6.00    7.00
        7.00    7.00
```

```
[JJA]

        32      23      1.28    0.51    1.24    0.46

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000

        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
        1.00    1.00    1.00    1.00    1.00    1.00    1.00    2.00    2.00    2.00    2.00
        2.00    3.00

        0       0

 se-D is empty

[SON]

        8       23      1.12    0.33    1.11    0.30

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000

        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
        1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00    2.00
        2.00    2.00

        88      23      1.50    0.80    1.39    0.78

        0.000   0.648   0.886   0.888   0.890   0.891   0.893   0.895   0.896   0.898   0.900
        0.902   0.903   0.905   0.907   0.908   0.910   0.940   0.965   0.980   0.990   0.996
        0.999   1.000

        1.00    1.00    2.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00
        3.00    3.00    3.00    3.00    3.00    3.00    3.00    3.00    4.00    5.00    5.00
        5.00    5.00

[RAD distributions]

        1178    23      20.34   8.16    20.55   8.38

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000

        0.12    6.70    8.84    10.83   11.78   12.69   14.40   15.20   16.69   17.39   18.88
        19.81   20.80   22.00   22.90   23.51   23.77   26.38   28.27   30.34   31.38   32.38
        33.59   36.58

        1066    23      19.49   6.88    19.27   7.06

        0.000   0.043   0.087   0.130   0.174   0.217   0.261   0.304   0.348   0.391   0.435
        0.478   0.522   0.565   0.609   0.652   0.696   0.739   0.783   0.826   0.870   0.913
        0.957   1.000
```

```
0.20   6.70   9.33   10.83  12.23  13.56  15.09  15.96  16.74  18.05  19.15
20.04  21.22  21.67  22.36  23.15  23.51  23.76  25.18  26.55  27.57  28.61
30.17  32.82

1209   23     16.54  5.77   16.49  6.23

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

1.17   6.70   8.81   9.85   10.46  10.91  11.78  12.69  13.56  14.60  15.52
16.62  17.39  18.67  19.25  19.81  20.56  21.24  22.02  22.66  23.35  23.70
25.00  32.93

1170   23     13.68  5.17   13.65  5.39

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.33   5.26   6.70   7.79   8.84   9.85   9.85   10.83  11.10  11.78  12.69
13.15  13.75  14.40  15.15  15.78  16.46  17.15  18.05  18.89  20.04  22.02
23.16  23.78

1208   23     11.41  5.43   11.69  5.90

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.29   3.81   4.89   5.65   6.64   7.27   7.79   8.53   8.84   9.33   9.85
9.86   10.49  10.83  11.78  12.09  12.84  13.62  15.20  16.69  18.92  21.24
22.66  32.67

1170   23     10.69  5.62   10.87  6.09

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.37   2.73   4.08   4.99   5.62   6.19   6.70   7.39   7.79   8.35   8.84
9.05   9.85   9.85   10.83  11.78  12.69  14.40  15.20  16.69  18.05  19.94
22.66  28.73

1239   23     11.35  5.51   11.51  5.82

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.10   3.38   4.88   5.61   6.30   6.80   7.63   7.94   8.64   8.97   9.64
9.85   10.21  10.83  11.78  12.69  13.56  14.40  15.96  17.39  18.67  20.32
22.66  30.91

1240   23     12.55  4.76   12.79  5.27
```

```
0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.17   5.09   6.70   7.52   8.36   8.84   9.85   9.85   10.58  10.83  11.33
11.78  12.40  12.69  13.56  13.77  14.40  15.20  15.96  17.07  18.05  19.81
22.02  32.67

1200   23     14.24  5.15   14.36  5.47

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.51   5.58   6.83   8.40   9.47   9.85   10.83  11.08  11.81  12.69  13.56
13.71  14.40  15.20  15.53  16.44  17.30  17.97  18.67  19.51  20.67  21.99
22.93  32.67

1234   23     16.35  6.24   16.13  6.29

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.48   6.70   7.79   8.84   9.85   10.83  11.78  12.61  13.16  13.90  14.57
15.41  16.61  17.39  18.46  19.52  20.49  21.24  22.27  22.93  23.61  25.12
26.77  30.60

1140   23     18.13  7.65   18.01  7.86

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

2.21   6.70   8.84   9.85   9.85   10.83  11.78  12.69  13.56  15.20  15.96
16.69  18.05  19.25  19.88  21.24  22.36  23.46  24.44  26.83  28.86  30.24
31.64  34.14

1188   23     19.17  8.33   19.38  8.73

0.000  0.043  0.087  0.130  0.174  0.217  0.261  0.304  0.348  0.391  0.435
0.478  0.522  0.565  0.609  0.652  0.696  0.739  0.783  0.826  0.870  0.913
0.957  1.000

0.83   6.70   8.84   9.85   10.83  11.48  12.44  13.56  14.40  15.89  16.84
18.05  19.75  20.54  21.54  22.36  23.23  23.71  26.01  28.77  31.05  32.84
33.80  35.69
```

```
[RAD monthly statistics: monthly mean max and min, N, monthly mean and sd]

        30.8    24.8    19.6    17.8    17.3    18.2    16.2    17.6    17.1    23.1    25.1
        26.6

        14.3    14.1    12.6    10.6    6.8     5.1     6.2     8.8     10.8    13.0    13.1
        12.9

        38      39      39      39      39      39      40      40      40      40      38
        38

        20.337          19.360          16.543          13.682          11.415
        10.691          11.355          12.554          14.235          16.361
        18.128          19.169

        4.289   2.713   1.641   1.996   3.091   3.842   3.682   2.177   1.436   2.544   3.803
        4.395

[END]
```

[SERIES WET AND DRY]: This block of output indicates the empirical distribution characteristics for the length of wet and dry series of days in the observed data. This information is given in blocks of four lines by season (i.e., winter [DJF], spring [MAM], summer [JJA] and autumn [SON]). The first two lines of each seasonal block refer to the WET series, whilst the last two lines represent the DRY series. As explained in Section 2, the wet and dry series are modelled based on histograms constructed from the observed data. The histograms consist of 10 intervals (or bins) and the cut-off points for each bin are given in the first line of each set of two lines. The second line corresponds to the number of events in the observed data falling into each interval.

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So, using debrecen.sta, it can be seen that the WET series intervals (hi) are 0≤h1<1, 1≤h2<2, 2≤h3<3, 3≤h4<4, 4≤h5<5, 5≤h6<6, 6≤h7<7, 7≤h8<8, 8≤h9<10 and 10≤h10<13, with corresponding frequencies of occurrence of 215, 136, 70, 39, 19, 8, 10, 1, 5 and 2, respectively (see Figure A2.3). Similarly, the winter DRY series intervals are 0≤h1<1, 1≤h2<3, 3≤h3<6, 6≤h4<10, 10≤h5<15, 15≤h6<22, 22≤h7<31, 31≤h8<42, 42≤h9<55 and 55≤h10<70, with corresponding occurrence frequencies of 183, 175, 92, 43, 9, 8, 1, 0, 0 and 1, respectively. The histogram intervals are derived from the observed data and are not pre-set. Hence, they will differ from site to site.

2. [WET and DRY SERIES: mean and sd]: The following block of data describes the mean and standard deviation, by month, of wet and dry series length. The first two lines are the mean and standard deviation for the WET series, followed by the same information for the DRY series. The mean indicates the average length, in days, of the appropriate series in each month, whilst the standard deviation gives an indication of the variability of the series length in each month.

3. [DISTRIBUTIONS OF RAIN]: Precipitation amount is modelled in the same way as series length, i.e., empirical distributions are derived using frequency histograms, the intervals of which are based on the observed weather data. An empirical precipitation amount distribution is derived for each month, resulting in the 24 lines in this block (listed from January through to December). Each pair of lines represents the histogram intervals followed by the frequency of precipitation occurrence within each interval.

4. [RAIN MONTHLY max, min, N, mean and sd]: Following the precipitation distribution characteristics are summary precipitation statistics by month. The first two lines represent the absolute maximum and minimum precipitation totals (mm) recorded in each month. The next line indicates the number of years of data in the record (N; 31 for the Debrecen example), followed by monthly mean precipitation total and standard deviation.

5. [MAX MONTHLY max, min, N, mean and sd]: Next are a number of statistics related to monthly mean maximum temperature, arranged as in (4) above. These are derived by pooling the mean maximum temperature for each month and year. The first two lines represent the extremes of monthly mean maximum temperature, i.e., the absolute maximum and minimum monthly mean maximum temperature values, respectively. N is the number of years of record followed by the monthly mean maximum temperature and standard deviation (i.e., the year-to-year variation for the month in question).

6. [MAX DAILY max, min, N, mean and sd]: LARS-WG also provides information about the statistical characteristics of daily maximum temperature, derived by pooling the daily maximum temperature values for each month and year. The first two lines represent the extremes of daily maximum temperature, i.e., the absolute maximum and minimum daily maximum temperature values, respectively. N is the number of days in the record (i.e., the number of days in the relevant month multiplied by the number of years of record) and this is followed by the daily mean maximum temperature and standard deviation (i.e., the day-to-day variation for the month in question).

7. [MIN MONTHLY max, min, N, mean and sd]: As (5), but for monthly mean minimum temperature.

8. [MIN DAILY max, min, N, mean and sd]: As (6), but for daily minimum temperature.

9. [SPELLS OF FROST and HOT TEMPERATURE]: Periods of cool and warm weather are also modelled using empirical distributions by season. A frost is defined as a minimum temperature less than 0°C, whilst a hot day occurs if maximum temperature exceeds 30°C. Each seasonal block of data consists of four lines with the first line of each pair describing the histogram intervals (spell length) and the second line the frequency of occurrence of events within each interval, respectively. The first two lines represent frost events, whilst the last two lines relate to hot spells.

LARS-WG: Stochastic Weather Generator 11

10. [RAD MONTHLY max, min, N, mean and sd]: Statistical characteristics of monthly mean solar radiation (MJm-2day-1) are given. First of all, the maximum and minimum monthly mean solar radiation values, followed by the number of years of record (N), monthly mean solar radiation and standard deviation. These values are obtained by pooling the monthly mean solar radiation values.

11. [RAD DAILY max, min, N, mean and sd]: Finally, the statistical characteristics of daily solar radiation are provided: maximum and minimum daily solar radiation, the number of days of record (N), daily mean solar radiation and standard deviation. These values are obtained by pooling the daily solar radiation values.

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APPENDIX 3: AQUATIC MACROINVERTEBRATE DATA FROM EXPERIMENT

Repeat	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3
Flume	3	3	3	4	4	4	5	5	5	6	6	6	7	7	7	8	8
Tray	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2
Treatment	Heat	Heat	Heat	Cont	Cont	Cont	Heat	Heat	Heat	Cont	Cont	Cont	Heat	Heat	Heat	Cont	Cont
Acari					2												
Anisocentropus spp.	1																
Aphilorheithrus spp.		1															
Austrolimnius spp.	8	50	11				12	3	3	2	10	5	6	3	3	1	4
Ceratopogonidae		2			1						1		2			2	
Chironomidae				1	3												1
Chironominae	8	30	11	13	6		26	14	16	3	6	26	6	8	8	19	
Conoesucus spp.			3														
Copepoda	28	1	26	1						1			7	31	30		1
Corydalidae													1	2			
Elmidae (not *Austrolimnius*)				22	11	10	1										
Gripopterygidae	2						1						13	6		6	2
Histiostoma	2																
Hydracarina	9			1									3	4	2	3	
Leptoceridae	16																
Liposcelidae																1	2
Nematoda												1	1		1		
Notalina sp.		3	18	8	10		3	1	3	1	6	9	9	2	1	11	3
Notonemouridae			1														
Nousia fuscula	16			8		3	27	17	24	8	28	34	10	26	31	17	6
Oribatidae															3		
Orthocladiinae	4										2	1	12	6	18	5	
Ostracoda													2			1	3
Podonominae			1														
Psephenidae (not *Sclerpcyphon*)						1											
Psychodidae	1		1										1			1	
Scirtidae							1						1				
Sclerocyphon sp.	1	2	1	1	1			2		2	1						
Tamasia spp.																1	
Tanypodinae	10	10	19	3	7		9	3	2	1	5	8	9	7	14	2	2
Tipulidae		2					1				1	2	2				
Triplectides sp.		1			1												
Ulmerophlebia pipinna		43	26	14				2		1	1	5	34	37		40	41

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