Position Analysis

MAKING CLIMATE SCIENCE IMPACTS CLEAR THROUGH END-USER ENGAGEMENT

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry and Science

Business Cooperative Research Centres Programme

Position Analysis: Making climate science impacts clear through end-user engagement

ISSN: 1835-7911

Requests and enquiries concerning reproduction rights should be addressed to:
Antarctic Climate & Ecosystems
Cooperative Research Centre
Private Bag 80, University of Tasmania
Hobart Tasmania 7001

Tel: +61 3 6226 7888
Email: enquiries@acecrc.org.au
www.acecrc.org.au

Cover image: Gordon Dam, Southwest National Park, Tasmania.

The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.

This research also had support from the Australian government's National Environmental Science Programme and the Earth System and Climate Change Hub.

Citation
Bindoff N.L., Remenyi, T.A., Love P.T., Harris R.M.B. (2019) ACE CRC Position Analysis: Making climate science impacts clear through end-user engagement. Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Australia. 40 pp.

Established and supported under the Australian Government's Cooperative Research Centres Program.

Australian Government
Department of the Environment and Energy
Australian Antarctic Division

Australian Government
Bureau of Meteorology

Australian Government
Department of the Environment and Energy

UNIVERSITY of TASMANIA

CSIRO

NIWA
Taihoro Nukurangi

AWI

Scientific Contributors

Nathan Bindoff
Tomas Remenyi
Rebecca Harris
Peter Love

Contents

AT A GLANCE

Context

Projections of climate change under a high emissions scenario show profound impacts and for some countries very significant costs. The 21st meeting of the Conference of the Parties (COP21) resulted in the "Paris Agreement" and has given new impetus across 195 United Nations to mitigate for climate change.

Australian Prudential Regulation Authority (APRA) is increasingly requiring "...company directors to properly consider and disclose foreseeable climate-related risks". Climate change can no longer be considered just an environmental policy issue as it now affects all economic and social systems.

The Tasmanian Government has recognised the changing circumstances at state and national level in Australia for managing climate change and has released Climate Action 21: Tasmania's Climate Change Action Plan 2017-21 (TCCO 2017).

Tasmania experienced an extra-ordinary dry spring in 2015 and wet autumn in 2016. The dry spring directly led to significant bushfires and low water yields and the wet autumn resulted in devastating floods. Together these three events (i.e. bushfire, drought and flood) cost the state about $300 million, or 1% of gross state product.

Simon Desalis

Tasmanian Irrigation Scheme.

Rob Blakers

World heritage risk assessments are being used by the Tasmanian Fire Service, Parks and Wildlife Service and the Tasmanian Wilderness World Heritage Area to inform long term planning, resourcing and infrastructure decisions.

Applications of the research

Climate Futures for Tasmania Project led to 27 major projects and a further 50 complementary projects related to climate change in Tasmania. These research activities have resulted in a suite of comprehensive reports.

The Climate Futures for Tasmania projects led to positive economic outcomes. A full and independent cost benefit analysis found large economic benefits created value of between $21.5m and $86.5m on an investment in $16.4m, based on present value terms.

Victoria's world class ski field operators are using climate futures projections to support long term investment, marketing and infrastructure decisions. The ability of alpine resorts to absorb rising costs will depend strongly on visitor perceptions of climate change and their responses to declining and less reliable natural snow cover.

Tasmanian Fire Service uses the bushfire weather and prescribed burning reports for planning. The total number of days per year categorised as 'Very High Fire Danger' is projected to increase by at least 120% (i.e. doubled). Projected changes show strong regional and seasonal variations. Regions currently with the greatest risk of fire are projected to get worse most rapidly. There is a narrower window of suitable conditions for prescribed burning which will affect the timing and resourcing of prescribed burning and alternative methods to manage bushfire risk may need to be considered.

Australia's wine industry is using the first fine-scale climate information over south eastern Australia to help adapt to climate change. Regional climate indices tailored for the wine industry are being used to guide adaptation responses within each wine region to maintain grape yield, value and wine style into the future.

Future Assessments of climate change risks

Coincident and compounding extreme events have not been considered in any of the earlier work before 2019. How the frequency of coincidence will be affected by climate change has led to new questions about their relationships and impacts. New research is now emerging on coincident and compounding events for Tasmania.

Water underpins many of the activities in the state and is critical to energy security and the future of agriculture. Since the last climate impacts assessments, new water infrastructure (namely the Tasmanian Irrigation scheme) has been put in place. The sensitivity of this infrastructure to certain types of climate extremes could be assessed.

Flood rescue in Cairns.

Agriculture is currently growing faster than any other sector of the state economy. The Climate Futures for Tasmania Project only covered dairy and wine grapes in detail (about $415 million of the state farm-gate value for 2015-2016 year), thus the remaining 80% of this sector is effectively unassessed and could be expanded.

A comprehensive assessment of the impacts of climate change on potential risk to the marine environment has yet to be undertaken. Aquaculture and wild fisheries are about half of the agriculture sector and climate change (and its extremes) pose a potential risk to food security through increased risks.

The potential for damaging agricultural pests to establish in Tasmania as a result of climate change has not been adequately assessed. New analytical methods for pest detection and new projections could be combined to estimate the emergence of viable populations in the different regions of the state.

Tourism is known to be negatively influenced by natural hazards such as bushfires and floods. However, there is a need to assess more broadly how natural hazards of all kinds (heat waves, storms, floods) will affect Tasmania's unique and highly valued biodiversity. Currently tourism to Tasmania directly and indirectly generates about 10% of the state's gross state product.

The World Health Organisation (WHO) has recently identified the projected changes in climate as being "overwhelmingly negative" (World Health Organisation 2017). While broad risk areas have been identified, the health impacts of a changing climate have not been fully assessed.

Tools that can help decision makers utilise the outputs of research are critical to uptake and impact. Decision-making by government and businesses is important from a climate change liability and financial risk perspective.

A key success of the Climate Futures for Tasmania Program was the extensive outreach and public engagement that was incorporated into the work plan. Sustained, frequent and broad engagement within both the public and private sectors of the economy resulted in awareness and uptake of relevant climate information by decision makers in Tasmania.

1

INTRODUCTION

Climate change is a pressing problem for society and affects all walks of life. The scientific evidence that the climate is changing is clear. The Intergovernmental Panel on Climate Change concluded in its fifth assessment report that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (Bindoff et al. 2013).

Projections of climate change under a high emissions scenario show profound impacts and for some countries very significant costs (Moore et al. 2015). The 21st meeting of the COP21 resulted in the "Paris Agreement" and has given new impetus across 195 United Nations to mitigate for climate change. The recent special report on limiting Earth's temperature to 1.5°C would require "far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence)" (IPCC 2018) and is urgent.

Relative to the other states of Australia, projected climate change in Tasmania tends to be weaker or will be observed later. This may mean that associated impacts are lower or are felt later, depending on the sensitivity of the relevant systems. Certain climate change thresholds occur earlier in the tropics and later in the mid-latitudes and polar regions. These thresholds are crossed earlier because of the more stable climate the areas are closer to the equator (Bindoff et al. 2013). While many mid-latitude regions are projected to have a distinct drying trend of up to 40% (IPCC 2013), Tasmania is near the boundary of this zone of projected drying, and is projected to have low or non-significant trend changes in the net annual rainfall (however, seasonal rainfall changes may be significant) and, because Tasmania is an island with a maritime climate, has smaller projected temperature changes by 2100 (Grose et al. 2010; Grose et al. 2013). The projected change is 2.5 to 4.0°C, which is slightly lower than the global change of 3.4 to 6.2°C for the same high emissions scenario.

Even though the relative climate changes are often smaller relative to other states of Australia, substantial impacts are already occurring (e.g. Johnson et al. 2011; Harris et al. 2018) and the impacts are significant causes for concern. The magnitude of these impacts is dependent on the sensitivity and vulnerability of each system to the changes. Assessing the impact of Tasmania to these projected changes requires an assessment of this vulnerability. Sometimes extreme climate events are also compounded with other events and magnify the negative consequences. An example of this compounding of events is the spring and summer of 2016 (Bindoff et al. 2016). This combination of dry spring and a very wet autumn has been attributed to human influence (Karoly et al. 2016). That summer was also associated with drought, fires, floods and marine heatwaves that led to the State of Tasmania


iStock

West Australian wheat fields.

experiencing only a 1.3% growth in its gross state product, well below the anticipated growth of 2.5%. This reduced stated growth was due to the decline in output from the agriculture, forestry, fishing and rationing of electric power in the energy sectors during this period. The total direct cost of the fires and floods to the Tasmanian State Government was assessed at AUD300 million.

Climate change will increase the risks of many of Tasmania's natural hazards, and will pose increased threats to Tasmania's current industries (e.g. biosecurity). However, the relatively smaller changes could also provide a relative advantage compared to other places and lead to new areas of activity in Tasmania's major economic sectors. Tasmania's major hazards have already been assessed independently in the 2016 Tasmanian State Natural Disaster Risk Assessment (TSNDRA) report (White et al. 2016), but the combined risk of all of these hazards, possibly in the form of coincident events, remains as a key gap that requires further investigation. This was identified throughout the TSNDRA process by a range of stakeholders across operational and strategic roles throughout the emergency sector (Remenyi T.A. & White C.J. pers. comm.) and was explicitly mentioned in the Heatwave chapter's treatment options from the 2016 TSNDRA report.

1.1 Policy Drivers (International, national and state)

In 2015, the COP21 created the "Paris Agreement" which includes the goal of limiting global warming to "well below 2°C" compared to pre-industrial levels and also calls for zero net anthropogenic greenhouse gas emissions to be reached during the second half of the 21st century (IPCC 2018). The "Paris Agreement" sets a new policy relevant target (upper bound) on the amount of carbon emissions nations need to adapt to in response to climate change. The Australian Federal Government has now ratified the Paris Agreement and has a formal commitment to reduce emissions by 26% to 28% below 2005 levels by 2030 and thus responding to climate change is an urgent issue at the Federal level. Acceptance of the goal of zero net anthropogenic emissions (or even slightly negative emissions) could mean that every State and Territory in Australia would also now have to progressively reduce emissions to meet the target of zero net emissions (or slightly negative emissions). From the perspective of climate impacts, the policy relevant questions to answer are around the benefit of the reduced warming relative to the 2°C warming target (or other emissions targets). There is clear evidence that in some systems important thresholds can be avoided if this lower target is met (IPCC 2018).

Townsville flooding.

In addition to the global agreements from the Conference of the Parties process, there is now greater pressure on the financial sector to satisfactorily account for the risks of climate change (Financial Stability Board 2017), motivated by factors such as the direct costs of hurricanes and associated storm surges in the Atlantic. The world's leading investment and re-insurance agencies responded to this urgency, first identifying that $4 to $43 trillion of global assets are at risk, prompting the development of market-based mechanisms to incorporate the risk of climate change into the investors selection making processes, relying on "adequate information" (Financial Stability Board 2017). This prompted the Australian Prudential Regulation Authority (APRA) to state "...company directors who fail to properly consider and disclose foreseeable climate-related risks to their business could be held personally liable for breaching their statutory duty of due care and diligence under the Corporations Act." (Summerhayes 2017). Climate change can no longer be considered just an environmental policy issue, impacts will be felt in both our economic and social systems. The World Economic Forum's Global Risks Report 2016 (World Economic Forum 2016) rated failure of climate change adaptation and mitigation as the most impactful risk to the global economy over the next decade. This is the first time they classified environmental risk as the greatest economic risk.

This additional imperative means that nearly all business enterprises that have climate related activities (either on the impacts or on the emissions side) will be increasingly required to assess their climate related risks. There is mounting pressure on organisational boards to ensure future strategy is stress tested against future climate change impacts. However, there is currently limited effort directed into this area.

The Tasmanian Government has recognised the changing circumstances at state and national level in Australia for managing climate change and has released Climate Action 21: Tasmania's Climate Change Action Plan 2017-21 (TCCO 2017). Similarly, Victoria's Climate Change Act 2017 and Adaptation plan aim to provide "the best available climate change science" for policy makers and decision-making to ensure all Victorian's have a prosperous future and become more resilient to the challenges of climate change. The Victorian Government is investing in regional climate modelling projections for Victoria (to be completed mid-2019). All six States have plans for adapting to and making themselves more resilient to climate change.

1.2 Climate Futures: Co-developed research driven by stakeholder needs

It has been a decade since the first Climate Futures for Tasmania Project. The Climate Futures for Tasmania project was an extraordinary partnership of 12 partner organisations that delivered downscaled climate change information for Tasmania with unprecedented detail and scope across a range of disciplines (Bindoff et al. 2018). It was designed to understand and integrate the impacts of climate change on Tasmania's weather, water catchments, agriculture and climate extremes, including aspects of sea level, floods and wind damage (Figure 1). Through the inclusion of over 50 "complementary" research projects supported by the project, new assessments were made of the impacts of climate change on coastal erosion, biosecurity and energy production (Bindoff et al. 2018). In addition, the project included the development of decision support tools to deliver climate change information to infrastructure asset managers (ClimateAsyt) and local government (LIST).

Climate Futures for Tasmania achieved this broad interdisciplinary scope through a multi-institutional collaboration between 12 core participating partners drawn from government, research and industry sectors at both state and national level. It achieved impact by ensuring that project activities were driven by the information requirements of end-users and local communities.

There were three primary objectives for Climate Futures for Tasmania:

- To produce fine-scale projections of climate over Tasmania based on a range of credible scenarios for global greenhouse gas emissions;
- To derive from the projections key climate variables of most importance to diverse industries, utility and service providers, planners and the community; and
- To inform industry, utility and service providers, the community and government on the range of expected values for key variables under alternative scenarios of greenhouse gas emissions and use these results to facilitate effective adaptation to the most likely climate of Tasmania's future.

This established the basis for the project with three main activities derived from the primary objectives:

- Climate modelling to produce new simulations;
- Targeted analyses and interpretation of the new simulations; and
- Communication and engagement with stakeholders and end-users.

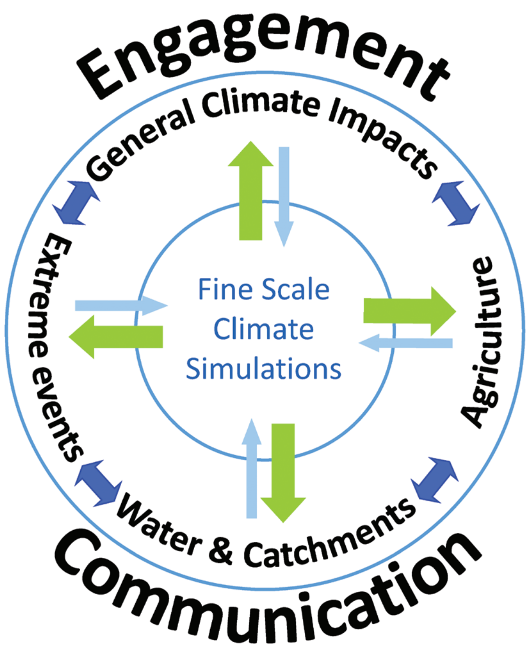


FIGURE 1: Climate Futures for Tasmania targeted the four key environmental sectors of the state economy, namely: general climate trends, water and catchments, extreme events, and agriculture. The project engaged with next users and end users to build end-to-end relationships and thus transformed the understanding of climate change on Tasmania and supported decision-making across the state.

The project was divided into the five key work areas of climate modelling; general climate impacts; water and catchments; impacts on agriculture; and extreme events (Figure 1). However, the analyses and the results were also frequently co-designed and co-produced with stakeholders. No stakeholder was confined to the outputs from one component nor were the results of any component necessarily only of interest to an exclusive stakeholder or group of stakeholders. This successful project model was subsequently adopted by similar projects in other states.

These projects lead to positive economic outcomes. A full and independent cost benefit analysis found large economic benefits generated by these programs (e.g. the Antarctic Climate & Ecosystems Cooperative Research Centre's Climate Futures program created value of between $21.5m and $86.5m on an investment in $16.4m, based on present value terms (pers comm. AgTrans report).

In order to achieve the objective of informing stakeholders and end-users the project had a strong emphasis on the research outputs. Five technical reports on the key work areas, accompanied by 5 plain-English companion summaries, formed the core outputs. These reports together with two supplementary technical reports on specific extreme events are summarised in Bindoff et al. 2018 (Table A1 in Appendix A.) Further project outputs included additional peer-reviewed reports, journal articles, conference presentations, flyers and fact sheets, climate model output and derived data products, as well as information delivery and feedback through stakeholder workshops and briefings to government.

Following the completion of the project in 2011, the partnership between the ACE CRC and the Tasmanian Climate Change Office (TCCO) and the process of stakeholder engagement has continued. In collaboration with stakeholder groups, gaps in the analysis of the original project were identified. This led to numerous follow-on studies that used the original project's climate simulations and followed the same method of co-designed research and targeted information delivery. For example, the scope of the original project did not encompass the impact of climate change on ecosystems, but through participation in the National Environmental Research Program Landscape and Policy Hub the Climate Futures for Tasmania regional climate model output was applied to a range of projects such as Climate Projections for Ecologists and the Tasmanian Future Fire Danger climatology (Bindoff et al. 2018).

The legacy of the Climate Futures for Tasmania project is broad (R2R2018). Beyond the series of reports, tools and datasets that it produced, there is a long and still growing list of reports and peer-reviewed publications by external data users. The model of government-research-industry partnership with stakeholder engagement and information delivery has been adopted by later projects in other states, such as the New

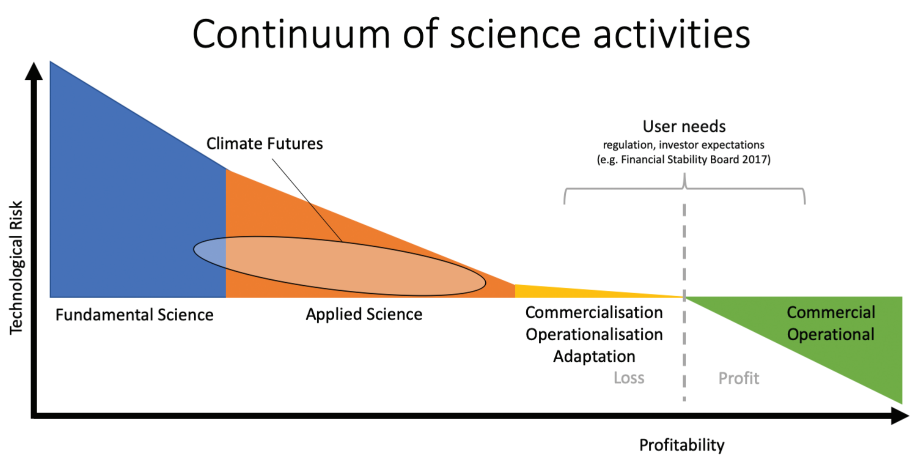


FIGURE 2: Climate Futures place in the spectrum of pure "blue sky" research to a service that provides consultation at commercial level and where the profit motivation is important. This figure shows the progression of climate research from fundamental science to an increasingly applied science that through the demand of regulation and societal need as discussed above is pulled through to being a service for all businesses and operates on a commercial scale and ceases to be research.

iStock

Coastal erosion.

South Wales and Australian Capital Territory Regional Climate Modelling Project (NARCliM). It is a model that is copied by more than one state of Australia and has demonstrated economic outcomes, and indeed unlike other research projects has sustained its activities through a succession of research contracts.

This type of climate change research is unusual in climate science, and other science disciplines, in that it has from the outset involved user/stakeholder engagement as part of the project development and design of research program. Consequently, it is not driven directly by the science but rather by the policy relevant questions climate change raises: often directly from weather events or hazards (e.g. bushfires) that have affected the stakeholder themselves. Climate impacts research of the type carried out by Climate Futures is not fundamental science per se., but it does sit very comfortably in the applied science category. In being designed in response to stakeholders, the projects are sometimes perceived as being more commercial types of activities, undertaken by consultants (of the type shown in Figure 2). However, this undervalues the engagement process, that inherently involves the upskilling of stakeholders during each project's lifecycle (development-completion-delivery). While designed on behalf of stakeholders, the Climate Futures climate impacts research is published in research journals, while also delivering a range of outputs that are useful and frequently used by users.

2

RESEARCH OUTPUTS

Addressing stakeholder questions and producing policy relevant research on the impacts of climate change typically requires detailed information at local scales that generate plausible scenarios. These projected future climate change impacts are used to inform decision-making. Constructing scenarios of future impacts from a changing climate requires sophisticated climate simulations that include the evolving weather systems coupled with the capacity to integrate these outputs with models (or information) related to stakeholders climate related research question. This intersection between stakeholder "problems" and the projections of climate change immediately demands an interaction between the stakeholders and researchers and consequently implies a joint design. The primary technique to deliver the projections is the same in each case and is through a process called dynamical downscaling. The approach taken by our partner CSIRO is described below (Box 1) although there are many technical variations of this approach. The next section shows four examples of this application of co-design of research into climate change impacts for four groups of stakeholders in the areas of the future of alpine resorts, bushfire risk, sea-level rise, and the wine industry.

Here we show four examples of research into climate change impacts for stakeholders. Each example is designed jointly with stakeholders to deliver the research they need. The examples come from the future of alpine resorts, bushfire risk, sea-level rise, and the wine industry.


Shutterstock

Australian drought

2.1 Victorian Alpine Resorts

The Victorian Alpine Resorts Co-ordinating Council commissioned the Climate Futures Group to assess the potential impacts of climate change on the resorts, to support decisions about future investment in ski resort infrastructure, including snow making.

A downscaled climate model for the Australian Alps region (Box 1) was used to develop year-by-year projections for mean temperature, precipitation, snow depth and season length at all of Victoria's popular ski destinations between now and the end of the century.

Australia has experienced warming of 0.1°C per decade since 1950 (Nicholls and Collins 2006) with the trend of change in the Southern Australian Alps running at about twice this rate. The Climate Futures for the Australian Alps projections provide regional details of climate change between the baseline period (1961-1990) and the end of the century (2070-2099). They show that, by the end of the century, under a high emissions scenario (RCP 8.5) average temperatures across the Australian Alps could increase by 4-5°C. For example, monthly temperature at Mt Baw Baw for the baseline and

Mt Hotham.

Box 1: Dynamical Downscaling

The Climate Futures group's analyses draw on a computational methodology known as 'dynamical downscaling', a technique by which fine scale projections are derived from large-scale global climate models. Dynamical downscaling improves the representation of local features such as mountains, changing the dynamics of how atmospheric systems respond to the space they are in. This improves how various phenomena are simulated, such as: rain shadows; temperature changes on slopes with a particular aspect; different vegetation types; or soil layers. In addition to these geographic and land surface processes downscaling also introduces additional physical processes that these fine scale projections can resolve inside weather systems such as fronts, clouds, cyclones, sea-breezes and squalls, or the location of rain associated with these synoptic weather patterns. For Tasmania, the process turns a global general circulation model's 3-4 grid cells at ~200 kilometer resolution into a grid of more than 3,000 useful locations at ~10 kilometer resolution. In topographically varied regions like Tasmania or the Australian Alps, dynamical downscaling can add high levels of information about climatic variability across space and time. Figure 3 illustrates the dynamical downscaling process used by the Climate Futures projects. It is typically a two-stage process that takes the global scale climate simulations with adjustments to 0.1° degree resolution. The computing power required for such a task is considerable (current collections of simulations are ~500 terabytes and some simulations use hundreds of processors in parallel).

A visual and statistical demonstration of the improvement in statistical skill of simulating the current climate as a result of increased resolution within the climate model is illustrated in Figure 4 and Table 1. The increased correlation of simulations with the observed climate shows the surface temperature and rainfall distributions are dramatically improved with the inclusion of more detailed orography (i.e. the mountains) and land surface (e.g. vegetation; soil moisture) and the better physics from finer grid spacing (i.e. more accurate equations). For example, the GCM, 1° resolution, has a correlation of less than 0.45 for temperature and this increases to 0.93 at 0.1° resolution. The rainfall correlation, also increases markedly to 0.86, showing the value of increased resolution enhancing the spatial information of these two variables over the surface of Tasmania.

Model Resolution	Mean Monthly Temperature	Mean Monthly Rainfall
GCM	0.45	0.28
0.5°	0.79	0.44
0.1°	0.93	0.86

TABLE 1: Spatial Correlations for Rainfall and Temperature. Spatial correlation between the 0.1° AWAP data and GFDL-CM2.1 as the raw GCM and downscaled to 0.5° and 0.1° for the period 1961–1990 (from Corney et al. 2013). A correlation of 1 would be a perfect correlation with the AWAP data.

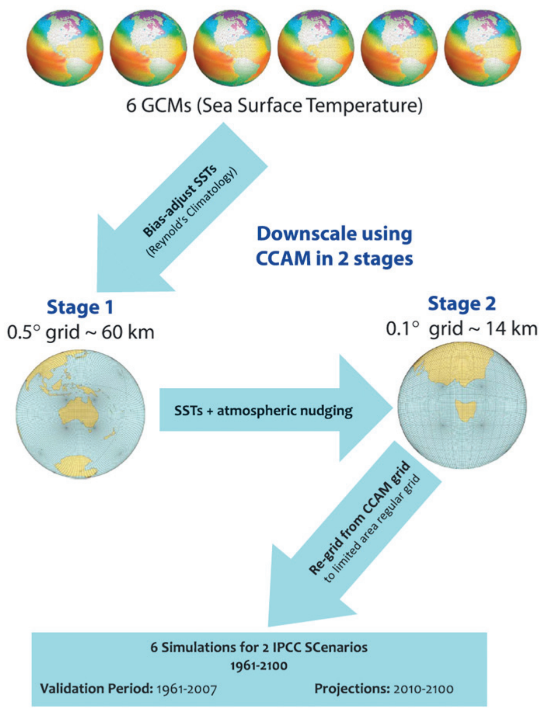


FIGURE 3: Schematic of the 2-stage dynamical downscaling process used in the Climate Futures projects with this example from the Climate Futures for Tasmania. It shows the low-resolution coupled GCM boundary condition (SST) through to the intermediate-resolution (0.5°) to the high-resolution CCAM 0.1° grid (adapted from Corney et al. 2013).

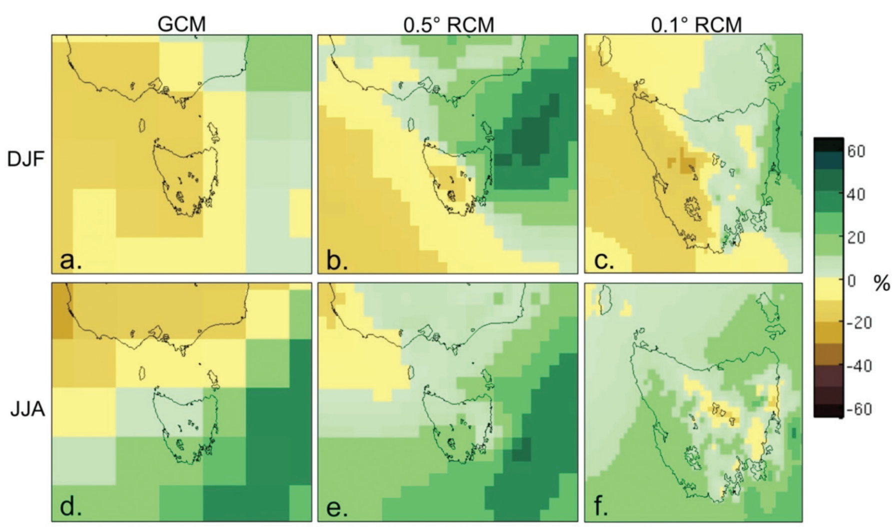
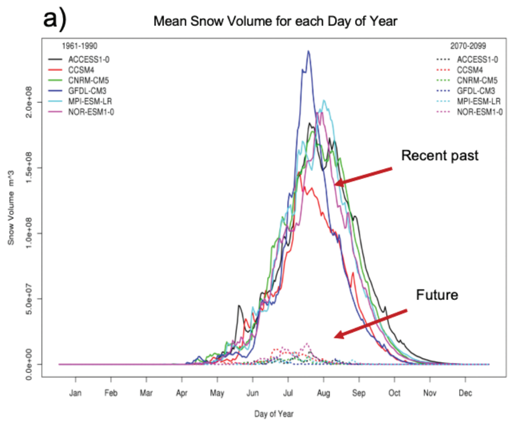


FIGURE 4: Projected changes in rainfall projections for Tasmania during this century. Areas of darker brown and yellow indicate drier areas, darker green indicates wetter areas. Finer resolutions increase the level of detail and accuracy of simulations of rainfall over Tasmania. Subfigures c and f represent the strong east-west gradient that is observed, and thus have greater relevance to decision-making than outputs like a, b, d and e. DJF are the December, January, and February periods with JJA being the June, July, and August periods.



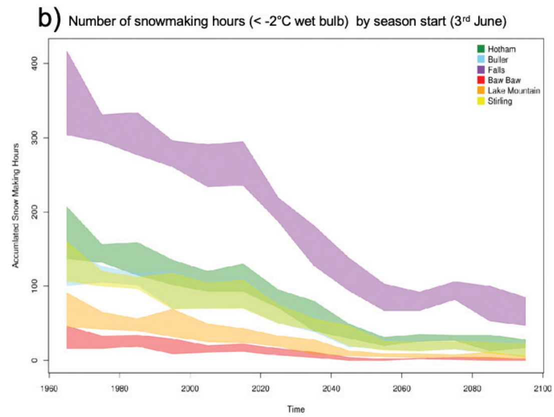


FIGURE 5:
Natural snow volume projections from 1961-1990 to 2070-2099 and projected snow making conditions using the downscaled fine resolution projections over the Southern Alps of Australia.

end-of-century periods are projected to increase in every month. By 2100, mid-winter is going to be more like the recent spring or autumn monthly temperatures. Summer will be warmer than previously experienced in the historical (or even recent paleo) records (Harris et al. 2016). Not only is temperature affected, but the high-pressure ridge over Australia tends to move southwards (e.g. Grose et al. 2010) and there are declines in seasonal and annual rainfall over the high elevation areas between 0-20%. Snow cover and volume will decline to the extent that eventually only the highest peaks (such as Mt Perisher and Falls Creek) will experience any snow (Figure 5); These changes vary seasonally and across the south east Australian region. These projected changes are likely to have a large impact on natural ecosystems and recreational use in the region.

They also affect the economic viability of snow-making under climate change. Research has focused on the supply side (climatic constraints on natural snow and snow-making conditions), as well as the demand side (visitor response) and the cost of snow-making operations and infrastructure. Several studies have shown that snow-making has an important role to play as alpine resorts adapt to declining natural snow cover around the world. There is overall consensus around the world that natural snow cover and depth will continue to decline and the length of the ski season contract further as the climate warms. Smaller resorts, those at lower altitudes, and those with inadequate snow-making facilities will be the most vulnerable to climate change. Snow-making is expected to sustain the ski industry in many regions until the middle of this century using current snow-making technologies and by mid-century there will be less natural snow and a significantly increased need for snowmaking at the same time as snow-making opportunities will decline. The projections of the annual hours for available for snow making ($<2°C$) is declining for all six of the Victorian ski resorts (Figure 5) and is typically reduced by a factor of 4(b). The economic costs of snow-making are expected to rise as natural snow cover declines (Figure 5 (a)), melting and evaporation rates increase (Harris et al. 2016) and water and electricity costs rise. More snow will need to be made at warmer temperatures, particularly at the beginning of the ski season (Harris et al. 2016). The economic viability of snow-making into the future will thus be determined by the extent of natural snow cover decline and the ability to make snow at reasonable cost required to sustain the ski season.

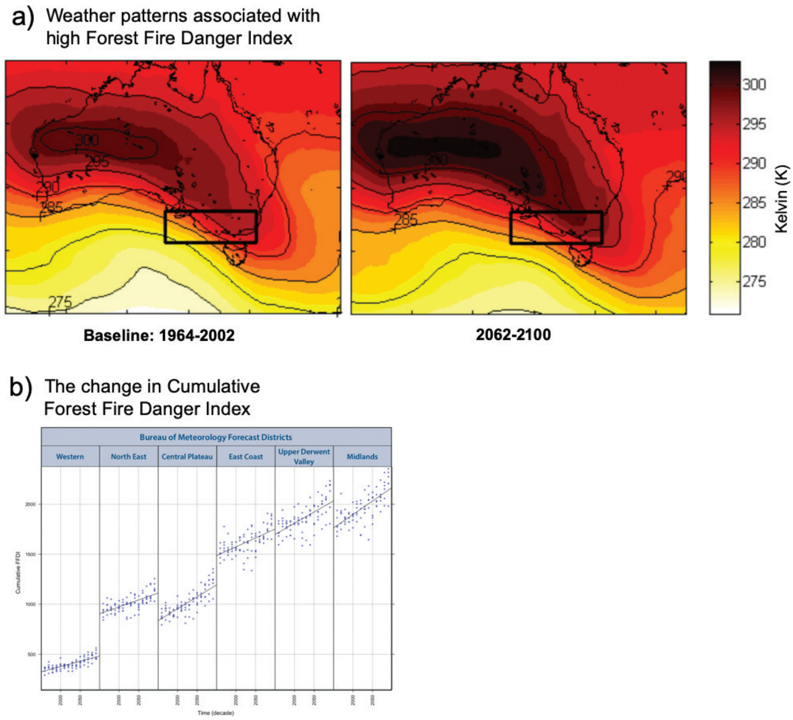
These projections for the Victorian ski resorts were used to assess changing conditions for making snow under warmer conditions and detailed visitation data and snow observations gathered by the industry were also assessed to understand the likely impacts on the preferences of visitors. Commercial operators at Victoria's world class ski fields are using this report to support long term investment, marketing and infrastructure decisions. The ability of alpine resorts to absorb rising costs will depend strongly on visitor perceptions of climate change and their responses to declining and less reliable natural snow cover.

2.2 Understanding Bushfire Risk

In 2015, the Climate Futures Group released a report assessing regional changes in fire danger in Tasmania through to 2100 under a high emissions climate change scenario. The projections indicate a continued, steady increase in fire danger, as well as a longer and more intense fire season throughout most of the state. Most importantly for those who manage fire risk on the ground, the report provides detail on which geographical areas are likely to face the largest increases in fire risk.

Perhaps most striking results from this fire report is the suite of peer reviewed research papers (Grose et al. 2010; Corney et al. 2013; Grose et al. 2013; Grose et al. 2014; Fox-Hughes et al. 2014; Fox-Hughes et al. 2015) that together provide a robust assessment of the future risk of fire and its causes

FIGURE 6: Panel (a) The air temperature at the 850 hPa level during high fire danger days of strong prefrontal winds and composited together for the Baseline period and future projected period. Panel (b) Cumulative Forest Fire Danger Index for the six regional climate models in this study, averaged by Bureau of Meteorology weather forecast district and by each decade from 1960 to 2090. Solid black line highlights the general trend, where a steeper slope indicates more rapid increase in Cumulative Forest Fire Danger Index values.



for Tasmania. The best available science supports the assessment (Fox-Hughes et al. 2014) of the following types of fire relevant changes by the end of the century. The type of strong weather systems that bring the majority of the worst fire weather days to south–east Tasmania is projected to become more frequent and more intense (Figure 6 (a)). The weather systems (composited together) in the baseline period and the future period show very strong northwesterly winds drawing dry air from over the Australian continent. The temperature gradient in the black box does not change markedly and the winds remain about the same, but absolute air temperatures increases dramatically. The implication being that under a high emissions scenario the high fire danger days are as windy, but much hotter than we have had in the past. All regions exhibit an increase in Cumulative Forest Fire Danger in each season (Figure 6 (b)). The most rapid increases in Cumulative Forest Fire Danger Index (about a 30% increase on 1961–1980 values) are in the regions that already have the highest values of this index: that is the East Coast, Midlands and Upper Derwent Valley.

The systematic analysis of future fire weather projections for Tasmania to 2100 (under a high emissions scenario) show that these changes are significant in terms of their impacts on fire risk and for the management of fire risk. The total number of days per year categorised as ‘Very High Fire Danger’ is projected to increase by at least 120% (i.e. doubled). In the future, this is about a 10% per decade increase to 2100. Projected changes show strong regional and seasonal variations. Regions currently with the greatest risk of fire are projected to get worse most rapidly. The area of Tasmania under 'Total Fire Ban' conditions during summer due to fire weather is projected to increase by at least 75%. This is a 6% increase per decade. The average area of Tasmania in spring categorised as 'Very High Fire Danger' is projected to increase by at least 250%. This is a 20% increase per decade. Paradoxically, there is no major change to the fire danger risk in autumn. The analysis also suggests that for this high emissions scenario the fire weather impacts could be conservative estimates of the potential future changes.

At its release, the study was the highest-resolution, long-term climate modelling study of future fire risk ever produced in Australia. The main results of this scenario were the increased number of catastrophic fires days, the doubling of the area of Tasmania experiencing high fire danger days and the lengthening of the season and advance of these days into spring season.

Ongoing research is investigating how changes to fire danger may affect the viability of prescribed burning as a tool to reduce fuel loads in the future. The results show that there may be a narrower window of suitable conditions for burning, as temperatures and fuel availability increase and fuels become drier across Tasmania in spring and autumn (Harris et al.

iStock

Future fire risk shows an increased number of catastrophic fires days and lengthening of the season.

2019). This will affect the timing and resourcing of prescribed burning, and alternative methods to build resilience and manage bushfire risk may need to be considered. Recent research into plant productivity and the changes in the distribution of key forest species (e.g. Eucalyptus species) has also highlighted the potential for future changes of fuel load and flammability under a changing climate.

Assessment of fire risk in Tasmania's iconic World Heritage Area was also undertaken after the disastrous fires in that occurred in January-February 2016. The observed trend of steadily increasing fire danger during spring (Fox-Hughes 2015) is projected to continue throughout the current century. For the soil dryness index (MSDI) (Mount 1972), this brings the onset of historical spring conditions forward by at least two weeks by the end of the century, while the onset of summer is more than one month earlier. In the near future there is a projected break from the historically steady autumn conditions towards increasing fire danger. By 2100 historical autumn conditions begin around six weeks later than currently and persist for less than two months. As a result, summer would be around 8 weeks longer, with percentage increases in the current summer peak dryness index by 50-100% (Love et al. 2017).

In moorlands of the Tasmanian Wilderness World Heritage Area (TWWHA) soil dryness appears to be the dominant driver of forest fire danger index (FFDI) which exhibits similar although less pronounced changes in seasonality and peak summer percentiles. Similar decreases in moisture factor are largely offset by decreases in wind speed resulting in relatively small increases in fire season mean moorland fire danger index (MFDI). At the higher percentiles the summer peak weakens throughout the century while the spring peak strengthens slightly and takes over as the dominant moorland fire danger period.

The changes in 30-day antecedent rainfall begin in the near future and are confined to summer and autumn. This is a tendency towards much more widespread occurrences of these dry periods. At higher percentiles the summer peak is already close to 100% of the TWWHA so large further increases in extent are not possible. The number of days per fire season on which the dry period criterion is met at any given location in the TWWHA is projected to triple by the end-of-century. In the adjacent areas these indicators show a very dramatic change in conditions with mean daily extent of affected area increasing from near zero to around 10% and 6% for MSDI > 50 and dry periods respectively (Love et al. 2018).

The results from the world heritage risk assessment are being used by the Tasmanian Fire Service, Parks and Wildlife Service and the Tasmanian Wilderness World Heritage Area to inform long term planning, resourcing and infrastructure decisions.

2.3 Sea-level Rise

Global sea levels have been rising slowly over the past 100 years and many coastal regions are currently experiencing the impacts of both erosion and inundation. These changes are expected to have a major impact on human societies because of the significant concentration of communities and infrastructure in coastal regions. Understanding the contributions to present sea level rise, and their causes, is crucial to projecting what might happen in the future.

As sea levels rise, the severity and frequency of extreme events driven by atmospheric pressure, tides and storm surges is expected to increase. With 85% of Australia's population living in coastal areas, understanding the risks to infrastructure and private property is critically important.

With some analyses projecting sea level rises of more than a meter by 2100 (Church et al. 2013), accurate sea-level projections are, today, vital for planning in coastal areas. An example of the sensitivity of coastal environments to seemingly small changes in sea level is Georgetown Tasmania. An analysis of extreme sea-level changes from low emissions scenario of the 1:100 year return period occurs shorter than 3 years, and for a high emission scenario the same 1:100 return period becomes every year. This is a 100-fold reduction in the return period by the end of the century (McInnes et al. 2011.

The ACE CRC has helped Australia plan and prepare for future sea level changes by providing specialised technical consulting, specialised vocational training for governments and industry, and developed a sea-level rise calculator tool called Canute2 (and it's replacements Canute3.0). Canute has been adopted by the Institute of Public Works Engineers Australia (IPWEA) to upskill their members in how to incorporate sea-level rise into future projects. The web tool provides estimates of the necessary elevation for infrastructure on hard shorelines. In the case of soft shorelines, the platform estimates the

iStock

Sea-level projections are vital for planning in coastal areas.

distance infrastructure needs to be set back from the water to avoid shoreline recession. In developing the system, scientists looked at data from tide gauges and storm surge modelling at 12,000 points roughly every 2.5 kilometers around the Australian coast. Using this data, ACE CRC scientists created a suite of calculators that allow coastal planners to estimate a range of factors, such as waves and tropical cyclones, that can impact on the positioning of infrastructure.

2.4 Climate Variability and the Australian Wine Industry

The Climate Futures group worked with the wine industry to identify the main weather and climate risks that affect them, assess how these risks change with climate change and identify ways to adapt to these risks. The research has provided an understanding of short-term climate variability, as well as trends in climate indices for the near and mid-term time scales. The legacy of the project is a very distinctive and comprehensive national atlas covering every wine region in Australia (Australia's Climate Future - A Climate Atlas) (Remenyi et al. 2019). This online atlas will provide climate information in an accessible, usable form to grape growers and winemakers across Australia.

To carry out this assessment, new high-resolution climate projections for southeastern Australia have been produced in partnership with CSIRO using their Conformal Cubic Atmospheric Model (CCAM) model. These projections represent a significant enhancement of the earlier Climate

Wine grapes.

What will the climate of my region be like in the future?

FIGURE 7: Examples of the viticultural indices calculated for four specific Australian wine regions and presented in the online atlas, Australia's Wine Future - a Climate Atlas. The four panels, in clockwise order represent the changing index of aridity in Margaret River, the changing distribution of the growing season in the Hunter Valley, the projected monthly minimum temperature in east coast Tasmania and the rising number of extreme heat days in the Barossa Valley. A total of nineteen different indices are presented for each wine region in Australia.

Futures simulations (for Tasmania and southern Australia) and utilise the more recent Climate Model Intercomparison Project version 5 (CMIP5) as the global driving data. These projections also include the new improvements in CCAM for precipitation and other processes.

The use of fine-scaled climate information has enabled the variability within and across Australian wine regions to be visualised (e.g. Figure 7). In the Climate Atlas, data are presented that show recent observed climate conditions during the period 1997-2017 for every Australian wine region. From the baseline conditions in each region, future changes in viticultural indices are presented. Tailored viticultural indices, identified as being relevant to the wine industry through extensive consultation, were calculated for every wine region (Geographic Indicators) in Australia. Indices representing temperature, rainfall and evaporative demand, heat accumulation and heat and cold extremes are presented to identify changing climate suitability in the near future and out to longer-term planning horizons.

The research provided industry with the first fine-scaled climate information to identify the most appropriate adaptation response within each wine region to maintain grape yield, value and wine style into the future.

3

FUTURE DIRECTIONS

3.1 Future Research

Climate impacts and related assessments is a growing activity and the demand will remain strong for the reasons outlined in Section 1.1. The questions that are being asked are becoming more sophisticated and require greater nuancing over earlier work. Fortunately, over the last decade there have been a significant number of developments in the analytical tools used to assess climate model simulations that can support this growing need for more sophisticated assessments. There are also new simulations of varying types becoming available (nationally and internationally). It is the authors' view that these new analytical approaches to the analysis of simulations is where the real advances will be made in future climate impacts assessments.

There are at least ten broad areas of new research approaches that have emerged in the scientific literature from which policy makers could benefit in their application. These are coincident events, compounding events, attribution of observed average changes, attribution of extremes (fractional attributable risk), time of emergence, synoptic weather typing, fire risk, run off and rivers flows, CMIP6 and related downscaled simulations and climate predictions (Bindoff et al. 2018, Table A4) and some of these are discussed briefly below.

Some developments have been reflected extensively in the previous IPCC assessments. For example, the testing of human influence in the observational record, in particular around the attribution of human influence on extreme events (Bindoff et al. 2013; King et al. 2016; Karoly et al. 2016). This question is central to determining whether the observed trends are really related to climate change. There are examples in the literature where there have been false attributions of trends to climate change with expensive consequences.

There is a new recognition that natural disasters magnify the consequences of climate change. An example of a coincident event in Tasmania is the record heavy rains and floods in 2016 in Northern Tasmania that resulted in extensive damage estimated to be $180 million and the loss of 3 lives. In this instance there were many regions flooding simultaneously (which is unusual in a Tasmanian context).

Another type of extreme is two or more consecutive events called compound events, such as the winter dry spell in 2015 and the floods in autumn of 2016, that together magnify the consequences of each other (Bindoff et al. 2016). Such compounding extreme events have not been considered in any of the earlier work assessing climate change in Tasmania (or Australia), and have led to new questions about their complex relationships. Similar questions arise around the incidence of fire and flood, fire and droughts and other extremes. Extremes (including coincident and compounding events) and climate impacts are highly connected and affect diverse areas such as human health (e.g. heat stress, mortality), agricultural supply chains (disruption) and the financial costs of climate change impacts on assets.

The IPCC WG2 in particular takes a hazard, exposure and vulnerability approach to its assessments of the impacts of climate change to estimate the changing risks from climate change (Field et al. 2014). This approach drives a more strategic analysis of the factors that affect risk from climate change and indeed formalising these types of assessments is important to providing more specific guidance framework for decision makers. The risk assessment also includes how risk from climate change can be diminished through adaptation and identification of adaptation limits.

Climate change projections feature intrinsic uncertainties, including: the emissions pathway society will follow; imperfect knowledge of natural climate variability; different mechanisms driving change, represented as differences between global climate models; and known inadequacies with the model capabilities (i.e. resolution limitations). Therefore, there is the opportunity to examine new climate model simulations with more updated configurations to uncover new insights they may have for Tasmania's future climate.

The new simulations, especially those that include ensembles that enable insight into the scientific drivers of particular extreme events, increase our capacity to more fully understand the uncertainty and the changes in risk for the future climate, while also assessing the risk that has already occurred. New approaches using massive ensemble simulations provide insight into the possibilities from projects like Weather@home and hosted in Hobart (Black et al. 2016).

The combination of new approaches (Bindoff et al. 2018, Table A4) to the understanding of extreme events and the emergence of climate change signals, combined with new models and simulations, makes it timely to undertake a re-examination of the future climate and what its consequences are for the Tasmanian economy.

There are many options open to a new program of climate change assessments. The goals and strategy of a program tie into stakeholder needs but also the legislative and political environment in which it operates – thus specific to the place and timeline. Practical realities include the cost and availability of new modelling or other analysis, the capacity and mechanisms for taking projections into applied research through to decision-making and policies.

3.2 Potential Future Assessments

A recent review of climate change research on Tasmania identified several gaps in knowledge that limit the State's ability to prepare for the impacts of climate change (Bindoff et al. 2018). One of the conclusions of that report is that, coincident and compounding extreme events, biosecurity and invasive pests and water security are likely new priority areas to form the core of the Climate Futures' research in the coming years (Figure 8). Communication of how climate risk may impact policy makers and industry, and how they can best use climate information will remain an important part of the Climate Futures' research. New research is now emerging on coincident and compounding events for Tasmania.

The largest gaps relevant to the Action 1.1 of Climate Action 21 are across key sectors of the state economy, its natural environment and the state infrastructure (Bindoff et al. 2018, Tables A1 to A4 detail the past and current work being undertaken in Tasmania and Australia with Table A5 summarising the gaps in the science that remain). While the number of projects that have been completed is large (> 75 projects) and have covered many aspects of the state economy, there are still some very significant aspects of the Tasmanian State economy that have not been considered. The gaps identified below are derived from recent consulting reports to Hydro Tasmania, from stakeholder engagements, surveys carried out by TCCO and a meta-analysis of the climate change reports and research papers already completed (Bindoff et al. 2018, all listed in Appendix A).

iStock

Wivenhoe Dam, Queensland.

Water underpins many of the activities in the state. Tasmania is relatively water rich, with 12% of Australia's total water supply, but less than 1% of Australia's land area (Bennett et al. 2010). There has been new infrastructure that is sensitive to changing climate (e.g. the $220 million investment in Tasmanian Irrigation Scheme). About 70% of Tasmania's electricity comes from hydropower and some of this power is sold on the national electricity grid through Bass link. Energy security is also an important aspect of the state economy (Tasmania Energy Security) and this was brought sharply into focus by the low rainfalls in spring of 2015, and the devastating floods in autumn of 2016. Tasmania is vulnerable to rainfall variations in successive years, as well as intense short period extreme events. Past projections concluded that the annual rainfall was unlikely to change significantly over the coming century, but that there would be significant changes in the seasonal distribution of rainfall (Grose et al. 2010). Tasmania is clearly vulnerable to exceptional seasonal and decadal variations from changes in the frequency of extreme rainfall and floods in a changing climate and these have remain largely unassessed on the near and long term. Future assessment should therefore prioritise assessments of the changing risk for state and national infrastructure for compound and coincident extreme rainfall events (including drought and flood) that affect water use.

Agriculture (together with aquaculture) is another key sector of the Tasmanian economy. Agriculture is currently growing at 8% per annum, faster than the other sectors of the state economy. The Climate Futures for Tasmania project only covered dairy and wine grapes in detail (about $415 million of the state farm-gate value for 2015-2016 year) (Holz et al. 2010) and thus the remaining 80% of the agricultural sector has effectively not been assessed for future climate risks, although there is additional adaptation work being undertaken by the Department of Primary, Industry, Parks, Water and Environment. One approach to prioritisation of the agriculture sector would be by economic turnover, and this would suggest a climate impacts analysis for meat and livestock with a value of $451 million, (beef $306 million, lamb and mutton, $88 million, and other livestock at $57 million) as a first priority followed by other agriculture including fruit and vegetables. Further consultation is required to those agriculture sectors that are more vulnerable to climate change impacts or where there are areas of potential growth as a result of more favourable conditions into the future due to climate change, but are clearly areas for new assessments and strategic planning.

Biosecurity and invasive pests are a concern for Tasmanian agriculture and also the state's natural assets. Tasmania is fruit-fly free, and this status is worth in excess of $100 million per annum to the State. However, there are many other

Victorian Alps.

damaging invasive species and there has been no systematic assessment across the potential invasive species that affect this sector for climate change (Harris et al. 2017). From a policy perspective, an estimate of the time of emergence of viable populations of pests in the different regions of the State is essential information for planning and adaptation.

Tasmania is surrounded by ocean. Aquaculture and wild fisheries account for around half the economic value of the agriculture sector. These areas are likely to grow and climate change (and its extremes) pose a potential risk with the increased risk of disease and reduced chance of commercially important marine species reaching maturity (e.g. Oliver et al. 2017). A comprehensive assessment of the impacts of climate change for this potential risk has yet to be undertaken.

Currently tourism to Tasmania (directly and indirectly) generates $2.79 billion or 10.7% of the state's gross state product, which is slightly larger than the farm-gate value of agriculture. Tasmania's natural environment is an important part of the tourism sector and is vulnerable to extreme weather events that are projected to become more frequent and more intense as the climate warms. An example of this sensitivity is the concern expressed by tourists and subsequent fall in visitor numbers after the bushfire in Tasmania's World Heritage Area (Press 2016). The risk of bushfire has already been assessed across the state and in the Tasmanian World Heritage Area. However, there is a need to assess more broadly how climate extreme events (heat waves, storms, floods) will affect Tasmania's unique biodiversity. Many questions concerning the diversity and stability of natural ecosystems need to be addressed (Harris et al. 2018), including the potential for the changing incidence of heat waves and precipitation to cause both gradual and rapid collapses in Tasmania's (and Australia's) rich biodiversity.

With regards to human health and wellbeing, the World Health Organisation (WHO) has recently identified the projected changes in climate as being "overwhelmingly negative", especially for regions with the poorest infrastructure that have the most limited capacity to adapt, prepare and respond to increased health risks (World Health Organisation 2017). Research has recognised climate change as "the biggest global health threat of the 21st Century" putting the "lives and wellbeing of billions of people at increased risk" representing "an unacceptably high and potentially catastrophic risk to human health" (Costello et al. 2009; Watts et al. 2015). In light of this, it is important to identify the pressing emerging local threats of climate change relating to human health and wellbeing, and conduct a vulnerability assessment of the prioritised issues.

Assessments of climate change and its consequences need to be translated into decisions (either explicitly or implicitly). Tools that help incorporate climate information seamlessly into decision-making and policy frameworks is an essential part of the process and has been identified as a gap. Software that has already been developed includes the ACE CRC sea level rise estimator, CANUTE and the award winning Pitt&Sherry ClimateAsyst tool. These are examples of tools designed in collaboration with industry to help day-to-day decision-making and planning, in this case for civil engineers. These types of tools are missing from most industries toolkit, and would be a high value activity to progress to support operational decisions, strategic long term decisions and policy development activities.

Of all the natural hazards, coastal inundation, and the associated risk of future sea-level rise due to climate change, is the most mature and developed in a policy context. An official policy and guidelines exist (Tasmanian Local Council Sea Level Rise Planning Allowances) and these have been incorporated into land use assessment and building approval processes by local governments around the State. New science is emerging around the sensitivity of sea-level rise from the melt of Greenland and Antarctica and from mountain glaciers (e.g. Church et al. 2013; Pollard and DeConto 2016).

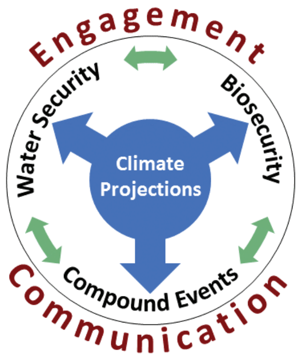


FIGURE 8: Moving forward, the Climate Futures Program aims to target three key environmental sectors of the state economy, namely: water security, biosecurity and compound events. The program of activities will be co-developed with stakeholders to ensure the design of the research acitivites, and the communication of the final outputs continue to useful, usable and used by our stakeholders and the broader community.

A recent position analysis from the ACE CRC, The Antarctic Ice Sheet & Sea Level, summarises the current science of the Antarctic Ice Sheet and its contribution to the sea-level rise. There is significant evidence that sea level rise is significantly underestimated. However, in the sea level rise community, future sea level and rates of sea-level rise is a contentious issue, because the uncertainty of the underlying science, in particular the processes and mechanisms required to project future sea level. From the perspective of the Tasmanian government the most appropriate time to review the current policies and guidelines would be following the more comprehensive assessment of sea-level rise which will come from the Sixth IPCC Assessment Report, due for release in early 2022.

The successful transformation of research into policy doesn't occur when the 'researchers get it right', it occurs only when there is a genuine collaboration between policy and research, fostering a mutual understanding across the policy-research divide. Previous successes in Tasmania have been largely driven by policy makers within government having sufficient scientific and domain expertise to champion a research question and solicit researchers input for targeted projects. When policy makers can be engaged and upskilled enough in a particular research domain to design their own research questions, their capacity to provide governance, guidance and input to a project dramatically improves, resulting in research outcomes that are more relevant and usable in a policy context. Similarly, when researchers are upskilled in the needs and demands of policy makers, it improves their ability to tailor the outputs to suit.

The Climate Futures for Tasmania Project had initial guidance from champions within government, but it was the regular meetings with policy makers throughout government that fostered the capacity of the policy makers to understand the science (and the researchers to understand the kinds of required outputs) and resulted in the long-lasting impact in government and the community.

However, even in ideal situations, stakeholder or community engagement is a real skill, requiring significant effort. In the Climate Futures for Tasmania Project, 30-60% of the researchers' time and energy was spent on stakeholder engagement, community outreach and communications. These activities were coordinated by a dedicated communications officer. This role is one of the core reasons for the on-going legacy and success of the Climate Futures for Tasmania Project. Future assessments would do well to learn from the previous programs approach to communications and improve on it wherever possible.

Transforming data into a usable form also has another important aspect. Data from the Climate Futures for Tasmania Project is open-access, freely available to everyone. However, the data archive is large (~200Tb), stored in a complex data format and requires significant specialised expertise to access, navigate and use. This is a major limitation for government departments trying to access the data for project-based activities. In order to improve how 'actionable' the outputs (i.e. bulk-data, derivative-layers, reports) from a future project could be, significant effort must be placed in developing online tools that simplify accessibility and usability for non-expert users. Tools would incorporate functions such as archive access and navigation; data-discovery and exploration; and analysis and visualisation.


iStock

Lake Mountain, Victoria.

REFERENCES

1 Bennett, J.C., Ling, F.L.N., Graham, B., Grose, M.R., Corney, S.P., White, C.J., Holz, G.K., Post, D.A., Gaynor, S.M. and Bindoff, N.L., (2010). Climate Futures for Tasmania: water and catchments technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
2 Black, M.T., Karoly, D.J., Rosier, S.M., Dean, S.M., King, A.D., Massey, N.R., Sparrow, S.N., Bowery, A., Wallom, D., Jones, R.G., Otto, F.E.L., and Allen, M.R., (2016). The weather@home regional climate modelling project for Australia and New Zealand, Geoscience Model Development, 9, 3161-3176, doi:10.5194/gmd-9-3161-2016.
3 Bindoff, N.L., Stott, P.A., AchutaRao, K.M., Allen, M.R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Mokhov, I.I., Overland, J., Perlwitz, J., Sebbari, R. and X. Zhang, (2013). Detection and Attribution of Climate Change: from Global to Regional. [In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
4 Bindoff, N.L., Grose, M.R., Bennett, J.C., Schepen, A. and Wang, Q.J., (2016). Precipitation and inflow trends and forecasting in Hydro Tasmania catchments: a review. Technical report. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia.
5 Bindoff, N.L., Love, P.T., Grose, M.R., Harris, R.M.B., Remenyi, T.A., White, C.J., (2018). Review of climate impact change work undertaken, research gaps and opportunities in the Tasmanian context: Technical report. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia.
6 Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D. and Unnikrishnan, A.S., (2013). Sea Level Change. [In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
7 Corney, S., Grose, M., Bennett, J. C., White, C., Katzfey, J., McGregor, J., Holz, G., and Bindoff, N. L., (2013). Performance of downscaled regional climate simulations using a variable-resolution regional climate model: Tasmania as a test case. J. Geophys. Res. Atmos., 118, 11,936-11,950, doi:10.1002/2013JD020087.
8 Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Friel, S., Groce, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., Mccoy, D., Mcguire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., De Oliveira, J. A. P., Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J. and Patterson, C., (2009). Managing the health effects of climate change. The Lancet, 373, 1693-1733.
9 Field, C.B., Barros, V.R., Mach, K.J., Mastrandrea, M.D., van Aalst, M., Adger, W.N., Arent, D.J., Barnett, J., Betts, R., Bilir, T.E., Birkmann, J., Carmin, J., Chadee, D.D., Challinor, A.J., Chatterjee, M., Cramer, W., Davidson, D.J., Estrada, Y.O., Gattuso, J.-P., Hijioka, Y., Hoegh-Guldberg, O., Huang, H.Q., Insarov, G.E., Jones, R.N., Kovats, R.S., Romero-Lankao, P., Larsen, J.N., Losada, I.J., Marengo, J.A., McLean, R.F., Mearns, L.O., Mechler, R., Morton, J.F., Niang, I., Oki, T., Olwoch, J.M., Opondo, M., Poloczanska, E.S., Pörtner, H.-O., Redsteer, M.H., Reisinger, A., Revi, A., Schmidt, D.N., Shaw, M.R., Solecki, W., Stone, D.A., Stone, J.M.R., Strzepek, K.M., Suarez, A.G., Tschakert, P., Valentini, R., Vicuña, S., Villamizar, A., Vincent, K.E., Warren, R., White, L.L., Wilbanks, T.J., Wong, P.P., and Yohe, G.W., (2014). Technical summary. [In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.
10 Financial Stability Board, Task Force on Climate-related Financial Disclosures, (2017). Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures, https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Report-062817.pdf.
11 Fox–Hughes, P., Harris, R.M.B., Lee, G., Grose, M. and Bindoff, N.L., (2014). Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. International Journal of Wildland Fire. 23(3) 309–321, http://dx.doi.org/10.1071/WF13126.
12 Fox-Hughes, P., Harris, R.M.B., Lee, G., Jabour, J., Grose, M.R., Remenyi, T.A., and Bindoff, N.L., (2015). Climate Futures for Tasmania future fire danger: the summary and the technical report. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
13 Grose, M.R., Barnes-Keoghan, I., Corney, S.P., White, C.J., Holz, G.K., Bennett, J.C., Gaynor, S.M. and Bindoff, N.L., (2010). Climate Futures for Tasmania: general climate technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
14 Grose, M.R., Corney, S.P., Katzfey, J.J., Bennett, J.C. Holz, G.K. White, C.J., Bindoff, N.L., (2013). A regional response in mean westerly circulation and rainfall to projected climate warming over Tasmania, Australia, Climate Dynamics Volume: 40 Issue: 7-8 Pages: 2035-

2048 Published: 2013, doi:10.1007/s00382-012-1405-1.
15 Grose, M.R., Fox-Hughes, P., Harris, R.M.B. and Bindoff, N.L., (2014). Changes to the drivers of fire weather with a warming climate — a case study of southeast Tasmania. Climatic Change, 124, 255–269.
16 Harris, R.M.B., Remenyi, T. and Bindoff, N.L., (2016). The Potential Impacts of Climate Change on Victorian Alpine Resorts. A Report to the Alpine Resorts Co-ordinating Council. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia.
17 Harris, R.M.B., Kriticos, D.J., Remenyi, T.A. and Bindoff, N.L., (2017). Unusual suspects in the usual places: A phylo-climatic framework to identify potential future invasive species. Biological Invasions, 19, 577–596, doi:10.1007/s10530-016-1334-8.
18 Harris, R.M.B., Beaumont, L.J., Vance, T.R., Tozer, C.R., Remenyi, T.A., Perkins-Kirkpatrick, S.E., Mitchell, P.J., Nicotra, A.B., McGregor, S., Andrew, N.R., Letnic, M., Kearney, M.R., Wernberg, T., Hutley, L.B., Chambers, L.E., Fletcher, M.-S., Keatley, M.R., Woodward, C.A., Williamson, G., Duke, N.C., and Bowman D.M.J.S., (2018). Biological responses to the press and pulse of climate trends and extreme events. Nature Climate Change, 8, 579–587, doi:10.1038/s41558-018-0187-9.
19 Harris, R.M.B., Love, P.T., Remenyi, T.A., Fox-Hughes, P., Bindoff, N.L., (2019). An assessment of the viability of prescribed burning as a management tool under a changing climate. A Report for the National Bushfire Mitigation – Tasmanian Grants Program (NBMP). Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Australia.
20 Holz, G.K., Grose, M.R., Bennett, J.C., Corney, S.P., White, C.J., Phelan, D., Potter, K., Kriticos, D., Rawnsley, R., Parsons, D., Lisson, S., Gaynor, S.M. and Bindoff, N.L., (2010). Climate Futures for Tasmania: impacts on agriculture technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
21 IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1-1535.
22 IPCC (2018). Summary for Policymakers. [In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (eds.)]. World Meteorological Organization, Geneva, Switzerland, 1-32.
23 Johnson, C.R., Banks, S.C., Barrett, N.S., Cazassus, F., Dunstan, P.K., Edgar, G.J., Frusher, S.D., Gardner, C., Haddon, M., Helidoniotis, F., Hill, K.L., Holbrook, N.J., Hosie, G.W., Last, P.R., Ling, S.D., Melbourne-Thomas, J., Miller, K., Pecl, G.T., Richardson, A.J., Ridgway, K.R., Rintoul, S.R., Ritz, D.A., Ross, D.J., Sanderson, J.C., Shepherd, S.A., Slotwinski, A.,Swadling, K.M. and Taw, N., (2011). Journal of Experimental Marine Biology and Ecology, 400, 1–2, 30 April, 17-32, doi: 10.1016/j.jembe.2011.02.032.
24 Karoly, D.J., Black, M.T., King, A.D., and Grose, M.R., (2016). The Roles of Climate Change and El Niño in the Record Low Rainfall in October 2015 in Tasmania, Australia [in "Explaining Extremes of 2015 from a Climate Perspective"], Bulletin of the American Meteorological Society, 97, 12, S127-S130, doi: 10.1175/BAMS-D-16-0139.1.
25 King, A.D., Black, M.T., Min, S., Fischer, E.M., Mitchell, D.M., Harrington, L.J., and Perkins-Kirkpatrick, S.E., (2016). Emergence of heat extremes attributable to anthropogenic influences, Geophysical Research Letters, 43, 7, 1944-8007. doi:10.1002/2015GL067448, 3438--3443 (2016)
26 Love, P.T., Fox-Hughes, P., Remenyi, T.A., Harris, R.M.B., and Bindoff N.L., (2017). Impact of climate change on weather related fire risk in the Tasmanian Wilderness World Heritage Area Climate Change and Bushfire Research Initiative, Technical Report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
27 Love, P.T., Remenyi, T.A., Harris, R.M.B., and Bindoff N.L., (2018). Tasmanian Wilderness World Heritage Area Climate Change and Bushfire Research Initiative, Technical Report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
28 McInnes, K.L., O'Grady, J.G., Hemer, M., Macadam, I., Abbs, D.J., White, C.J., Corney, S.P., Grose, M.R., Holz, G.K., Gaynor, S.M. and Bindoff, N.L., (2011). Climate Futures for Tasmania: extreme tide and sea-level events technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.
29 Moore, F.C. and Diaz, D.B., (2015). Temperature impacts on economic growth warrant stringent mitigation policy, Nature Climate Change, 5, 127–131.
30 Mount, A.B., (1972). The derivation and testing of a soil dryness index using run-off data, Bulletin 4, Forestry Commission of Tasmania.
31 Nicholls, N. and Collins, D., (2006). Observed change in Australia over the past century. Energy and Environment 17, 1-12.
32 Oliver, E.C.J., Benthuysen, J.A., Bindoff, N.L., Hobday, A.J., Holbrook, N.J., Mundy, C.N. and Perkins-Kirkpatrick, S.E., (2017). The unprecedented 2015/16 Tasman Sea marine heatwave. Nature Communications, 8, 16101 doi:10.1038/ncomms16101
33 Pollard, D. and DeConto, R.M., (2016). Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591–597, doi: 10.1038/nature17145.
34 Press, A.J., (2016). Tasmanian Wilderness World Heritage Area Bushfire and Climate Change Research Project. Tasmanian Government, Department of Premier and Cabinet, Hobart.
35 Remenyi, T.A., Rollins, D.A., Love, P.T., Earl, N.O., Bindoff, N.L., and Harris R.M.B., (2019). Australia's Wine Future - A Climate Atlas. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart.
36 R2R2018: How Australia's island state prepares for climate shifts, 25 August 2018: https://www.utas.edu.au/news/2018/8/25/789-how-australias-island-state-prepares-for-climate-shifts/.
37 Summerhayes, G., (2017). Australia's new horizon: Climate Change challenges and prudential risk. Insurance Council of Australia Annual Forum, Sydney, (available here).
38 TCCO (2017). Climate Action 21 - Tasmania's Climate Change Action Plan 2017-2021, (available here), Tasmanian Government, Department of Premier and Cabinet, Tasmanian Climate Change Office, Hobart.
39 Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H. and Costello, A., (2015). Health and climate change: policy responses to protect public health. The Lancet, 386, 1861-1914.
40 White, C.J., Remenyi, T.A., McEvoy, D., Trundle, A. and Corney, S.P., (2016). 2016 Tasmanian State Natural Disaster Risk Assessment, University of Tasmania, Hobart.
41 World Economic Forum (2016). The Global Risks Report 2016, 11th Edition, Geneva, Switzerland.
42 World Health Organisation (2017). World health statistics 2017: monitoring health for the SDGs, Sustainable Development Goals. Geneva.

WEBSITES

Canute 2.0: http://canute2.sealevelrise.info/index.php
Canute 3.0: https://shiny.csiro.au/Canute3_0/
ClimateAsyst: http://climateasyst.pittsh.com.au/app/
TheLIST: https://www.thelist.tas.gov.au/app/content/data
Weather@home ANZ: https://www.climateprediction.net/weatherathome/

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE