Climate Impacts AND ADAPTATION SCIENCE

Issue 1 |

Planned Adaptation to Climate Change

Edited by: *Adam Fenech*
Don MacIver
Neil Comer

Climate Impacts and Adaptation Science

An interdisciplinary journal on understanding
the theory and practice of responding to climate change

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Aims and scope.

Climate Impacts and Adaptation Science aims to provide an international and interdisciplinary forum for highlighting the concerns and needs in adapting to the effects of climate change. This journal aims to provide a forum for up-to-date study, research and thinking on the impacts of climate change; the vulnerability to future climate change; current adaptation plans, strategies and actions; and future adaptation options and needs.

The urgency for climate change adaptation is highlighted by projections from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2007. Under a business as usual scenario, greenhouse gas emissions could rise by 25 to 90 per cent by 2030 relative to 2000 and the Earth could warm by 3°C this century. Even with a temperature rise of 1 of 2.5°C, the IPCC predicts serious effects including reduced crop yields in tropical areas leading to increased risk of hunger, spread of climate sensitive diseases such as malaria, and an increased risk of extinction of 20 – 30 per cent of all plant and animal species.

Original papers on climate change impacts science and climate change adaptation science will be considered for publication. Papers dealing with case studies of activities or adaptation projects with local, national, regional and international impacts will also be considered. The journal is formatted to include original papers, case studies, book reviews, conference reports and a calendar of future events. All contributions are subject to review by at least two independent referees. Contributions from and on developing nations, nations in transition and newly independent states are encouraged.

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Preface

Welcome to the inaugural issue of the *Climate Impacts and Adaptation Science* journal published by the Climate Lab at the University of Toronto (CL@UT) located at the Department of Physical and Environmental Sciences, University of Toronto Scarborough. CL@UT was established over ten years ago by William A. Gough, now Chair of the Department of Physical and Environmental Sciences at the University of Toronto Scarborough, as a focal point for climate research and students. CL@UT membership expanded five years ago with the co-location of Environment Canada climatologists at the Department of Physical and Environmental Sciences as major collaborators in CL@UT research.

CL@UT conducts, facilitates and hosts research and science on the impacts of, and adaptation to, past and future climate change. Over the past few years, CL@UT has launched a climate seminar series, an annual climate science symposium, a climate student award, a summer institute climate training session, a diploma programme on applied climate change, and now a journal.

Climate Impacts and Adaptation Science aims to provide an international and interdisciplinary forum for highlighting the concerns and needs in adapting to the effects of climate change. This journal aims to provide a forum for up-to-date study, research and thinking on the impacts of climate change; the vulnerability to future climate change; current adaptation plans, strategies and actions; and future adaptation options and needs.

Our first issue emerges from a science symposium hosted by Environment Canada titled *Planned Adaptation to Climate Change* in Victoria, British Columbia, Canada from 9-11 March 2009 on climate change adaptation science, management and policy options. The following ten papers were among those presented at the symposium, and we present peer-reviewed versions of them here as a testament to the symposium as well as to our collective efforts to build our capacity to adapt to climate change.

Adam Fenech
William A. Gough
Monirul Mirza

Editors-in-Chief

Planned Adaptation to Climate Change: Some Observations From a Recent Science Symposium

1

Fred Roots[1]

[1] *Scientist emeritus*, Environment Canada

Editor's note: The author reflects on the Science Symposium on "Planned Adaptation to Climate Change", from which the papers in this volume emerge. Environment Canada hosted a science symposium titled Planned Adaptation to Climate Change in Victoria, British Columbia, 9-11 March 2009. About 75 people, including researchers, data and information experts, planning and management personnel, and policy-makers from a variety of agencies and authorities shared information, and discussed progress and problems and concepts related to the increasingly important and complex subject of how individuals, communities, and governments can or should cope with and adapt to a changing climate. At the conclusion of the symposium, Dr. Roots was asked to present a general perspective on the meeting and make some comments on issues ahead. His observations follow.

Abstract: In order to assess the progress and desired actions needed for adapting to current and impending rapid changes in climate, it is useful first to ask: "what are the scientific aspects of the concept and the practice of adaptation?", and then to consider the adequacy of the scientific knowledge of climate change and of human behaviour in response to those changes. It is helpful in this regard to review our understanding and basis for adaptive action against the philosopher's "staircase of knowing" that describes the step-wise progression from objective observation to increasingly subjective data, information, knowledge, understanding, and wisdom. Against this background, the various papers, new information and discussions of this symposium highlight or provide a basis for looking at the adequacy of our present understanding of changes and trends in the physical climate, and in policies and public response to climate issues. Some weaknesses and gaps in our scientific understanding of the changes in climate and its consequences for society and the economy, some obvious and apparent paradoxes in public and policy awareness, and obstacles to effective adaptation become evident. Adaptation strategies and actions must have a broad interdisciplinary response from understanding of the dynamics of the physical and biological environment, input from the social, economic and cultural sciences, together with adequate and continuing monitoring of changes in key parameters. It is seen that although there is recent stronger and broader attention to the seriousness of impending climate change and to the urgency of adequate measures to cope with its effects, the issue has long been recognized in the Canadian and North American scientific establishment. Calls for adequate policy response and changes in public behaviour have been largely unheeded to date, and it is hoped that this symposium may help toward more positive action.

Keywords: climate change, adaptation, knowledge

1. Introduction

It was the purpose of the symposium to provide a state-of-Canadian-science update on adaptation to climate change including:

- Climate change science, particularly coupled global climate models (GCMs), regional climate models (RCMs), and statistical downscaling methods for assessing the range of changes that Canada might experience in this century;
- Data availability and tools for developing scenarios for climate extremes, for assessing the risks of climate change at the regional and local scales, and for performing the uncertainty analysis in climate variability and extremes;
- Climate change impact assessments based on mean climate and extreme weather in various sectors such as infrastructure, water resources, energy, health, agriculture, fisheries and transportation; and
- Synthesis of available methods to support adaptation planning and research, and to supply the information for risk assessment studies with coherent uncertainty analysis; and
- An opportunity to observe emerging trends in adaptation science and research.

The symposium brought together top researchers, industry representatives and managers of climate change adaptation activities from across Canada. It provided an opportunity for researchers and decision makers from a wide range of disciplines to share results and information in a national context. The symposium program included invited keynote and plenary presentations, panel presentations, and poster sessions.

Judging by the comments and sustained enthusiasm of the symposium, one can conclude that it was a good meeting. Two days were spent away from the regular work but devoted entirely to subjects each are working on. The topics addressed have been subjects that are deeply cared about for they are very important to our future. Old friends and new acquaintances from across the country have been meeting and building a coherent Climate Change Science community; listening to, absorbing, questioning, and sometimes challenging finished lectures and some unfinished reports of on-going research and data management. This is together with lively discussion with our peers and not a little scheming and frustration over how to get the general public and government decision-makers to accept the fact that a seriously changing climate is upon us and that we all must do something about it. Yes, it has been a good two days.

But we did not come here just to enjoy ourselves and see what our colleagues were doing. We need to ask ourselves: has the Science Meeting achieved its purposes? You will recall that when the symposium was first announced, the purposes were outlined quite specifically. The meeting was to:

- provide an up-date on Canadian science related to adaptation;
- exchange information on data availability, and on tools for developing scenarios and assessing risks;
- show and discuss some example assessments and demonstrations of methods;
- lead to a synthesis of available methods that would support policy and public planning for adapting to climate change;
- highlight new or emerging trends in research in the subject field of adaptation to change.

It is appropriate to consider whether, after two days of presentations and discussions, these purposes were accomplished? My quick impression, at the close of the meeting, is that we touched on or tried to address each of these purposes, except that no one specifically attempted a synthesis of methods to support policy and public understanding. Perhaps we, at the working scientist level, were the wrong group to attempt this. Perhaps "adaptation science" as we understand the subject, is still too immature; or perhaps the synthesis that policy-makers and the public need is not a science matter at all.

2. What is Adaptation Science?

To consider where our meeting fits in the complex and increasingly important subject of adaptation to a changing climate, it is perhaps useful to think back for a moment to first principles. Change in climate, on any scale - from planetary to very local - is like any other change in a dynamic system; simply an expression of Newton's laws of thermodynamics. The climate is a net resultant of energy and moisture flows and the distribution of chemical components, which are themselves the net results of changes in the scale, magnitude, and direction of forces from solar energy and their actions on the planetary architecture and the interactions of its components. Thus, if we talk about the "science of adaptation" we are talking about how do we increase our knowledge of human behaviour in response to a dynamic disturbance of an already dynamically mobile physical/chemical system. This is Newton's Third Law; but on top of it, we have in adaptation science the subjective implication that we should focus our investigations on how to avoid inconvenience or tragic disruption of the human societies and their institutions which have developed within and have become accustomed to the dynamic climate of the last few centuries (which we now know has been anomalously stable in comparison with preceding millennia).

So there are two essential components to adaptation science: the physical/chemical/biological sciences of climate dynamics, as objective as we can make them; and the behavioural/psychological/economic sciences, which determine whether our increased knowledge will have a societal and policy benefit.

An interesting aspect of this subject is the obvious fact that humans and their societies have, by-and-large, a slower response time to stress than the fluctuations in atmospheric energy flows, but a faster response time than changes in oceanic dynamics or soil/nutrient flows. So, as the environment changes all about us, humans, their values and expectations, and institutions are caught in the middle - the climate, quick-responding ecosystems and life-support systems are changing more rapidly than ever before in human experience and ecological disruption is widespread, while the overall planetary processes are very slow to adjust. The science of adaptation to climate change is, in essence, the science of this dilemma.

With only a few exceptions, most people and most societies are finding that the changes in climate we are currently experiencing in most of the world and which according to our best knowledge today are almost certain to become more profound, are undesirable or, according to some, disastrous. Our libraries and responsible journals are filling with material on this topic (Kolbert, 2007; Lynas, 2007; Draper, 2009). Naturally, our first instinctive reaction, as a responsive and intelligent animal, is, if we cannot move to avoid the effects of the changes, to try to stop the undesirable changes, to remove the cause or reduce their severity. These are the actions or intentions that, at least in the science domain, have come to be called “mitigation”. But, as Nicholas Stern and many others have tellingly pointed out, the scale of the problem and the nature of Earth processes is such that any conceivable mitigation action, even if it were successful and applied on an heroic scale, would take a very long time, in human terms, to undo or reverse the harmful changes now in train. Therefore, we must learn to live with, and adapt to what is here and now, and coming. As Stern (2006) states: “Adaptation is the only response available for the impacts that will occur over the next several decades before mitigation measures can have an effect.”

3. How can we adapt?

How to adapt? Observations of Nature through geological time, of human species and groups during the last fifty millennia, and organized societies and individuals in the last few centuries – and lots of historical and social/economic studies – show, obviously, two main ways of adapting to a changed environment.

One, move away from the undesirable affected area to a more desirable or productive location. This is migration in one form or another. Nature does it all the time, and our ecosystems as we know them are the result. The Arctic tern who flies 25,000 kilometers annually to find an environmentally suitable place to raise its young, and the urban office worker who has a summer cottage in the woods have much in common. But when the climate itself changes at the places where life support has been previously established, and the choice is to move, or to die in the former place, there must be another kind of migration. In biology, this phenomenon is sometimes referred to as range translocation. It is perhaps best known in regard to marine life, where the oceanic climate changes slowly enough for habitats and their inhabitants to adjust, as for example in the Greenland Sea where the ranges of shrimp and cod have alternated over a couple of centuries in response to fluctuations in water temperature. With humans responding on a shorter time scale to more rapid changes in the atmospheric climate, this option has, in its more severe aspects, led to environmental refugees. We have, unfortunately, several distressing examples in the world today.

The other obvious option is to cope with the changes. How plants and animals cope, in a fixed or limited location, with changes in climate is a whole separate subject. For humans, there are four main paths that people commonly can take to cope with, or adapt to, rapid changes in climate:

(i) they can arrange for economic compensation for short-term changes (for example, crop insurance, loans, subsidies);

(ii) they can change their expectations and sensitivities, and develop new "normals", of behaviour, institutions, and community structures;

(iii) they can develop new technologies and practices; and

(iv) they can take advantage of the new conditions.

I am sure that you can see that modern societies use all of these paths. And this is what the science of planned adaptation to climate change is all about. This is why we are here.

4. How does our Adaptation Science help Canadian societies, and people in other parts of the world, do these things?

Any consideration of the scientific aspects of planned adaptation to changes in climate must be based on a scientific understanding of the climate itself, of its dynamic characteristics, of the forces that influence its various components, and their effects and feedbacks. How good is our understanding of these characteristics and influences? After listening to the talks and summaries of the past two days, and with a little familiarity with the overall subject, I might venture an opinion of where we stand in 2009, in the areas of the natural sciences:

Physical sciences: We have a pretty good handle on the processes, and the range of space and time scales over which they act, at least on land. We are not so good at understanding the causes and dynamics of shifting "weather types" on a regional or sub-regional scale (we are still at the description and monitoring stage); and we are really no good at all in getting answers about the specific climates in rugged mountainous areas or complex coastlines (the amount of detail required overwhelms us and our resources, and we revert to averages, approximations or sample locations, and have learned to accept that). We have some confidence about the large-scale dynamics of the atmospheric climate over large ocean areas, but admit to considerable ignorance of the dynamics of the ocean climate itself (the climate within the water), which we have recently learned is more complex and variable that we had assumed. We are not good at identifying the multiple specific causes of extreme events.

Chemical sciences: Although it is a fallacy to try to separate the chemical aspects from the physical ones, because Nature does not work that way, I think it is fair to say that our understanding of the atmospheric chemistry role in climate change is spotty. We have lots of data and observations on changes in local and regional atmospheric chemistry from industrial activities, and some on the chemical effect of deforestation and other land-use changes, but the effects of these activities, over, say, the thirty years that we take as the basis for climate descriptions are at best shaky. Specific insults like acid rain, the factors leading to smog, or the processes of long-range transport of air pollution are well-studied and understood; but arguments over the energetics of different LRTAP scenarios show that this is a research problem, not yet good knowledge of the chemistry of changing climate. And we seem to need much more knowledge about the link between ocean chemistry and atmospheric chemistry.

Biological/ecological sciences: I suspect that most people working in or reviewing this incredibly complex subject field will agree that with respect to ecological responses to a changing climate the tasks are just well started, rather than having good knowledge in hand. Every issue of the Journal of Ecology or Climate Change or similar periodicals reports new discoveries or unexpected concepts. On the whole, I think it is fair to say that we are gathering a lot of descriptive information on the effects of changes in climate, or of extreme events, on plant and animal communities, and on changes in biodiversity in selected locations or regions; but the links between physical changes in climate and the rate of response of ecosystems through changes in species communities, changes in habitat or translocation of ranges is a real challenge.

We have, especially in Canada, focused much of our scientific attention in this area on the biological and ecological response to changes in climate, as if the climate is the dominant factor and the ecosystem a passive recipient. But every day, we are learning that the biological component on the surface of the Earth is an important driver and influence on climate. The 2008 conference on "Climate Change and Biodiversity in the Americas", which many here attended and of which the newly-published report is available at this meeting, includes several examples of the feedback effect of a regional ecosystem on climate.

5. Our Staircase of Knowledge

But how do we use this scientific background, extensive although open-ended as it is, to improve planned adaptation to climate change? How do we make our scientific information and knowledge the basis of adaptation? I suggest that here again it may be useful once again to go back to first principles and to consider for a moment the philosopher's *Staircase of Knowing* (Figure 1)(Roots, 1992).

Note that on this staircase, there is a progression from observation of a phenomenon or situation, through data and information to knowledge, understanding and eventually to wisdom. To proceed from one step to the next, it is necessary to add some subjective human-selected quality. Simple observation or measurement cannot become data unless it is verified according to some approved standard; data by itself does not become information unless it is selected and tested; information does not become knowledge until it is organized and interpreted according to some purpose; knowledge does not became understanding until it is integrated and made comprehensible for some objective or interest area; and judgment applied properly to understanding can become wisdom.

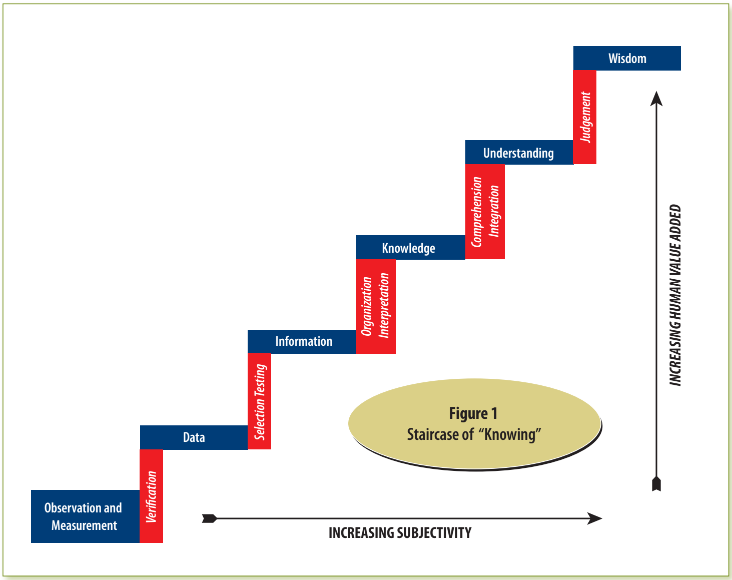

Figure 1 | Staircase of Knowing.

Where does science fit on this staircase? Clearly, on the first three steps, and sometimes it contributes to knowledge, the fourth step. But clearly, information alone will not produce knowledge or understanding, let alone wisdom. How many times have you heard it said that we need more data on this and that, or that if we only had more information, we would know better what to do or would avoid mistakes? Surely, in our world today, especially through its science, we have more data and more information than any people in history; but is our judgment better because of that?

Think, for a moment, of the wisest or most trustworthy person you know. Chances are, that person has information adequate to her or his needs, but the wisdom does not come from the enormity of data that person has, but from integrated understanding and judgment based on the useful information.

I suggest that we keep this staircase and these relationships in mind as we think about the contribution of science to planned adaptation to climate change. The responsibilities of the Adaptation and Impacts Research Division of Environment Canada itself extend from information and knowledge, based on our science, to the tasks of cultivating the understanding among our decision-makers and politicians so that they can adapt to changing environmental conditions and take action with regard to public safety, maintenance of the economy, or public well-being. This will almost always require both technical adaptation and behavioural adaptation, which in turn often require institutional and bureaucratic adaptation.

The various sessions and papers presented at this meeting reflect this situation. This is not the place to comment on individual papers, but we have had a good sampling of the lower part of the staircase. The different models described allow us to organize or simulate what we know about climate changes, and to test our assumptions about the relationships between important factors and influences. We had a progress report on how our understanding, for better or worse, affected building codes, safety, and investment; and several examples or case histories of the application of the increased knowledge and awareness of climatic changes in public life and economy. We learned of the facility for increased accessibility and coherence of information; and several papers displayed methods, schemes, and tools for getting our information to the public or to those who can take action or change behaviour. Some of these are forays up toward higher steps of the staircase, and they are important. And there were up-dates on the progresses and shortcomings of international assessments and thinking in this area, and on the effects of climate change and adaptation efforts on the national economy. All good stuff; as a scientific community, we really benefited from two days of listening to one another. But we are still only halfway up the stairs.

Participants at the meeting made some attempts, mostly informal, to relate issues of adaptability to climate change to the present-day realities of political policy, business interests, public concerns or habits, and the world economy. The evidence of current changes in climate and for future serious changes was so overwhelming that I think we all felt that those who denied it were blind to what was happening and based their denials on narrow philosophy or rigid faith. We felt strongly that the climate change science community had an urgent responsibility. The problems were crowding in on society, on economic systems, and on policies. There was a general public awareness that "things were happening in Nature which do not bode well for human prosperity or for the environment of the planet", and that something should be done about it. But the issues are so complex, and strike at the very heart of the economies of most of the world and the habitual behaviour of most people, that help is wanted from the group who know most about climate - the climate scientists. It is time to move up the stairs.

6. Paradoxes

Several papers, and much discussion, drew attention to the inherent paradoxes or contradictions that were encountered in trying to put the knowledge and results of climate change science into policies, economic practices, and public awareness/ demand; that is, if one may use the staircase analogy, to move from knowledge to understanding and action. Chief of these problems was the often expressed demand from the public and politicians for certainly in forecasts - "What is really going to happen to the climate of my area, and what will be the effects?" The easy course for individuals and policy-makers to take is to do nothing until there is greater certainty that calamitous things are happening. The cognitive dissidence of psychiatry is very much in evidence in this issue.

Awareness of changes in the environment and economy is widespread and deepening, and knowledge that at least part of the change is due to individual habits and use of our technologies is accepted; but there is reluctance or a feeling of inability to change those habits. The expectation that "everyone, especially those in other countries, should change but that does not really apply to me" is deeply entrenched, together with the notion that unless everyone changes, individual actions will have no effect and will result in individual economic and social hardship. Thus, there is on the one hand a call for strong policies which would curtail further emissions and practices that could harm the environment and climate, but on the other hand there is strong support for policies that increase our use of wasteful technologies and do not curtail the pleasures and practices that have led to the problem - another paradox.

It seems, on reflection, and several participants mentioned this, that the demand for "certainty" about future climate changes is not as strong as is often assumed. There are instructive examples in other subject fields. People or politicians do not demand certainty in economic predictions, yet they commit large amounts of money on the best knowledge at the time. As another example, the public does not demand certainty in aircraft safety, but is satisfied that the risks are low and the other benefits outweigh those risks. For many people, gambling – playing with uncertainty – is enjoyable. So in many ways the demand for "certainty" seems pointless. But simply saying so as a scientist does not change the demand.

In looking at the problems of making progress in adapting to climate change, I have found it of interest to compare the contrasts and the parallels of two topics of policy and public concern with which I have been associated for a couple of decades - the management of radioactive wastes, and climate change. Both of these topics have a sophisticated science background, with much research, modelling, and monitoring in Canada and internationally; both still have several scientific unknowns; both have an essential public awareness component; both have had political attention at the highest level; and both will involve heavy public investment. Under current concepts and practices, the management of radioactive wastes has a very, very low probability of any harmful release to the environment for thousands of years, but if there were to be a mishap, the consequences could be severe and of a kind quite without parallel in our history. And so, for a small but influential segment of society there is a high alarm component which does not appear to be amenable to penetration by rational science. In contrast, climate change is already happening and the likelihood of it becoming more intense in the next few decades is very high; but the consequences, although almost certainly likely to be very severe, are mainly in the realm of problems familiar to humankind, and of the type which in their milder forms we have muddled-through before. But in neither case is most of the public, despite the alarms and concern, ready to make a significant change in their demand for energy, which lies at the basis of both the radioactive waste and the climate change problem. I think that it helps to have this kind of perspective in looking at the issues before us.

7. Omissions and Weaknesses

While listening carefully to the papers and discussions, I tried to keep my ears open for topics or concepts that I expected to hear about but did not, or which seemed to me to be very lightly touched upon. Of course a two-day meeting could not touch on all aspects of this wide subject, and it is preposterous for me to pretend to have a broad knowledge, but for what they may be worth here are some impressions from an outsider.

Models: There were good discussions of downscaling and regional comparisons, but no attention to how regional models and modelling of anomalies could improve or were contributing to global models, which themselves are being modified to accept complexities - so-called upscaling. In this area, the climate modellers might learn from the oceanographers, and give attention to ocean/atmosphere coupling variations in short time periods, which are the focus of atmospheric climate change.

Trends: There was some mention of trends in means, and trends in variability, but a thoughtful discussion of these would be of real interest at this stage of our research. “Trends in extremes” is very tricky, even though the media keep calling for it; but a bit more discussion on the scales and causes of extremes would be useful. There is no doubt that assurance of improving skill in forecasting extremes will be most sought-after by the public and investors.

Behavioural sciences: An important gap in our discussions was the absence of modern input from behavioural and psychological researchers on how Canadians at all societal levels, including their politicians, are responding to changing climate and the threats of more severe changes to come. There has been a lot of research in the academic social sciences on how people respond to stress, how they switch or “roll-over” their value systems, etc. It seems that in the social sciences at least, a lot more is known about how people change from, for example, denial to acceptance, than was known a decade ago. This knowledge is pertinent to the science of climate change adaptation, but seems not to have had much attention at the policy or planning level. Southcott (2009), for example, has stated that “Very little research exists on the social and economic aspects of climate change on sustainability in Canada”.

First Nations: There was no specific reference to, or input from, First Nations, even though native people have an acute awareness of climate and its changes in the past. Although the rapidity of current climate changes is unprecedented in our human experience, the First Nations have much knowledge of the connections between climate and ecosystems and human living. Sensitive and careful input from the people themselves about changes in climate could be valuable in the present Canadian situation. There is a growing literature on this. Particularly in Arctic regions, where native peoples are moving from a hunter-gatherer societal organization directly into the knowledge society without the transition through agricultural and industrial societies, there may be much to learn from First Nations about adaptation to a rapidly changing environment.

Economic aspects: We had an excellent review of economic methods and tools that can be used to assess or determine the costs of changes in climate and the economic costs and benefits of various adaptation actions and their results. This was all there was time or space for in our crowded agenda. But to look at the options and expectations of planned adaptation to a changing climate, it would be good to hear a little about the progress of economic modelling of climate changes (à la Nicholas Stern, applied to Canada), about the economics of adapting to climate changes in specific areas such as the grain-growing regions of the prairies, or in the Arctic where actions to adapt to climate-caused changes in living resources have an effect on the spiritual economy as well as the money economy.

Wholly human-centred: All of the issues and considerations of adaptation to climate change that were talked about were assessed from the human point of view. ”Planned adaptation” is a subjective human idea. The response of the ecosystem to changed climatic conditions is a process of change that affects further changes in environments or resources, to which humans must adapt; but we gave little attention to ecosystem adaptation itself. This could be considered “unplanned natural adaptation”. We did not dwell on it, but in some of the presentations, the authors appeared to look at the changes, and the response to changes, from the point of view of the environment or the planet in its own right. This was refreshing.

8. An Old Problem, Still with Us

The current public and political concern about climate change, and the need to do what we can to mitigate the undesirable effects and to adapt to the new conditions, is of course quite recent. It is true that the changes in climate seem to be accelerating in the past decades, and we are certainly pouring more substances into the atmosphere and changing the land surface in such a way as to further speed up the process. Most of us here at this meeting only began to work on climate change issues in the last ten years; even if we were involved in atmospheric sciences before that, climate change did not have the same priority. But within the atmospheric science community, the concern has a long history, as science issues go. In 1975 there was an important conference in Toronto entitled "Living with Climate Change", sponsored by the Canadian Meteorological Society, the Mexican Geophysical Union, the American Meteorological Society and the Science Council of Canada. It was attended by leading persons in atmospheric sciences at the time from Mexico, the United States, and Canada, many of whom became familiar figures in climate change issues in subsequent years. I think that it is of interest, and provides important perspective to our work today to quote from the first sentence of the report of thirty-four years ago (McTaggart-Cowan and Beltzner, 1976):

> "There is growing evidence that the world is entering a new climate regime. Both the rate of change of the climate and the amplitude of short-term climatic variations will be much more pronounced than in the recent past."

And the last sentence of the preface reads:

> "We hope that this discussion will be a significant impetus toward furthering our ability to live more securely and more contentedly with climate change."

Could not this statement from 1975 apply equally well to our symposium in 2009? But the group meeting in Victoria was not the only group that was at the time giving comprehensive consideration to the problems of adaptation to climate change. At the same time as the Victoria symposium, an international meeting, organized by UNESCO, on "Climate Change and Arctic Sustainable Development; Scientific, Social, Cultural and Educational Challenges" was held in Monaco. The background paper for this meeting summarizes the issue and the challenges:

"Understanding and responding to climate change is a challenge that requires the combined efforts of the scientific community, civil society, governments, and national and international organizations. Research on climate change must extend beyond assessing causes and monitoring impacts and trends. It is now clear that major change in the world's climate is an unavoidable reality. Adaptation and response are now essential. The development of appropriate adaptation and response strategies has therefore emerged as a central preoccupation of all actors, including the United Nations System."

"Adaptation strategies require a broad interdisciplinary response. They must be rooted firmly in the knowledge-base of scientific monitoring and assessment, which provides data on changes in climate and their impacts on the physical and biological environment. Adaptation to climate change adds a social, economic and cultural problematic as it encompasses the ability of countries to respond to the challenges put before them by the changes in climate."

This is where we are today, and this is our job.

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Section
1

Tools for Facilitating Adaptation to Climate Change

Downscaling Global and Regional Climate Models

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ABSTRACT: Statistical Downscaling (SD) methods were first developed for applications in weather forecasting. Numerous methods are now in operation across the world. Since the end of the 1990s, these methods have been used intensively to develop high spatial and temporal resolution climate change information. Climate change scenarios are mainly based on the results of Atmosphere-Ocean Global Climate Models (AOGCMs) and more recently those of Regional Climate Model (RCM) outputs, which operate at horizontal resolutions of 300-km and 45-km, respectively. More reliable information at much finer scales, utilising the appropriate SD approach, is essential for decision-makers and planners tasked with adaptation to climate change. Impact and adaptation solutions are highly demanding in terms of topographic resolution and the representation of physical processes, and neither AOGCMs or RCMs can currently meet those needs. We will therefore require SD applications. Until now, SD methods have mostly downscaled output from AOGCMs, but there is no reason why SD methods could not be applied to higher resolution models. This paper investigates the reliability of atmospheric input variables when used in the SD process, from both AOGCMs, global and regional reanalysis products, and RCMs. This allows us to evaluate the potential added value from particular single site regression-based SD approaches, by comparison with the use of raw AOGCM and RCM outputs over various areas across Canada. This work also investigates the ability of the SD scheme to reproduce observed trends and variability within the predictand under consideration. New developments within multivariate and multisite SD methods are also suggested through on-going projects and collaboration between Environment Canada and various universities across Canada.

Keywords: climate change, statistical downscaling, global climate model, regional climate model, local climate information, predictors and predictand.

1. Introduction

Scientific and socio-economic global climate change research has (thus far) focused mostly upon scenarios of gradual warming, as suggested by Atmosphere-Ocean Global Climate Model (AOGCM) simulations (see IPCC, 2001 and Meehl *et al.*, 2007). However, such scenarios cannot be applied directly at the regional or local scale due to their coarse resolutions. Regionalization techniques are thus needed in order to develop high resolution climate scenarios at the temporal and spatial scales relevant for impact studies: These include Regional Climate Models (RCMs) and Statistical Downscaling (SD) methods. RCMs do not, however, provide information on the scales needed for impact and adaptation solutions, even where they offer improvements over AOGCMs in terms of resolution or representation of physical processes. SD methods are required for the development of local scale information and the higher resolution climate variables (equivalent to point observations) required by many impact applications.

Forecasts of numerical weather prediction (NWP) models have certain defects that can be removed by statistically post-processing their output (Wilks, 1995). Two of the more popular post-processing approaches are Model Output Statistics (MOS) and the Perfect Prog approach (Klein, *et al.,* 1959; Glahn and Lowry, 1972), both of which are based on the idea of relating model forecasts to observations through linear regression. This is the central principle from which SD methods have been developed. Vislocky and Fritsch (1997) included observations as both predictor and predictand, and Marzban (2003) additionally allowed for nonlinear relationships among the various variables. Both techniques have subsequently been inplemented into SD. Numerous methods are now in operation across the world. Since the end of the 1990s, these methods have been used intensively to develop high spatial and temporal resolution climate change information. SD methods are primarily used to relate large scale climate variables drawn from atmospheric and oceanic analyses of temperature, flow, and other quantities, created by processing historical data using fixed state-of-the-art weather forecasting models and data assimilation techniques (i.e., reanalysis products), AOGCMs (for predictors), and local or station scale observations (for predictands). These data sets are used to determine a statistical model that establishes the relationship between large and local scale climate factors. The statistical model is often calibrated and validated under the current climate condition using a reanalysis data set, such as the NCEP (National Centers for Environmental Prediction) reanalysis (Kistler *et al.*, 2001), large-scale outputs of an AOGCM simulation are then fed into the statistical model to estimate (i.e., “downscale”) corresponding local and regional climate characteristics for the future. Both NCEP reanalysis and AOGCM output must be screened to produce reliable predictors, in order to prevent the introduction of biases from the host AOGCM to any given SD process. The procedure to select the optimum combination of predictors also needs careful attention. Despite the fact that SD methods have historically been used to downscale from AOGCM output, there is no systematic reason why SD methods could not be applied to higher resolution models, including RCMs. This would allow for the incorporation of more information from regional forcing (not included at the coarse scale of an AOGCM) in the SD process.

SD methods are currently under development at Environment Canada (EC) within the Adaptation and Impacts Research Section (AIRS) in strong collaboration with various universities including McGill/GEC3, the Institut National de la Recherche Scientifique – Eau Terre Environnement, and the University of Regina (see further information at **http://www.cccsn.ca**). These methods complement the impacts, research and adaptation science of EC, specifically in terms of the global and regional climate models developed by the Climate Research Division (CRD, see **www.cccma.bc.ec.gc.ca/**).

This paper gives an overview of current developments within SD research, and investigates the added value of one particular, point-observation, regression-based SD approach, against AOGCM and RCM outputs over various areas across Canada. Benefits to be obtained from the use of RCM, instead of AOGCM, predictors are also suggested, in particular, in terms of potential added value derived from the incorporation of regional scale forcing factors in the downscaling process. The atmospheric variables used to develop the statistical relationships within the SD method are also analysed in order to see if they are statistically significant contributors to the variability in the predictand. Finally, new developments toward multivariate and multisite SD methods are discussed.

The paper is organized as follows, using the various steps presented in Figure 1. Section 2 presents those predictors that are reliably simulated by AOGCMs (compared to those developed from reanalyses), the atmospheric predictors chosen for use in the SD process and the steps required to select the relevant combination of predictors. A new development towards the inclusion of regional scale predictors into the SD process is also presented in Section 2. Section 3 presents the potential for added value or new insight that has been gained through the use of SD methods, rather than raw data directly from AOGCM or RCM output. Section 4 discusses the reproduction of a predictand regime within observed data by the SD model, including trend behaviour as well as the short and long term variability of the predictand. The last section presents the main conclusion, on-going development, and further steps required in SD research.

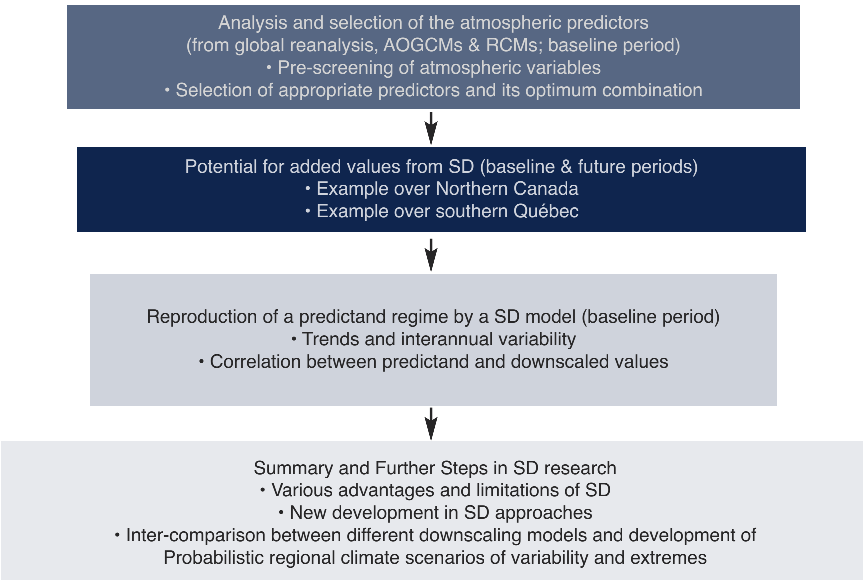

Figure 1 | Chart with the list of the steps followed in the paper.

2. Atmospheric input variables used in the SD process

In principle, all predictors employed in the SD process need to fulfill the following criteria and assumptions: (1) They should show skill in representing large-scale variability as simulated by the AOGCM; (2) They should be statistically significant contributors to the variability in the predictand, or they should represent important physical processes in the context of an enhanced greenhouse effect; (3) They should not be strongly correlated to each other (see further explanations in Wilby *et al.,* 2004, and Benestad *et al.,* 2007). It is also important to limit the set of predictors to only those which are relevant. von Storch *et al.* (2000) list a number of criteria which must be fulfilled for SD: "(1) The predictors are variables of relevance and are realistically modeled by the AOGCM; (2) The transfer function is valid also under altered climatic conditions. This is an assumption that in principle cannot be proven in advance. The observational record should cover a wide range of variations in the past; ideally, all expected future realizations of the predictors should be contained in the observational record; (3) The predictors employed fully represent the climate change signal". It is therefore important to understand the physical mechanisms and connections at work between predictor and predictand. In the following, the main criteria related to the relevance, reliability and optimum combination of various predictors in the SD process are analyzed in further details from AOGCMs and RCMs, as well as from reanalyses products.

From Atmosphere-Ocean Global Climate Model output

In order to follow the suggested criteria concerning predictors and their physical links with the predictand, a systematic assessment of the various candidate predictors is required prior to the development of an SD model (see the works in eastern and northern Canada in Gachon *et al.*, 2005, Gachon and Dibike, 2007, Hessami *et al.*, 2008, and Dibike *et al.*, 2008). Climate model limitations need to be identified when screening potential predictors using both NCEP and AOGCM variables. The variables commonly used as predictors in the downscaling of both temperatures and precipitation are listed in Table 1. From these potential predictors, the first step is to analyze the spatial correlation of these fields with the predictand of interest, and to evaluate the compatibility between NCEP and AOGCM candidate predictors. Indeed, it is necessary to specify the optimum location of the large scale predictor fields to achieve the best performance in downscaling local climate variables (e.g. Wilby *et al.*, 2004). Figures 2 and 3 give an example of a correlation map based around southern Québec, using data observed from a station in Montréal. These plots show correlations between daily precipitation (the predictand) and daily predictors of the mean sea level pressure (MSLP) and the V-component of the wind at 850-hPa (Figure 2), and, between daily maximum temperature (Tmax) and 500-hPa geopotential heights and specific humidity at 850-hPa (Figure 3). These maps suggest higher correlation values for grid points closer to the Montreal area (i.e. the location of the predictand), and stronger correlations for temperature than for precipitation. The selection process for relevant predictors is more complicated for precipitation due to the fact that the explanatory power of individual predictor variables may be low or vary either spatially or temporally (e.g. Wilby *et al.*, 2004; Gachon *et al.*, 2005, and Gachon *et al.*, 2007). Occurrence and intensity of precipitation are controlled by complex mechanisms which may be linked to: large-scale upward or downward motion of a relevant air

Table 1 | List of daily predictor variables commonly used (i.e. not systematically all for all regions and climate conditions across the globe) from AOGCMs and global NCEP reanalysis products in SD models (see www.cccsn.ca). A glossary is added at the end to define all terms listed above.

PREDICTOR VARIABLES	FOR TEMPERATURE			FOR PRECIPITATION		
	Pressure Levels (upper air fields, in hPa)					
	500	850	1000	500	850	1000
Geopotential Height	x	x		x		x
Specific or Relative Humidity		x		x	x	
Wind (U & V components, Speed & Direction)	x				x	
Vorticity	x					
Divergence				x	x	x
Surface or near surface (ex. at 2-m)						
Mean sea level pressure (MSLP)					x	

mass; small-scale processes, such as localised convection; cloud development; turbulent motion of wet or dry air in the boundary layer; orographic effects, including convergence of an air mass, which may induce upward motion on a windward slope area. Simple correlation between predictand and one single, a-priori predictor variable, is therefore not effective for the selection of predictors for downscaling precipitation. This kind of work requires a mechanistic analysis to optimize the choice of individually pertinent predictors. More often, the optimum choice is provided by the right combination of multiple variables linked with the precipitation process (see Choux, 2005). Indeed, the use of a single correlation map can not constitute the only criterion for the selection of predictors over a downscaling area, as partial correlation analysis must also be performed to select the relevant combination of candidate predictors during the downscaling calibration (e.g., Wilby *et al.*, 2002).

Considering the validation of climate model outputs at the space and time scales used in the SD process, a few grid points surrounding the Montréal area are compared in Figure 4, using both predictor values from NCEP (shown in Figures 2 and 3) and the

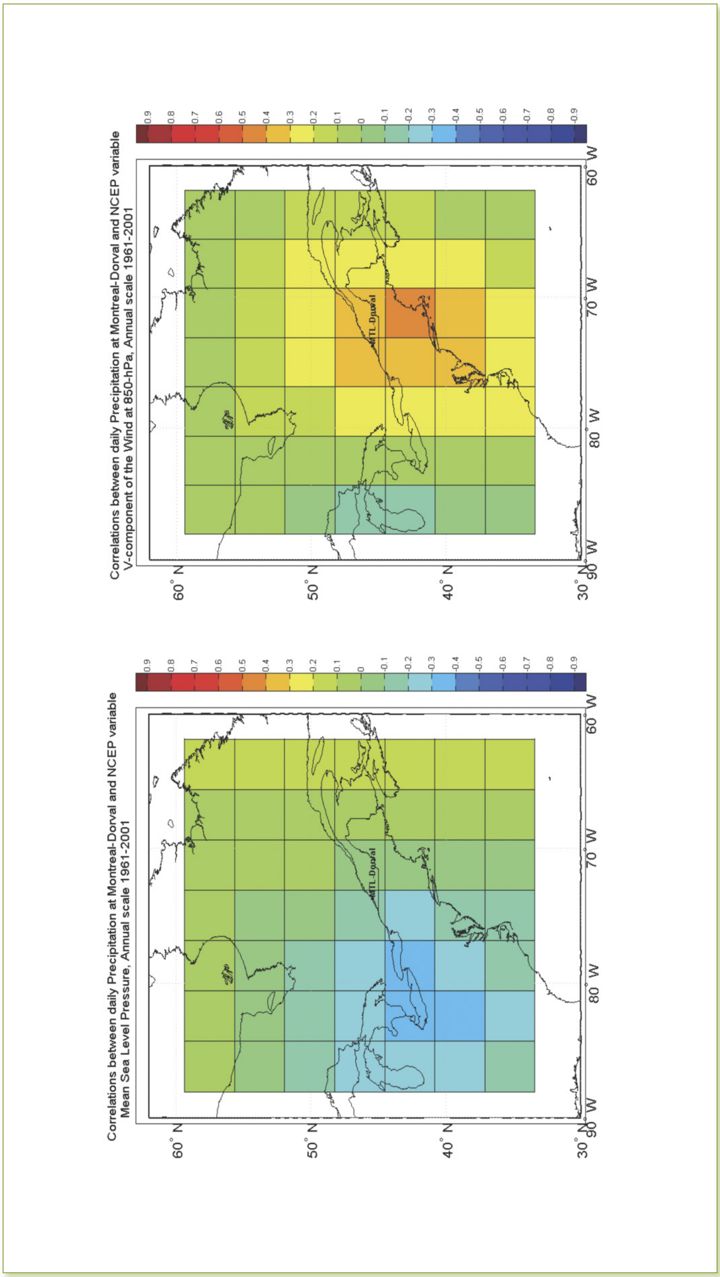

Figure 2 | Correlation map between daily Precipitation at Montréal, Québec and mean sea level pressure (left panel), and between precipitation and the V-component of the wind at 850-hPa (right panel), as derived from the NCEP reanalysis. The correlation is performed with the full inter-annual time series between 1961 and 1990.

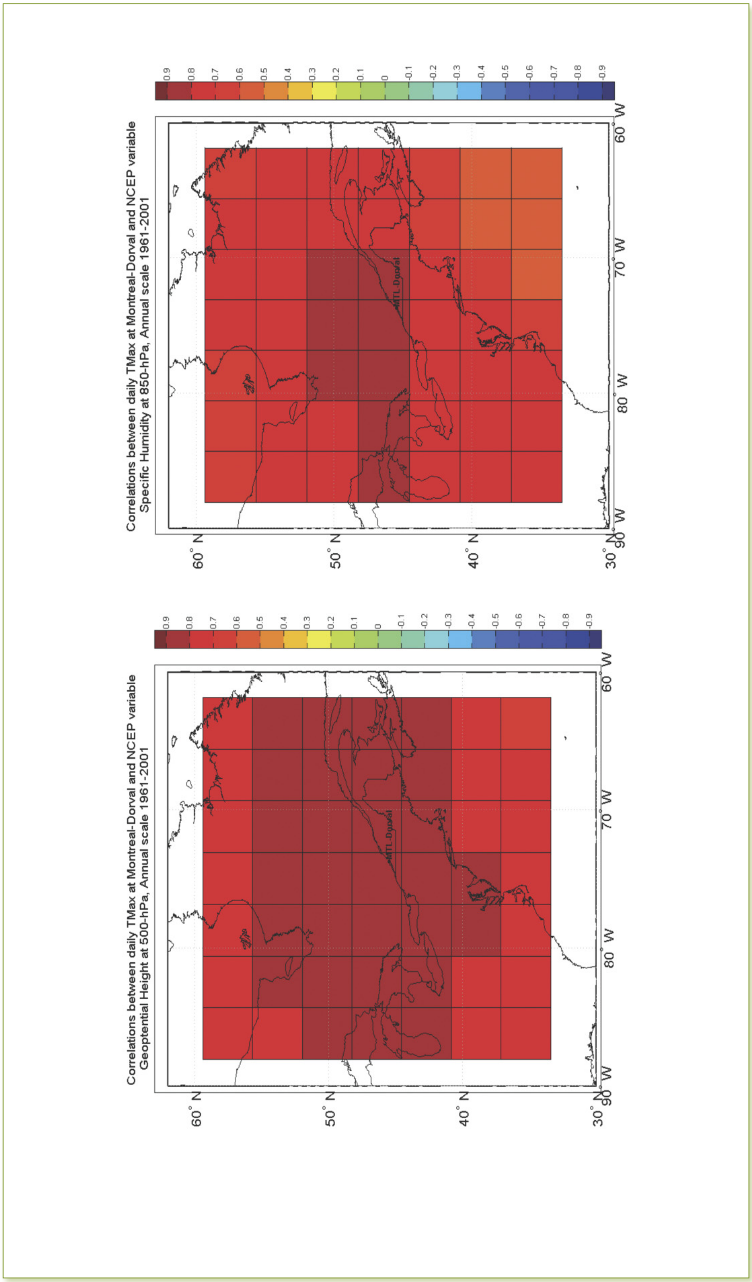

Figure 3 | Correlation maps between daily maximum Temperature (Tmax) at Montreal and geopotential height at 500-hPa (left panel), and between Tmax and specific humidity at 850-hPa (right panel), as derived from the NCEP reanalysis. The correlation is performed with the full inter-annual time series between 1961 and 1990.

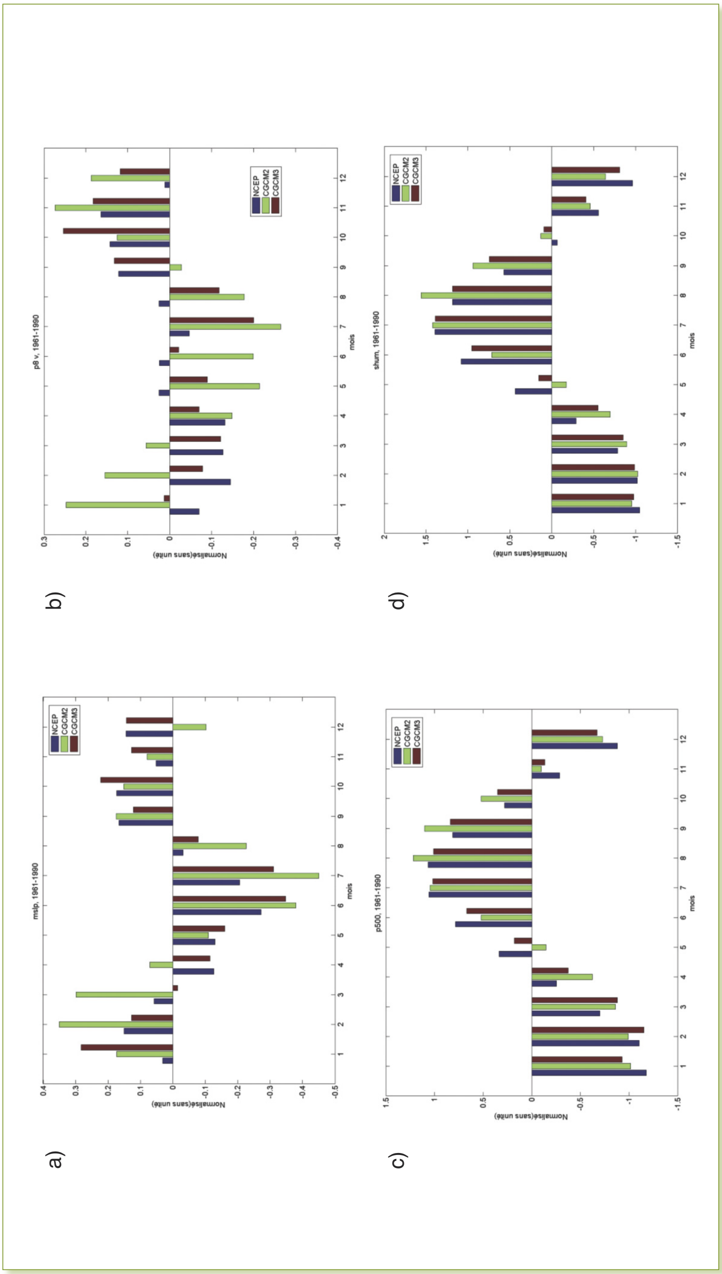

Figure 4 | Monthly evolution (1-12 in panels, i.e., J-D months) of a) mean sea level pressure, b) V-component of the wind at 850-hPa, c) geopotential height at 500-hPa, and d) specific humidity at the 850-hPa level, from NCEP, CGCM2 and CGCM3 predictors. Each plot corresponds to the four grid points closest to the Montréal climate station. All values are normalized with respect to the mean (subtracted) and the standard deviation (divided by) for each series of predictors for the 1961–1990 baseline period.

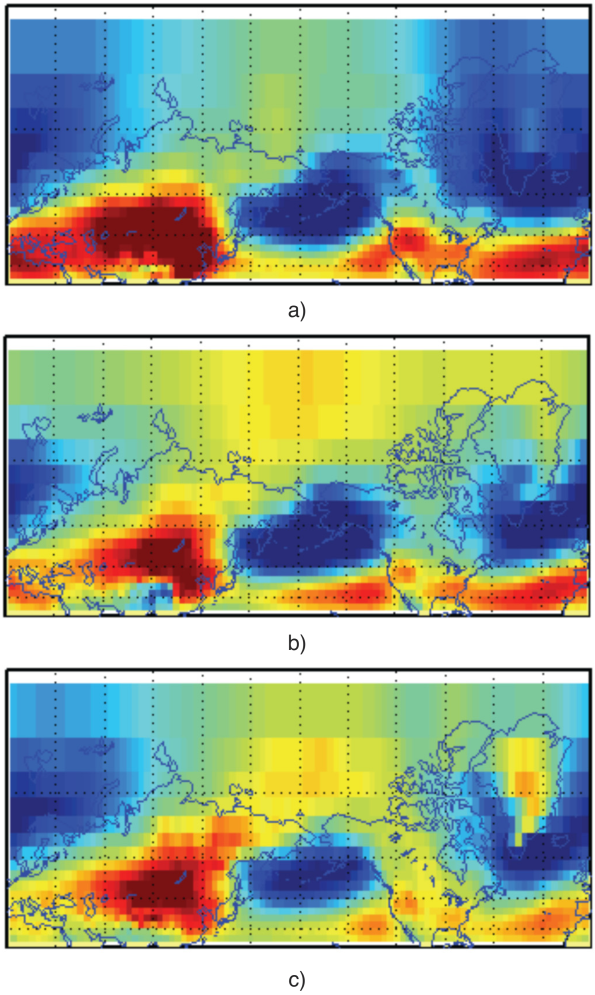

Figure 5 | A comparison of leading modes of variance in mean sea level pressure (annual scale) from a) CGCM2 (96.6% of total variance), b) CGCM3 (96.8%), and c) the NCEP-NCAR reanalysis (97.0%) applied for an area covering all longitudes and above 20°N (Source: Harding *et al.*, 2010).

corresponding values from two AOGCMs (i.e., versions 2 and 3 of the Canadian AOGCM - CGCM2 and CGCM3, Flato and Boer, 2001, and Kim *et al.*, 2002, respectively). Strong biases are revealed in the MSLP of CGCM2 in winter and summer months, and a stronger level of agreement can be seen between CGCM3 values and those from NCEP. The V-component of the wind at 850-hPa is also more strongly biased in the older version of the Canadian AOGCM. For the specific humidity at 850-hPa, values obtained from the CGCM2 are shifted in time, or give a poor estimation of the humidity pattern (and therefore the temperature pattern). This is especially the case in both summer months and for the fall, as also noted in the recent study by Gachon and Dibike (2007) in the northern area of Canada. Figure 5 shows that such inter model variation is not limited to Canada or the mean. Principal components analysis of MSLP reveals that modes of variance are also more accurately captured by CGCM3 than by CGCM2 (see further information in Harding *et al.*, 2010). The systematic discrepancies described above suggest that these variables, when derived from CGCM2, should not be used as predictors, in order to prevent the propagation of discrepancies from the host AOGCM into the SD process (see further explanations in Gachon and Dibike, 2007).

From Regional Climate Model output

Using RCM output instead of AOGCM output for the SD process may constitute a supplementary step in the regionalization procedure. In theory:

- RCMs should perform well in simulating circulation features affecting regional climates (e.g., jet streaks, thermodynamic variables, such as low level air temperature or diabatic fluxes; see definition in the glossary section) due to a resolution of processes that are sub-grid scale for an AOGCM. Hence, more surface or small-scale variables should be available as candidate predictors from an RCM, when compared to AOGCM output;
- Physical parameterizations of RCMs originate from a few “families” and mainly derive from the same AOGCM physical packages. This suggests that RCM and AOGCM outputs are not fully mutually independent, and that errors present in these physical packages or in interpolated atmospheric and oceanic fields from the AOGCM outputs into the RCM grid may propagate or be exacerbated into the RCM domain (i.e. if the RCM is not coupled with a regional-scale oceanic model). For example, surface oceanic conditions are more often taken from the coupled AOGCM and are generally inadequate when representing sea-ice margins or thickness, or sea surface temperature over sub-

arctic basins in regional scale models (see further discussion in Barrow *et al.*, 2004, and in Gachon and Dibike, 2007). The seasonal sea-ice margin and other coastal regions (Canada's coastline is in excess of 5000 km) represent a complex challenge for the development of realistic climate change scenarios at the regional scale; and

- The main advantage of using an RCM is that, for all variables, internal physical consistencies are maintained.

In order to analyze the potential added value for the SD process with respect to downscaling output previously obtained from AOGCMs, a new series of daily variables is under development from RCM runs as well as from regional reanalysis products. This new series of regional predictors is presented in Table 2. Derived values include ground temperature, surface diabatic fluxes, vertical motion and advection terms at various pressure levels, both dynamical (vorticity) and thermodynamical (temperature and humidity). Each of these new predictor variables has the potential to incorporate regional scale forcing factors linked with the evolution of predictand surface variables, such as temperature and precipitation. For example, turbulent fluxes of temperature and humidity play a key role in both temperature change and in the advection of temperature (Gachon *et al.*, 2003). These new variables, derived from 3 or 6-hourly values of both the North American Regional Reanalysis (NARR - Mesinger *et al.,* 2006) and RCM output, will be able to take into account fine scale effects and changes in surface conditions over both land/sea areas and complex coastal or island locations. Regions of highly heterogeneous land-cover or topography are not resolved at the scale of an AOGCM (Barrow *et al.*, 2004; Gachon and Dibike, 2007). The combination of various (vertical motion) predictors from both large-scale and mesoscale influences is particularly crucial to the improvement of our ability to downscale precipitation (compared to temperature, Dibike *et al.*, 2008), which is semi-stochastic in terms of both occurrence and magnitude. Predictors centred around divergence and convergence (linked to large-scale synoptic systems) as well as convective heat and humidity fluxes (in mesoscale weather systems) are inherently important for our ability to capture the variability of occurrence and intensity within any given precipitation regime. As suggested in the studies of Choux (2005), over Montréal, and in Parishkura (2009), over the Sahelian monsoon area, the combination of advection terms of vorticity and humidity have allowed us to improve downscaled precipitation occurrence when using NCEP, coarse-scale, variables. There is, therefore, the potential to improve downscaling of the precipitation regime further using equivalent regional-scale variables. In Figure 6, SD daily precipitation results developed by applying the "Automated Statistical Downscaling" (ASD e.g., Hessami *et al.*, 2008) model to a station in Ottawa, using predictors from NCEP, are compared to those using equivalents from NARR and the Canadian RCM (CRCM). Common variables are used, including specific humidity, vorticity, u-component winds at 850-hPa, and divergence and u-component winds at 500-hPa. The use of regional-scale predictor variables in the SD process allows us to improve both median values and quantile values of daily precipitation and its variability (see Figure 6 a and b, respectively). The use of other variables, including advection terms, is currently under evaluation for application to downscaling precipitation occurrence and intensity.

Table 2 | List of daily predictor variables in development from RCMs and regional re-analysis products (i.e. North American Regional Reanalysis, NARR, e.g. Mesinger *et al.*, 2006) to use in SD models.

PREDICTOR VARIABLES
Pressure Levels (upper air variables, ex. from 1000 to 300 hPa)
Geopotential Height Differences between 2 consecutive pressure levels (i.e. Thickness) Specific or Relative Humidity Wind (U & V components, Speed & Direction) Vorticity Divergence Advection terms (Temperature, Humidity & Vorticity) Vertical motion
Surface or near surface (low-level air and land surface variables)
Mean sea level pressure Specific or Relative Humidity Temperature Maximum/Minimum of Vorticity (from mesoscale or synoptic weather system) Diabatic fluxes (radiative, sensible & latent heat release) Ground Temperature (land & sea surface)

3. Potential for added value from SD

The potential for added value and the strengths and limitations of two particular single site regression-based SD approaches are shown in this section, using AOGCM and RCM outputs over various areas across Canada. A regression-based SDSM model (Wilby *et al.*, 2002) is used to downscale Tmax and Tmin values from two AOGCM

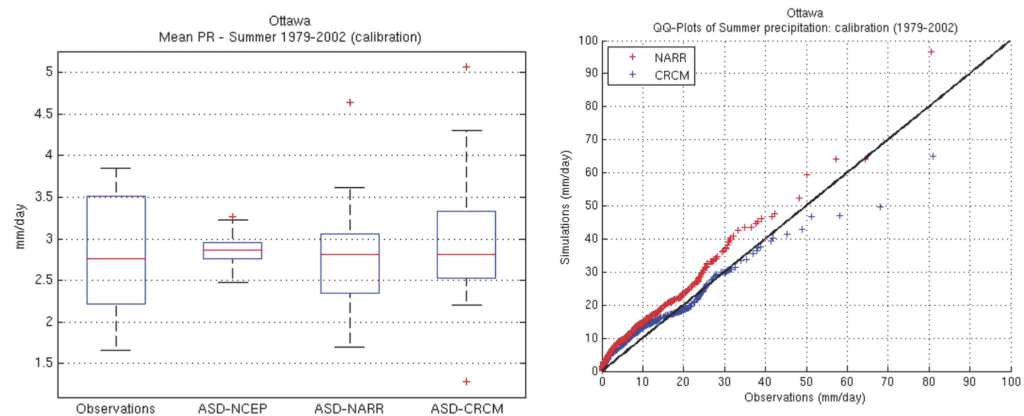

Figure 6 | Comparison between downscaled daily precipitation in summer from the ASD model (e.g. Hessami *et al.*, 2008) at Ottawa using specific humidity, vorticity, and U-component winds at 850 hPa, and divergence and U-component winds at 500-hPa, from a.) NCEP (ASD-NCEP), NARR (ASD-NARR), and the CRCM (ASD-CRCM). (Box plot values for mean daily precipitation) and b.) NARR (ASD-NARR) and the CRCM (ASD-CRCM) (Quantile-Quantile plot). In both graphs, observed values are used as reference (i.e. Observations).

predictor data series (i.e. CGCM2 and HadCM3), for the north Canadian areas used in recent studies by Gachon and Dibike (2007), and Dibike *et al.* (2008). The insight gained through the use of SD methods with respect to the raw-AOGCM data is briefly analyzed over both current and future periods (2080s). The other regression-based model, ASD, is used to downscale daily precipitation from two AOGCMs (CGCM2 and CGCM3), for the southern Québec area. In this latter case, simulations from two generations of the Canadian RCM (CRCM3.7.1 and CRCM4.2.0, see **http://loki.qc.ec.gc.ca/DAI/rcm_CRCM-e.html**), each driven by the relevant Canadian AOGCM (CGCM2 and CGCM3, respectively) are also compared with ASD results, using kriged predictand values over the CRCM 45-km grid. This comparison allows us to evaluate the added value gained through each downscaling technique, and also explores the uncertainty due to the choice of downscaling method using climate change simulations over the 2050s (a period only available from CRCM runs obtained through Ouranos, see **www.cccsn.ca**).

Example over Northern Canada

Over the current period (i.e. 1961-1990 period), Figure 7 reveals that Tmax and Tmin data simulated by two AOGCMs have strong biases (in terms of monthly mean) for the majority of the year (see also Figure 1 in Dibike *et al.*, 2008). The raw-AOGCM data shows a warm bias for the autumn months while the rest of the seasons show cold bias, as also suggested by seasonal Probability Density Functions (PDFs) shown in Figure 8. In general, monthly biases in raw CGCM2 temperature values are higher than those from HadCM3. The CGCM2 monthly temperature bias ranges between 2 and 20°C, while that of HadCM3 is in the order of 2–12°C, suggesting a more systematic problem with surface process representation in CGCM2 when compared against HadCM3 (Dibike *et al.*, 2008). Figure 7 also shows that SD has improved AOGCM output by strongly reducing the temperature biases compared to raw-AOGCM information. However, the downscaled data from CGCM2 does still contain some negative bias in the spring season and positive bias in the autumn months, larger than the bias visible within downscaled values from HadCM3. This is illustrated in more detail through uncertainty analysis in Dibike *et al.* (2008).

For the scenario runs, Figure 8 shows that seasonal changes in the downscaling results for Tmin, except in winter, are essentially due to a single shift of the PDF. In winter, the shift in the median values of downscaled data, with a warming of around 4°C, is associated with a slight increase in the variability due mainly to an extension of the

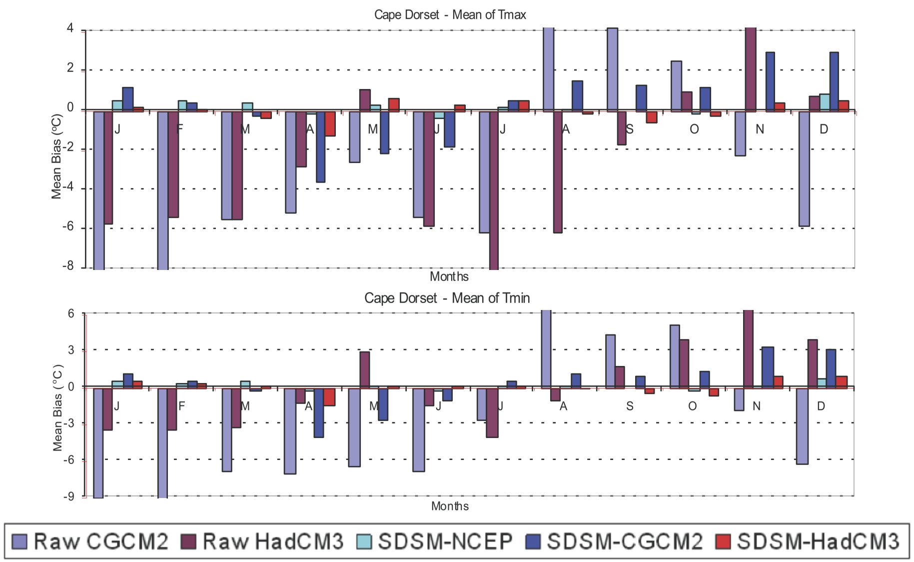

Figure 7 | Histograms of mean biases between the monthly mean values of observed data and the corresponding raw-AOGCMs and SDSM downscaled data of Tmax and Tmin (in °C, upper and bottom panels, respectively) at Cape Dorset over the baseline period (1961–1990). For further information see Dibike *et al.* (2008).

upper tails of the statistical distribution. This suggests a greater probability of hot extremes during winter for the 2080s. In other seasons, no substantial change in variability is shown. Figure 8 also suggests that the statistical distribution from the raw-AOGCM data is strongly biased. Results show a strong shift in median values, the presence of a nearly bimodal distribution in summer, and a strong overestimation in the frequency of 0°C values. These biases are due mainly to an inaccuracy in CGCM2 concerning the timing of the retreat and advance of sea ice and the thawing and the freezing of soil over the adjacent land area. The study of Gachon and Dibike (2007) in northern Canada suggests that the SD model is able to capture the major part of the temperature change signal, with a plausible climatic regime for higher warming in winter than in summer, and for A2 over B2 scenarios. A combination of relevant atmospheric predictors in the SD process is able to take into account most of the key factors in the temperature change signal, with strong convergence in both the magnitude and the timing of the changes across all results. Downscaling signals are more consistent and physically-plausible than the raw AOGCM anomalies.

Example over southern Québec

Over the current period (i.e. 1961-1990), Figure 9 reveals that the two downscaling techniques give quite different results for both wet days and mean intensity per wet day over the majority of the year (example given over southern area of Québec). The SD model is able to reproduce the monthly mean values of wet days and the relevant annual cycle quite well, especially when the SD model is driven by CGCM3 predictors. In the case of the CRCM model, both versions have some difficulty in reproducing the annual cycle. There is a strong overestimation of the wet day regime in spring and in summer, with a shift in the maximum wet day amount as compared to observed values. This behaviour has also been suggested over regions in the eastern United States (Roy, 2009). For the monthly mean intensity per wet day, the SD model reproduces the observed annual cycle, but with a slight overestimation of around 1 mm/day during the majority of the year and of 2 mm/day in May. In the case of the dynamical downscaling model, a systematic underestimation of mean intensity per wet day is revealed for the two versions of the CRCM model, suggesting a problem in reproducing the annual cycle, as for wet days (see Figures 9a and b).

In the scenario mode, Figure 10 reveals an inconsistent signal between the two downscaling methods concerning changes in wet days, mainly through May to December. For SD results, changes are consistently upward, with convergence in the

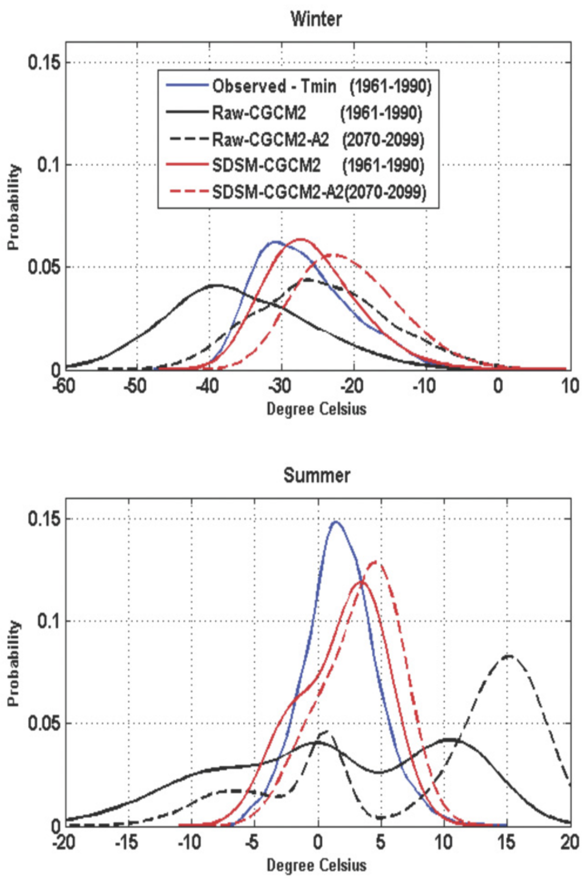

Figure 8 | Comparison of seasonal Probability Density Function (PDF) for Tmin at Cape Dorset for the future (2080s, A2 scenario) and the current (1961–1990) periods between observed, downscaled and AOGCMs values: SDSM with CGCM2 predictors (SDSM-CGCM2) and raw-CGCM2 (CGCM2). For further information see Gachon and Dibike (2007).

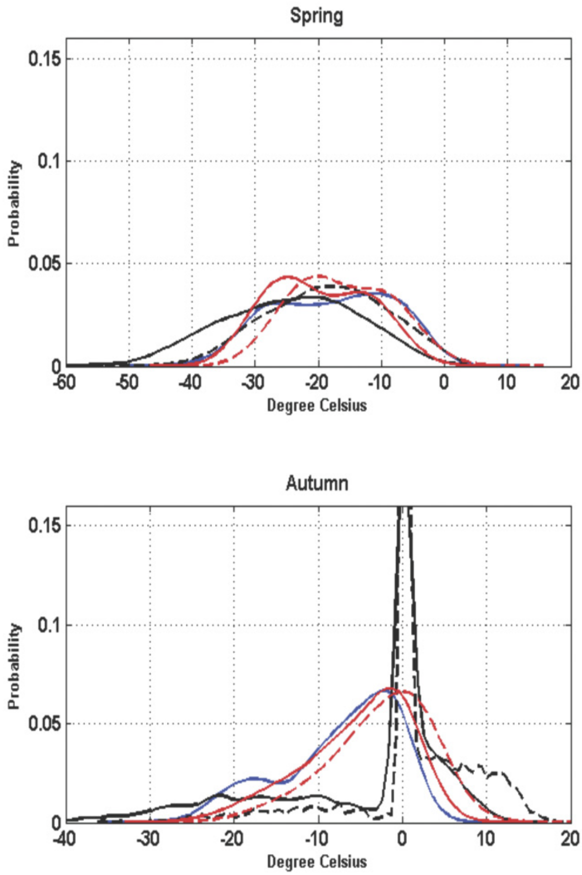

Figure 8 cont... | Comparison of seasonal Probability Density Function (PDF) for Tmin at Cape Dorset for the future (2080s, A2 scenario) and the current (1961–1990) periods between observed, downscaled and AOGCMs values: SDSM with CGCM2 predictors (SDSM-CGCM2) and raw-CGCM2 (CGCM2). For further information see Gachon and Dibike (2007).

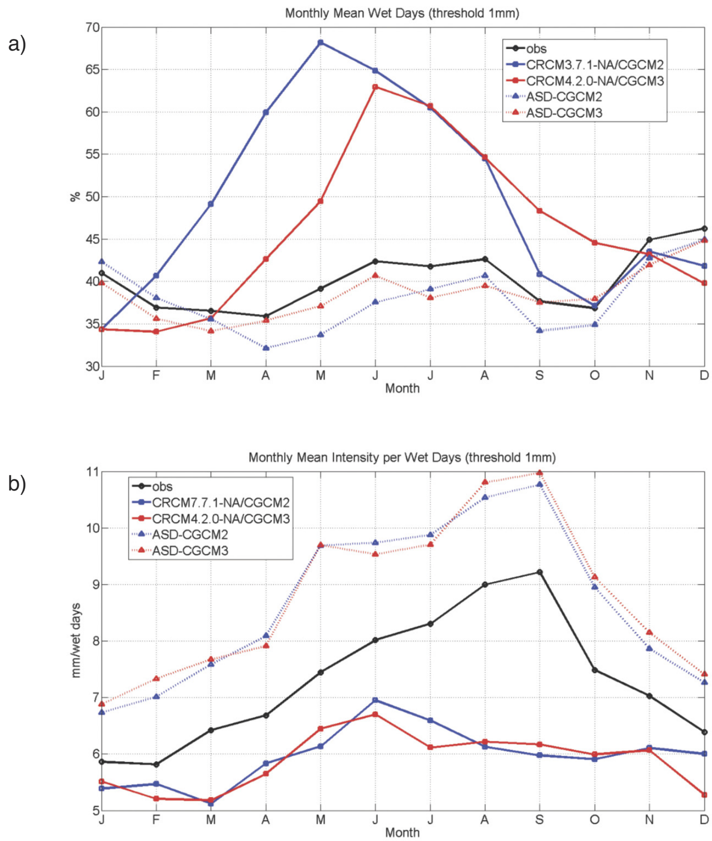

Figure 9 | Monthly mean comparison among kriged observed values (i.e. interpolated on the 45-km grid of the CRCM, see further information about the model versions in **http://loki.qc.ec.gc.ca/DAI/rcm_CRCM-e.html**), SD results using the ASD model (downscaled values over the kriged observed values), and two versions of the CRCM for a) wet day (in %, threshold of 1 mm/day, see Gachon *et al.*, 2005), and b) intensity per wet days (in mm/day). The two downscaling techniques are driven by both CGCM2 and CGCM3 (i.e. ASD-CGCCM2/3 and CRCM3.7.1-CGCM2 and CRCM4.2.0-CGCM3). 10 x 10 grid points from downscaling values are compared over the 1961-1990 period over southern Québec.

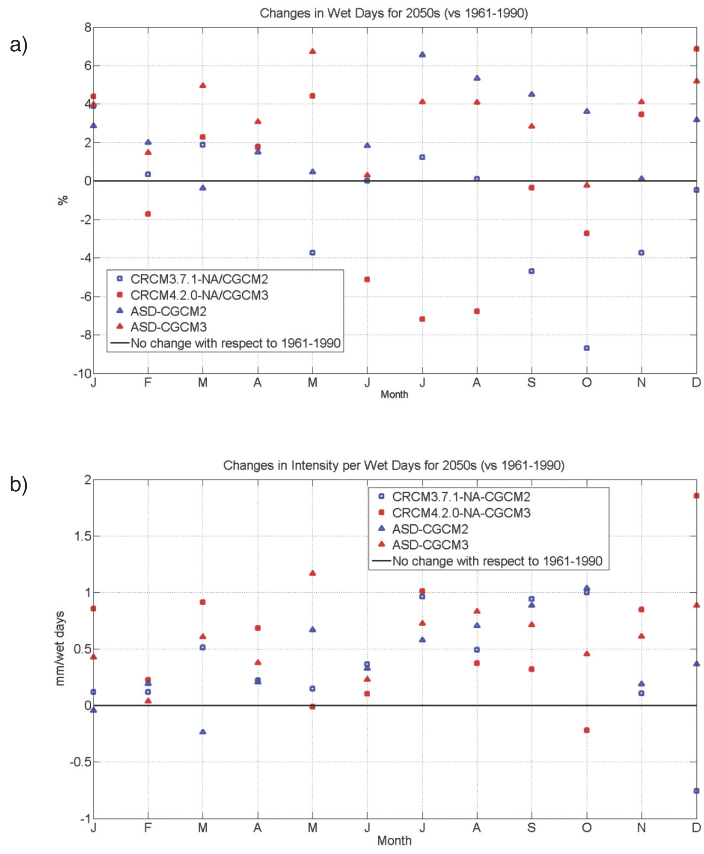

Figure 10 | Monthly changes over the period 2041-2070 (with respect to 1961-1990, A2 scenario) from the ASD model, and two versions of the CRCM for a) wet days (in %), and b) intensity per wet days (in mm/day). The two downscaling techniques are driven by both CGCM2 and CGCM3 (i.e. ASD-CGCCM2/3 and CRCM3.7.1-CGCM2 and CRCM4.2.0-CGCM3). 10 x 10 grid points from downscaling values are compared over southern Québec.

amplitude of the signal over the majority of the year. Results from CRCM3 and CRCM4 are ambivalent, with a change in wet days depending on the month and version of the dynamic model under consideration, especially through May to December. For one of the CRCM versions no change can be seen in August or September. The lack of confidence in either the simulated or historic wet day regime in the CRCM, from both versions of the model, results in strong uncertainties concerning these precipitation outputs. Caution is required when deriving climate change information for local application in impacts studies. For mean intensity per wet day, changes are more consistent and coherent between downscaling models and months, with a quasi-systematic increase in intensity of daily precipitation. This increase is largely greater during summer and fall, regardless of the AOGCM driven conditions (i.e., for both CGCM2 and CGCM3). The usefulness of this comparison, between the two downscaling schemes, is that the confidence in estimates of regional or local climate change will only be improved by the convergence between dynamical and statistical signals or by the emergence of clear evidence supporting the use of a single preferred method (Murphy, 2000).

4. Reproduction of a predictand regime by a SD model

The reproduction of a climate regime of a predictand using an SD model constitutes one of the most important criteria in the evaluation of any downscaling model, and in the selection of the preferred method to develop scenario information. The ability of the downscaling scheme to reproduce observed trends and variability for a given predictand is paramount. Not all models are able to reproduce (partially or entirely) observed climatic trends, or inter-annual variability, over short (seasonal) and long (decadal) timescales, apparent in the observed data series. As suggested in section 2, the selected predictors need to be statistically significant contributors to the variability in the predictand, or they should represent important physical processes in the context of the main fluctuations of the predictand. It is particularly important to observe whether or not the statistical model can be extrapolated to situations where local climate is warmer, cooler, drier or wetter than the climatic conditions for which the SD model has been calibrated. An example follows concerning northern Canada, where changes in temperature are inherently greater at all timescales than in other regions of Canada. This amplification of fluctuation is due to significant changes in surface albedo, mainly from changes in the snow cover, and also due to modifications in surface diabatic fluxes (i.e. sensible and latent heat fluxes) over oceanic areas, according to the state of sea-ice extent and thickness.

In order to analyze the effects of fluctuations in large-scale circulation indices on local predictands, a comparison is made in Figure 11 between interannual fluctuations of the North Atlantic Oscillation (NAO) index and Tmax and Tmin from both observed and SD values at Iqaluit (see its location in southwestern Baffin Bay, in Figure 1 in Gachon and Dibike, 2007). Mean seasonal values of Tmax and Tmin are analyzed alongside cold and warm extremes (i.e. 10th percentile of Tmin, and 90th percentile of Tmax, respectively) over the winter season (DJF). Figure 11 confirms strong links suggested by previous authors (see Hurrell and Van Loon, 1997) between the positive (negative) phase of the NAO and the cooling (warming) of temperatures in northeastern Canada. Recent observed shifts in winter extreme events are related to the strengthening of the winter time NAO, with a strong negative correlation between the NAO and temperature values close to -0.7 (except for Tmin 10th percentile at -0.52, see Table 3). As also shown in SD results using NCEP predictors (see the choice of predictors in Gachon and Dibike, 2007), downscaled values reproduce both trends and the interannual anomalies of both mean values of temperatures and extremes of Tmin and Tmax. A range of correlation close to 0.81-0.92 is obtained between downscaled values and observed values, suggesting that the SD model with the right combination of predictors is able to maintain and develop the main forcing mechanism responsible for the winter variability of temperature. The SD model is also able to reproduce the correlation between Tmax and Tmin time series with NAO interannual anomalies with a range of correlation between -0.52 and -0.75 (Table 3). For the other stations in the North and for other seasons this relationship is less sensitive. The link between the NAO and changes in temperature is less pronounced, and the spatial influences of the NAO index decrease, over the rest of Canada. It is also worth noting that the NAO mainly affects the winter months through November to March. It is difficult to reproduce the exact evolution of the NAO in AOGCMs (see IPCC, 2007; Harding *et al.*, 2010), for several reasons. Mainly, it is due to the chaotic nature of this event and model misrepresentation associated with the low resolution of ocean dynamics, ocean-atmosphere coupling, sea-ice, and topography. Greenland, for example, is largely “smooth” at the scale of an AOGCM, whereas its landmass plays an important role in storm tracks and the blocking of pressure systems over the North Atlantic, all of which affect the NAO pattern (see Hurrell and Van Loon, 1997).

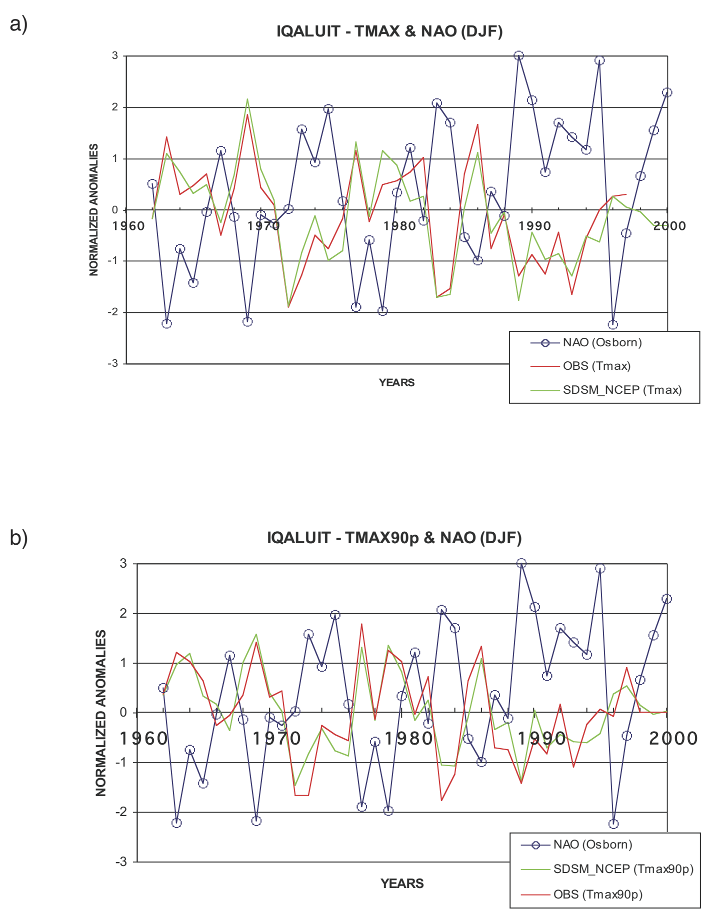

Figure 11 | Comparison of interannual winter normalized anomalies over the period 1961-2000 (with respect to 1961-1990) between observed and SD values of temperatures, and with the NAO index at Iqaluit, Nunavut for a) the mean daily Tmax, b) the 90th percentile

cont.

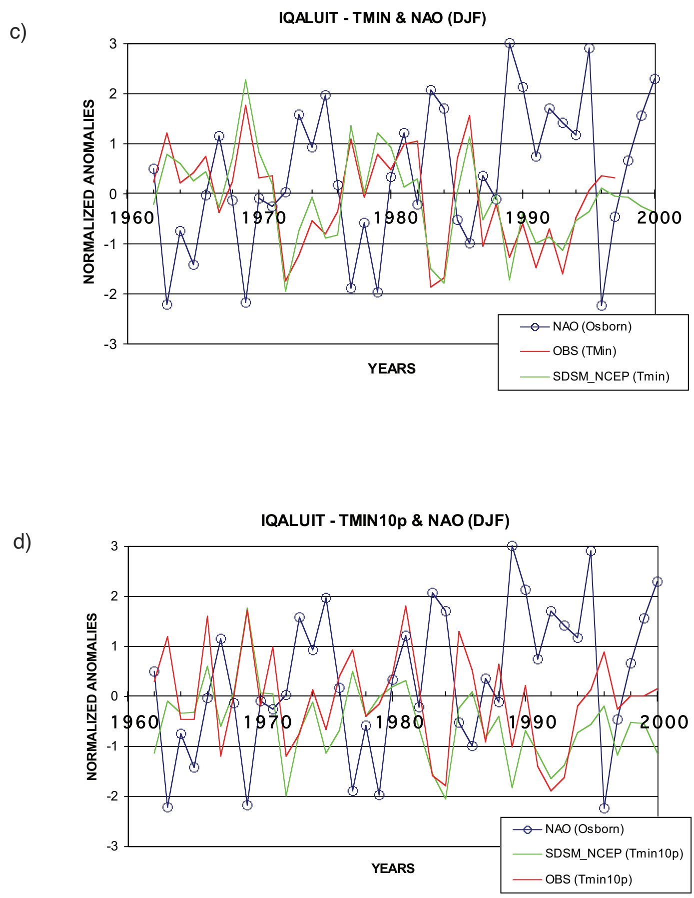

Figure 11 cont... | of daily Tmax, c) the mean daily Tmin, and d) the 10th percentile of daily Tmin. All temperatures and NAO values are averaged over the three winter months of December, January and February (DJF, respectively). The NAO index is defined from Osborn *et al.* (1999).

Table 3 | Temporal correlation values between the observed (i.e. predictand) and SD (i.e. downscaled values from SDSM using NCEP predictors) values of temperatures, and the NAO index (from Osborn, e.g. Osborn *et al.*, 1999) for the winter (DJF) season at Iqaluit, Nunavut (located in southern Baffin Island). Tmax and Tmax90p correspond to the mean value and the 90th percentile of daily maximum temperatures, and Tmin and Tmin10p to the mean value and the 10th percentile of daily minimum temperatures, respectively. The correlation is made using normalized values. NB: the correlation between the downscaled values and each respective predictand is high, i.e. between 0.81 and 0.92. All correlations are statistically significant at the 95% level.

OBSERVED & SD VALUES	NAO INDEX (OSBORN)
Predictand (Tmax)	-0.7
SDSM_NCEP (Tmax)	-0.75
Predictand (Tmax90p)	-0.69
SDSM_NCEP (Tmax90p)	-0.72
Predictand (Tmin)	-0.69
SDSM_NCEP (Tmin)	-0.71
Predictand (Tmin10p)	-0.52
SDSM_NCEP (Tmin10p)	-0.61

5. Conclusion and Further Steps in SD research

SD methods offer various advantages and constitute some useful alternative techniques for climate modelers and impact researchers, mainly because they are:

- Much less computationally demanding than RCMs, and can easily produce ensemble runs of high resolution climate scenarios;
- Able to employ a full range of available, physically appropriate predictor variables (both from AOGCMs and RCMs), as long as a pre-screening of predictors is conducted;
- Able to adequately reproduce a predictand climatic regime in terms of explained variance, correlation, and statistical distribution;
- Able to reproduce the trend (if any) and interannual variability of a predictand, for seasons where the predictand is strongly linked with the large-scale behaviour of selected predictors, i.e., this is not true for all seasons or locations, or where links with atmospheric circulation indices are less clear;
- Able to take into account non-stationarity in predictor/predictand relationships with the relevant combination of predictors, but this needs to be explored with a large variety of long data series and climate regimes.

However, as for other downscaling methods, SD methods have their own limitations, namely:

- Specialist knowledge is required to apply these techniques correctly;
- The relationships for some variables may lie outside the range of the calibration period;
- It may not be possible to derive significant relationships for some variables (e.g., extremes of precipitation);
- The degree of stationarity in the relationship under consideration may constitute a limitation for the downscaling of extremes (precipitation), especially with linear SD methods.

The need to improve and develop more sophisticated SD approaches has hence emerged in order to:

- Develop more spatial coherence (i.e. regional-scale physical distribution of the considered variable over the targeted area) within the downscaling of precipitation (i.e., no spatial coherence is obtained from a single site SD approach);
- Develop a multisite & multivariate SD model using various approaches, be they multi-linear, machine learning based, kernel-gaussian, etc., in order to evaluate the potential added values from each;
- Develop non-linear regression or other approaches with genetic algorithm, or weather typing approach to improve the relevant combination of predictors;
- Develop and identify links between local predictands and regional-scale predictors from RCM runs and other sources in order to gain information on links with extremes and stationarity issues;
- Develop ensemble runs with various AOGCM/RCM driven conditions to construct probabilistic scenarios.

An on-going project in which Environment Canada is engaged with partners at Universities across Canada (namely McGill, UQÀM, INRS-ETE, University of Toronto, University of British Columbia), under the NSERC-SRO (Natural Sciences and Engineering Research Council of Canada, Special Research Opportunity) initiative will allow us to develop new SD methods. i.e. multivariate and multisite statistical approaches. This project on the "Probabilistic assessment of regional changes in climate variability and extremes" is developed in collaboration with European and US colleagues through the ENSEMBLES **http://www.ensembles-eu.org/** and US NARCCAP **http://www.narccap.ucar.edu/** projects, in which a large variety of downscaling models are inter-compared. In order to more coherently address regional climate change and the associated uncertainties, these coordinated efforts will improve the integrated hierarchy of models, will help to evaluate different methodologies, and to apply both dynamical and statistical downscaling approaches in a comprehensive strategy over various regions of interest.

Finally, the internal climate variability of northern Canada's nordic conditions is huge compared to other temperate regions in the Northern Hemisphere. This issue needs to be carefully addressed, especially through downscaling methods applied to a more systematic analysis of the stability in relationships between predictors and predictands with time. Further research is also required in order to distinguish large versus regional scale influences on both climate variability and change. This is true for regions in which low and high frequency variability in the atmosphere and ocean affect the mean climate state and related physical processes at the regional scale, both linked to the occurrence and frequency of extreme events. Plausible causes for changes in the timing and magnitude of these climatic events need to be urgently addressed at high spatial resolution. They are of primary importance for impacts studies, environmental modeling and risk assessments.

Glossary

- Geopotential Height : a physical height measurement representative of air thickness beneath a given pressure level.
- Vorticity : spin of airflow.
- Divergence : outflow or inflow of an airstream.
- Diabatic fluxes: heating or cooling rate of an air parcel due to divergence or exchange of energy from various processes, i.e. through latent heat release, radiative transfer and/or divergence of sensible heat.

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Societal and Economic Research and Applications (SERA) for Adaptation to Atmospheric Hazards in Canada

3

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Abstract: Economics and other social science disciplines offer a wide range of methods and tools that can be applied to atmospheric hazards to determine the need for adaptation and the costs and benefits associated with various forms of planned response—including the provision of better weather, climate, and climate change information. Unfortunately the limited number of studies and applications that have been conducted in Canada are insufficient to adequately document the economic implications of atmospheric hazards and the costs and benefits of adaptation. The rationale and priorities for pursuing a renewed research agenda in Canada are examined based on deliberations that occurred during the *SERA North: Economics of Weather, Climate, and Climate Change* meeting held February 2008 in Waterloo, Ontario. While progress is being made towards the recommended activities, much remains to be done to fill research gaps and overcome methodological and practical challenges such as the aggregation and generalization of impacts across scales or regions and the valuation of environmental and social costs and benefits.

Keywords: atmospheric hazards, economic valuation, climate change, adaptation.

1. Introduction

This paper is based on material presented and discussed at a recent forum: the *SERA North: Economics of Weather, Climate, and Climate Change* meeting held February 2008 in Waterloo, Ontario (Mills, 2008). A rationale and priorities for pursuing a renewed research agenda in the area of weather and climate-related societal and economic research and applications (SERA) are introduced along two primary and interrelated lines of inquiry:

1) What is the value of weather, climate, and climate change information to Canadian society; and
2) What are the costs of impacts resulting from weather, climate, and climate change, with and without the adoption of adaptive and mitigative response measures?

The overriding context for the theme selection stems from the mandate and core functions of Environment Canada (EC) which are captured in the mission statement of the current and peer-reviewed EC Science Plan (2006a):

> *To deliver the high-quality knowledge, information and data that enable the Minister, the Government, the Department and other decision makers to enhance the health*

and safety of Canadians, protect the quality of the natural environment, and advance Canada's long-term competitiveness.

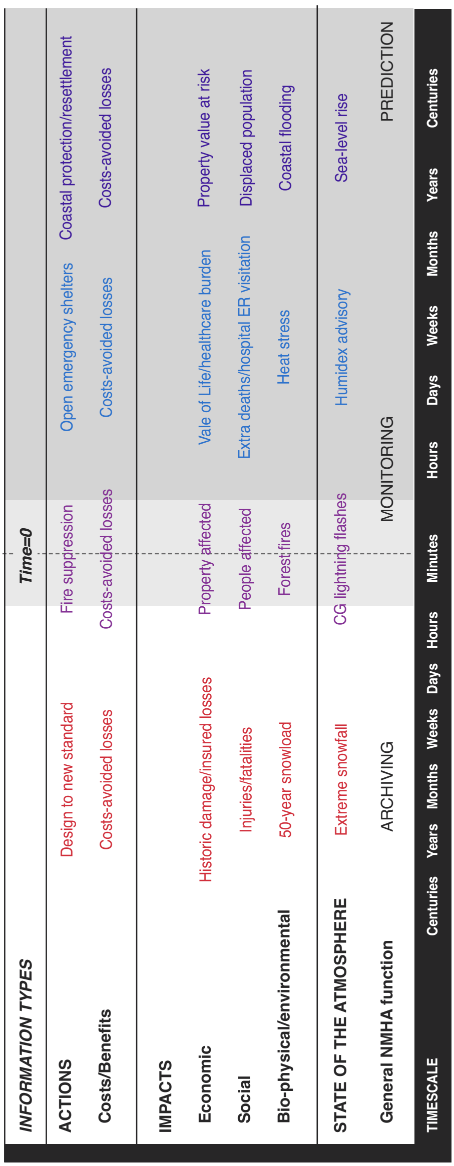
The mission and mandate imply that Environment Canada produces information to enable better decisions and provide clear indicators, if not well-defined thresholds, of societal value that extend beyond goods and services traded in markets. Although Environment Canada, partner organizations, and others in Canada have developed and disseminated substantive amounts of information concerning weather, climate and climate change, there is often a disconnect between the production of this information and the value it provides to Canadian society. SERA activities can help bridge this gap and the February 21-22 meeting in Waterloo was one step towards defining a path forward while building on past efforts (i.e., Morss *et al.*, 2008; Stratos Inc., 2004).

2. What is the value of weather, climate, and climate change information?

Hundreds of thousands of weather forecasts, severe weather warnings, and climate predictions are issued to the public each year in Canada. Along with billions of archived environmental observations, data from numerical weather and climate prediction models, and associated applications, this information is intended to encourage adaptive behaviour among the public and decision-makers in health, agriculture, energy, forestry, transportation, construction, insurance, and many other sectors. The production of this information is dependent on a federal public monitoring, computer, telecommunication, and research laboratory infrastructure valued at over $330 million and the efforts of about 2,000 meteorologists, scientists, technicians and support staff. Unquantified, yet significant (perhaps greater?), contributions are also made by international, provincial, local, or non-government agencies; and academia. Contributions by the private sector, which includes meteorological service providers, media and experts employed directly by large user businesses, institutions and organizations, are increasing.

In light of such investments, Environment Canada and many other public National Meteorological and Hydrometeorological Agencies (NMHAs) have become increasingly interested in identifying, tracking and evaluating the costs and benefits of providing timely, precise and accurate information about the past, current and future states of the atmosphere. This desire is also driven by broader globalization pressures that have encouraged the proliferation of international quality control, quality assurance and other standard-setting and performance-measuring practices. Clearly there is a need to justify the cost of *current* operations and this objective has underpinned public agency support for societal and economic valuation research. A small but growing literature has emerged over the past 40 years that documents and estimates the use and value of weather and climate information. Katz and Murphy (1997) provide one of the most critical and comprehensive collections of referenced work, critiquing a wide spectrum of methods available to determine economic value (e.g., contingent valuation, market-based cost-loss functions, cost-benefit analysis, etc.). Rubas *et al.* (2006) review a selection of both applied and theoretical modeling approaches to value climate information (e.g., decision theory, general equilibrium modeling, game theory). Elsewhere, recent examples of sector-specific studies on aspects of agriculture (Johec *et al.*, 2001; Fox *et al.*, 1999), energy (Gurtuna and Davison, 2007; Roulston *et al.*, 2002), human health (Ebi *et al.*, 2004), forestry/fire management (Gunasekera *et al.*, 2005), transportation (Keith, 2003; Smith and Vick, 1994; Stewart *et al.,* 2004), and water resources management (Hamlet *et al.*, 2002) are complemented by broader evaluations of multiple sectors and public or household willingness-to-pay for weather services (Rollins and Shaykewich, 2003; Lazo and Chestnut, 2002; Brown, 2003) and public satisfaction surveys (e.g., Ekos Research Associates, 2007). Such studies most often examine the value of information that is currently received or that could be obtained with some specified level of improvement in quality (i.e., precision, accuracy, delivery frequency or medium). Other researchers have examined a particular component of the monitoring and forecast system, such as the impact of an expanded network of Doppler radar infrastructure in Canada (Vodden and Smith, 2003) or *Weatheradio* (Cavlovic *et al.*, 1997).

These analyses serve as a useful base and, in most cases, provide suitably large numbers to more than justify past NMHA expenditures. For example, the research by Vodden and Smith (2003) found that the discounted benefits of the improved national radar program in Canada would amount to $433M relative to costs of $88M over a ten-year horizon. Overall though, the cost-benefit research in Canada remains ad hoc, fragmented, under-funded, inconsistently peer-reviewed, and underutilized. A more systematic, strategic, and long-term approach to funding, designing, conducting and applying societal and economic valuation research could yield much greater benefit. For public agencies, better understanding of the value of providing meteorological, hydrometeorological and climatological information could be fundamental inputs to measuring and improving products and services. This knowledge would also inform



NHMA – National Hydro-Meteorological Agency; CG – Cloud-to-Ground

Figure 1 | Types of information potentially provided by National Meteorological and Hydrometeorological Agencies at different timescales.

critical decisions with respect to the application of new technologies and changes to existing monitoring networks, observation strategies, communications, computer infrastructure, human resource management, and priorities for research and development—or the most appropriate mix of adjustments.

As an example, one of the many critical decisions currently being debated relates to the type of information being generated and communicated to the public by NMHAs. Figure 1 is a simplified attempt to map a generic set of information types. Different classes of information are indicated along the left-hand column while timescales, centred on the Time=0 line, are defined along the bottom of the figure. In general, user-relevance and presumably value increases as one moves from *state of the atmosphere* through *impacts* and up to *action*-oriented information types. Four sample "information chains" are indicated in like-coloured text above the applicable time period. Three general functions common to most NMHAs are identified above the appropriate timescale: *monitoring* of current atmospheric and related environmental conditions; the *archiving* and analysis of this data; and *prediction* of future states of the atmosphere.

Typical NMHA products include current weather conditions, forecasts and warnings that are disseminated via the Internet and various media to the public in an array of text, audio and graphic formats. Much of the information that is distributed relates to observations, analyses and predictions of physical or bio-physical quantities such as temperature and precipitation amounts. Historically, the users of this information have implicitly been assumed by NMHAs to follow a linear model of decision-making whereby the provision of more accurate information at higher spatial and temporal resolution leads directly to improved safety, environmental protection, and economic productivity. SERA activities can be used to explore the validity of this and other assumptions prior to committing to costly, long-term, and inflexible investments. For instance, it may be more effective to change the message or the medium rather than invest in a new monitoring technology or supercomputer. Often this involves greater consideration of users and the decisions they face. Along this line of thought, recent efforts by Environment Canada and other NMHAs to move towards broader environmental prediction—where atmospheric data and simulation tools are coupled with biophysical and eventually socio-economic impact models—are effectively attempting to move up the information chain presented in Figure 1. Heat alert systems (e.g., Sheridan, 2007) and the development of air quality health index forecasts (e.g., Environment Canada, 2009) are encouraging examples of this shift. However, like the traditional information products that they are replacing or augmenting, they are being constructed in isolation, and often without the benefit of SERA valuation work and underlying monitoring of key indicators from which progress towards societal objectives can be verified.

3. Costs of weather, climate, and climate change

At the extreme right side of Figure 1, one is confronted with information concerning atmospheric-related phenomena and predictions that won't be verifiable for decades or centuries. The centre-piece at this end of the timescale is anthropogenic climate change, an issue that has emerged over the past 25 years as one of the most significant challenges facing humanity. Citizens, non-government organizations and decision-makers at all levels of government and throughout industry are grappling with ways to manage greenhouse gases (mitigation) and adjust to the implications of a changing climate for society's welfare (adaptation). Many decisions must be taken now in the face of considerable uncertainty about the extent and nature of future global and regional climate and, more importantly, societal vulnerability and adaptability (i.e., related to values, geo-political stability, trade and wealth distribution, natural resource availability, technology, etc.).

In Canada, a significant amount of research has been conducted to provide information about possible future states of climate under various emission growth scenarios (e.g., CCCma[1], CCCSN[2]). Scientists have directly or indirectly used this information to analyze potential impacts and evaluate the efficacy of measures to manage risks and opportunities. Much of this effort has focused on defining biophysical and first-order socio-economic impacts of weather, climate, and climate change within specific regions (e.g., Cohen, 1997; Mortsch *et al.*, 1998, 2000), sectors (Auld and MacIver, 2005; Mirza, 2004; Mills *et al.*, 2006; Ogden *et al.*, 2006; Scott and Suffling, 2000), issues (MacIver, 1998 – biodiversity) or for particular hazards and events (e.g., Koshida *et al.,* 1999; Etkin and Myers, 2000; Cheng *et al.*, 2007; Auld *et al.*, 2004). In many cases adaptive responses or strategies have been identified, modeled and evaluated using criteria and methods drawn from natural hazard and climate adaptation frameworks (e.g., Burton *et al.*, 1993; MacIver and Wheaton, 2005; Fenech *et al.*, 2004) and the intense engagement/involvement of regional or sectoral decision-makers

1 Canadian Centre for Climate Modelling and Analysis **http://www.cccma.bc.ec.gc.ca/**
2 Canadian Climate Change Scenarios Network **http://www.cccsn.ca/index-e.html**

or stakeholders (e.g., Cohen *et al.*, 2006). More recently, studies have been proposed and undertaken to integrate climate change research within a broader sustainable development framework that encompasses mitigation and adaptation responses (e.g., Bizikova *et al.*, 2008; Swart and Raes, 2008).

Only a few studies, however, have explicitly been designed to include an evaluation of the economic impacts of weather, climate, or climate change in Canada—or the costs and benefits of adaptation. Specific weather and climate events, generally those that are severe or extreme and have led to substantial media coverage, have been the focus of several detailed investigations. Canadian examples include assessments of heavy snowfall in the B.C. Lower Mainland (Pan Pacific Communications, 1997), 1997 Red River flood in Manitoba (Haque, 2000), Ice Storm 1998 (Lecomte *et al.,* 1998), January 1999 Toronto snow emergency (Mills *et al.*, 2003), and 2001-02 drought (Wheaton *et al.*, 2008). Such studies normally provide a chronological account of the specific physical hazard, often set within the bounds of local experience, and then proceed to document social and economic impacts and responses. The latter are assembled using a broad range of data sources of varying quality (e.g., media accounts; interviews or focus groups with stakeholders, segments of the public, and key officials; statistics collected/reported by insurance and government agencies). Wheaton *et al.* (2008) likely provide the most comprehensive and sophisticated assessment completed to date in Canada, employing a multitude of data sources and analytical methods, including input-output modeling to ascertain direct, indirect and induced effects on the economy.

Event-based analyses provide great detail for a unique situation but results may not be transferable to other locations, may not provide much information on changes through time, and are not easily aggregated. Although a few studies have estimated composite impact costs for particular hazards at the national scale (e.g., lightning, Mills *et al.*, 2010), there is no national Canadian economic study examining the sensitivity of sectors and regions to climate that is comparable to efforts in other countries (e.g., U.S., Lazo *et al.*, 2008). A modest effort by Herbert and Burton (1994) to define the costs of climate adaptation across multiple economic sectors and activities in Canada (Table 1) remains the most commonly cited effort to establish an aggregate national estimate.

Table 1: Estimates of the Cost of Adaptation to Current Climate in Canada and Possible Trends Under Climate Change

Sector/Activity	Total Cost ($ million)	% Attributable to Climate Adaptation	Cost of Climate Adaptation ($ million)	Possible Trend under Climate Change
Transport:	7,367.5		1,657.3	decrease
Air	83.5	100	83.5	decrease
Marine	258.8	55	143.8	decrease
Rail	702.0	29	203.2	uncertain
Roads	6,323.1	19	1,226.5	decrease
Construction	2,000.0	100	2,000.0	uncertain
Agriculture	1,887.3	70	1,329.6	increase
Forestry	556.3	72	402.6	increase
Water:	1,058.0	73	767.3	increase
Flood Control	4.7	80	3.8	
Household Expenditure	6,023.0	88	5,296.4	decrease
Emergency Planning	14.4	75	10.8	increase
Weather Information	189.4	100	189.4	increase
TOTAL	19,095.9	61	11,653.0.4	
Source: Adapted from Herbert and Burton (1994)				

Source: Rothman *et al.,* 1998:18

Despite the significant attention afforded to the issue, Canadian studies focused on the economic impacts of future climate change, or costs of associated adaptation, are also limited in number (e.g., Buttle *et al.*, 2004; Environment Canada, 2006; Hauer *et al.*, 2003; Hrasko and McNeill, 2006; Maoh *et al.*, 2008; Mendelsohn and Reinsborough, 2007; Millerd, 2005; Reinsborough, 2003; Dore and Burton, 2001; Watt *et al.*, 2003; Yevdokimov, 2005). The scope of most of the individual studies is constrained to one sector (i.e., agriculture or transportation), region (i.e., New Brunswick, Great Lakes, Okanagan watershed), or issue (sea-level rise, water management). Methods range from relatively straightforward direct loss (e.g., Millerd, 2005) and adaptation cost (e.g., Watt *et al.,* 2003) estimations to more intricate statistical models relating climate factors to the value of land (e.g., Ricardian approach used by Mendelsohn and Reinsborough, 2007). In most cases the cost estimations are static comparisons between a baseline and some future period. Assumptions concerning the degree of climate change and adaptation vary significantly.

The lack of economic research presents a major gap—past workshops and national assessments of potential impacts and adaptation repeatedly draw attention to the dearth of economic analyses (Stratos Inc., 2004; Maxwell *et al.*, 1997; Rothman *et al.*, 1998; Lemmen and Warren, 2006). To the author's knowledge, nobody has attempted to even qualitatively assess the full costs of climate change in Canada—costs of mitigation plus costs of adaptation plus residual costs (benefits of mitigation and adaptation subtracted from the costs of inaction). It may be possible to infer or generate Canadian economic impacts from the results of international research (e.g., Mendelsohn *et al.*, 2000; Tol, 2002). However, a recent review and synthesis of climate change damage functions for a variety of sectors (e.g., agriculture, energy, tourism) and issues (e.g., extreme or catastrophic events, sea-level rise) suggests that significant effort is required to modify and apply them to the Canadian context (Marbek Resource Consultants, 2009). It is important that generalized findings and assumptions be examined from a Canadian perspective, informed by regional and sectoral research, and contested using alternative economic/value frameworks. As has been demonstrated by the Stern Review report (Stern, 2007) and interpretations of its methods and results (Pielke, 2007; Yohe *et al.*, 2007; Neumayer, 2007; Dietz *et al.*, 2007), assumptions concerning levels of adaptation, mitigation, climate sensitivity, discounting, treatment of non-market costs, substitutability of natural capital, equity weighting and incorporation of low probability risks with catastrophic implications can dramatically affect the social costs of climate change.

4. Moving Forward

Clearly there is a need to improve our understanding of the value of weather, climate, and climate change information and the costs and benefits of a range of impacts and adaptations in Canada. Exactly where to start, how to prioritize, and what is required to support a renewed research agenda were subjects discussed at the *SERA North meeting* (Mills, 2008). For the valuation of information theme of inquiry, the following activities were suggested:

1. An improved (consistent, systematic, long-term, accessible) collection and management system for weather- or climate-related impact/damage/response data. Such an open-access web-based database, perhaps modeled from the best qualities of similar resources (e.g., NOAA Storm database, SHELDUS[3], EM-DAT[4]) would make it easier for new researchers to become engaged. Common data would facilitate comparisons across methods;

3 **http://webra.cas.sc.edu/hvri/products/sheldus.aspx**
4 **http://www.cred.be/**

2. A national household valuation study to assess the public benefits of weather forecasts;
3. Micro- or bottom-up studies focused on community-level decisions that can be influenced by weather, climate, and climate change information; and
4. A national econometric study to evaluate the sensitivity of Canadian economic sectors and regions to weather and climate.

Priorities to advance our knowledge of the economic impacts of climate change and the costs and benefits of adaptation included:

1. A resource document explaining what has and what needs to be done in Canada in terms of costing climate change impacts and adaptation. Such a report would ideally be constructed from a working inventory or database that references the scope, methods, data, and key results for all studies across Canada;
2. A national "expert-based" sectoral analysis of the economic impacts of climate change and potential costs and benefits of adaptation;
3. Development of a series of sector-specific empirical studies. Infrastructure, water, and food security were identified as being especially important; and
4. Establishment of a common suite of national climate change and socio-economic scenarios that ideally include some interpretation of reliability and uncertainty. Such a resource will enable comparison of results across methods, regions and sectors.

Progress is being made to implement a number of these suggested priorities. For example, the *SERA North meeting* web site[5] is in the process of being revamped to become a resources site for valuation and costing research. Preliminary studies led by Environment Canada and its university partners are underway to develop the initial elements of a damage database, household valuation instrument, and a methodology to determine the benefits of incorporating better climate and new climate change information into infrastructure design. A review of climate change economic damage functions has been completed (Marbek Consultants, 2009) and other organizations, such as the National Round Table on the Environment and Economy[6], are scoping and initiating a series of bottom-up studies. Catalyzing these somewhat disparate elements of progress into meaningful results and decision support will require a sustained and collaborative multi-year effort that reaches across jurisdictions,

5 **http://www.fes.uwaterloo.ca/research/aird/sera/index.html**

6 **http://www.nrtee-trnee.com/eng/issues/programs/economics-climate-change/economics-climate-change-eng.php**

disciplines, and institutional boundaries—the challenge is great but the rewards promise to be even greater.

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Linking Climate Change Adaptation and Mitigation with Sustainability Planning in Richmond, British Columbia, Canada

4

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Abstract: Sustainability encompasses a broad range of considerations, including climate change response, social inclusion and equity, sustainable resource use, economic development and ecological health. The emergence of more sustainable communities depends upon progress made towards the system as a whole; it is about having all the parts being considered and having all the parts working collectively. Yet, despite the broad range of considerations, sustainability action can often be narrowly defined to one or two areas of focus. Often this narrow focus can mean that action intended to advance sustainability, is itself, not inherently sustainable – resulting in unintentional impacts and in some cases, impairing overall advancement. A scoping exercise completed in 2008 identified climate change as an important sustainability focus area for the City of Richmond. Yet, how can progress be made on this challenge in a manner which supports overall community sustainability? The City of Richmond is collaborating with external partners and experts to embark on a whole systems approach to corporate sustainability planning and action – one which integrates climate change response. This paper explores the successes, challenges and lessons learned to-date on a model where climate change response is being pursued as part of a whole systems approach to sustainability.

Keywords: climate change, adaptation, sustainability, planning

1. Introduction

While the international debate on climate change continues to evolve within research communities, municipal governments are seeking ways to effectively respond and take action. However, there remains a large gap between climate change knowledge evolving at the global scale and localized knowledge and expertise which enables information to be understood and applied in practice at the community level. To take meaningful action, local governments need to be able to understand what climate change means specifically for their respective local communities. This necessitates that communities be able to translate trends and predictions in climate change at the global scale to the local scale and evaluate what these changes mean for local systems. Taking meaningful action by municipal governments also necessitates that local governments strategize to identify and advance initiatives which fit within the local governance system, community context and overarching sustainability objectives.

Part of the municipal planning reality is the importance of existing ties to place and current conditions. Whether residents have a multi-generation history in a community, or are relative newcomers, attachment to place is very strong, a sign of pride in public facilities, as well as in access to natural landscapes, recreational and cultural activities. While responding effectively to climate change may necessitate significant changes in community structure, including land-use decision-making and municipal service delivery, the magnitude of these potential changes poses a significant challenge in light of currently-held attachments to place.

At the same time, local governments are faced with a multiplicity of local scale issues, including financial concerns, jobs, social programs, municipal service delivery and overall challenges in maintaining and enhancing quality of life for community residents. Communities like Richmond, British Columbia are endeavouring to effectively address these various issues in the context of a wide spectrum of changing conditions, including but not limited to climatic changes. Examples of other dynamic conditions are demographic and population changes, economic change, biodiversity and natural resource condition changes, changing social needs and changing technology.

Given this complex context, how can climate change be effectively integrated into local government planning in a manner which effectively considers the multiple objectives of local government?

This paper explores roles, responsibilities and planning activities undertaken by the City of Richmond, a low lying coastal community located south of Vancouver, in which climate change response is being pursued as part of a whole systems approach to sustainability.

2. Local Sustainability and Climate Change Planning

The City of Richmond is currently in the process of developing an Enhanced Sustainability Initiative aimed at improving the sustainability performance of the municipal government. A recent review identified over 80 existing initiatives aimed at advancing various dimensions of sustainability, including action towards addressing climate change. The City's Enhanced Sustainability Initiative aims to build upon the City's corporate success by increasing the benefit return value of corporate action. A

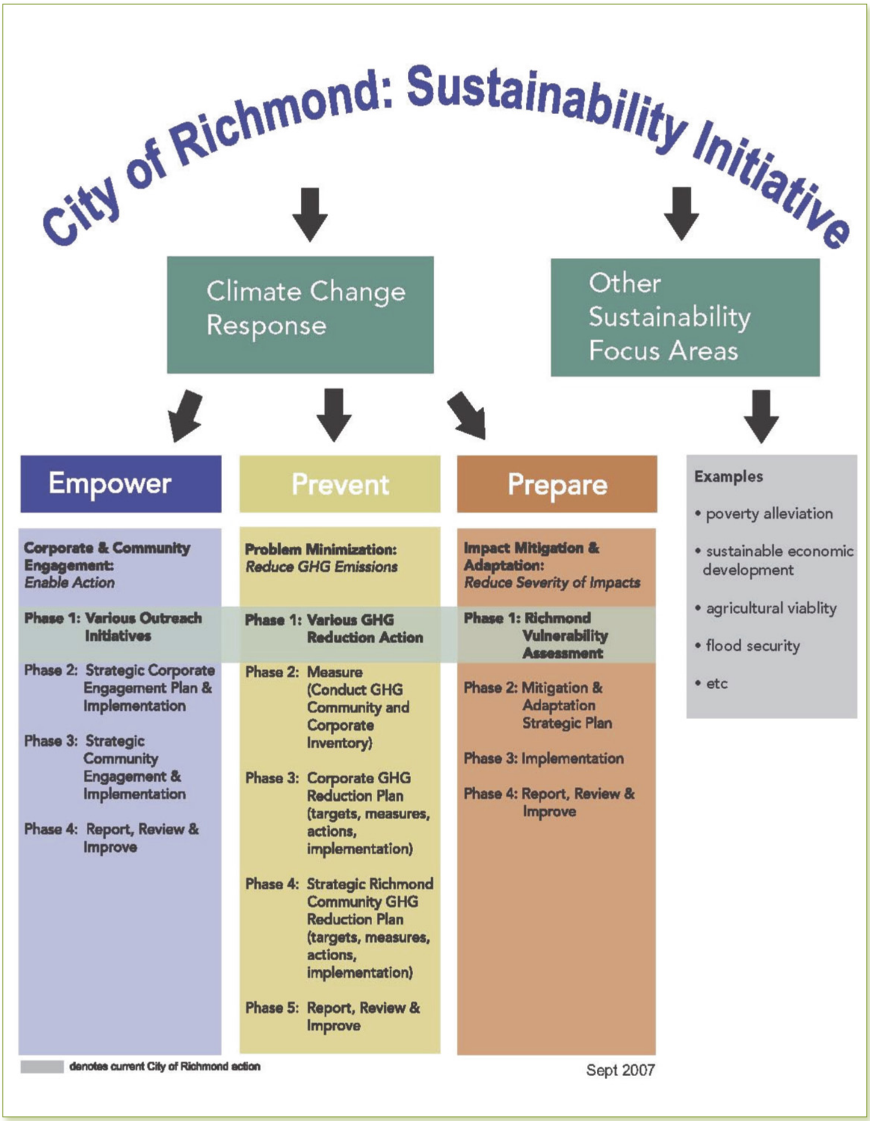

Figure 1 | City of Richmond Sustainability Initiative incorporating climate change response.

key area of focus is to develop and advance a well-managed systems approach to sustainability, one that strives to integrate a suite of action initiatives into a cohesive and collective approach.

The City's enhanced sustainability initiative encompasses a broad range of topics and objectives that are essential for the long-term well-being of the Richmond community. Climate change response is one of the many important areas of consideration under the broader sustainability umbrella. The City of Richmond has undertaken various actions towards addressing climate change, including international policy advocacy, greenhouse gas (GHG) emission reduction, sustainable community development, early adaptation planning and community outreach. To focus climate change action towards priority areas in a comprehensive manner, the City of Richmond adopted an overarching Climate Change Response Agenda. This Response Agenda is based on three pillars of action: *Empower, Prevent and Prepare* as shown in Figure 1. The Empower component includes corporate and community engagement to enable action. The Prevent component is designed to reduce greenhouse gas emissions,while the Prepare component includes planning to mitigate unavoidable changes and better enable the corporation and community to adapt. While advancing strategically, the City of Richmond is continuing to take action on the ground, moving forward on various existing action initiatives and capitalizing on opportunities as they arise.

3. Climate Change Impacts Scoping Exercise and Adaptation Workshop

In 2007-2008, the City of Richmond, Environment Canada and the University of British Columbia (UBC) formed a partnership to assist in developing a strategy for climate change adaptation. A key aspect of the exercise was to identify adaptive approaches that explicitly integrate opportunities for reducing greenhouse gas emissions and support long-term sustainable community development.

The work consisted of an early impacts scoping study (Bizikova and Neale, 2008; Environment Canada *et al.,* 2008) aimed at identifying projected local climatic changes and initiating understanding of potential implications and impacts. As part of the scoping study, City staff interviews were conducted to:

- identify current climatic change effects that could be used to illustrate decisions needed to respond to progressing climate change in the future;

- provide insights on how existing policies, practices and systems may pose either barriers or opportunities in preparing for climate change; and
- assist in exploring the capacity of existing systems (human and natural) to accommodate changes in climate.

A workshop on adaptation was held for the municipal government in June 2008 at Richmond City Hall. Workshop participants were provided with the findings from the scoping study, including climatic change projections as specific to Richmond as possible. A number of short-term and long-term adaptation potential actions were identified related to natural resource management, development policies and land use, coastal defences, the built environment, and potential requirements for land acquisition for flood protection.

4. Outcomes and Lessons Learned

i. Initiating dialogue

The scoping study and workshop were intended to initiate dialogue on climate change adaptation. While a number of potential strategies and actions were identified, there would need to be more detailed analyses of any proposed adaptation measures with consideration of the local context. One tangible outcome has been that the City formed a strategic interdepartmental team on climate change as a first step towards building institutional capacity and has embedded the climate change agenda within the City's overarching sustainability initiative. Recognizing the value of research-practitioner partnerships, the City's climate change team has continued to collaborate with external climate change researchers.

ii. Strengthening and understanding the value of cross-professional collaboration

The partnership approach offered an opportunity to highlight the value of combining expertise in climate change research with local government practitioner experience and knowledge. This collaborative approach is seen as a way to develop more sustainable responses by:

- Engaging a broader range of expertise and knowledge and better supporting whole system approaches (e.g., sustainability and climate change policy development, community land-use planning, infrastructure planning, municipal operations and service delivery, etc.); and

- Strengthening the relevance and utility of climate change information by tailoring climate change information to meet practitioner needs and integrating scientific understanding with site-specific and experiential practical knowledge.

The specific benefits realized through researcher/practitioner collaborations will depend upon a wide variety of factors, including the phase of the work. For example, adaptation work is presently in initial stages, both with respect to research and practical application. In this early phase, the researcher/practitioner collaboration served to effectively raise awareness of climate change considerations amongst a range of local government professions (e.g., policy-making, planning, engineering, environmental management, parks development, public works, etc.). By tailoring climate change information in a manner that conveys local relevance, practitioners were more readily able to engage in dialogue, contribute to increasing understanding of potential implications and explore potential response options. The collaboration also served to inform the research community, which is becoming more interested in linking global scale climate change science with local scale response.

Knowledge gained through the process served to promote shared learning among the researchers and municipal planners. Fundamentally, the partnership provided the opportunity for identifying the value of "whole-systems" thinking, and establishing a basis, early on, for holistic and collaborative approaches. The collaborative process followed in this exercise also contributed to the development of a guidebook to support future studies and integrative planning processes (Bizikova *et al.*, 2008).

5. Summary

While a holistic approach is seen as the basis for realizing a more sustainable future, practices for advancing an understanding of climate change are often developed without the whole in mind. By embedding climate change as part of an overall framework for sustainability, the City of Richmond is endeavouring to advance a "whole systems" approach – one which considers the multiple components of sustainability and how they work collectively. The adoption of a complete systems approach, however, necessitates deeper consideration and understanding of the multiple linkages and connections across the various dimensions of sustainability.

Greater connections among climate change researchers and practitioners is one important means for enabling greater whole systems approaches. Currently, however, there is a large gap between climate change science, knowledge and practice. The 3-party partnership among the City of Richmond, Environment Canada and UBC revealed the many benefits of collaboration between academic research and practical application.

Unfortunately, without considerable personal effort, current institutional and organizational structures do not inherently foster collaborations between researchers and practitioners. Forging new collaborations between researchers and practitioners and establishing mechanisms that support collaboration on a sustained basis offers valuable opportunities for increasing the uptake of climate change knowledge and accelerating action on the ground.

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GIS-Based Climate Change Adaptation Decision Support Tool (ADST): Indices to Assess Agricultural Vulnerability

5

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Abstract: There is a need to address the issue of how climate change and water resource and agricultural impacts assessment can be transformed into useful information for use by agricultural decision-makers to reduce climatic risk in agricultural production and explore approaches to bridge the gap between the assessment process and decision-making endpoints. A GIS-based Climate Change Adaptation Decision Support Tool (ADST) can help agriculture decision-makers in considering climate change adaptation in future plans and strategies. This tool builds up a few GIS databases covering key climate-water-agriculture information under current and future climate (2050s) along with a list of agricultural adaptation options. For the case study area - Ningxia, China – a series of ADST indices were computed for describing agro-climatic vulnerability, agricultural adaptive capacity and an agricultural investment plan. The approach to developing the vulnerability maps is based on the IPCC definition of vulnerability as a function of adaptive capacity, sensitivity, and exposure. Indices of adaptive capacity, climate and non-climatic sensitivity, and climate change exposure were constructed to examine the vulnerability to climate change in the region. The analytic hierarchy process (AHP) method is used to prioritize indicators to assess the potential contributions of various aspects to systems' coping capacities. Adaptive capacity for agriculture is considered to be an outcome of biophysical, socio-economic, and technological factors. Climate exposure is determined through the use of scenario results from the Hadley Center's PRECIS regional climate model and Environment Canada's scenarios network (CCCSN).

Keywords: Geographic Information Systems, Climate Change, Adaptation Decision Support Tool, agriculture

1. Introduction

Geographic Information Systems (GIS) allow for interdisciplinary efforts to foster collaborative science, spatial data interoperability, and knowledge sharing in climate change impacts and adaptation studies. The use of GIS has made data sets compatible, and created a bridge between the atmospheric sciences, geography, ecology, other more spatially-based sciences, and the natural resource management and planning communities. There is a need to address the issue of how climate change and water resource and agricultural impacts assessment can be transformed into useful information for use by agricultural decision-makers to reduce climatic risk in agricultural production and explore approaches to bridge the gap between the assessment process and decision-making endpoints. GIS-based Climate Change

Adaptation Decision Support Tool (ADST) can help agricultural decision-makers in considering climate change adaptation in future plans and strategies. This tool builds up a few databases covering key climate-water- agriculture information under current and future climate in (2050s) along with a list of agricultural adaptation options.

ADST can link agro-climatic Indices with Global Climate Models/Regional Climate Models Originated Climate Change Scenarios. Key agro-climatic indices for crops (e.g., crop heat units, growing degree-days, effective growing degree-days, precipitation deficits, seasonal crop coefficients of water demand) can be defined and used together with other indices (adaptive capacity and vulnerability in agricultural production) to measure the changes of climatic risk. Vulnerability assessment is a key aspect of anchoring assessments of climate change impacts to present development planning. Methods of vulnerability assessment have been developed over the past several decades in natural hazards, food security, poverty analysis, sustainable livelihoods and related fields. These approaches - each with their own nuances - provide a core set of best practices for use in studies of climate change vulnerability and adaptation (Chambers, 1989; Bohle and Watts, 1993; Adger and Kelly, 1999; Downing *et al.,* 2001).

While social determinants of adaptive capacity are difficult to observe and measure, some aspects of adaptive capacity, including physical infrastructure, resources and the distribution of those resources, may be assessed relatively easily both at national scales and at lower or higher levels of aggregation. A number of sets of national-level indicators developed within the UN system are used to build up a picture of national performance or status in areas as diverse as human health and economic trade (e.g data assembled by World Health Organization, World Bank, United Nations Development Programme, United Nations Conference on Trade and Development, International Labour Organization and others). Some proxies for generic adaptive capacity at the national level can be borrowed easily from other data sources for an initial holistic assessment of generic adaptive capacity. Adaptation efforts by governments and civil society must be targeted at specific groups within vulnerable countries, and further research into the underlying causes of vulnerability at the sub-national scale are necessary (Burton, 2001).

ADST can help to address one or more of the following questions: 1) how will agricultural investment decision processes be affected by climate information and how feasible is it for decision makers to make changes based on this information? What additional climate-water-agriculture information is needed by these decision processes to modify or adapt agriculture responses to make the water resource management and agricultural development more resilient to climate variability and change? What levels of risk and certainty are required to base decisions on modifying or adapting agricultural infrastructure and investments? 2) What are potential agricultural adaptations to climate change and what is the effectiveness of these options? How can the effectiveness of these adaptations be measured? What are the costs and benefits of these adaptations? What are the barriers to successful adoption of these measures?

This paper develops a series of ADST indices computed for describing agro-climatic vulnerability and agricultural adaptive capacity and an agriculture investment plan in a case study area – Ningxia, China – in order to identify proper adaptation options and measure the effectiveness of these adaptations. The methodology and data sources used to create the regional agricultural vulnerability maps are presented in section 2. Detailed definitions of indices are also provided in this section. Results of our case study are given in Section 3. Different indices were computed with local socio-economic and climate data including scenario results from the Hadley Center's PRECIS regional climate model and Environment Canada's scenarios network (CCCSN). Discussion and conclusions are presented in Section 4.

2. Methodology – computation of ADST Indices

The ADST Indices include those summarizing factors of agriculture adaptation mainly by profiling climatic stress, sensitivity and a system's adaptive capacity. Indices representing regional agroclimatic conditions are usually integrated with crop impact models which will not be discussed here.

2.1 Construction of an index of adaptive capacity (IAC)

Adaptive capacity includes three broad sets of vulnerability factors: social, technological, and biophysical (Chambers 1989; Bohle *et al.,* 1994). We have constructed a composite index for each these factors based on data from 2000 and 2001 (China Statistical Yearbook).. The final index of adaptive capacity for each district (county and county-level city) is calculated as the average of these three indices.

Each of the three indices is the average value of a set of normalized variables. Concerning normalization, all of the variables in the vulnerability profiles are normalized based on the method in the UNDP's Human Development Index (UNDP

2002). In some cases, the index values are reversed by using 100 – the index value to ensure that high index values indicate high vulnerability in all cases. Each indicator was evaluated in this manner prior to construction of the composite indices.

Social Vulnerability Index

Agricultural dependency is measured by the percentage of the district workforce employed in agriculture. A high level of agricultural dependency will increase the district's vulnerability to climate variability.

Table 1 | Social Vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Agricultural dependency	Percentage of agricultural workforce	Agricultural Dependency Index
Human capital	Gross Domestic Product per capital	Gross Domestic Product index
Literacy	Literacy rate	Education Index [100 – index value]

Note: All data for the social vulnerability index is taken from the 2000 –2001 China yearbook.

Increased overall literacy levels reduce vulnerability by increasing people's capabilities and access to information and thus their ability to cope with adversities.

Technological Vulnerability Index

The Technological Vulnerability Index of a district uses indicators that measure a district's technological capacity or access to technology.

Table 2 | Technological Vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Vulnerability to rainfall variability	Irrigation rate	Technological Vulnerability Index
Infrastructure development	Composite index of infrastructure development	Infrastructure Development Index

Irrigation rate is the net irrigated area as a percentage of net sown area. Water scarcity is the main productivity constraint for Ningxia agriculture. Our case studies show that an assured supply of water for irrigation reduces farmers' vulnerability to low and erratic rainfall.

Infrastructure Vulnerability Index

Quality of infrastructure is an important measure of relative adaptive capacity of a district, and districts with better infrastructure are presumed to be better able to adapt to climatic stresses. The index is published as a single composite index number for each district based on the following indicators and weights:

Table 3 | Infrastructure Development Index

SECTOR	WEIGHT
Transport Facilities	30
Energy	28
Banking Facilities	10
Communication Infrastructure	8
Educational Institutes	12
Health Facilities	12
Total	**100**

Biophysical Vulnerability Index

Areas with more productive soil and more groundwater available for agriculture are assumed to be more adaptable to adverse climatic conditions and better able to compete and utilize the opportunities of trade.

Table 4 | Biophysical vulnerability Index

DIMENSION	INDICATOR	DIMENSION INDEX
Soil quality	Depth of soil cover	Biophysical Vulnerability Index
Groundwater availability	Replenishable groundwater available for future use, in million cubic meters	Groundwater Scarcity Index

Indicators for soil quality are the depth of the soil cover in centimetres and severity of soil degradation. The soil cover map polygons were converted to a grid with a cell size of 50 km to maintain the same scale as the output from the PRECIS Regional Climate Models. By converting the polygon data to grid level it was possible to create fuzzy boundaries between soil cover classes and interpolate new cell values for areas on the borders of polygons. The gridded data was then averaged up to the district (polygon) level where each district was given an average soil cover value.

The same procedure followed for soil cover was used to convert the polygon data to a grid, and then back to district-level polygons. Data on ground water resources was calculated as the total amount of groundwater which is replenishable annually, measured in million cubic meters/year (MCM/Yr). This depends on the amount of rainfall, recharge from the canals, surface water bodies and change in land cover.

2.2 Construction of Climate Sensitivity Index (CSI)

The Climate Sensitivity Index (CSI) is an average of two indicators which were calculated for two time periods:

a) The observed climate period of 1961-1990 (called Observed CSI)
b) A future scenario climate period of 2041-2070 (called Exposure CSI)

Observed CSI portrays current or near current climate sensitivity in Ningxia. Exposure CSI builds upon Observed CSI. It represents the combination of both climate sensitivity and potential exposure to climate change by incorporating Global Climate Models/Regional Climate Models scenario results with the observed CSI data.

The Dryness Index (Table 5) is normalized and averaged to create the final CSI. The higher the CSI value (either Observed or Exposure), the higher the relative climate sensitivity for a district.

Table 5 | Dryness Index

DIMENSION	INDICATOR	DIMENSION INDEX
Vulnerability to Dryness (Observed and Exposure)	The ratio of annual potential evapotranspiration to precipitation (average over the normal or scenario time period).	Dryness Index

Observed CSI

The indicators used for Observed CSI were calculated using climate data from the 'China Meteorological Administration's (CMA) website. For the purpose of this study, only the temperature (degrees Celsius * 10) and precipitation (mm per month) parameters were used. To capture the borderless changes in the climatic variables, it was important to construct the CSI indicators at grid level. The final analysis, which involved combining the individual CSI indicators, was conducted and presented at the county level.

Monthly and daily data from 1961 to 1990 for Ningxia were extracted for the construction of Observed CSI. It is believed that this time period adequately reflects the current or near-current climatic conditions in Ningxia.

Dryness Index (DI) (Table 5) is used to give a relative impression of the dryness of an area. It is the ratio of average annual potential evapotranspiration to precipitation for the time period 1961-1990. Areas with the highest DI value are considered to be the most sensitive because a lack of adequate rainfall can be detrimental for agriculture. Although some areas with high DI values may have adapted agricultural practices to the drier conditions, it is thought that even with drought tolerant crops and irrigation, if little to no rain is received, most adaptation efforts will have little effect. The higher the Observed CSI value, the higher the relative climatic sensitivity.

Exposure CSI

Exposure CSI is based on the same indicators as outlined in Table 5. However, this version of CSI is the combination of climate sensitivity and exposure. Climate sensitivity in observed CSI is represented by the original China Meteorological Administration climate data. Climate exposure is determined through the use of scenario results from the Hadley Center's PRECIS regional climate model and Global Climate Models from the Canadian Climate Change Scenarios Network (CCCSN). Exposure CSI is based on the time period 2041-2070.

Exposure is defined here as the difference or ratio between the two scenario datasets for each climate parameter (temperature and precipitation). For each dataset (Control and Green House Gas Forcing), the daily data for temperature and precipitation were averaged to produce monthly values for the time period 2041-2070. The monthly difference between the Control and the Green House Gas Forcing datasets was then calculated for temperature while the ratio between the Control and Green House Gas Forcing was determined for precipitation. The temperature difference was then added to the observed monthly climate dataset (1961-1990) to create average monthly scenario temperature datasets for 2041-2070. The precipitation ratio was multiplied with the observed monthly climate datasets to create average monthly scenario precipitation datasets for 2041-2070. The scenario datasets were then used to calculate Exposure CSI (Dryness Index (Table 5) indicator) in the same fashion as described above. Districts with the highest Exposure CSI value have the highest climate sensitivity under the modeled scenarios of climate change exposure.

3. Assessing climate risks on agriculture using ADST-Indices: a case study of Ningxia

3.1 Background: Ningxia and its climate and agriculture

Ningxia is located in northwest China (Figure 1) and is one of the poorest regions in China. It is particularly exposed to extreme climatic events such as drought. Ningxia's climate is dry and highly seasonal – annual mean temperature ranges from 5-9°C. Annual precipitation decreases from south to north – the mountainous area in the south receives around 600mm, which declines to only 100mm in the north, with an overall average of 262mm. Winters are dry and very cold, summers are hot and receive most of the precipitation. The Yellow River is the main surface water source in the region.

The human population is close to six million, with 65% in rural areas. In 2004 the regional Gross Domestic Product was 6.57 billion US$ and GDP growth was around 11% per year. The population below the absolute poverty line in the southern mountainous areas of Ningxia is nearly 150 thousand in 2004.

Ningxia has three main types of agricultural production, each related to a different set of climatic and other factors, such as topography, traditional customs, and availability of water from the Yellow River:

1) Southern mountainous area: rain fed cultivation in the more humid climate, but still fairly dry, with an average annual rainfall above 400mm. Potato is the

major crop grown over a large area. Cattle, sheep, pigs, and chickens are the major livestock.

2) Central arid area: a mix of rain and riverfed irrigation with some extensive grazing. Average annual rainfall between 250-400mm. The dry conditions only allow corn, spring wheat, potato, and some cattle and sheep husbandry.
3) Northern irrigation area: primarily irrigation, using water diverted from the Yellow River, with an averaged annual rainfall of <250mm. Intercropping is the major planting system. The main crops in this area are corn, spring wheat, paddy rice, and potato. Cattle, sheep, pigs, and chickens are the major livestock.

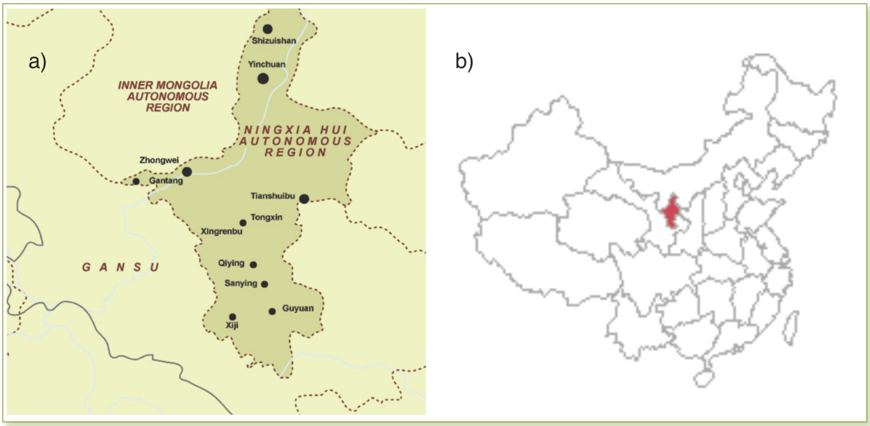

Figure 1 | Ningxia, location in China (b right panel) and main urban areas (a left panel).

Each sub-region has specific vulnerabilities and risks related to climate change. Agriculture in Ningxia depends heavily on irrigation and is very sensitive to climate change. The purpose of this case study was to evaluate the vulnerability of agriculture to climate change in Ningxia by mapping the socio-economic adaptive capacity and exposure. This case study describes an example of creating the maps of adaptive capacity (IAC), climate sensitivity (CSI) and climate change exposure using a set of ADST Indices.

To assess the main climate-related risks to rural communities and agriculture system in Ningxia, it is necessary to document the characteristics and impacts of current climate variability and extreme events and define the range of future climate change in the region based on the use of computer climate models. It consisted of a number of activities illustrated in following sections.

3.2 Characterising the extent and impacts of recent climate variability and trends

Lin *et al.* (2008) analyzed observed datasets from roughly 23 stations distributed throughout Ningxia with records dating back to the early 1950s. These provided an overview of the presence and magnitude of trends or changes in temperature, precipitation and other climate variables. Figures 2 and 3 show, respectively for temperature and precipitation, long term annual values. The mean annual temperature of Ningxia was fairly stable from the early 1950s to the 1980s but then developed a modest positive trend which is consistent with the global average temperature increase. Temperatures in winter months show increasing trend (roughly 0.5°C/decade) which has increased in most recent decades (with a range of 0.6-1.2°C/decade during 1991-2007).

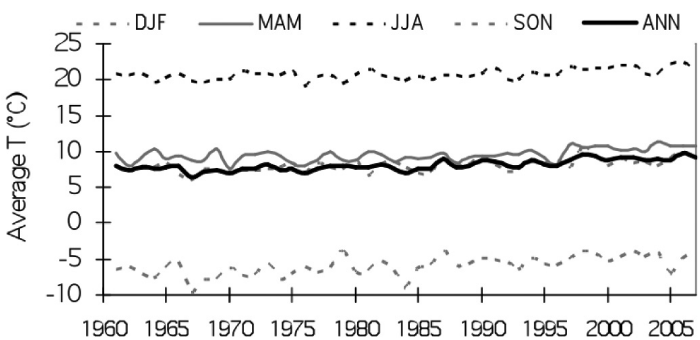

Figure 2 | Seasonal and annual temperature series for the whole of Ningxia, 1961-2007 (Lin *et al.*, 2008)

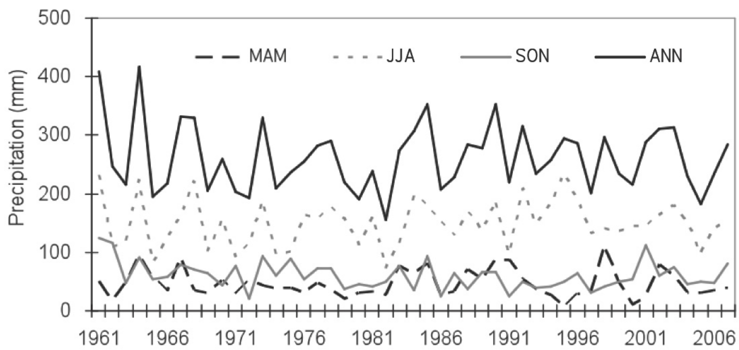

Figure 3 | Seasonal and annual precipitation series for the whole of Ningxia, 1961-2007 (DJF not shown as <10mm) (Lin *et al.,* 2008).

Precipitation in most months shows very modest evidence of a trend with a slight increase in Summer (JJA) (roughly 1.0-5.4mm/decade) and a slight decrease during Autumn (SON) to (roughly 1.0-4.5mm/decade). A marked feature of recent climate in Ningxia has been a major drought, due to three very dry years from 2004-2006, which was similarly experienced in 1981-82.

Recent studies have documented precipitation changes in China. Using daily precipitation dataset of 740 stations in China, Zhai *et al.* (2004) analyzed trends in annual and seasonal total precipitation and in extreme daily precipitation for the period 1951–2000. Results suggested that annual total precipitation has significantly increased in western China (including Ningxia) and has increased for both cold and warm seasons. The precipitation increase in western China is due to increases in both precipitation frequency and intensity.

3.3 Projections or scenarios of future climate

To estimate potential risks that climate change represents to agricultural production and activities it is important to provide guidance about the rate and magnitude of future climate change during the short to medium term future and to give measures of confidence to projections of future change. In this study, the Canadian climate change scenarios network (CCCSN) was used to provide detailed projections of how Ningxia's climate may change in the near future. Table 6 shows the changes in temperature and precipitation for mid-term future periods in central arid Ningxia, based on the Intergovernmental Panel on Climate Change – Fourth Assessment Report, Global Climate Models from the CCCSN website. Changes include shifts in the average conditions (such as warmer temperatures) but will also include changes in the frequency and severity of more extreme weather events (heatwaves, rainstorms) which are likely to cause greater socio-economic impacts. Computerized climate models represent the most reliable means currently available for describing the future climate, however, such models are not predictions; it is important to recognize that the 'scenarios' they produce are associated with large uncertainties.

Table 6 | Changes from (2041 - 2070) annual mean temperature and precipitation using Global Climate Models (GCMs) from the IPCC 4th Assessment Report from the Canadian Climate Change Scenarios Network (CCCSN). Models labelled CSIRO from Australia; NCARPCM from the Untied States; HADCM3 from the United Kingdom and CGM3 from Canada. A2 refers to a high greenhouse gas emission scenario; A1B to a medium scenario; and B1 to a low scenario – Tongxin (Central Ningxia)

MODEL RUN	TEMPERATURE (°C)	PRECIPITATION (%)
AR4.CSIROMk3.5.SR-A2	1.58	-22.98
AR4.CSIROMk3.5.SR-A1B	1.57	-27.96
AR4.CSIROMk3.5.SR-B1	1.26	-25.51
AR4.NCARPCM.SR-A2	1.77	-2.97
AR4.NCARPCM.SR-A1B	2.11	-8.08
AR4.HADCM3.SR-A2	2.91	-11.19
AR4.HADCM3.SR-A1B	3.21	-13.29
AR4.HADCM3.SR-B1	2.59	-14.14
AR4.CGCM3T47—Mean.SR-A2	3.48	-27.09
AR4.CGCM3T47—Mean.SR-A1B	3.26	-25.90
AR4.CGCM3T47—Mean.SR-B1	2.55	-19.89
Average	**2.39**	**-18.09**

Table 7 | Changes in future annual maximum and minimum temperature and precipitation using PRECIS the Hadley Centre's Regional Climate Model – results averaged across Ningxia (Lin *et al.,* 2008)

DIFFERENCE FROM BASELINE	TMAX °C		TMIN °C		PRECIPITATION (%)	
	B2	A2	B2	A2	B2	A2
2011-2040	1.6	1.8	1.6	1.8	+3	+5
2041-2070	2.6	3.6	2.7	3.7	+4	+8
2071-2100	3.5	6.0	3.7	6.4	+6	+12

In some cases it may be appropriate to prepare more detailed scenarios of future climate (better resolution using dynamical downscaling techniques), for example in relation to decisions about very large investments for infrastructure such as reservoirs and coastal defence. Lin *et al.* (2008) projected the changes in temperature and precipitation for three periods in the future, based on the regional climate model PRECIS (Table 7). In other cases it may be sufficient to use already available sources of information such as the Intergovernmental Panel on Climate Change's recent reports alongside analysis of recent climate trends that can be used as a crude guide to conditions over the next five to fifteen years for near-term decision-making.

Finally, an important source of uncertainty in scenarios of climate change is that different climate models can produce different results for the same regions. For Ningxia most climate models show increases in temperature so we have reasonable confidence in this result, but there is a wide range in the magnitude of warming which affects the level of confidence. However, results in Tables 6 and 7 can be used to identify critical areas of climate risks important to Ningxia. Risks relating to higher temperatures were prioritized because there is high confidence that warming will continue in the future. Droughts and changes in extreme events were also prioritized due to the significance of their current impacts and threat of greater impacts in the future.

3.4 Assessing vulnerability and adaptive capacity under climate change in Ningxia

Lin *et al.* (2008) subjectively ranked risks across sub-regions with a simple method. As the three sub-regions of Ningxia possess very different agricultural production systems, it was important to treat them separately. The approach used here combined a simple ranking from High to Medium to Low for three aspects of climate risk: L = likelihood of change occurring in the future; I = Potential significance of the impacts; and C = Confidence in the direction and detail of the future change. By combining these indices an overall assessment of the level of risk priority based on expert-judgement and local consultation was obtained. Table 8 present the results of the analysis.

Datasets from Ningxia Statistical yearbook were used to calculate present regional capacity to adapt to the identified climate risks. The adaptive capacity is divided into five grades according to the calculated relative values of the indicators. A preliminary result for current and future period was mapped in Figure 4. Observed and Exposure CSI was also calculated for each county for three sub-regions in Ningxia.

Figure 5 shows climate data for estimating the Dryness Index (DI) in central sub-region. Changes of DI are projected to the future to give hints on the rate and extent of future hazards. Exposure CSI was computed both with PRECIS and downscaled Global Climate Models data to allow comparison.

Table 8 | Summary of climate risk prioritization by sub-region*(Lin *et al.*, 2008)

MAIN CLIMATE RISKS/ SUB-REGION OF NINGXIA	DROUGHT	SURPRISES / EXTREME	DRYING	CHANGES IN YELLOW RIVER FLOWS
North	M	M	H	H
Central	H	M	H	M
South	H	H	M	L
All Ningxia	H	M	M	H

**Colours refer to; Red – High risk, Brown – Medium risk, and Green – Low risk.*

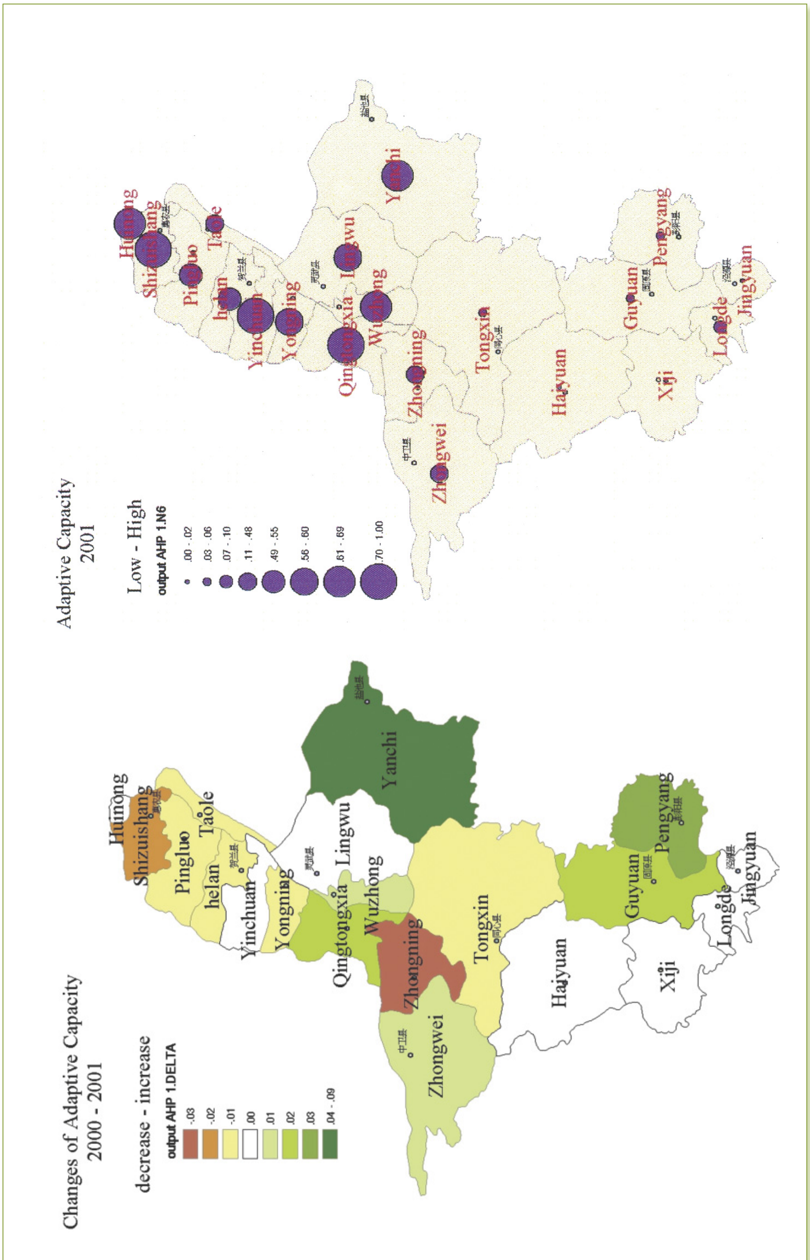

Figure 4 | Adaptive capacity to climate risk in Ningxia (right: present – 2001, left: changes to baseline in 2041-2070).

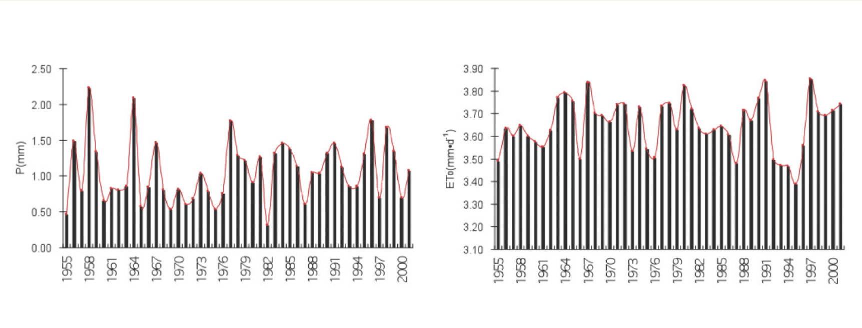

Figure 5 | Present CSI data: left panel - Precipitation and right - Daily Potential evapotranspiration (ET0) in Center Ningxia (Tongxin station, 1955-2000).

4. Conclusion

The preliminary results of this study using ADST indices indicate that counties in northern Ningxia generally have stronger adaptive capacity than those in the south. The northern counties have good irrigation facilities and general infrastructure except for industrially-developed cities like Qingtoongxia and Shizuishan. The strong industry and trade give these two counties a higher adaptive capacity, where Gross Domestic Product and gross industrial output are higher than in other regions in Ningxia. The worst area appears in the central arid sub-region where less precipitation and low irrigation rate were observed. Under climate change scenarios, the drought in the spring and hazard weather events is foreseen to increase dramatically.

This study has shown that economic, institutional, political and social factors are likely to play an important role in enabling the agriculture sector to adapt to climate change. It suggests that different sub-regions should adopt different prioritized adaptation measures to carry out adaptation actions. Climate risk and adaptation objective analysis are foundations to ensure adaptation is appropriate for local development. Next steps for future research include integrating policy-relevant indicators to assess the effectiveness of adaptation actions.

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Planning for Climate Change in a Flood-prone Community: Municipal Barriers to Policy Action and the Use of Visualizations as Decision-support Tools

6

Sarah Burch, Stephen R.J. Sheppard, Alison Shaw, David Flanders and Stewart J. Cohen

Abstract: Efforts are intensifying to design effective flood management strategies that account for a changing climate and that make use of the wealth of resources and latent capacities associated with action at the local level. Municipalities, however, are subject to a host of challenges and barriers to action, revealing the critical need for sophisticated participatory processes in support of municipal decision-making under conditions of considerable uncertainty. This paper examines a new process for envisioning local climate change futures, which uses an iterative, collaborative, multi-stakeholder approach to produce computer-generated 3D images of climate change futures in the flood-prone municipality of Delta, British Columbia, Canada. The process appeared to forge communicative partnerships, which may improve the legitimacy and effectiveness of the flood management and climate change response discourse in the municipality of Delta, and may lead to locally-specific and integrated flood management and climate change response strategies. We concluded that, while an enabling context and normative pressures are clearly integral to effective action, so too is the type and mode of presentation of information about climate futures.

Keywords: flood management; climate change; visualizations; municipalities, decision support; scenarios

1. Introduction

For many coastal communities, it is expected that changes in sea level and storm frequency and severity resulting from a changing climate will dramatically enhance the risk of extensive flooding in low-lying areas (Nicholls *et al.,* 2007). Perhaps as a result of these projections, efforts to localize both climate change impact assessments and response design have gained momentum (Adger *et al.,* 2005; Bai, 2007). This 'localization' of climate change response has accompanied the evaluation of successes and failures of the response effort at the global scale (Böhringer and Vogt, 2004; Buchner *et al.,* 2002). In a variety of fields, it has often been recognized that the local scale is indeed an effective realm within which to pursue collective action on environmental issues (Bulkeley and Betsill, 2003, Bulkeley and Betsill, 2005). Pragmatically, most, if not all, communities around the world will need to implement plans and response actions to address local adaptation needs and mitigation mandates. In part, because of the challenges inherent in downscaling global climate models the study of barriers to local and regional climate change responses remains a nascent realm of investigation. It is already known that municipal governance institutions are rife with barriers to effective action on climate change (Betsill, 2001, Burch, 2010). The challenge of local climate change responses in communities across Canada requires the application and testing of methodologies that address complexities in governance structures and uncertainties in climate change impacts and responses, while simultaneously building capacity and buy-in among community members through personalization of climate change impacts and potential responses. Integrated flood risk management is an especially critical set of climate change responses in low-lying and flood-prone regions. However, implementation of risk management actions faces a host of challenges including fairness in public engagement (Johnson *et al.*, 2007), sustainable long-term coastal management in the face of climatic uncertainty (Ledoux *et al.*, 2005), and the complexity of implementing resilience-based (rather than resistance) management strategies (Klijn *et al.*, 2004).

The Local Climate Change Visioning Project in British Columbia, Canada, represents one approach that may assist local decision-making. Building on recent advances in backcasting and scenario-building to bridge the divide between predictive, quantitative approaches and narrative-based qualitative methods, the Visioning Project incorporates novel 3D visualization techniques with elements of participatory integrated assessment to explore visions of the future under climate change for the Lower Mainland community of Delta. This community is highly vulnerable to even small changes in sea level, storm surge frequency and severity, and alterations to the nearby Fraser River's spring freshet (a seasonal swelling of river water due to melting snow and ice in the nearby regions of higher elevation). Using the wealth of scholarship and current practice in community development planning (see for example: Tress and Tress, 2003, Sheppard, 2005a) the Local Climate Change Visioning Project incorporates participatory processes which introduce practical knowledge, preferences, and experiences in order to enrich the integrated assessment of the complex problem of climate change (Rotmans and Van Asselt, 1996, van Asselt and Rijkens-Klomp, 2002). While the process was not designed specifically to focus on overcoming particular barriers, it was intended to increase awareness, inform policy, and potentially motivate action on climate change. The Visioning Project's objective is consistent with other local and regional case studies in British Columbia that have used participatory approaches to link research knowledge and local (traditional, practitioner, managed system) knowledge (Walker *et al.*, 2007; Cohen and Neale, 2006; Williamson *et al.*, 2007). However, the application of 3D visualization offers a unique learning opportunity. As such, this work has the potential to enhance the capacity of this community to strengthen flood risk management practices and facilitate equitable stakeholder engagement.

The goals of this paper are threefold. First, the paper gathers insights from disparate literatures to explore a small sample of significant barriers to local action in response to flooding and other projected climate change impacts. Second, the paper presents an innovative method of participatory scenario generation, the effectiveness of which has been tested with both expert and lay groups in the Corporation of Delta, a low-lying community in Southern British Columbia. Finally, the paper explores ways in which this style of participatory integrated assessment, including the co-production of scenarios and 3D computer-generated visualizations, may help to identify and overcome barriers to climate change responses and flood risk management in serving as decision support tools. In sum, this paper aims to advance municipal best practices in flood risk management and climate change planning to incorporate more effective and equitable modes of public participation, innovative tools for the communication of complexity and uncertainty, and an appreciation of the institutional and behavioural complexities that may inhibit the development and implementation of flood management policies.

2. Background: Barriers to action on climate change at the local level

2.1 Institutional barriers to flood management responses

In the context of municipal action on climate change, the critical finding that humans often operate on the basis of routines and standard operating procedures rather than (or at least in addition to) a rational calculus of costs and benefits (Olsen and March, 1989) forces a shift in attention away from making a logical, scientific case for the avoided costs yielded by climate change actions to reduce greenhouse gas emissions. Instead a need is identified to embed new risk management norms and values associated with climate change adaptation and integrated flood risk management throughout the familiar and established practices and procedures of an institution.

Equally important are the historically-evolved and path-dependent structures that limit the options of decision-makers in municipal institutions and deeply influence the context within which responses to climate change impacts, such as flooding, are designed and implemented. (Thelen, 2003). Once a path is taken, alternatives become increasingly difficult as time passes, learning accumulates and scarce capital is invested (Berkhout, 2002, Thelen, 2003). Flood management and climate change response policies must be developed within these highly structured organizational fields, which assist in efforts to deal rationally with uncertainty but also constrain the variety of response options available (DiMaggio and Powell, 1983). This is especially important with regard to climate change responses, because a system in which fewer path dependencies exist may be one in which the ever-evolving climate change science (such as evolving models of flood risk) may be more effectively integrated into practices and procedures (O'Riordan and Jordan, 1999).

The prevalence of path dependency reveals the importance of providing opportunities for iterative, collaborative partnerships between municipal practitioners and flood management experts.

2.2 Participatory processes and flood risk management

The study of participatory processes reveals both an additional category of barriers that originates in the socio-cultural or public realm, as well as important strategies that may be employed to help overcome these barriers. Participatory processes provide the means through which a communicative partnership can occur among a variety of state, expert, business, and civil society actors (Burgess *et al.*, 2005).

Traditional decision-making strategies tend to de-emphasize interests and values in favour of objective analysis, often leading to diminished legitimacy, irrelevant or incompetent outcomes, and a lack of popular acceptance (Renn *et al.*, 1995). As a result, it has been argued that non-traditional forms of deliberation, such as story-telling and gaming (Lewis and Sheppard, 2006; Robinson *et al.*, 2006), may obtain more meaningful and inclusive results (Dryzek, 2000). Part of the solution to these problems may be the development of consent-producing mechanisms within and among institutions and groups that help to institutionalize partnerships between decision-makers, a range of technical experts, and affected stakeholders (Renn *et al.*, 1995; Jones and Burgess, 2005). These innovative modes of decision-making and problem identification represent potentially powerful means by which barriers (such as lack of buy-in, insufficient legitimacy of decision-making procedures, and policy responses that are deficient in scientific robustness or inconsistent with public values) to policy action in response to climate change may be overcome.

The ways in which participatory processes feed into municipal decision-making and governance is of great relevance to the design and outcomes of the Local Climate Change Visioning Project. This project draws on processes used in interactive social research which "seeks to establish relationships between sponsors of research, research teams, independent organizations, and the interested public" (Robinson and Tansey, 2006). A substantial portion of the task of the Local Climate Change Visioning Project was identifying and navigating through the intricate patterns of expectations present among municipal politicians and staff. These expectations were fundamentally shaped by past and current policies, disciplinary biases, and local and regional politics, and may in themselves represent barriers to novel policy action in response to climate change.

2.3 Capacity to respond to climate change

As climate change research has shifted from a focus on modeling the potential causes and impacts of climate change to a strong focus on responses to the problem, interest in the concept of capacity has grown. Mitigative capacity is defined as "a country's ability to reduce anthropogenic greenhouse gas emissions or enhance natural sinks" (Winkler *et al.*, 2007). Adaptive capacity is defined as "the ability or potential of a system to respond successfully to climate vulnerability and change," (Adger *et al.*, 2007). They are viewed as the mirror image of each other. For instance, Yohe (2001) argued that both adaptive and mitigative capacity are comprised of resources such as financial, human, and social capital, risk-spreading mechanisms such as insurance, decision-making capacity, and availability of technological options. Psychological elements were later added to the growing list of capacity indicators, such as perceived capacity to respond (Grothmann and Patt, 2005) and the normative or motivational context of climate change responses (Haddad, 2005).

The concept of capacity reveals two issues that are especially significant to the study of local responses to climate change impacts, including flood management. The first is simply the quantity and quality of capacity. Does the jurisdiction in question possess substantial stores of financial capital, institutional capacity, and locally-specific scientific information relevant to climate change responses? Similarly, does the jurisdiction possess the legal tools (both the authority to impose regulations as well as the responsibility to do so) necessary to catalyze action? The second issue relates to the dynamic patterns of human interaction which characterize the relative success or failure of jurisdictions to mobilize capacity in response to climate change. In other words, despite the presence of capacity, some jurisdictions may still be unable to respond to climate change. This ‘gap’ between capacity and action in response to climate change is only beginning to be explored by the climate change research community (Burch and Robinson, 2007; Burch, 2010; Yohe *et al.*, 2007). Innovative participatory visioning processes may be one set of tools that can help to both build capacity and to facilitate action.

2.4 Implications for policy action in response to climate change impacts and flood risk

These varied literatures lead us to the insight that the same concept or characteristic of a system can become either a barrier to, or enabler of, action on climate change (Burch, 2010). For instance, socio-cultural characteristics such as identity formation and institutional issues such as the extra-jurisdictional policy context can, in one scenario, act to inhibit the formulation and implementation of climate change policies if identities clash or provincial policies conflict directly with municipal climate change goals. In contrast, however, the development of norms and identities that support forward-looking policy action (including traditions of fruitful collaboration among scientists, policy-makers, and the lay public), complemented by policy consistency at multiple levels of government, may lead to highly effective climate change policy-making. The legal responsibility to act, and adequate tools to do so, are a critical ingredient in this process. For instance, municipalities in Canada must rely on provincial governments to raise the standards of building codes, and on the federal government to determine fuel efficiency standards. In the past, this has hampered the ability of communities to take significant action on both climate change adaptation and mitigation.

Most importantly, however, the literature presented above allows speculation about potential strategies that can be employed in order to transform barriers into enablers of action in response to climate change impacts and flood risks. For instance, the influence of habits, organizational culture, and organizational structure highlighted by new institutional theory suggests that climate change and flood management responses should be embedded, or ‘institutionalized’ in standard operating procedures. Iterative and collaborative partnerships paired with opportunities for institutional learning and innovation may also assist in stimulating effective flood management responses. Research into participatory processes points to the usefulness of storytelling and gaming to improve the quality of deliberation and understanding, while enhancing value transparency and the utilization of local knowledge in planning procedures (Burgess *et al.*, 2005; Robinson and Tansey, 2006). Framing the problem as one that is embedded in the local context and local solutions represents a further opportunity to increase saliency, legitimacy, and credibility. Finally, research into capacity reveals the need to ground local responses in robust global science and provincial, national government policies and responses while building the store of local resources by sharing best practices.

3. The Influence of Landscape Visualization on Human Perception and Behaviour

An emerging approach to enhancing participation and awareness-building at the local level is the use of 3D landscape visualisation to depict alternative future community scenarios. Various forms of imagery including GIS-based tools, 3D modeling and photo-manipulation have been explored to investigate landscape change and management (Al-Kodmany, 1999; Tress and Tress, 2003; Lewis and Sheppard, 2006), including some early research on the potential to visualize climate change futures (Dockerty *et al.*, 2005; Nicholson-Cole, 2005; Sheppard and Shaw, 2007). These highlight the potential for visualization to influence individuals' perceptions of landscapes, floods, and a changing climate, which in turn may influence cognitive and affective (or emotional) understanding and influence individual and collective behaviour. Further study is required if such methods are to be used widely as a decision support tool in planning and policy. Sheppard (2005a) summarizes many of the capabilities and responses to landscape visualization that may contribute to it being an effective tool for municipalities in building their capacity to address the impacts and causes of climate change. These include:

1. Integration of the predictive and science modeling capabilities of GIS-based software, with the emotionally rich and intuitive media of photo-realistic software;
2. The potential for stronger socio-cultural content and more attractive representation may assist in engaging lay-people into public processes (Conroy and Gordon, 2004; Nicholson-Cole, 2005; Sheppard and Meitner, 2005; Lewis and Sheppard, 2006);
3. Representation of recognizable places and local information in a realistic or semi-realistic manner, increasing personal relevance as opposed to more abstract representation (Daniel and Meitner, 2001; Sheppard, 2005a);

4. Presentation of multiple alternative futures, and choices for the future to assist with decision making (Al-Kodmany, 2000; Appleton and Lovett, 2003; Steinitz *et al.*, 2003; Sheppard, 2005a);
5. Computer visualization techniques which allow for modification and user-feedback in a participatory manner for refinement and analysis (Sheppard, 2005b); and
6. Varying levels of cognitive, affective, and behavioral responses which may result from varying content, levels of realism and detail (Daniel and Meitner, 2001; MacEachren, 2001; Appleton and Lovett, 2003; Sheppard, 2005b; Lewis and Sheppard, 2006).

Potentially disadvantageous human responses to landscape visualizations, however, also exist in the context of climate change and flood risk management. Bias, advocacy, and non-neutral roles of scientific visualization (Orland *et al.*, 2001; Sheppard, 2005a) represent significant risks to the legitimacy of planning processes using visualizations. Similarly, the potential exists that highly realistic, yet inaccurate and non-transparent, imagery can generate false assumptions of authority (Sheppard, 2005a; Sheppard, 2005b). Especially relevant to the portrayal of flood risks, ineffective or inaccurate visualizations may cause disbelief, confusion, apathy or fear. Presentations must be sensitive to individual abilities to process and comprehend large amounts of imagery that represents many layers of information (Sheppard, 2005a).

4. Development of visualizations in a municipal context

This section documents the participatory scenario development process that was used to downscale, synthesize and visualize local climate change in the community of Delta. First, a description of the case study community is provided and key climate change vulnerabilities (including the potential for extensive flooding and storm damage) are identified. Then an overview of the methods used, and findings gathered, from both the 'visioning' process and the semi-structured interviews with municipal employees after being exposed to the visioning presentation are presented.

4.1 Municipal context: climate change policy in the Corporation of Delta

The corporation of Delta is one of the 21 municipalities that make up the Metro Vancouver Region in the Southwestern coastal region of British Columbia, Canada. It is home to approximately 96,000 individuals and is comprised of a blend of agricultural land, suburban residential development, and industrial operations.

Geographically, Delta is uniquely situated on the west coast of Canada, bounded by the Strait of Georgia to the west, the Canada-US border to the South, Boundary Bay to the Southeast, and the Fraser River to the North. Delta is largely comprised of the floodplain of the Fraser River, the basin of which drains 240,000 km^2 of the province of British Columbia (Fraser Basin Council, 2004). Much of Delta lies between zero and two meters above mean sea-level, and thus is protected by over 60 km of dikes.

Figure 1 | Corporation of Delta, British Columbia, Canada (Credit: David Flanders, UBC-CALP)

Delta has recently developed a climate change action plan geared towards managing both municipal emissions and facilitating adaptation to changing flood frequency and severity. At present, Delta is undertaking a revision of its flood management strategy that incorporates local climate change scenarios, and is carrying out public consultations to evaluate the desirability of a suite of flood risk responses.

Management of floods, natural areas, staff training and community education were addressed in Delta's climate change action plan, although without a high level of specificity in terms of budget and workplan. More detailed flood risk and management studies were commissioned around the same time, and Natural Resources Canada chose Delta's Roberts Bank shoreline as the focus of a detailed study of sea-level rise impacts (Hill, 2006). Delta has since placed a senior environmental officer in charge of climate change issues, and is planning on further development of both adaptation and mitigation policy.

4.2 Participatory scenario development and 3D visualizations of flooding in Delta

Approximately eight months prior to the development of the Climate Change Initiative described above, a team of researchers from the Collaborative for Advanced Landscape Planning at the University of British Columbia chose Delta to represent the first case-study in the Local Climate Change Visioning Project. This research program was designed to develop and evaluate a new prototype process for raising awareness, building capacity, increasing motivation, and supporting decision-making on both integrated food management and climate change at the local level.

The first phase was the relatively autonomous development of a conceptual framework which allowed for the organization of a plethora of qualitative and quantitative data, bridging from the global to the local level (Sheppard and Shaw, 2007). Key biophysical and socioeconomic drivers were collated from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000; Banuri *et al.*, 2001), the Millennium Ecosystem Assessment (Raskin, 2005), and the scenarios of the Global Scenario Group (see for example Raskin *et al.*, 2002). These scenarios were downscaled by integrating national, regional, and local impact assessment with climate-related policy information. The framework development also involved the use of a pre-existing socio-economic model, GB-QUEST (see for example: Tansey *et al.*, 2002; Robinson *et al.*, 2006), which numerically specified four corresponding regional scenarios for the Metro Vancouver area. The coherence of the regional trends also provides the validity for the assumptions made in the four global scenarios. Regional storylines and narratives were developed which utilized the combined data provided by global models, regional assessments, local expertise, and GHG emission assumptions. These storylines were organized around four alternative scenarios, or 'worlds,' representing a continuum from no action on climate change to a 'deep sustainability approach' involving extensive greenhouse gas reductions, a shift in values, and proactive adaptation to climate change impacts (See Figure 2). Using principles of participatory scenario development, these alternative climate futures were used to stimulate dialogue with key municipal, expert, and community participants to consider what the local landscape would look like under the impact and response assumptions of each 'world.'

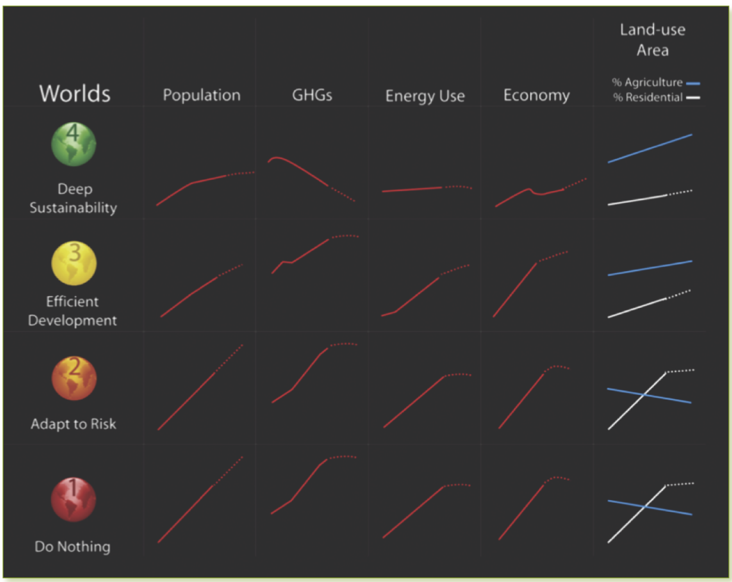

Figure 2 | Underlying socio-economic assumptions for each scenario. The GB-QUEST model provided general consistency among these main indicators. The horizontal axes represents time from 2007 to 2100; vertical axes vary by indicator. Dotted trend lines are extrapolations after 2050. GHGs stands for greenhouse gases.

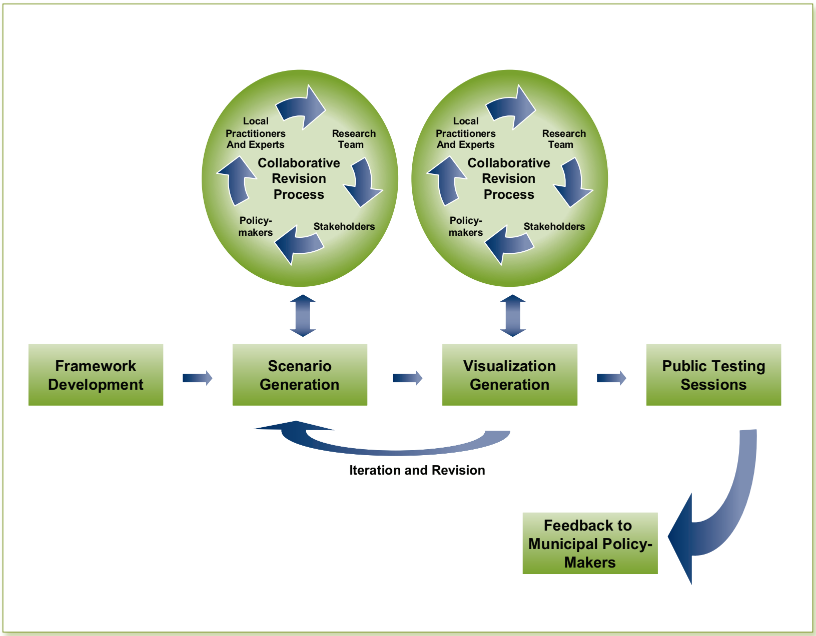

Figure 3 | The research process included opportunities for iteration, revision, and consultation with an extended team of stakeholders, local experts, and municipal decision-makers.

The output was local scenarios and projected changes in temperature, precipitation, and sea level in 2020, 2050, and 2100, which reflected the local policy context and landscapes of Delta. Using these outputs, the research team then illustrated each of these four scenarios using mapping and 3D computer-generated visualizations of key climate change impacts (such as sea-level rise or forest character and species changes) and various combinations of response options (including, for example, an adaptive response involving the raising of dikes, or a combined adaptation/mitigation strategy leading to compact mixed-use development patterns and alternative transportation choices).

The process of developing these four alternative scenarios was fundamentally shaped by a team consisting of municipal planners, engineers, environmental service providers, regional practitioners, federally-employed scientists and arms-length

University of British Columbia researchers (see Figure 3). The *core research team* (CRT) consisted of five individuals (principal investigator, co-principal investigator, two research associates, and a doctoral student) from the University of British Columbia. The *extended research group* (ERG) included fourteen university researchers and seventeen federal and provincial government researchers (with background in climate change modeling, impacts, responses), seven local and regional practitioners (planning and engineering), and five non-governmental experts. The CRT collaborated with the ERG to receive reliable inputs, to access technical data, to vet and approve the information and underlying assumptions for the global and regional scenarios (particularly for the “Deep Sustainability” scenario). The collaboration varied with respect to medium (in person, via e-mail, or telephone) and participants (plenary meetings, sub-groups) depending on availability (Shaw *et al.*, 2009).

Finally, *the local working group* (LWG) included two provincial government scientists, four practitioners from the municipality (planning and engineering), five local committees members (including agriculture and community advisory), and two private sector representatives (from the Port of Vancouver). The LWG was assembled to help contextualize the regional information by suggesting and reviewing local scenario content, advise on visualisation priorities, and review both the scenario narratives and visualizations. The participants had experiences in local climate change projects and/or were members in community groups. Three working group sessions were held in the form of workshops (Shaw *et al.*, 2009).

Final “visioning packages,” referred to below as the ‘treatment,’ combining the visualizations and supporting information were presented to Delta decision-makers and community members. Using pre-treatment and post-treatment questionnaires (delivered to 116 individuals), the influence of the presentation and the 3-D imagery on viewers’ cognitive awareness, affective response, and intended behaviour change were gatherered and evaluated. These results were a critical part of the visualization process and included enhanced levels of cognitive and affective engagement, an increased sense of urgency regarding flood management and climate change responses, improved awareness of climate change impacts, and increased behavioural intent to support or implement response options. A full examination of these results is explored elsewhere (Sheppard *et al.*, 2008; Shaw *et al.*, 2009).

4.3 Semi-structured interviews with municipal practitioners

One month following the final review of these visualizations and scenarios with municipal staff and decision-makers, interviews were held with a subset of these individuals to gather general information on barriers to action on climate change and to evaluate the impact of the visioning process[1]. In particular, the goal was to determine which images were most useful in terms of decision-making on climate change, and which images had remained in the memories of the participants. These semi-structured interviews also contained questions regarding the effect of institutional structure and culture on:

- climate change policy-making;
- past and future plans to respond to climate change through mitigation and adaptation;
- the effect of the external (and inter-jurisdictional) context on potentially reaching climate-related goals;
- various aspects of capacity (including financial, human, and technical capacity);
- external institutional factors (such as the jurisdiction at play, legislation and regulation, and external policy context);
- leadership (both political and technical); and
- issues related to the values, attitudes, and knowledge of each city's public.

The interviews provided an opportunity to gauge the usefulness of the images generated by this intensely collaborative process, and also insights into ways in which the visioning process might be improved in the future to overcome barriers. Interviews were analyzed using ATLAS TI qualitative analysis software, and responses were coded according to references to capacity, institutional structure/culture, policies and practices, external institutional context, and specific references to the visioning process (among others).

Interviewees had been presented with images of four iconic locations in Delta. The first depicted a higher-elevation residential community, the second showed a low-elevation non-residential region protected by sub-standard dikes, the third illustrated a highly-valued low-elevation habitat refuge, and the fourth showed a low-elevation neighbourhood protected by standard dikes. Images were created to depict the current

1 Sample size of semi-structured interviews: in Delta (total n=12): 3 politicians; 3 planners; 2 engineers; 4 environmental services/operations staff.

circumstances in each of these locations, followed by visions of each of the four scenarios (showing both climate change/flooding impacts and response options, depending on the scenario). In general, interviewees indicated that the images depicting the flooding of a familiar neighbourhood were the more powerful and memorable than images at the neighbourhood scale (see Figure 4).

This reaction varied somewhat, however, depending on the background and discipline of the staff member. For instance, city planners were more likely to respond to and recall images depicting dramatic changes in land use as a result of an influx of environmental refugees (see Figure 5), while engineers with the Corporation of Delta indicated that images of flooding and dikes (Figure 6a-c) were the most powerful.

All interviewees agreed that the images were highly credible, and that bringing together a variety of stakeholders and experts enriched the process considerably. Many were eager to use the process to assist in future planning and climate change policy-making, and commented on the ability of the visioning process to raise awareness about climate change impacts in local areas. It was noted, however, that climate change impacts were most clearly communicated, relative to the menu of available response options that were shown. Interviewees indicated that more information on response options (eg. cost, feasibility) was required if the process was to be truly useful as a decision support tool.

Interviewees indicated that capacity, in the form of financial capital and technical climate change expertise, was scarce in Delta, but the recent commitment of the mayor to address climate change provided much-needed political leadership and direction. Furthermore, interviewees noted that the images were both powerful illustrations of familiar places, but were also clearly rooted in science. Criticisms of the process included doubt about whether or not awareness-building tools will in fact stimulate behaviour change on the part of the public, and complaints about the absence of a straightforward list of actions that individuals can take in response to climate change. Additional analyses of the levels of capacity, barriers to climate change policymaking, and a comparison of Delta to other communities in the Lower Mainland regions, see Burch (2010).

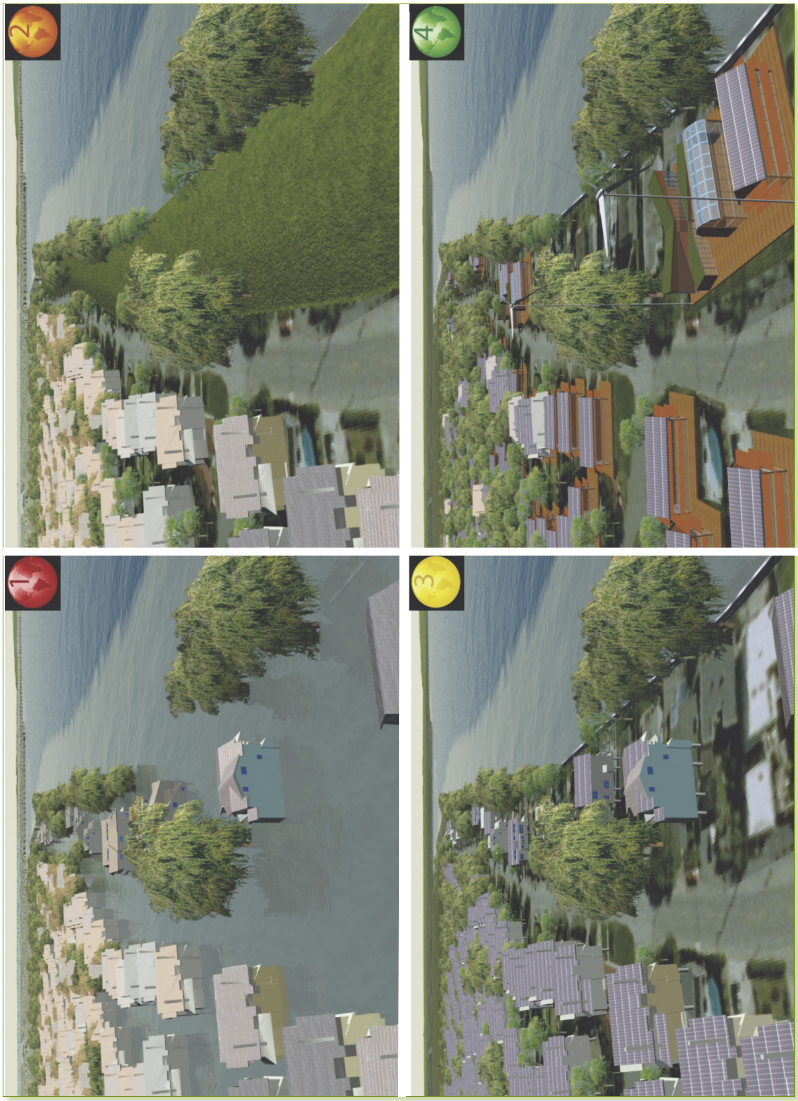

Figure 4 | Four iconic flood response and greenhouse gas mitigation scenarios for a low-lying community in Delta, British Columbia. The images shown here depict the community in 2100. (Credit: David Flanders, UBC-CALP).

Figure 5 | Tsawwassen and surrounding area under scenario 1 "Do Nothing" by 2100. Current (white), planned (yellow), and the unplanned development of neighbourhoods due to environmental refugees (beige, top right) (Credit: David Flanders, UBC-CALP).

Figure 6 a-c | (from left to right) a. Current mean sea level illustrates the dike with extensive mudflats on left side, with trees and protected agricultural land on right side; b. In scenario 1, by 2100 the dike is breached and agricultural lands are flooded; c. In scenario 2 (adaptation), by 2100 the dike is raised. (Credit: David Flanders, UBC-CALP; all sea level and LiDAR data provided by Natural Resources Canada).

5. Discussion

As outlined in the brief literature review presented earlier in this paper, institutions, participatory processes, and capacity strongly influence the design, implementation, and uptake of flood risk management at the local level. The ways in which the Local Climate Change Visioning Project addressed some of these barriers are discussed below, as well as opportunities for an enhanced version of this process to overcome barriers more effectively. This discussion draws upon an interpretation of both the conceptual advantages of the process, as applied to barriers, and specific results from the interviews.

The municipal institutions which shape local responses to flood risk are subject to forces of change that have been well-documented in the field of institutional theory. Although path dependence may play a significant role in perpetuating institutional inefficiencies (Thelen, 2003) and potentially undesirable environmental outcomes, learning (whereby actors rationally identify gaps and take corrective steps) and competition (gradual refinement of institutional design resulting from competitive pressures) are forces of institutional enhancement (Pierson, 2004). The visioning process conducted in Delta represented one of the first steps toward institutional learning for the municipality in the face of a changing climate, and began to suggest ways in which both decision-making processes and the ultimate flood risk management initiatives must incorporate an integrated view of climate change impacts and responses, including both adaptation and mitigation. In particular, this process brought together engineers, planners, and policymakers in the process of generating credible images which communicated useful information about the local impacts of climate change and potential response options. Such cross-sectoral collaboration helps to overcome barriers related to limited technical capacity and the absence of best-practice information (Betsill, 2001).

The Local Climate Change Visioning Project incorporated strong elements of public participation – from the development of the images in conjunction with staff and policymakers within the municipality, revision of the images with the help of local experts and stakeholders, and testing of these images with a public audience. Even among municipal experts, the mere provision of information was deemed unlikely to address concerns regarding the uncertainty of local climate futures, the portfolio of response options available, and the effect of regional, provincial, and federal policies on local spaces and actions. As such, the project used as a general guide an 'analytic deliberative process,' (Stern and Fineberg, 1996) which "combines sounds science and systematic uncertainty analysis with participatory deliberation by an appropriate representation of affected parties, policy-makers, and specialists" (Pidgeon *et al.*, 2005).

This deliberative process of scenario and visualization design may be an important means of overcoming barriers to effective flood risk management for three reasons. First, as mentioned above, communicative partnerships were forged between politicians, municipal staff and scientists. These partnerships may improve the legitimacy and effectiveness of the flood response discourse in the municipality of Delta, and may lead to locally-specific and integrated adaptation and mitigation policies. Second, the development of four iconic, highly localized, and meaningful scenarios aided in the explicit incorporation of values into an alternative mode of deliberation – namely storytelling using visual media. These media provide a common language with which experts from disparate disciplines may communicate and express anticipated climate change impacts and desirable responses, and thus help to overcome the barrier of miscommunication. Finally, the Local Climate Change Visioning Project, through a series of iterative consultations with various municipal groups and advisors, provided a mechanism by which the fruits of the participatory visualization development process may be fed into decision-making procedures. Collaboration with the Project was officially endorsed by the Delta City Council, and the products of the process were presented to the Council upon completion. This served the purpose of allowing Delta's political leaders to explore the implications of future climate change impacts in their region, obtain valuable technical advice from their staff in a focused and highly effective manner, and explore linkages between climate change responses, existing flood management practices, and other policy priorities.

The final realm of barriers to local action on climate change pertains to capacity to respond to climate change. Although the presence of capacity does not make responding to climate change inevitable (Burch and Robinson, 2007; Burch, 2010), capacity is nonetheless a necessary pre-condition to climate change response strategies (Adger *et al.*, 2007). The most important way in which the visioning process helped to build capacity in the community of Delta was to bring together experts, practitioners, and municipal staff to discuss feasible climate change response options and best practices. Given the small size and limited human resources of Delta, such inter-disciplinary and inter-jurisdictional discussions are not often facilitated. Interviewees indicated that the use of locally-significant 3D imagery of climate change impacts (especially those related to flood risk) and response options added power and meaning to these discussions, and aided the exploration of desirable futures in Delta (Sheppard *et al.*, 2008). On the surface it may appear that the main goal of this study was to simply provide more information to members of the Delta community and expect this to stimulate a greater quantity and quality of action. However, the 'deficit' model of behaviour change - in which it is claimed that the behaviour will be changed simply through the provision of information - that has been roundly criticized (Irwin and Wynne, 1996; Kaiser and Wolfing, 1999; Kollmuss and Agyeman, 2002) was accounted for very early in the research design process. The unique process that the Visioning Project followed leads to the conclusion that, while an enabling context and normative pressures (Karp, 1996; Stern, 2000) are clearly integral to effective action, so too is the type and mode of presentation of information about climate futures.

Despite the usefulness of the Local Climate Change Visioning Project in bringing together a diverse group of experts and decision-makers to discuss highly localized and meaningful climate change futures for Delta, a number of gaps in the process were identified that are specific to decision-making in the realms of flood risk management and climate change responses. First, time constraints prevent the project from providing highly specific and tangible inputs into the climate change policy development process in the Corporation of Delta. A number of municipal representatives were interested in seeking advice from the research team. While this is traditionally an appropriate role for scientists and researchers it was believed that the underlying process of co-constructing the scenarios with the decision-makers and community was a way to contribute to decision-making within the local context without advising directly.

Secondly, issues also arose with regard to the allowable level of drama contained within the imagery. In order to avoid stimulating an overwhelmed or apathetic response on the part of the visualizations' audience, the researchers avoided creating images that depicted the more severe impacts of extreme climate change events (such as loss of life due to flooding). As a result, however, some members of the public testing group noted that in order to most effectively build awareness, these types of images should be included. Furthermore, a deliberate decision was made to reduce the realism of the developed areas in close-up views, to avoid possible adverse reactions from participants and potential legal repercussions around individually recognized property in the area (Mendez, 2008). Finally, objections arose (although infrequently) in regard to the 'do nothing' scenario. One set of visualizations associated with this scenario depicted urban sprawl extending across valuable agricultural land and onto flood-prone areas. This was deemed, by a local practitioner, to be highly unrealistic and potentially misleading to the public. Nevertheless, the image remained in the visualization packages used in public testing sessions in order to explore the possibility of regressive planning practices taking over in times of extreme climatic stress and political or economic duress. This raises the question of the necessity of full participant buy-in to the visualizations, and the wisdom of using visualizations to push the boundaries of accepted planning, flood management, and urban design practices.

Requests were made by municipal staff for a concise and practical list of response priorities for the municipality, but the project team concluded that added investigations into costing and feasibility would be necessary before this could be provided. The lack of analyses that explored in detail the different costs and benefits associated with the adaptation and mitigation choices was viewed as a gap as the results relate to real-world municipal decision-making. In future iterations of this work, scenarios will be created with costs attached to the various response options in order to explore the full series of trade-offs involved in pursuing one scenario over another. It is hoped that this will more effectively feed into existing policy-making processes and facilitate integrated flood management in response to climate change. However the project provided a certain empowerment to decision-makers by generating a comprehensive understanding of key vulnerabilities and climate-related issues facing Delta and the response options available to the interests and concerns of their constituents. It would be premature, however, to judge the effect of this process on policy, as the municipality of Delta is only now beginning a critical revision of its Official Community Plan, to which the Visioning Project's results have much to contribute. Nevertheless, the team has been invited to participate in ongoing efforts to review and revise flood management policies in the community, and contribute insights into the forms that integrated adaptation and mitigation planning might take in the future. It is anticipated that more specific impacts on barriers may become clearer as policies develop. An additional effect of the visualisation work may also turn out to be via the considerable exposure in the media that the research has received, with possible 'knock-on' effects on municipal staff and policy.

6. Conclusions

Local government clearly needs more systematic research on overcoming barriers to implementing effective flood management policy given the implications of a changing climate and the host of challenges inherent in municipal institutions. This paper has explored key municipal barriers and suggested an array of possible ways to overcome such barriers. A new approach to Local Climate Change Visioning has been reviewed in the context of these municipal barriers, as a first step to more in-depth evaluation of the success of processes in overcoming barriers to municipal action. The Visioning Process provides a novel way to communicate science and uncertainty within a local context. It encourages a deliberative process that moves beyond uncertainties to craft four alternative visions of the future, which illustrate different levels of adaptation and mitigation responses (viewed to be appropriate and applicable at this scale). Visualizing these futures begins the dialogue about preferences for the future and the types of decisions that need to be made now in order to shift behaviours. It brings together a range of stakeholders without whom effective flood risk management and climate change policy-making cannot occur. This process has revealed, and in part addressed, a number of the well-established flaws in current models of flood risk management, including fairness in public engagement, uncertainty in predictive models, and lack of technical and human capacity.

Linking global science to locally significant places with visioning processes and visualisations represents a powerful tool for decision-making in the context of flood risk management. Visualization could also be applied to other types of climate change adaptation challenges, and participants in the Visioning Project have pursued applications on changing snowpack in the District of North Vancouver, and changing forest fire risk in Kimberley. In the future, providing an integrated and concise assessment of the ways in which the results of the testing sessions could be built into concrete and effective climate change response policies represents the final link in closing the loop among municipal governance, scientific expertise, and public participation. Other municipalities facing similar risks may consider existing flood risk management practices in light of the unique challenges posed by a changing climate, and the emerging public participation and scenario co-production tools explored here. With these tools in hand, municipalities and other jurisdictions may better equipped to design and implement equitable flood management responses that account for cognitive, behavioural, and institutional barriers.

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Section

2

Canadian Regional Climate Change Adaptation Science Activities

A Bibliographic Review of the Climate Change Adaptation Literature

7

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Abstract: This report attempts to develop a general, accessible doorway into climate change adaptation (CCA) literature which is indifferent to one's starting position and evolves with one's knowledge base. It is intended to provide an understanding of the major issues associated with the field, as well as tools to access its informational resources. This is accomplished in two parts: first, a rough overview of the IPCC AR4 Synthesis report is provided to introduce the reader to the major CCA topics; and second, a framework for organising the CCA information landscape is provided to aid researchers in keeping abreast of emerging trends. A broad overview of the CCA field is then presented along with a discussion of methodological issues, and options for further research.

Keywords: climate, climate change, adaptation, bibliometrics, literature review

1. Introduction

Newcomers to the science and policy of climate change[1] are immediately confronted by a field of study which has grown to include almost every aspect of human endeavour[2]. A simple web search quickly confirms just how expansive this landscape has become (e.g. a Google™ search on the key words "climate change," resulted in 101 million sites, and 1.67 million sites for "climate change adaptation" Oct. 16, 2007). Unfortunately, this information is unstructured and extremely difficult to navigate despite the best hopes of visionaries[3]. Even from within the formal environment of peer reviewed academic journals[4], researchers face a daunting task of staying informed and disseminating results not only to the public and policy makers, but amongst themselves as well (Bord *et al.,* 1999; Farbotko, 2005; Wall and Smit, 2006). The purpose of this report therefore, is to find a general, accessible doorway

1 The author includes himself in this group.

2 Even Formula 1 racing, is becoming conscious of the need to respond to the challenges of climate change. (**http://www.formula1.com/news/interviews/2007/5/6174.html, Accessed October 20, 2007**)

3 For example see the discussion of the future of the internet (Web 3.0) (Borland 2007; Tossell 2007).

4 Which some place at over 40,000 active peer-reviewed academic publications **http://www.libraryjournal.com/article/CA374956.html** (accessed October 20th, 2007)

into climate change adaptation (CCA) research, which is indifferent to one's starting position and evolves with one's knowledge base.

Numerous information sources and media formats exist to disseminate information regarding 'climate change' (CC), each with its own particular advantages and disadvantages. Aside from the web, the most obvious access points into this knowledge landscape are book length introductions\reviews (Weart, 2003; Coward and Weaver, 2004; Fagan, 2004; Flannery, 2005; McGuffie and Henderson-Sellers, 2005; Beerling, 2007; Strom, 2007; Cohen, 2007). While this is likely the best place to establish a foundation, this medium nevertheless has its limitations: books present subject matter that may be dated, they can be overly verbose given their content, and author bias may be over-stated given the lack of formal peer review (i.e. for example, see the work of Lomborg (2007) in the context of reviewers (Dasgupta, 2007; Mitchell, 2007). At the other end of the spectrum, the news media is a relatively immediate source of information, but is often fickle in terms of subject matter, shallow in terms of content, and has the potential to be systematically biased despite an implicit policy of 'balanced' reporting (Boykoff and Boykoff, 2004; Boykoff, 2007; Ward, 2007).

Proceeding through these various informational sources haphazardly (i.e. from books, to the web, to magazines, to research papers, to reports, etc.) is often the only way researchers can manage their information portfolios. For most scientists a periodic, all-inclusive overview of their chosen field and its effects upon human endeavour is simple fantasy. For climate change researchers though, this is precisely what happens. The 'Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)' was released in 2007. It is composed of three reports: a) The Physical Science Basis: Working Group I (IPCC, 2007); b) Impacts, Adaptation and Vulnerability: Working Group II (IPCC, 2007) which is the focus of this survey; and c) Mitigation of Climate Change: Working Group III (IPCC, 2007), and a Synthesis report (IPCC, 2007) which condenses results from the three working reports. Together this work is considered to be the most comprehensive and balanced assessment of climate change available.

The IPCC[5] was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) as a response to the problems accompanying global climate change. Its mandate is to collect and assess

5 Information regarding the IPCC can be found at their web page **http://www.ipcc.ch/about/about.htm** (accessed October 20, 2007).

scientific, technical and socio-economic information relevant for the understanding of climate change, and its potential impacts and options for adaptation and mitigation. It does not carry out research itself, but bases its assessments on peer reviewed and published scientific/technical literature. Its reports (released in 1990, 1997, 2001 and 2007) have been critical for informing climate change policy negotiations, directing research programs and agendas, and providing methodological input for developing mitigation and adaptation strategies.

In no other field has so encompassing a series of reviews been produced, making this the obvious starting point for informing oneself of climate change and a yardstick for any future research. Nevertheless, it is important to understand the manner in which these reports are created so as to recognise their limitations. Although the IPCC collects its information from peer reviewed journals, its' reports require consensus among members, which include government representatives. It has been suggested that this creates a conservative bias in IPCC reporting, as governments can unduly influence the process (Homer-Dixon, 2007). Additionally, the review process may also be open to bias given its' inherent methodological and structural preconceptions, which have historically favoured the physical over the social sciences (Cohen, Demeritt *et al.,* 1997). Finally, the process is a complex and cumbersome endeavour, the product of numerous authors, enormous datasets and thousands of reviewed articles. Not surprisingly, the reports are somewhat disjointed, and the reviewed literature dated (Homer-Dixon, 2007).

Despite such criticisms, no one would deny that the IPCC has been remarkably successful in raising awareness of the impacts of climate change and the potential for human response[6]. 'CCA for Neophytes' is not meant to compete with the IPCC AR4, but rather to complement it by providing new CCA researchers with an understanding of the major issues associated with the field, as well as tools to access its informational resources. This is accomplished in two parts: first, a rough overview of the AR4 Synthesis report is provided to inform the reader of the larger issues within the field at the time of AR4 publishing (Section 2.0); and second, a framework for managing one's access to the CCA information landscape is provided to keep researchers abreast of emerging issues (Section 3.0). In a sense we provide a snapshot

6 The IPCC received the Nobel Peace Prize in 2007: **http://nobelprize.org** in 2007.

of the CCA field from a given perspective (i.e. the IPCC AR4), and then provide an efficient means of critically evaluating that snapshot from alternate perspectives to reveal enduring and emerging trends.

2. Synthesis of the IPCC AR4 Synthesis

From a neophyte's perspective, the advantages of the IPCC reports are that they bring the lion's share of relevant climate change information together in one accessible location, they describe how the science has changed since the last report, and they provide a roadmap of where the field may go in the future. Before the release of each of the working groups' reports (i.e. WG I (IPCC, 2007), WGII (IPCC, 2007) and WGIII (IPCC, 2007) reports), a Summary for Policy Makers is released, which highlights the key findings of the individual working groups. Once all the reports have been released, a final synthesis report (IPCC, 2007) is published which brings all the information from the working groups together in an integrated fashion.

The Synthesis report delivers the 'big messages' of the IPCC review process and is composed of five major headings: the first section presents empirical evidence which supports the notion that human-induced climate change has actually occurred. The second section describes theory/modeling that explains how human behaviour has affected the atmosphere leading to a changing climate. Section three discusses potential impacts given various future possibilities, while section four describes ways of intentionally altering those possibilities through adaptation and/or mitigation. Finally section five discusses long term projections. Unfortunately, the reports taken together represent a large amount of information which can appear somewhat overwhelming if 'climate change' is not your primary research focus. The following is a brief overview of the key issues reported by the IPCC AR4 Synthesis, and is not meant to replace the reports, but rather give a flavour of what might be found there.

TOPIC 1 - Observed changes: The findings in Topic 1 describe empirical evidence (as opposed to modeling projections) in support of the contention that climate change has occurred. It recognises that atmospheric modeling is insufficient to establish the fact of global warming (McGuffie and Henderson-Sellers, 2005) and that projections of climate change must be verified (Weart, 2003). It employs strong wording, stating that the warming of the climate system is 'unequivocal.' Evidence includes an increase in global average temperatures (i.e. eleven of the last twelve years are among the warmest on record), an increase in observations of ocean temperatures, increased observations of rising precipitation levels in specific regions, as well as the widespread melting of snow and ice (i.e. arctic sea ice has shrunk by 2.7 % per decade) and rising global sea levels.

The report further states that specific systems are responding as expected (according to theory) in the face of global warming. For instance, the number and size of glacial lakes has increased, as has ground instability in mountainous and other permafrost regions. Hydrological systems have responded to warming with increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers. The warming temperatures have also affected the thermal structure and water quality of rivers and lakes. More specifically, evidence from over 29,000 observational data series of physical and biological systems are consistent (89% of the time) with the direction of change expected with climatic warming. These changes include: earlier timing of terrestrial spring events and poleward (upward) shifts in plant and animal ranges; shifts in ranges and changes in algal, plankton and fish abundance in marine and fresh water ecosystems; changes in ice cover, salinity, oxygen levels and circulation.

As well, changes in human environments are consistent with global warming (although this is confounded by additional factors). Examples drawn from agricultural and forestry management at Northern Hemisphere higher latitudes, include earlier spring planting, and alterations in disturbance regimes of forests due to fires and pests. Human health has also been affected by climatic changes, including: heat-related mortality in Europe; changes in infectious disease vectors in some areas; and allergenic pollen in Northern Hemisphere high and mid-latitudes. And human activities in the Arctic (e.g. hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports) have been affected as well.

TOPIC 2 – Causes of change: This section of the report deals with the current scientific understanding of the causes of human-induced climate change. Determining the significance of issues raised within this section can be challenging if the reader is unfamiliar with the underlying theories of atmosphere weather and climate, and the current debates within that literature. Nevertheless, a number of primers can provide sufficient background to follow the discussion, including: popular accounts of atmospheric processes (Flannery, 2005; Cohen, 2007), introductory texts on atmospheric science (Barry and Chorley, 2003), or more specific reviews of the development (Weart, 2003) and technical aspects of climate modeling (McGuffie and Henderson-Sellers, 2005).

The section starts with the basic presumption that atmospheric concentrations in green gases (GHG), aerosols, land-cover and solar radiation have the affect of altering the energy balance of the climate system. The relative extent of these various drivers of the climate is established by first determining the historical changes in these various components of the climate systems: global human GHG emission increases of 70% between 1970 and 2004; concentrations of CO_2, methane (CH_4) and nitrous oxide (N_2O) have increased markedly since 1750; and concentrations of CO_2 and CH_4 in 2005 far in excess of the natural range over the last 650,000 years. CO_2 increases are primarily due to fossil fuel use, while CH_4 increases are predominantly due to agriculture and fossil fuel use.

Given these anthropogenic trends, the challenge for climate modellers has been to show the relative affect of these drivers upon the climate, in contrast to natural drivers. According to the literature, over the past 50 years, the sum of solar and volcanic forcings would likely have produced cooling, not warming. Additionally, increases in GHGs tend to warm the surface while the net effect of increases in aerosols tends to cool it. But the net effect due to human activities since the pre-industrial era is one of warming (+1.6 [+0.6 to +2.4]W/m^2), while solar irradiance are estimated to have caused only a small warming effect (+0.12 [+0.06 to +0.30]W/m^2). It is therefore concluded that the net effect of human activities since 1750 has been one of warming, changes in wind patterns, altered precipitation patterns and changes is extreme events.

TOPIC 3 – Climate change & impacts under different scenarios: The purpose of this section is to report on the projected impacts of human-induced climate change. As such, it represents one of the most critical sections of the IPCC reports given its direct relevance to decision and policy making. To determine these impacts, a number of subtleties associated with predicative modeling have to be taken into account. In an ideal sense, a single integrated model, itself the product of a thorough understanding of both natural and socio-economic systems, would produce a series of possibilities from which an optimal pathway for human agency could be determined. This perfect ideal would take into account all interactions and feedbacks between the natural and socio-economic systems, as well as value assessments of various outcomes.

In reality natural and socio-economic models are composed of numerous sub-systems, each of which is inherently incomplete, and typically modeled in isolation despite important feedbacks among systems. Results are produced by various research groups, each with their own competing theories and accompanying methodologies, as well as their own unique sets of initial and future input conditions. The more complex models are computationally heavy in the sense that they take large amounts of time and resources to run, implying that they can only perform a limited series of runs or simulations. Hence the ideal of optimality is typically abandoned in favour of producing a series of likely or contrasting scenarios for consideration. The problem for the IPCC has been the lack of consistency among the scenarios used by various research teams.

In the past modellers had used a range of emission scenarios as GCM inputs to examine the impacts of elevated GHGs (e.g. doubling of CO_2). Aside from the lack of consistency, this was not very revealing in terms of the conditions that would have produced a doubling of CO_2 in the first place, nor did it take into account the inherent circularity of the problem (i.e. humans affect the environment which in turn affects humans, etc.). Actual prediction of future anthropogenic GHG emissions would require consideration of very complex, ill-understood dynamic systems, driven by forces such as population growth, socio-economic development, technological progress (IPCC, 2001), and of course climate. Not only is such prediction impossible, but there are an infinite number of alternative futures to explore given the ranges of future emissions and driving forces (IPCC, 2001).

The solution has been to effectively freeze the relationship between the climate and society into plausible storylines by developing a standard set of alternative GHG emissions scenarios to analyze long-range developments of the socio-economic system and corresponding emission sources. SRES refers to these scenarios as described in the IPCC Special Report on Emission Scenarios (IPCC, 2000). Scenarios cover a wide range of the driving forces of future emissions, including demographics, land use change, technology, economy, energy, and agriculture. They encompass different future developments that might influence greenhouse gas (GHG) sources and sinks, such as alternative structures of energy systems and land-use changes. They do not address any future policy considerations (e.g. mitigation or adaptation) nor are they meant to infer policy preferences, or even suggest a business-as-usual scenario. They are based on an 'internally consistent and reproducible' set of assumptions about the key relationships and driving forces of change, derived from an understanding of history and the current situation (IPCC, 2001).

Using this framework as a foundation, projected impacts of the individual scenarios were gleaned from the literature. Some of the results suggest that across the entire range of SRES emissions scenarios we can expect a minimum warming of about 0.2°C per decade. In other words, without any active mitigative action, we are committed to climate warming. The report goes on to list the actual range of climate impacts for each of the SRES scenarios (e.g. in tabular and graphic form Figure SPM-5 and Table SPM.1). These ranges are consistent with the previous IPCC report (TAR), but upper ranges are larger due to the inclusion of stronger climate-carbon cycle feedbacks in some models (e.g. warming will reduce terrestrial and ocean uptake of atmospheric CO_2, increasing the fraction of anthropogenic emissions remaining in the atmosphere).

In terms of climatic changes warming will be greatest over land and most high northern latitudes. It will be least over the Southern Ocean and parts of the North Atlantic Ocean. The contraction in snow cover area will continue, including increases in thaw depth over most permafrost regions, and decrease in sea ice extent. Arctic late-summer sea ice may disappear almost entirely by the latter part of the 21st century. In other regions, there is a very likely increase in frequency of hot extremes, heat waves, and heavy precipitation. A likely increase in tropical cyclone intensity and a poleward shift of extra-tropical storm tracks. Precipitation is very likely to increase in high latitudes and likely decrease in most subtropical land regions, continuing observed recent trends. As such, annual river runoff and water availability are projected to increase at high latitudes (and in some tropical wet areas) and decrease in some dry regions in the mid-latitudes and tropics. Many semi-arid areas (e.g. Mediterranean basin, western United States, southern Africa and northeast Brazil) will suffer a decrease in water resources due to climate change.

Critical impacts are listed in tabular form for regions (Table SPM.2) and sectors (SPM.3). Table SPM.7 illustrates impacts to systems and sectors over an increasing global temperature, superimposed over the likelihood of those temperature increases under the different SRES scenarios. More specifically terrestrial ecosystems such as the tundra, boreal forest and mountain regions are likely to be affected by climate change, as are Mediterranean-type ecosystems and tropical rainforests. Coastal systems including mangroves and salt marshes, and marine systems including coral reefs, and sea ice are to be affected as well. In terms of human systems, agriculturalists in low-latitudes areas, and those who inhabit low-lying coastal systems (i.e. threat of sea level rise and increased risk from extreme weather events) are to be severely affected. Regions such as the Arctic, Africa, small oceanic islands and Asian and African mega-deltas are to be severely affected.

Finally, Figure SPM.8 describes estimated long term (multi-century) warming corresponding to the six AR4 WGIII stabilisation categories (Table SPM.3). Stabilisation targets are compared in terms of CO_2 concentrations and range from 445-490 ppm, all the way up to 855-1130 ppm. The graph shows the corresponding global temperature increases of 2-2.4°C up to 4.9-6.1°C. Table TS.2 shows as well the change in 2050 CO_2 concentrations in relation to year 2000 emissions. The timing of emission reductions depends on the stringency of the stabilization target. Stringent targets require an earlier peak in CO_2 emissions. In the majority of the scenarios in the most stringent stabilization category (I), emissions are required to decline before 2015 and be further reduced to less than 50% of today's emissions by 2050 (IPCC, 2007). In other words, this informs policy makers of the levels of emission reductions required to stabilise temperatures at the given levels.

TOPIC 4 – Adaptation, mitigation options and responses: This section deals with human responses in the form of mitigation and/or adaptation to climate change. It can read like a cookbook of ad hoc heuristics and lists describing either adaptation or mitigation actions. In terms of 'adaptation' this is partially due to the inherent difficulties in defining it, measuring it and/or projecting it. Comprehensive estimates of global costs and benefits of adaptation are very limited. Equally difficult is determining the ability or capacity to adapt. Adaptive capacity is intimately connected to social and economic development, unevenly distributed across and within societies, is dynamic and is influenced by a society's productive base including: natural and man-made capital assets, social networks and entitlements, human capital and institutions, governance, national income, health and technology.

The requirement of adaptation can be exacerbated by additional factors including current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalisation, conflict and incidence of diseases such as HIV/AIDS. Though a wide array of adaptation options exists, more extensive adaptation will be required than is currently occurring to reduce vulnerability to climate change. Adaptation is not being implemented due to barriers, limits and costs that are not well understood. When implemented, it often occurs as a result of multiple drivers, such as economic development and poverty alleviation, which are embedded within broader development, sectoral, regional and local planning initiatives such as water resources planning, coastal defence and disaster risk reduction strategies. Thus a guiding principle of adaptation (i.e. a heuristic rule of thumb) is that it is more likely to be successful when it is embedded in broader sectoral initiatives.

Table SPM-4, describes some selected examples of planned sectoral adaptation (i.e. *Water, Agriculture, Infrastructure/settlement* (including coastal zones), *Human health, Tourism, Transport,* and *Energy*) in terms of: 1) adaptation options and strategies; 2) the relevant underlying policy framework; and 3) key constraints or opportunities to its implementation. If we examine *Infrastructure* as an example, adaptation options include: seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural; and relocation. The underlying policy framework it affects includes: standards and regulations that integrate climate change considerations into design; land use policies; building codes; insurance. And the key constraints and opportunities to implementation are: financial and technological barriers; availability of relocation space; integrated policies and managements; synergies with sustainable development goals.

Adaptation and mitigation are complementary responses to climate change, and we are entreated to consider them together, as well as in the context of sustainable development. Nevertheless, in the synthesis report, the two are largely treated separately. This distinction becomes even more pronounced as we consider the manner in which these two strategies are dealt with. As with adaptation, we are treated to heuristic rules of thumb to guide implementation of mitigation options, such as the fact no single technology can provide all of the mitigation potential in any sector, or *"A wide variety of policies and instruments are available to governments to create the incentives for mitigation action … [which] … depends on national circumstances and sectoral context."* We are also presented with a table of mitigation examples for key sectors. Table SPM.5 lists key sectoral mitigation technologies, policies and measures, constraints and opportunities for the Energy Supply, Transport, Buildings, Industry, Agriculture, Forestry, and Waste sectors.

If we use as our example the *Building* sector, we find under key mitigation technologies and practices: efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; and solar photovoltaics integrated in buildings. Examples of policies, measures and instruments for implementing these strategies include: appliance standards and labelling; building codes and certification; demand-side management programmes; public sector leadership programmes, including procurement; and Incentives for energy service companies (ESCOs). The key constraints or opportunities include: periodic revision of standards needed; attractive for new buildings. enforcement can be difficult; need for regulations so that utilities may profit; government purchasing can expand demand for energy efficient products; as well as access to third party financing.

But this is where the report's treatment of adaptation and mitigation diverge. While in the adaptation section there was mention of limited comprehensive estimates of global costs and benefits of adaptation, for mitigation strategies, actual numbers are attached to mitigation strategies by sector, as expressed through carbon prices. Mitigation potential is meant to assess the scale of GHG reductions that could be made, relative to emission baselines, for a given level of carbon price. Graph SPM.10 illustrates the economic mitigation potential by sector in 2030 derived from bottom-up studies, compared to the respective baselines assumed in the sector assessments for: *Energy Supply, Transport, Buildings, Industry, Agriculture, Forestry,* and *Waste* sectors. Given carbon prices of \$20, \$50 and \$100 US\$/tCO_2 eq – the Transport sector has a potential of between 1.5 and 2 GtCO_2 – eq/yr; the Buildings sector on the other hand had a potential of 5 to 6 GtCO_2 – eq/yr, while the Industry sector, Agricultural and Forestry sectors had much better response curves (e.g. Industry could sequester 1 to 4 GtCO_2 – eq/yr).

This important consideration of mitigation potential, has the advantage of offering policy makers guidance in terms of where to place their limited resources for the greatest return. It becomes readily apparent that the Transport sector not only has a much smaller affect upon carbon budgets than the Building sector, but that it would not respond as much to changes in carbon prices as would Industry or Agriculture. Such guidance is essential if limited resources are to be effectively applied to respond to climate change. Adaptation science would do well to attempt such monetarization of options and strategies as a similar offer of guidance.

TOPIC 5 – The long term perspective: In the final topic, the issues of long terms goals and prioritization are introduced, as well as a final word on the means and costs of meeting those goals. AR4 enlists the concept of 'key vulnerabilities' as derived from TAR to respond to IPCC's ultimate raison d'etre, that of avoiding "dangerous anthropogenic interference with the climate system" (Article 2 of the UNFCCC). Key vulnerabilities are associated with climate sensitive systems which include but not limited to: food supply, infrastructure, health, water resources, coastal systems, ecosystems, global biogeochemical cycles, ice sheets, and modes of oceanic and atmospheric circulation. They can be identified based upon a number of criteria including: magnitude, timing, persistence/reversibility, the potential for adaptation, distributional aspects, likelihood and 'importance' of the impacts.

There are five reasons for concern, regarding climate change and they include: 1) risks to unique and threatened systems; 2) Risks of extreme weather events; 3) Distribution of impacts and vulnerabilities; 4) Aggregate impacts; and 5) Risks of large-scale singularities. AR4 concludes that the reasons for concerns are assessed as 'stronger' than they were with TAR, in that many of the risks are identified with higher confidence, some are larger than projected or are to occur at lower temperatures. Additionally, understanding the relationship between impacts (the basis for "reasons for concern" in the TAR) and vulnerability (that includes the ability to adapt to impacts) has improved.

In terms of (1) risks to unique and vulnerable systems, there is new and stronger evidence of observed impacts on systems such as polar and high mountain communities and ecosystems. Also the risk of species extinction is projected to have increased; 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.58°C over 1980-1999 levels. Society has been found to be more vulnerable to extreme weather events (2) than was revealed in TAR. There is also higher confidence in the projected increases in droughts, heatwaves, and floods as well as their adverse impacts.

There have been differences (3) across regions and their ability to respond to impacts. Those in the weakest economic positions, such as low-latitude and less-developed, or elderly or poor, in either developed or developing countries are found to be most vulnerable to climate change. In terms of (4) aggregate impacts, older estimates of net market-based benefits are now projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming. Finally, (5) there is new evidence of impacts from large scale singularities. Sea level rise is project with high confidence to increase from thermal expansion alone, with further risks coming from increases from the Greenland and possibly Antarctic ice sheets. Associated impacts are naturally expected to increase as a result.

Given this litany of potentially negative impacts, the authors of AR4 attempt to paint a picture of possibilities in this final Topic. In Table SPM.6 and Figure SPM.11, required emission levels are summarized for different groups of GHG stabilisation concentrations, and the accompanying equilibrium global warming temperatures and sea level rise. So for example (Table SPM-6), there are six categories of stabilisation that represent carbon concentrations, a stabilisation level of 485 – 570 ppm in the atmosphere (Category IV), is associated with a peaking year in terms of emissions around 2020 – 2060. This represents a 10 to 60% increase by year 2050 over year 2000 concentrations, and is associated with a global average temperature increase of 3.2 – 4.0°C, and a sea level rise of 0.6 – 2.4 m. Economic costs (Table SPM-7) of this category (categories are not perfectly consistent between the two tables) could be anywhere from 3 to 5% GDP with a reduction in average growth rates of less than 0.12%.

The IPCC conclusions appear self-evident: the sooner we attempt to achieve stabilisation, the easier it will be to achieve. Delayed emission reductions constrain the opportunities to achieve lower stabilisation levels and increase the risk of more severe climate change impacts. Stabilisation levels will be achieved through a portfolio of technologies that are either currently available or expected to be commercialised in coming decades. But this will require appropriate and effective incentives for their development, acquisition, deployment and diffusion and addressing related barriers. Any strategy will also include both adaptation and mitigation which can complement each other to reduce the risks of climate change. Such strategies must also take into account climate change damages, co-benefits, sustainability, equity, and attitudes to risk.

Summary of Synthesis: The IPCC report makes it clear that climate change has already occurred in the form of increased global warming, increased ocean temperatures, increased regional precipitation, widespread melting of snow and ice, and rising global sea levels. Alterations in human systems have been consistent with these climatic changes (i.e. in the form of adaptations), as are ecosystems responses (i.e. terrestrial, marine, hydrological and cryospheric alterations and species migrations). These modifications of the climate are also consistent with our theoretical understanding of how human activities have influenced the atmosphere (i.e. most notably through the emissions of green houses gases).

Projecting our theoretical understanding of atmospheric behaviour into the future over a standard set of socioeconomic scenarios (SRES) and accompanying emissions profiles, modellers suggest that we can expect a warming of about 0.2°C per decade, without any mitigative effort. Warming will be greatest over land and most high northern latitudes and least over the Southern and North Atlantic Ocean. There will continue to be a contraction of snow cover area, increases in thaw depth over most permafrost regions, and a decrease in sea ice extent. There will also be an increase in the frequency of hot extremes, heat waves, and heavy precipitation. The tundra, the boreal, the tropical rainforest, montane regions, mediterranean-type ecosystems, coastal and marine systems (the extent of sea-ice) will be most affected. In terms of human systems, those most affected will be agriculturalists in low-latitudes areas, inhabitants of low-lying coastal systems, and in regions such as the Arctic, Africa, small oceanic islands and Asian and African megadeltas.

Given what has already occurred and what may be possible, there is naturally much speculation and debate over what should be done. At the most general level, there are two basic responses: to mitigate or to adapt. Presumably the guiding rationale for the IPCC is to avoid *"dangerous anthropogenic interference with the climate system"* (Article 2 of the UNFCCC) which suggests a mitigation effort. Accordingly, the Synthesis lists examples of mitigation actions for key sectors including the policies, measures and instruments for implementing these strategies, and the constraints or barriers that prevent their implementation. Furthermore, it attempts to monetarize those options in a comparative framework and offer stabilisation strategies which are accompanied by timeframes for action.

Adaptation options are also listed and their accompanying policy implications, barriers and constraints, *but comparative frameworks appear lacking*. It is noted that adaptation is confounded by numerous factors, including current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalisation, and conflict and incidence of diseases such as HIV/AIDS. *The best adaptation results appear to occur when strategies are associated with other initiatives.* A need is identified to discover systems that would allow the integration of adaptation and mitigation, in the context of sustainable development, but beyond individual examples it is difficult to ascertain how this would be accomplished. Nevertheless, the AR4 paints a clear picture of the need for immediate and simultaneous action on mitigation, and adaptation strategies.

The IPCC review process represents a monumental undertaking which has been successful in accumulating, interpreting and disseminating "greater knowledge about man-made climate change" as well as laying the foundations for *"measures that are needed to counteract such change[7]."* Nevertheless, AR4 cannot help but be a single snapshot of an extremely large and evolving field. AR4 gives some direction in terms of where the field may be heading, but is necessarily outdated even as it is published. It provides a heavily aggregated, implicitly biased perspective, leaving the reader with no sense of what was left out, or where speculative or innovative research may be found. It should be noted that this is not a flaw of the authors but rather inherent to the review process itself. This current review is meant to offer the researchers tools to access the CCA literature, and a framework(s) upon which to structure their mental models.

3. The CCA Information Landscape

Claude Levi-Strauss (1962) stated that humans are essentially a classifying animal; they make sense of the world around them by classifying like objects and processes to facilitate the creation of generalisations upon which their actions may be based (Berlin, Breedlove *et al.,* 1973). We will attempt to create a classification scheme of the CCA literature in the hope that patterns inherent to the field will become apparent so as to inform and guide our research activities. In our case, we wish to develop a framework for exploring the literature associated with CCA by ordering (categorising\ranking) the given articles in a manner suggested by the content and relationships within the literature, as well as the stated/implicit intentions of the field.

7 Quote from the declaration of the accomplishments of the IPCC and Al Gore for the Nobel Peace Prize **http://nobelprize.org/nobel_prizes/peace/laureates/2007**.

As such, the author, title, abstract and keywords will be used to categorise articles, and discern some sense of content, relevance and informational value. Key articles are identified by their relationship to their category, the importance of the category itself, the author's reputation, the journal's status, the article's overall ranking (as determined by its citation count), and ranking within the category. This should provide researchers with an awareness of relative occurrence of the critical climate change adaptation issues within scientific journals, which in conjunction with the AR4 synthesis, should provide a fundamental understanding of the field. To accomplish this we must first address the six questions of content analysis (Krippendorf, 2004):

1) Which data are analyzed?
2) How are they defined?
3) What is the population from which they are drawn?
4) What is the context relative to which the data are analyzed?
5) What are the boundaries of the analysis?
6) What is the target of the inferences?

We are fortunate in that we can easily define our data, the population it comes from, how it is defined, its limits, and for whom and to what end it is intended. The data is derived from the vast SCOPUS literature dataset which covers the physical sciences, life sciences, health sciences and social sciences. It is the largest abstract and citation database of research literature, with over 15,000 peer-reviewed journals from more than 4,000 publishers. Using this population of 33 million records, articles were sought that contained the terms *"climate change adaptation"* or *"climate change adapt"* in their title, abstract or keywords. As we are looking for trends in the CCA field, it is our assumption that the articles in this dataset reflect a representative sample of the intellectual activities occurring within the field itself. Clearly this assumption can be challenged because a large number of journals, non-reviewed articles, books and reports are not contained within the dataset; nevertheless a complete survey is logistically unattainable and our purpose is primarily exploratory. We further presume that the inter-disciplinary community of CCA researchers and professionals (Bodansky, 2005) is the target of the inferences derived, and that this community holds a common understanding of our search terms.

Our specific *"climate change adaptation"* search resulted in 2210 articles (Scopus Export date: September 20, 2007) which compares favourably with a SCOPUS search of *"climate change mitigation"* (1452 Articles, Scopus Export date: September 10, 2007) and yet is only a small portion of *"climate change"* articles (1,832,660 articles, Scopus Export date: October 16, 2007). These numbers represent datasets before they are 'cleaned' (i.e. checked for consistency and relevance). To aid in this process, we entered the SCOPUS dataset into an Endnote® bibliographic database manager (Version X1) and were able to easily identify and remove 168 duplicate articles. Endnote has various features that make it attractive for researchers, but other bibliographic managers would likely also suffice.

After reviewing each article's title and abstract, numerous irrelevant results were encountered (375 articles) likely due to the breadth of our search. Most of these articles were derived from a period before the 1990s, in disciplines as varied as sports medicine and human physiological response to cold climates. Clearly, the usage of the phrase 'climate change adaptation' has come to be dominated by climate change researchers over the last 10 to 15 years, as there are almost no references to these topics after this period. And though a rich literature exists concerning distant human evolutionary and cultural responses to climate change (Baker, 1984; Schule, 1992; Bobe and Behrensmeyer, 2004), 84 articles were removed for not aligning with our temporal scale of interest (i.e. the past\future 100 years). In addition, climate change adaptation is relevant for species other than *homo sapiens* (i.e. plant and animal species that are affected by climate change). Despite the relevance of such issues to human well being (i.e. through ecosystem services), 459 articles were also removed from our dataset for essentially misinterpreting our perspective of the concept of adaptation.

In the end, we were left with a climate change adaptation database of 1167 articles from which to work. Unfortunately, this is still an enormous dataset[8] to examine. We wish to devise a method for accessing this information as efficiently as possible, taking into account the differential value of each article in view of our interests. If we presume: 1) that a general, pragmatic purpose pervades the field (i.e. adapting society to human-induced climate change); 2) that an implicit structure underlies the field's knowledge landscape (see Toulmin and Goodwin (1965) for a discussion); and 3) that some papers\articles are more influential than others with respect to 1) and 2), we may begin to make sense of this dataset. To facilitate the construction of our

8 We can assume at the minimum 5,000 pages, not considering books length treatments or larger reports.

intellectual scaffolding, we start by determining some simple, yet revealing statistics of articles, journals and authors.

3.1 Dataset Statistics

It appears self-evident that not all articles are perceived, or valued, equally among researchers. Numerous explanations beyond the typical folk variety exist to describe this differential (e.g. see Kuhn (1962) for a start), yet it is not our purpose to enter into this discussion. The question confronting us is how to access this differential? Fortunately, SCOPUS provides us with one of the most direct means of determining the weight researchers deliberately attribute to individual articles: that of citing an article or paper within their own work. SCOPUS keeps track of an enormous number of individual articles and their accompanying references, enabling them to identify associations between articles (i.e. the cited article to the article citing it). It is simply a matter of adding up all the citations to a specific article to create a citation ranking among articles. This direct expression of social networks is currently the centre of much research which holds great potential for CCA (Watt, 2003).

When we rank CCA articles by the number of citations referring to them, we discover a dramatic disparity. Our top CCA article was cited 237 times, yet the next two articles are cited less than half that (111 & 110), after which the numbers drop off quickly. Fully 81% (950 articles) of the 1167 articles were cited ten times or less, 12% (142 articles) had only one citation, and 35% (410 articles) were not cited at all. A non-linear, relationship clearly exists between articles in terms of their citation numbers as seen in Figure 1.0 which illustrates the average number of citations for each sorted range of 25 articles. If we take this as representative of the differential value of articles, it means that relatively few articles have a strong influence upon the CCA field. This implies that we do not necessarily have to read every single CAA paper to get a sense of the major issues or trends in the field.

Unfortunately, the diversity of topics and sources associated with these articles suggests that this information is not necessarily coherent with respect to CCA as a general goal. The top articles in our ranking are from journals not typically devoted to climate change research; of the five most cited papers (Wilks, 1992; Walsh, Molyneux *et al.,* 1993; Hulme, Barrow *et al.,* 1999; DeMenocal, 2001; Hughes, Baird *et al.,* 2003), two are in the journal *Science*, one is from *Nature*, and one is from the medical journal *Parasitology.* Additionally, the articles are spread out temporally (i.e. over the 1990s

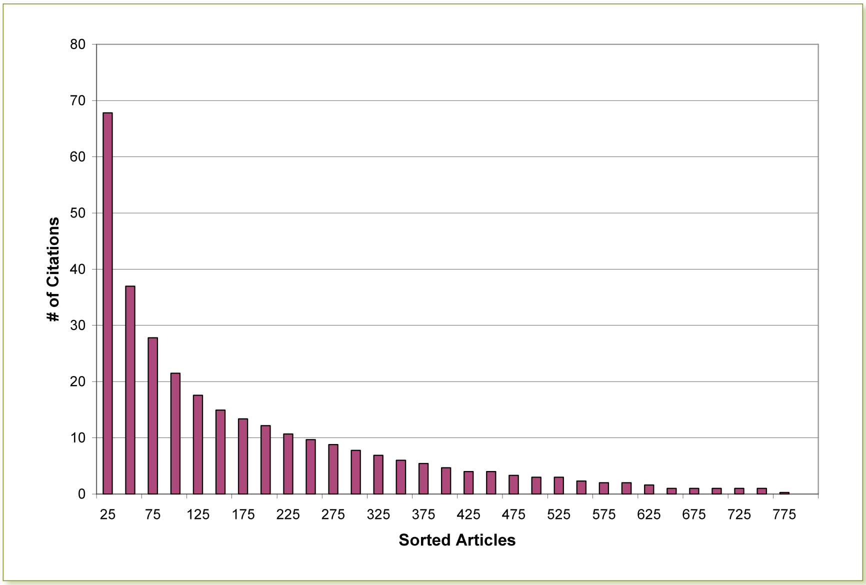

Figure 1 | The average number of citations for each range of 25, sorted articles. The most cited article was cited 237 times, but the range over the top 25 articles was 67.8. Clearly a non-linear, not quite negative exponential relation ship exists over article citations. Of the complete dataset (1167 articles) 35% were not cited even once, while 12% had only 1 citation, and 81% were cited ten times or less.

and early 2000s) making them difficult to compare. Not only does it take time to accumulate citations (recently published articles have had little time to disseminate), but the nature of the CCA field itself has evolved. As alluded to earlier, CCA has only recently emerged in its current form as a field of academic study. Figure 2.0 (CAA articles per year) illustrates the spectacular growth of interest in CCA beginning in the early 1990s as evidenced by the fact that four of the top five CCA journals were established after 1989 (Table 1).

This growth is inconsistently spread out among journals as well. Table 1 ranks journals by the cumulative number of CCA articles published within them, and Figure 3.0 compares these numbers for the top 30 journals (as ranked by number of articles). Not surprisingly, of the 373 journals that made it into our CCA database, the top five deal explicitly with the subject matter of 'climate change adaptation' accounting for 27% of all CCA articles. The top thirty journals (8% of the journals) account for

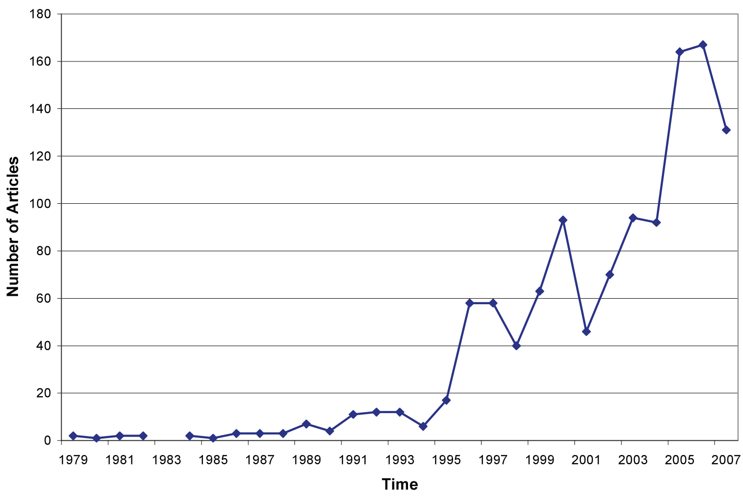

Figure 2 | The number of climate change adaptation articles within the SCOPUS database. Note, some articles published in 2007 have yet to make it into the SCOPUS dataset. Also note the years 1990, 1997, 2001, and 2007 are IPCC report years.

Table 1 | Number of climate change adaptation articles for the top ten journals in our SCOPUS search, the year the journal were founded and the Impact Factor. The impact factor is calculated by dividing the number of citations in the JCR year by the total number of articles published in the two previous years. An impact factor of 1.0 means that, on average, the articles published one or two year ago have been cited one time.

RANK	NUMBER CCA	JOURNAL NAME ARTICLES	JOURNAL YR. FOUNDED	IMPACT FACTOR
1	120	Climatic Change	Vol 1. - 1977	2.459
2	58	Mitigation and Adaptation Strategies for Global Change	Vol. 1 – 1996	NA
3	49	Climate Research	Vol. 1 - 1990	1.519
4	47	Global Environmental Change	Vol. 1 – 1990	2.6
5	26	Climate Policy	Vol. 1 – 2000	0.339
6	23	Building Research and Information	Vol. 1 – 1972	0.659
7	19	Environmental Monitoring and Assessment	Vol. 1 – 1981	0.793
8	17	IDS Bulletin	Vol. 1 – 1970	0.317
9	15	Forestry Chronicle	Vol. 1 – 1925	0.831
10	14	Agriculture, Ecosystems and Environment	Vol. 1 - 1979	1.832

approximately 50% of all articles. Again, most journals (228 journals or 60% of the total) have only one article about climate change adaptation. Although this broad allocation among journals may appear quite large, given the ubiquity of climate change impacts, it could be argued that the tail of this distribution (partially revealed in Figure 3) should be much longer.

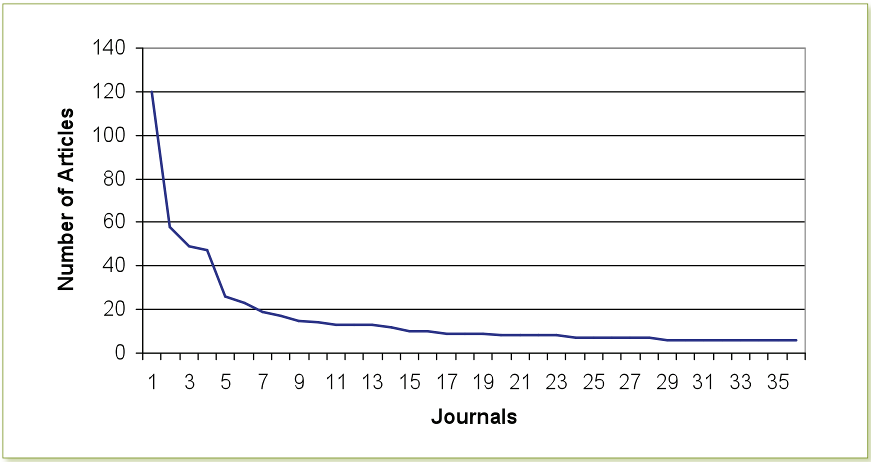

Figure 3 | The number of climate change adaptation (CCA) articles per journal, for the top 36 journals of 373 journals in total. Most journals (228 or 60%) have only one CCA article, while a small number publish a substantial portion of the total CCA landscape (the top 5 journals account for 27% of all articles).

We also sought to determine the importance of journals relative to each other. To do this we employed journal impact factors from the ISI Web of Knowledge® as listed in Table 2. We compared statistics for the top 20 journals in terms of overall articles in our database, with the addition of Science and Nature for comparative reasons. A journal impact factor is approximately the average number of times published papers are cited in the two calendar years following publication. Impacts factors can be controversial (Ball, 2006; Saha, Saint *et al.,* 2003): they cannot account for the differences in absolute number of researchers, the average number of authors on each paper, the nature of results in different research areas, and variations in citation habits between different disciplines. All these factors are relevant considerations for CCA which draws from numerous disciplines. Nevertheless, the calculation is an effective,

Table 2 | Impact factor and various statistics for the top 20 journals. The journals Science and Nature were added for comparative purposes.

No.	Total Citations	Impact Factor[10]	Immediacy Index[11]	Cited Half-Life[12]	Journal	No. CCA Articles
1	3306	2.459	0.327	6.7	Climatic Change	120
2	NA	NA	NA	NA	Mitigation and Adaptation Strategies for Global Change	58
3	1063	1.519	0.362	4.9	Climate Research	49
4	779	2.6	1.2	5.3	Global Environmental Change	47
5	186	0.339	0.6	4	Climate Policy	26
6	222	0.659	0.391	3.8	Building Research and Information	23
7	1839	0.793	0.067	6	Environmental Monitoring and Assessment	19
8	334	0.317	0.562	6.7	IDS Bulletin	17
9	869	0.831	0.127	7.8	Forestry Chronicle	15
10	4308	1.832	0.388	6.3	Agriculture, Ecosystems and Environment	14
11	1768	1.362	0.155	4.7	Energy Policy	13
12	415	1.052	0.452	3.9	Environmental Science and Policy	13
13	10445	1.839	0.356	5.8	Forest Ecology and Management	13
14	14434	5.861	0.994	5.6	Environmental Health Perspectives	12
15	5077	2.903	0.669	6.7	Agricultural and Forest Meteorology	10
16	NA	NA	NA	NA	IAHS-AISH Publication	10
17	2600	1.223	0.152	6.2	Ecological Economics	9
18	110	0.316	0.042	5.5	Natural Resources Forum	9
19	5703	1.205	0.09	9.1	Water, Air, and Soil Pollution	9
20	3937	0.737	0.197	6.2	Current Science	8
21	361389	30.028	5.555	7.7	Science	6
22	390690	26.681	6.789	7.8	Nature	1

10 The impact factor is calculated by dividing the number of citations in the JCR year by the total number of articles published in the two previous years. An impact factor of 1.0 means that, on average, the articles published one or two year ago have been cited one time.

11 The Immediacy Index The immediacy index is the average number of times an article is cited in the year it is published. The journal immediacy index indicates how quickly articles in a journal are cited.

12 The Cited Half-Life is Half of a journal's cited articles were published more recently than the cited half-life. For example, in JCR 2001 the journal Crystal Research and Technology has a cited half-life of 7.0. That means that articles published in Crystal Research and Technology between 1995-2001 (inclusive) account for 50% of all citations to articles from that journal in 2001.

consistent, and transparent means of comparing journals, given caveats. Figure 4 shows the relationship between the journals' relative impact factors and their ranking.

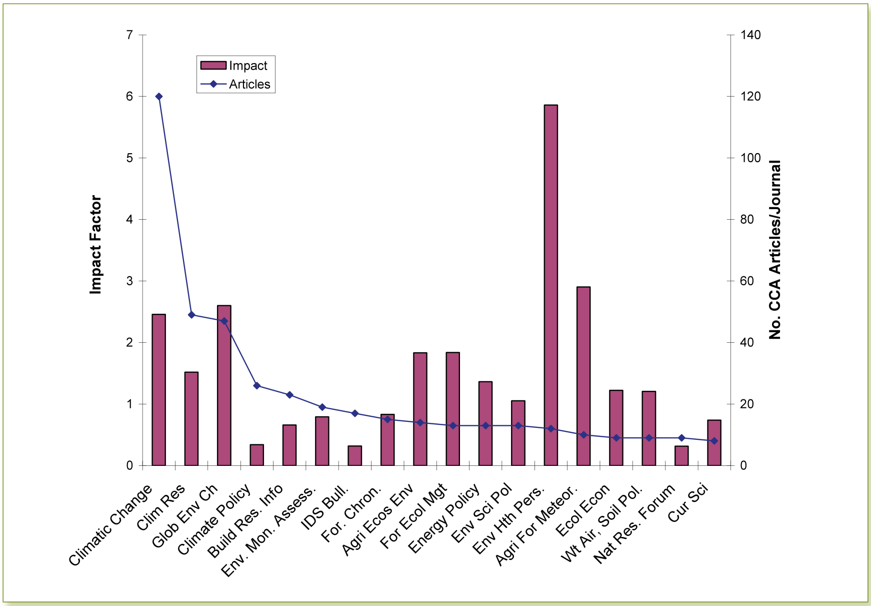

Figure 4 | Ranked Impact Factor of the top 18 journals. The journals Science and Nature were removed to facilitate comparison.

Aside from *Science* and *Nature*, it is clear that Environmental Health Perspectives dominates the field, with Agricultural and Forest Meteorology following not too far behind in terms of impact factor. Within the CCA community though, *Climatic Change* has a high impact as well as the greatest number of articles, with *Global Environmental Change* close behind. Unfortunately, we could not assess the relative importance of *Mitigation and Adaptation Strategies for Global Change,* since ISI does not rank the journal.

Finally, we can also assess who the key authors of the CCA field are by determining the number of articles that specific individuals publish (Table 3). Although these twenty authors represent only 0.8% of total author numbers, they are responsible

Table 3 | Authors of CCA articles with accompanying number of articles in SCOPUS, number of times the author was cited in the SCOPUS dataset irrespective of which of the author's articles are cited, and the ratio of # Articles to # times cited. List is sorted by the number of articles in the SCOPUS dataset.

#	Articles (A)	No. of Times Author Cited in CCA SCOPUS Dataset (B)	Ratio A to B	Author
1	15	122	8.13	Klein, R.J.
2	15	140	9.33	Smit, B.
3	14	133	9.50	Adger, W.N.
4	13	190	14.62	Tol, R.S.J.
5	12	20	1.67	Smith, J.B.
6	12	123	10.25	Easterling, W.
7	11	188	17.09	Rosenzweig,C.
8	9	101	11.22	Mendelsohn,R.
9	9	124	13.78	Yohe, G.
10	8	173	21.63	Burton, I.
11	8	70	8.75	Cohen, S.
12	8	121	15.13	Huq, S.
13	8	52	6.50	Strzepek, K.M.
14	7	57	8.14	Dowlatabadi,H.
15	7	86	12.29	Dixon, R.K.
16	7	75	10.71	Ebi, K.L.
17	6	18	3.00	Alexandrov, V.
18	6	39	6.50	Dessai, S.
19	6	72	12.00	Fankhauser, S.
20	6	82	13.67	Kane, S.

(with co-authors[9]), for 16% of the total number of papers in the field. We can further tease out an author's influence by examining the citation index of each of her papers within the database. Alternatively, we can determine how many papers in our database cite a specific author. Though somewhat imprecise this metric is easy to compute and gives a larger sense of the author's presence. Table 3 identifies the citation\paper ratio which is the number of articles that cite the author over the number of papers written

9 The average number of authors per paper was 2.06.

by the author in the CCA database. This ratio allows us to identify authors who may not write a great deal in the field, but still have a high number of citations (e.g. Holling, 2004, Nordhaus 1995). The only authors that make the top 20 of all three measures are: Tol, R.S.J.; Rosenzweig,C.; Burton, I.; Yohe, G.; Adger, W.N.; Easterling, W.; Huq, S.; Mendelsohn,R. ; Dixon, R.K.; Kane, S.; Ebi, K.L.; and Fankhauser, S.

3.2 Structural and Contextual Overview

The metrics from the previous section are quite useful in terms of identifying key articles, journals and authors but offer no guidance in terms of content. To facilitate a broader understanding of current trends, we offer two additional techniques for perceiving patterns within the literature. In the first section we examine the relative and temporal incidence of concepts by means of simple word counts. In the second we attempt to construct a structural scaffolding for the CCA literature, as guided by a systems perspective, and the occurrence of key topics in the literature.

3.2.1 Relative Concept Incidence

In this section, we employ simple counts (see Table 4) of specific words or phrases (i.e. as inferred by the literature) to roughly gauge their comparative utilisation in the field through time. A word count is the aggregate number of occurrences of specific words or combinations of words within the CCA dataset (i.e. a single occurrence represents the presence of a word/combination, one or more times, within the article's title, abstract or keywords). It can be used to determine when a word or phrase first appeared within the literature, and whether or not it was or has been adopted.

Two examples will offer a sense of the utility of this method. One of the major issues associated with CCA, is the conceptual and practical relationship between adaptation and mitigation as strategies for responding to climate change. The Working Group II report of the AR4 refers specifically to this issue throughout, and a special of Climate Policy (Johnson *et al.,* 2007) focuses entirely upon this issue. At its most simplified, this issue is about determining the optimal mix of mitigation and/or adaptation for responding to climate change (Kane and Shogren, 2000). If we search for articles in which adaptation and mitigation co-occur, we can obtain a rough sense of when these issues emerged, and how prevalent they have been since then. Referring to Table 4 we can see that the terms adaptation and mitigation occur in 37% of all articles and in 44 titles from as early as 1990. If we refer to Figure 5 we can observe the proportion of articles that refer to both adaptation and mitigation over time. Sometime after

1996, this issue became important enough to be referenced by between 30 and 45% of all articles in the field.

A further debate continues over the conceptual relationship of adaptation/ mitigation to sustainable development (Swart, Robinson *et al.,* 2003). If we search on 'sustainable development,' 'adaptation' and 'mitigation' we can see in Table 4 that 150 articles refer to all three concepts, and Figure 5 shows that the conceptual relationship between these three terms has been slowly growing in importance since the mid 1990s, accounting for up to 20% of all CCA articles. This is suggestive of the importance of the issue when compared to other terms and concepts (Table 4).

3.2.2 CCA Structure

The second tool offered, affords the ability to structure the informational content of the field. A loose scaffolding has been developed, based upon the pragmatic[13]

Table 4 | Word Occurrences in articles from the SCOPUS derived CCA database. An occurrence represents the presence of the word in an article, not the number of times the word occurs in articles. Unless otherwise noted, word counts relate to the fields: title; abstract; keywords. A word count in parenthesis indicates the number of times the word occurred in article titles.

Word(s)	Word Occurrence	Word	Word Occurrence
Adaptation;	1167	Biodiversity	146
Adaptation; & Mitigation	433 (44)	Complexity	23
Adaptation; & Mitigation; & Sustainable Dev.	150	Mainstreaming	26
Adaptive Capacity	123	Response Capacity	4
Vulnerability	564	Development pathway	7
Resilience	113	Risk	485
Scale	319 (13)	Uncertainty	309
Ecosystem	365	Emergence	22
Downscaling	16	Threshold	50
Security	129	Gender	9
Justice	40	Landuse	65
Ethic(s)	23	Optimal	25

13 In this case the term pragmatic is used in a philosophical sense (see James, 1907) wherein knowledge is at the service of practise.

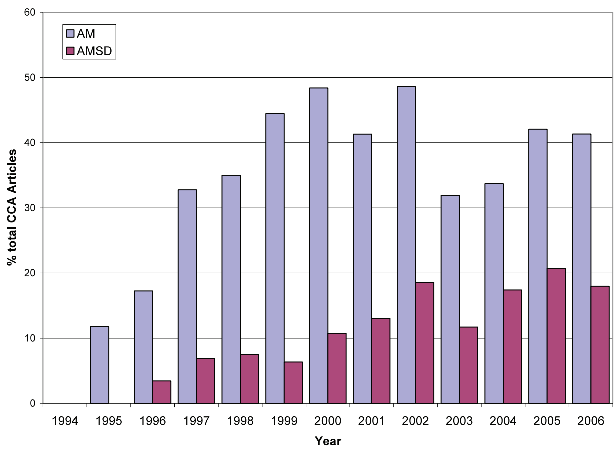

Figure 5 | The co-occurrence of the terms 'adaptation' and 'mitigation' in the CCA literature over time. This is compared with the co-occurrence of the terms 'adaptation' and 'mitigation' and 'sustainable development.'

assumption that CCA literature can be interpreted in terms of facilitating adaptation to human-induced climate change. As such, it is assumed that articles can be systematically classified into functional categories, starting with the most abstract or general topics and gradually leading towards more specific or particular topics and applications. Ideally, the categorization process is driven by the articles themselves and their relationship to one other. An initial set of categories is proposed, and then articles are sorted according to the content inferred by their title, abstract or keywords[14]. In the sorting process, inconsistencies are revealed, and a new categorization is proposed. The process continues iteratively until a satisfactory structure is determined, and the articles sorted accordingly. The final scheme is intended to reveal implicit relationships between, and among articles given the aforementioned pragmatic end (Table 5).

14 The keywords provided by journals can be misleading; while some articles provide a handful meaningful keywords, others may be overly zealous, offering extensive lists that are barely relevant.

Table 5 | CCA Literature Classification.

1.0 THEORY
- 1.1 'Adaptation' and Ancillary Terms
- 1.2 Other Theoretical Considerations

2.0 DISCIPLINES
- 2.1 Economics
- 2.2 Political Science
- 2.3 Sociology
- 2.6 Development
- 2.4 Ethics
- 2.5 Communication & Education
- 2.7 Law
- 2.8 Psychology
- 2.9 Anthropology

3.0 METHOD
- 3.1 DSS Systems Analysis
  - 3.1.1 Data
  - 3.1.2 Models
  - 3.1.3 Vetting
- 3.2 Scale
- 3.3 Integration

4.0 SECTORS/RESOURCES
- 4.1 Agriculture
- 4.2 Water
- 4.3 Forestry
- 4.6 Health
- 4.4 Infrastructure
- 4.5 Wildlife/Ecosystem Services
- 4.7 Tourism
- 4.8 Energy
- 4.9 Fisheries
- 4.10 Emergency Services
- 4.11 Transportation
- 4.12 Service Sector

5.0 GEOPOLITICAL PLACE
- 5.1 Land-use Policy Issues
- 5.2 Place
  - 5.2.1 Local
  - 5.2.2 Regional (National)
  - 5.2.3 National
  - 5.2.4 Regional (International)
  - 5.2.5 International/Global

Before continuing, it should be pointed out that: 1) the SCOPUS dataset represents only a small (albeit privileged) portion of the CCA literature; and 2) numerous other categorisation schemes are possible (although the literature likely follows established theoretical, disciplinary and methodological boundaries). Ideally readers should categorize the literature themselves as this encourages the development of the reader's own conceptual framework (i.e. accommodation in a constructivist sense), while tailoring the structural schema to meet their own needs. Categorisation is a continuous process: resources are regularly added from SCOPUS[15] and outside sources, and categories altered to meet the evolving needs and understanding of the researcher[16]. The metrics from Section 3.1 should aid in this process by identifying key journals and authors to initially focus upon. Ultimately, promising articles will have to be consulted directly to identify additional sources outside the SCOPUS domain, keeping in mind differential value.

Fundamental Categories: The following proposed structure of CCA literature (see Table 5) is based upon the simple premise that *theory* informs *method*, which in turn informs practise. Fundamental generalities (theory) about the way the world works (i.e. climatic and\or behavioural) are suggestive of various methodologies (e.g. modeled atmospheric relationships, rational economic decision making, etc.), which can be used to direct human practises (i.e. levels of mitigative and adaptive agency). Although science is not so linear (i.e. practise can inform theory, etc) this assumption is a reasonable starting position given the exploratory nature of this analysis. This premise was translated into the following five core classifications or themes: Theory, Disciplines, Method, Sectors\Resources, and Geopolitical Place, as seen in Table 5.

Theory and Method refer specifically to topics concerned with climate change adaptation (e.g. discussions of the concept of adaptation or integrated assessments methodologies) while Disciplines acts as an intermediary between these two. Disciplines provides additional information regarding the various fields that inform CCA theory and methodology (e.g. for instance there is a strong theoretical distinction between the social and physical sciences[17]). Delineating method and theory in this way facilitates greater interpretation, as most researchers are trained from within

15 Possibly using an RSS feed to be alerted to regular updates in the search.

16 A manifestation of this approach is embodied in certain visions of the semantic web (Borland, 2007; Tossell, 2007).

17 See MacLellan (2006), Chapters 3 and 4 for an extended discussion.

specific disciplinary fields. In a similar vein, Sectors\Resources, and Geopolitical Place, together represent the conditions for CAA *practise* which is concerned with increasing or maintaining human values (i.e. manifest as resources or affordances) associated with a specific place (i.e. as geopolitically defined) in the face of climate change. This format recognises that resources (i.e. economic, natural and social capital) are usually spoken of in terms of both sectors (i.e. agriculture) and geo-political distinctions (e.g. the agricultural sector in the Canadian prairies).

Given these categories and accompanying sub-categories (Table 5), individual articles are placed within those which most suit their content[18]. Though most will be assigned to a single category, multiple classifications are possible for articles that effectively span more than one topic. Once all articles have been sorted, it is possible to gauge the relative intellectual activity among topics, based upon the number of articles within the associated category. This is not intended as a measure of a topic's importance[19], it merely indicates the relative *attention paid by* members of the CCA community to the topic in question. Tables 6.1 to 6.4 provide the relative academic activity occurring in each category. Most articles (714 articles or approximately 61% of total CCA articles) specifically dealt with resource questions (i.e. Sectors\Resources) and associated Place distinctions (57%), while CCA Theory and Method accounted for 11% and 16% respectively, and the intermediary category Disciplines, accounted for 28% of all articles.

This focus upon *practise* is indicative of a field committed to assessing the impacts of, and responses to, climate change. In the following treatment, we attempt to further tease out such general insights as guided by the relative intellectual activity within different categories (see Tables 6.1 to 6.4). Some results will appear obvious as above, while others may only become apparent when their omission is recognised. In our analysis, greater attention will be paid to categories with higher article counts. Thus we begin with a short discussion of the major topics of Theory. This is followed by a discussion of Disciplines which will examine the contribution of the top three disciplines, as identified by article count, and how they might be integrated. We then discuss Method in terms of its essential components. And finish with a discussion of

18 This process utilized the custom grouping feature of ENDOTE XI which allows the user to define sub-categories and groupings of their bibliographic library.

19 In positing his Anna Karenina principle, Diamond (1997) reminds us that environmental adaptation must account for numerous factors simultaneously. In essence this makes all essential factors equally important; ignoring any single factor will result in the same overall failure. The principle is taken from the first sentence of Tolstoy's novel 'Anna Karenina': "Happy families are all alike; every unhappy family is unhappy in its own way."

Sectors\Resources and associated Place in terms of their top three sectors and associated geopolitical distinctions.

Table 6.1 | Article counts for given categories. The percentage reflects the number of articles in the given category as a portion of the total number of articles in the entire CCA SCOPUS dataset.

Section	Climate Change Adaptation Category	Number of Articles (%) per Category
1.0	Theories, Concepts, Generalities or Terms	130 (11 %)
2.0	Academic Distinctions	324 (28 %)
3.0	Methodology	182 (16 %)
4.0	Sectors/Resources	714 (61 %)
5.0	Place	670 (57%)

Category 1 (Theory): This category deals specifically with abstract issues or generalities surrounding the field of climate change adaptation (11% of all CCA articles). A short overview of this literature reveals a great deal of effort expended upon the concept of adaptation and its relationship to other terms. The category was divided into sub-sections dealing with the concepts of Adaptation (17% of all Theory articles), of *Adaptation and Mitigation* (22%), and *Adaptation, Mitigation and Sustainable Development* (11%). Ancillary terms such as 'vulnerability' and 'resilience' are strongly associated with the concept of adaptation, accounted for a further 17% of all theoretical articles. Thus, the dominant theoretical exercise in the field (two thirds of all theoretical papers) is concerned with defining and clarifying the concept of adaptation and its relationship to other concepts. The remaining third deals with topics such as *history, integration* and *scale*.

Table 6.2 | Article counts and percentages (of total CCA dataset) for given categories.

Section	Climate Change Adaptation Category	Number of Articles (%) per Category
2.1	Economics	105 (8.9 %)
2.2	Political Science	95 (8.1. %)
2.3	Sociology	56 (4.7. %)
2.6	Development	35 (2.9 %)
2.4	Ethics	27 (2.3 %)
2.5	Communication & Education	12 (1.0 %)
2.7	Psychology	5 (0.4 %)
2.8	Anthropology	5 (0.4 %)
2.9	Law	6 (0.5 %)

Category 2 (Disciplines): Table 6.2 gives some indication of the comparative makeup of the different disciplines within the field of climate change adaptation[20]. There appears little question regarding the privileged position of Economics within the field given the number of articles identified as such (8.6% of the CCA dataset), but Political Science and Sociology are also well represented with 7.5% and 4.1% of the total CCA articles respectively. The remaining disciplinary distinctions include International Development, Ethics, and Communications & Education. The discipline of Psychology (0.4%) can be interpreted in terms of the need to examine adaptation at the level of the individual. Likewise, Anthropology (0.4%) provides a methodological perspective on local phenomena, and an awareness of how cultures and societies have adapted in the past. Finally, the presence of Law seems self-evident given the many legal issues (i.e. international etc) involved in CCA.

How these various disciplines fit together is not readily apparent until the Political Science literature is considered. One of the main tasks of this field is the development of appropriate CCA policies that can effectively integrate key considerations (i.e. economic, sociological, ethical, etc.). A consequence of this purpose is an apparent, ideal typic article format that adheres to the following structure: 1) political science articles generally start with a review of current, past or proposed policy instruments (58% of Political Science articles); 2) then they discuss the implications or impacts of climate change for the aforementioned policy within a given geo-politically referenced sector, resource, or value (35%); and finally 3) they project the impacts of proposed policy options (strategies) based upon the given criteria (35%). Critiqued and proposed policy options are considered in terms of integration (16%), mainstreaming (9%), sustainable development (7%) and/or goal orientation (5%).

In this context, economics becomes an input in a process of climate change policy critique and formation. This assumption seems borne out by the fact that 23% of articles in the economics domain deal specifically with determining the financial impact of climate change. Other articles are also suggestive of this policy agenda: 9.5% of economics' articles concern the measurement of goods and services, 15.2%

20 There is some discussion in the literature as to how different disciplines should relate to one another (Schneider, S. H. (1997). "Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions?" *Environmental Modeling and Assessment* 2(4): 229-249.), including the sciences themselves (Lorenzoni, I., M. Jones, *et al.* (2007). "Climate change, human genetics, and post-normality in the UK." *Futures* 39(1): 65-82).

deal with risk and its avoidance, 13.3% examine the temporal aspects associated with the longer time scales relevant to climate change, and 8.6% deal with methodological questions involving choice. The field is rounded out by reviews (11.4%), methodology (12.4%), and international development (5.7%).

Sociology also focuses upon climate change impacts (47% of sociology articles), except it cannot rely upon a single metric to compare outcomes (i.e. the monetary standard). Sociology attempts to get beneath this economic simplification by measuring the actual drivers that facilitate or hinder adaptation. Thus a substantial portion of sociological discussion is concerned with determining metrics of vulnerability (11%), adaptive capacity (18%), social capital (4%) and the scales over which these metrics operate (11%). Climate change impacts and proposed solutions are discussed in terms of social networks (22%), institutions (42%), social capital (4%) and gender (15 %). Policy proposals are further discussed in terms of social learning (15%) and participatory approaches (9%). The topic is rounded off with reviews (22%).

Category 3 (Method): CCA methodology can be somewhat difficult to categorise given the multitude of approaches available. The reader is referred to Chapter 2 of Working Group II AR4, for a methodological overview reflecting current trends and emerging issues (IPCC, 2007). As per the previously discussed policy framework, it is presumed that CCA methodology is ultimately concerned with facilitating societal wellbeing in the face of climate change through the application of appropriate policy instruments (i.e. strategies). To do so, method must assess the impacts of various responses to climate change for specific sectors or resources, over specified geopolitical scales. From a systems perspective, this search for policy frameworks can be understood in the context of decision support.

An extremely simple framework is utilised here that captures the essence of a decision framework for CCA. Decision making includes: 1) the consideration of a defined set of alternatives through time; 2) and the likelihood or probability of their occurrence; 3) assignment of 'preferences' to the set of possible outcomes; given 4) a criteria such as maximal or optimal desirability of chosen alternatives with respect to the preference ranking (Doyle, 1999). This structure can be simplified further into three essential components: A) *Data*, B) *Predictive Modeling,* and C) *Choosing\Vetting Possibilities* (MacLellan and Innes, 2002; MacLellan and Fenech: Chapter 1).

Descriptive Data is information describing past atmospheric, biotic or abiotic environments including social and cultural conditions. In our case this category includes the choice of indicators, the scale over which data is relevant, whether data is probabilistic or spatially explicit, how data is collected, monitored, its relevance to other indicators, and to modeled processes, etc. This category accounts for 2.8% of all CCA articles. From these representational elements, dynamic relationships among elements can be inferred (i.e. modeled), and ultimately projected to describe future environmental conditions. The dominant *Predictive Models* (2.0%) in the CCA literature are obviously climate models, although their presence is often implicit. CCA is largely concerned with interpreting their results for other processes by utilising: hazard models, energy models, demographic models, industrial output models and/or hydrological models, productivity models, forest successional models, etc[21].

Once these projections have been defined (i.e. as output of the data\modeling relationship), it becomes a matter of choosing the future(s) that best suits society or a subset therein[22]. Various factors confound this aspect of decision making such as the uncertainty associated with modeling future conditions, the inability to represent all future states (most problems are unbounded or open), and the inability to successfully search through projections for solutions[23]. *Choice\Vetting Possibilities* (4.8% of CCA dataset) represents any process that allows the decision maker to find\reveal a favoured solution or set of solutions that can be implemented. Many such activities are implicit in a decision framework including the selection of models and methodologies, the selection scenarios (see Topic 3 in Section 2.1), the choice of technique to search the projected human possibilities (i.e. optimization methods), and methods to determine choice (i.e. democratic forums) (MacLellan and Fenech, Chapter 1).

Aside from these three essential factors (data, models, vetting), other aspects of environmental decision making must also be taken into account when constructing methodology. These include questions of *Scale* (1.5%), *System Integration\Testing* (3.8%) (including the utilisation of case studies), and *Uncertainties and Risk* (1.1%). Finally the output of this process (i.e. a strategy for CCA) must be turned into a prescription (i.e. the implementation of that strategy). This consideration also includes monitoring and adaptive learning.

21 Though forecasting often utilises computer simulation models, it should be remembered that Predictive Models also include knowledge-based systems (individual human cognition) where lies the vast majority of what we 'know'.

22 Or disqualifying those that are not acceptable.

23 See MacLellan, J. I. (2006). Ecologic Agency: Human Behavior within the Boreal Forest. *Faculty of Forestry*. Toronto, University of Toronto. PhD: 368., Chapter 1 for an overview of the limitations of modeling.

Category 4 (Sectors/Resources): Ultimately we want to know how climate change will affect natural, social and economic capital in local, regional, national and international communities, through time. Most importantly, we want to know what we can do to alter our developmental pathways towards possibilities that are closer to our individual and collective preferences (i.e. towards economically prudent, socially and ethically responsible development). As such, all the previous topics come together to guide our relationships to specific forms of capital in specific, geo-politically referenced 'places.' An essential relationship exists therefore, between Category 4.0 and Category 5.0 which can be hard to dissect. In many instances it is difficult to assess the impact to a specific resource or sector (i.e. its production or utilisation) without reference to a specific place. Nevertheless, we have divided the literature on practise, into two categories because it provides additional, useful information to researchers.

With this in mind, we observe from Table 6.3 that *Agriculture* was clearly the dominant subject matter of CCA literature (almost 20% of all CCA articles). *Water* (16.6%) placed second, *Forestry* (7.4%) third and *Human Health* (5.1%) fourth. After this were *Infrastructure* (4.3%) and *Ecosystem Services* (2.7%). And all other categories came in at under 2%: Tourism (1.5%), Energy (1.5%), Fisheries (1.0%), Emergency Services (0.7%), Transportation (0.3%) and finally the Service Sector (0.1%).

Table 6.3 | Article counts and percentages (of total CCA dataset) for given categories.

Section	Climate Change Adaptation Category	Number of Articles (%) per Category
4.1	Agriculture	233 (19.9 %)
4.2	Water	194 (16.6 %)
4.3	Forestry	87 (7.4 %)
4.6	Health	59 (5.1 %)
4.4	Infrastructure	50 (4.3 %)
4.5	Wildlife\Ecosystem Services	31 (2.7 %)
4.7	Tourism	18 (1.5 %)
4.8	Energy	17 (1.5 %)
4.9	Fisheries	12 (1.0 %)
4.10	Emergency Services	8 (0.7 %)
4.11	Transportation	4 (0.3 %)
4.12	Service Sector	1 (0.1 %)

In terms of content, we will examine the top three sectors to offer an indication of the sort of analysis that is undertaken. The *Agriculture* category is predominately comprised of climate change impact assessments for a specific geopolitical place. Analysis is typically undertaken by estimating species specific responses (mostly plants but 5.2% of the agriculture category was livestock) to climate change and/or carbon fertilisation (14.7%), as derived either empirically (13%) or through simulations (30.7%), for a specific region or locality (42% mention a location). Almost a quarter of the articles examine how to manage these changes (22.5%), including consideration of soils (3.5%), pests (2.6%), carbon sequestering, agrobiodiversity (Kotschi 2006), wildlife affects, pollution etc. Analysis often includes some form of economic assessment (14.7%) and or policy implications (13.4%) such as food security (3.4%). Finally, agriculture reviews (16.4%) discussed knowledge domains, knowledge dissemination, methodology and future research.

The *Water* category is bisected along two lines: one line deals with ocean systems (29.4% of Water articles) the other with terrestrial hydrological systems (40.2%). Sea level rise is the dominant concerns for oceans systems, while terrestrial hydrological systems are considered in terms of flooding, drought, water delivery, water quality, energy, etc. In either case, methodology is dominated by climate change impact assessments for specific geopolitical locations (69.6%). Assessments are typically undertaken by applying some form of hydrological simulation model (29%) to predict water behaviour under climate change conditions, with proposed management solutions (41.2%). Socio-economic analysis comprises 14.9% of the articles and policy considerations are covered in 8.2% of the articles. Unique aspects of *Water* include a discussion of hydrological systems on ecosystems (2.6%) and energy in the form of hydropower (1.5%). Another key aspect of the category is its relationship to both agriculture (8.7%) and urban environments (8.7%). Finally, reviews (13.4%) included discussions of impacts, knowledge domains and their dissemination, method and future research.

Forestry as a category was somewhat incoherent. As with the other sectors, many of the articles referred to specific impacts on specific places (56% of the category refers to a specific place). But the assessments (28%) did not appear to be explicitly devoted to climate change per se. There appeared to be less concern in defining the actual climate change impacts over time, than there was highlighting new techniques, etc. Forestry models were mentioned explicitly in 36% of the total number of articles.

And 17% of the articles were of an economic or sociological nature. 15% of the articles were specifically about policy implications, while 29% focused on management or adaptation options. A large number of articles, focused on species specific responses to climate change (28%). While specific forestry issues included: fire (7%), pests (3%), ecosystem impacts (9%), and carbon sequestration (6%). 21% of the articles dealt specifically with reviews or information dissemination.

Category 5 (Geopolitical Place): Category 5.0 is divided into two major parts: the first section deals with place sensitive policy and land-use issues (4% of all CCA articles), while the second section is a discussion of the impacts\possibilities associated with climate change and their affect in the context of various geo-political hierarchical distinctions (53.4% of all CCA articles) (see Table 6.4). As mentioned earlier, much of the research undertaken in CCA is identified as place specific (i.e. enlists some geo-political distinction). Hierarchical distinctions were adopted that were consistent with the literature: Local, Regional (National), National, Regional (International) and International or Global. Local is meant to represent any settlement, community, town, urban centre, or municipality (9% of total CCA articles). Regional (National) (18%) is understood as being between the National and Local designations (i.e. a province, state, etc.). The National designation is self-evident (20%), and the Regional (International) (10%) represents any collections of nations or a region that crosses borders (i.e. South East Asia, developing countries, the south Pacific, etc.). Finally International or Global is meant to represent the entire world (2%).

Table 6.4 | Article counts and percentages (of total CCA dataset) for given categories.

Section	Climate Change Adaptation Category	Number of Articles (%) per Category
5.1	Land-use Policy Issues	47 (4%)
5.2.1	Local	110 (9.4%)
5.2.2	Regional (National)	212 (18.2%)
5.2.3	National	229 (19.6%)
5.2.4	Regional (International)	114 (9.8%)
5.2.5	International\Global	20 (1.7%)

Those articles designated as National can be further delineated by specific countries. An examination of the literature reveals that certain nations appear more often as subject matter. And though these trends must be taken with caution (i.e. totals are low) they can be quite revealing in a comparative sense. In terms of total articles, the USA and Canada are similar in number, with the UK about half of that and China half again. In terms of trends, the USA has shown a steady increase in articles numbers and then seems to have levelled out after 2003. Canada has steadily increased from 1996 onward, UK has increased steadily from 2002 onward and China has been sporadic with a general increase from 2003 onward. Australia also seems to have a fair number of articles (i.e. a quick search suggests numbers slightly less than the UK).

Summary: We have created a simple means of structuring our data given the objectives of our research. The structure not only offers a mental model for logically organising the information in the CCA domain, but suggests what is not in the literature, and where to look for new insights (i.e. theoretical papers and outliers). Though it is tempting to take this further and create some meta-theory regarding the necessary relationship between these parts, we should not forget that this structure is only a heuristic aid. *"The 'world of ideas' is self-contained, cogent, and certain, just because we fashion it deliberately so that our minds can move freely and confidently within it."* (Toulmin and Goodfield, 1965). A silver, integrative bullet is unlikely for such a diverse field. In the following section we will attempt to utilise the results from the previous sections, and provide some general insights regarding the CCA field.

4. Discussion & Conclusion

Despite explosive growth of the CCA field since the mid 1990s (Figure 3), successful completion of IPCC AR4[24], a Nobel peace prize for the IPCC[25], presumed field maturation (i.e. towards development studies and disaster risk reduction (IPCC, 2007; Klein, Huq *et al.,* 2007)) and increasing requests for assistance to develop local adaptation strategies[26], some authors feel that now is time for a collective re-evaluation of the field (Pielke, Prins *et al.*, 2007)[27]. Though the 'taboo' of CCA has been lifted, it is not a matter of simply embracing adaptation as it has come to be known. "New ways of thinking about, talking about and acting on climate change are necessary if a changing society is to adapt to a changing climate" (Pielke, Prins *et al.,* 2007).

24 **http://www.ipcc.ch/**

25 **http://nobelprize.org/**

26 Witness the recent activity by US urban centres to develop adaptation plans despite the lack of US Federal support. (The Economist, 2006. A survey of climate change: Dismal Calculations: Sept 7, 2006.).

27 Oppenheimer, M., O'Neill, B.C., Webster, M. & Agrawala, S. *Science* 317, 1505–1506 (2007). The Limits of Consensus. and Hagg, 2007 "What's next for the IPCC?

At some level, this will require dealing with the core issues of the field: CCA's relationship to the physical sciences (Cohen, Demeritt *et al.,* 1998); its relationship to the 'sustainable development' community (i.e. as a single instance of sustainable development); and the strategic trade-offs between mitigation and adaptation. Though such issues are readily apparent from our review of the IPPC Synthesis (Section 2.0), word/phrase counts (Table 4 and Figure 5) and articles counts (Section 3.2.2, Category 1), their solutions are not. Such issues reflect policy biases (Cohen, Demeritt *et al.,* 1998), inertia (Pielke, Prins *et al.,* 2007), and planning concerns that resist formal analysis (i.e. wicked problems (Rittel and Webber, 1973).

This report has been undertaken with the conviction that solutions will require more openness to change, greater participation from other fields (i.e. more neophytes), and greater accessibility to the CCA information domain. Understanding the domain of the field is the first step in any innovative process (Wallas, 1926)[28] and is our focus here. Csikszentmihalyi (1996) suggests that creativity can be understood as a confluence of three factors: the domain which consists of a set of rules, practises and knowledge; an individual who makes a novel variation in the contents of the domain[29]; and a field which consists of experts who act as gatekeepers to the domain, and decide which novel idea is worth adding to the field. And though individuals lie at the heart of the creative process, a great deal can be accomplished by making domain knowledge more readily accessible (Csikszentmihalyi, 1999).

In Section 3.1 we attempted to develop simple bibliometric tools to facilitate access to the knowledge domain. Using the data management features of ENDNOTE, and the citation metrics offered by SCOPUS, articles were examined in terms of the number of citations referring to them, their authors, and where and when they were published. Journals were also examined in terms of the number of CCA articles they had published, as well as their impact factor. Key authors were identified in terms of the number of publications they had written, their citation ranking, and the number of references made to the author. In all cases, non-linear, preferential attention by the CCA community was given to specific articles, journals and authors, leading one to

28 According to Wallas (1926) any creative process lists five steps in the creative process: 1) preparation (immersing oneself in the knowledge domain); 2) incubation; 3) insight; 4) evaluation; and 5) elaboration.

29 In many cases, even the problems which dominate a field may not be clearly defined; it is easy to find a solution to a well defined problem, yet much harder to formulate a problem that no one has previously recognized (Csikszentmihalyi, 1999).

speculate that a great deal of informational value can be accessed with little effort if the means to identify those papers are available and caveats kept in mind. A simple program of bibliographic library maintenance is suggested to sustain a current awareness of the information domain.

Bibliometric statistics are useful but offer little guidance in terms of domain content and structure. To acquire a better sense of the field, we therefore offered two additional techniques, which despite their crudeness, were quite helpful. The first technique (Section 3.2.1) utilises the search features of ENDNOTE to derive simple word counts. This method is useful only in a comparative sense, and for determining how concepts emerge and dissipate. For example the term 'resilience' is often utilised in the literature as a counterpart to terms 'adaptation' and 'vulnerability,' and yet it is far less prevalent. Moreover, the lead proponent of the 'resilience' concept C.S. Holling has only one publication in the CCA database (Holling, 2004), yet his name appears 60 times in the dataset (i.e. referred to by other articles). This perplexing set of statistics, is nicely elaborated upon by Janssen, Schoon *et al.*, (2006) revealing a fundamental limitation of our dataset (i.e. its disregard of an entire field of enquiry directly relevant to CCA).

The second technique attempts to structure the literature around the assumption that a general, pragmatic purpose (i.e. adapting society to human-induced climate change), pervades the field, which results in a specific structure of the CCA knowledge landscape. In reality numerous perspectives and structures are possible; IPCC reports are based upon one such structure which some believe is biased against adaptation (Cohen, Demeritt *et al.,* 1998). The purpose here was twofold: 1) to formalise a CCA information framework focused primarily upon climate change adaptation (as opposed to mitigation); and 2) to demonstrate a methodology. No grand scheme to integrate all information relevant to CCA is offered, just a given perspective and the means to organise data.

In this technique, the author, title, abstract and keywords are be used to categorise articles, and discern some sense of content, relevance and informational value. Key articles are identified by their relationship to their category, the importance of the category itself, the author's reputation, the journal's status, the article's overall ranking (as determined by its citation count), and ranking within the category. The articles are systematically classified into functional categories with the most abstract or general topics gradually leading towards the most specific, particular or applied topics. The structure reflects the idea that method and theory from various disciplines is ultimately directed towards actual decisions or actions within a specific geopolitical arena.

There are five fundamental categories of the literature: general theories and concepts, academic distinctions, methodological issues, sectors and resources and assessments as defined by their geopolitical place. Most theoretical issues concern the concept of 'adaptation' and its relationship to ancillary terms/concepts such as mitigation, sustainable development, vulnerability, adaptive capacity, etc. Economics appeared to be the dominant disciplinary source of information, methodology and decision criteria. Sociology and Political Science were also quite important. Not surprisingly, most articles dealt with resource or sector issues within a specific geopolitical place. Agriculture and Water resource questions dominated the field, with Forestry and Health issues not far behind. Surprisingly Fisheries and Ecosystem Services appeared to be under-represented.

Explanations could easily be promulgated as to why or why not, certain sectors are over, or under represented. For example, it appeared somewhat surprising that *Fisheries* is relatively under-represented given the incredible importance of fisheries to global food security and the strong evidence of marine species migrations (IPCC, 2007). It was also unexpected, that only 2.7% of the articles could be classified as Wildlife/Ecosystem Services given the overwhelming importance of ecosystem services to society's wellbeing. Why? The easy answer is that we removed such articles from the database when we discounted the behavioural and evolutionary adaptations of other species to climate change. But by doing so, we have effectively eliminated a discussion of ecology from our literature (in Category 2: *Disciplines*). The ambiguity this has created suggests that more attention will have to be paid to incorporating such distinctions in the future.

Another aspect of this omission may be that the phrase 'climate change adaptation' is specific to the disciplines associated with the IPCC process. 'Resilience' is a term utilised to convey a similar meaning by those concerned with ecosystem studies. This idea is explored more fully by Janseen *et al.* (2006) as noted above. They use bibliometric analysis to examine the 'knowledge domains' associated with these terms. Their results suggest that the 'resilience' knowledge domain is only weakly connected with the adaptation domain in terms of co-authorships and citations. 'Resilience' researchers typically have a background in ecology and mathematics, while adaptation researchers possess a background in geography and natural hazards with a focus on case studies and climate change research. It is not a simple matter of bringing the two fields together as strong theoretical disputes exist between the two fields[30]. The lesson here is that we must recognise the limitations of our methodology, the language that it uses, and compensate by expanding our level enquiry.

Finally, a categorisation that divides *Methodology* topics into: *Data, Predictive Modeling,* and *Choosing\Vetting Possibilities* appeared helpful in resolving the basic relationships between topics in the field (see Chapter 1). It was based upon the notion that a general purpose pervades the field and a systems approach can be utilised to order or structure information so that inferences can be made about key relationships. If a researcher accepts the goals and intent of the perspective offered here, the structure may give some indication of where their research fits into an overall scheme, or it may generate new ideas for future research. The inter-relationship of the three factors (data, models, choice) also implies that other formulations may be possible which may then open new doors to analysis. Many perspectives are possible.

In conclusion, adaptation is one of those omnipresent processes that are difficult to pin down. On the one hand we are all intimately familiar with adaptation (i.e. we all adapt daily to weather), yet there is a growing realisation that responses based upon past climatic experience will be far from adequate given what awaits us. An underlying assumption of this report is that we possess the capacity to creatively adapt[31] given that we are provided with the correct tools, environment and attitude (Csikszentmihalyi, 1999). An attempt has been made here to provide the tools to understand the CCA information landscape. Clearly much more needs to be done to move from static, dated, sporadic reviews (i.e. IPCC assessment reports) to more dynamic approaches that incorporate real time bibliometric analysis of climate change articles. Larger datasets, extended analysis, and more user friendly tools would certainly facilitate the migration of neophytes into the field which would facilitate a more extensive debate on climate change adaptation. And given the nature of the core CCA issues, this cannot but help.

30 Roe's book "Taking Complexity Seriously" generated a strong debate with authors such as C.S.Holling, as witnessed in the journal *Ecology and Society* Vol. 4, Issue 2 (2000).

31 Although see Homer-Dixon, T. (2000). *The Ingenuity Gap: Can We Solve the Problems of the Future?* Knopf, Toronto.

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Recent and Current Climate Change Impacts and Adaptation Research at PARC – Key Projects, Findings and Future Direction

8

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Abstract: PARC has recently organised and published important impacts and adaptation research projects, including the "Prairies Chapter" of Natural Resources Canada's National Assessment (From Impacts to Adaptation), the *Climate Scenarios for Saskatchewan* report and the *Saskatchewan's Natural Capital in a Changing Climate: an Assessment of Impacts and Adaptation* report. Key implications for Prairie region adaptation emerge from this body of work. The main biophysical impacts of climate change are seasonal, annual and geographic shifts in the distribution of water resources, and of associated plant and animal species. Extra water will be available in winter and spring, while summers are generally projected to be drier. The longer growing season will favour crop diversification and productivity, but moisture constraints will limit or outweigh these gains. Droughts and extreme weather events are the major threat. The key gap in our knowledge is an understanding of climate variability under conditions of climate change. PARC will engage in further research on climate variability issues, in particular, characterization of drought and drought risk under climate change. Tree species range mapping and policy development and general ecosystems protection policy under climate change will continue to be foci, as will development of a web-based tool to help stakeholders understand and adapt to the climate change impacts challenge on the Prairies. PARC will continue to train new researchers and support scholarship in the impacts and adaptation field, and will continue with an active program of media engagement and information dissemination.

Keywords: climate change, impacts, adaptation, Prairies

1. The Prairies Chapter of the National Assessment

The "Prairies Chapter" of the National Assessment (Sauchyn, *et al.,* 2008) was the chief focus of PARC energies for several years leading up to the Assessment's release in 2008. In the case of the Prairies chapter, the project involved the review and synthesis of hundreds of research papers by a team of 14 authors. Shortly after the release of the Assessment, PARC wrote and released a summary document that highlighted the key findings of this state-of-knowledge study.

The chief findings of the "Prairies Chapter" described below are drawn from the summary document (Henderson and Sauchyn, 2008) based on Sauchyn *et al.* (2008):

Water and Soil Resources

The sustainability and wealth of the Prairie Provinces are intimately linked to the quality and quantity of available water. Water impacts our health and well-being, food production, infrastructure, energy production, forestry, recreation, and communities large and small. Some of the greatest stresses endured in the Prairies have been directly related to hydrologic extremes of drought and flood.

Reduced winter snowfall in the latter half of the twentieth century (Akinremi *et al.*, 1999) contributed to the observed trend of declining streamflows. This is already a critical issue for many rivers in the southern Prairies, such as the Bow, Oldman and Milk, particularly in dry years. Winter warming will reduce snow accumulations in alpine areas (Leung and Ghan, 1999; Lapp *et al.*, 2005) and across the Prairies. This will cause declines in annual streamflow and a shift in streamflow timing to earlier in the year, resulting in lower summer water supplies – unfortunately summer is the season of greatest demand for water.

Continued glacier retreat (Demuth and Pietroniro, 2003) will exacerbate water shortages already apparent in many areas of Alberta and Saskatchewan during drought years. Drier soils result in decreased subsurface recharge, which will lead to a decline in the water table in many regions. Increases in the demand for water will compound issues of declining water supply and quality.

In the Alberta Rockies an increased frequency of landslides, debris flows, rock avalanches and outburst floods is probable, given current and projected future trends that include increased rainfall (especially in winter), rapid snowmelt and shrinking glaciers (Evans and Clague, 1994; 1997). The decay of permafrost could accelerate slope failures at high elevations for many decades (Evans and Clague, 1997).

In the taiga and boreal forest regions, increased drought frequency, including persistent multi-year droughts (Sauchyn *et al.*, 2003), will result in declining soil moisture and increased forest fire extent. During recent extreme droughts, organic soils have dried and burned together with forests, resulting in an almost total loss of vegetation and soil cover. Thereafter runoff becomes instantaneous, resulting in flash floods.

In agricultural regions, droughts could result in enhanced soil erosion and increased sand dune activity (Wolfe and Nickling, 1997). Slopes and stream channels exposed to less frequent but more intense rainfall will also be vulnerable to increased erosion and shallow slope failures (Sauchyn, 1998; Ashmore and Church, 2001). Erosion will increase stream sediment and nutrient loads in local water systems, leading to eutrophication of water bodies and increased pathogen loading in streams during the summer (Hyland *et al.*, 2003; Johnson *et al.*, 2003; Little *et al.*, 2003). The Millennium Ecosystem Assessment (2005) identified the joint effects of climate change and nutrient overenrichment as the major threat to agro-ecosystems. Phosphorus and nitrogen, while often useful inputs for agricultural production in the Prairies, impinge water quality and encourage eutrophication when run-off events move these nutrients into waterbodies.

Changing the timing of irrigation to after sunset and using more efficient irrigation methods can help offset increasing water demands (Bjornlund *et al.*, 2001). Increasing water recycling or issuing licenses to industries that are based on best water management practices and water recycling standards are other adaptation opportunities (Johnson and Caster, 1999).

Future water scarcity could lead to abandonment or underutilization of major infrastructure (canals, pipelines, dams and reservoirs) worth billions of dollars. Equally, rising water demand combined with a decline in summer runoff in some years will lead to calls for new infrastructure for increased storage and diversion of water. However, reservoirs emit greenhouse gases (St. Louis *et al.*, 2000), and dams and diversions have well-documented negative environmental impacts (Environment Canada, 2001; Mailman *et al.*, 2006).

Ecosystems

Models of vegetation zonation have shown a northward shift of the forest-grassland boundary in the Prairie Provinces with climate change (Hogg and Hurdle, 1995; Vandall *et al.*, 2006). In water-stressed forest regions there will be a general reduction in tree growth, regeneration failure in dry years, a gradual reduction in tree cover, and expansion of grassland patches. Major changes in species representation are projected for the boreal forest, especially at its southern boundary (Herrington *et al.*, 1997; Henderson *et al.*, 2002; Carr *et al.*, 2004). Increased average winter temperatures will lead to greater overwinter survival of pathogens and increased disease severity (Harvell *et al.*, 2002). Drought conditions weaken trees' defences to more virulent pathogens (Saporta *et al.*, 1998). Henderson *et al.* (2002) noted two pathways of forest change: 1) slow and cumulative decline; or 2) catastrophic loss, such as a major fire.

In the aspen parkland there will be shrinking of aspen groves and decreasing shrub cover. Aspen parkland and fescue prairie of the present northern grassland fringe will give way to variants of mixed prairie. The most significant impacts will occur at ecozone boundaries, for example, where grassland meets parkland or forest, or where drier lower-elevation grassland meets moister foothills grassland (Vandall *et al.*, 2006).

Prairie-parkland national parks can expect increases in forest fire frequency and intensity, increased forest disease outbreaks and insect infestations, and loss of boreal forest to grassland and temperate forest (Scott and Suffling, 2000; de Groot *et al.*, 2002). In Alberta's mountain parks, climate change has already caused the treeline to advance to higher elevations, a trend that will accelerate. Isolated island forests will suffer serious challenges to ecosystem integrity. Highly intensive management will likely be necessary to preserve some type of forest cover at these sites (Henderson *et al.*, 2002).

Possible adaptation actions to protect forest systems range from maintaining a diversity of age stands and responding aggressively to pathogen disturbances, to regenerating the forest with alien tree species that are better adapted to new climate parameters. Current policies disfavour alien introductions (e.g., Alberta Reforestation Standards Science Council, 2001; Alberta Sustainable Resource Development, 2005; Manitoba Conservation, 2005). However, western conifers, such as Douglas fir and ponderosa pine, and hardwoods of the southern Prairies, such as Manitoba maple and green ash, may be suited to future climates of the western boreal ecozone (Thorpe *et al.*, 2006).

The prairie pothole region of central North America is the most productive habitat for waterfowl in the world (Clair *et al.*, 1998). Increasing aridity and habitat loss in the prairie grasslands is likely to negatively impact migratory waterfowl populations (Poiani and Johnson, 1993; Bethke and Nudds, 1995).

Aquatic ecosystems will be stressed by warmer and drier conditions. A large number of prairie aquatic species are at risk of extirpation (James *et al.*, 2001). Many fish species and amphibians are sensitive to small changes in temperature, turbidity, salinity or oxygen regimes. The size of the massive algae blooms in Lake Winnipeg correlates with higher summer temperatures (McCullough *et al.*, 2006). Larger algal blooms, accelerated eutrophication, and serious impacts on fish species are expected, due to a combination of climate change, increasing nutrient runoff, and increasing human use pressures on natural water systems (Schindler and Donahue, 2006; Xenopoulos *et al.*, 2005).

Actions to increase connectivity between protected areas to facilitate migration of species populations is commonly proposed as one method of coping with climate change (Malcolm and Markham, 2000; James *et al.*, 2001; Joyce *et al.*, 2001). Although some species may be able to migrate, others will be threatened by the arrival of new competitors or by the pathogens that increased connectivity supports. Thus, increased connectivity may also hasten the decline of some ecosystems by favouring alien invasions.

Conservation management that aims simply to retain existing flora and fauna, or to restore historical vegetation distributions, will fail as the climate moves farther away from recent and current norms. Biodiversity protection planning may need to build resilience into ecosystems, rather than seeking stability (Halpin, 1997). Selection of protected areas may need to focus on site heterogeneity and habitat diversity (as these provide some buffer against climate change) rather than on representativeness (Henderson *et al.*, 2002).

Climate change means ecosystem change is inevitable. Therefore, biodiversity managers must become less practitioners of preservation and more stewards of new and unprecedented ecosystems and landscapes.

Agriculture

Higher levels of atmospheric CO_2 improve water-use efficiency of photosynthesis, and may increase some crop yields (particularly for plants using the C3 carbon-fixation pathway, like wheat and canola). However, the picture is complex, since weeds may also be more vigorous under a carbon-enriched atmosphere. Warmer and longer growing seasons could be positive for crop growth and yield. Shorter and milder winters may put less stress on livestock. Potential negative impacts include changes in the timing of precipitation, more intense precipitation events, the emergence of new pests, and, especially, the increased frequency and intensity of droughts.

Manitoba, the least water-deficient province, has been projected to benefit from warming as producers shift to higher value crops (Mooney and Arthur, 1990). By contrast, the more arid mixed grassland ecoregion of southern Alberta and Saskatchewan, an area of approximately 200,000 km^2, is at risk of desertification.

Historically, federal and provincial governments have responded to drought with safety net programs to offset negative socioeconomic impacts (Wittrock and Koshida, 2005) and, more recently, through development of drought management plans. More intense and longer droughts will be expensive challenges to safety net programs.

Grassland production is limited by moisture supply. Although a drier climate would suggest declining production and grazing capacity, actual changes in grassland production are likely to be modest, given a longer growing season, reduced competition from shrubs and trees, and increases in warm-season grasses that have higher water-use efficiency (Thorpe *et al.*, 2004).

Soil conservation and irrigation are major agricultural adaptations to annual soil water deficits. Soil conservation is a prime example of a ‘no regrets' strategy, since preventing soil loss is beneficial whether or not impacts of climate change occur exactly as projected. The Permanent Cover Program (Vaisy *et al.*, 1996) has reduced sensitivity to climate over a large area. The move in recent decades to more efficient irrigation techniques has dramatically increased on-farm irrigation efficiencies. However, the continued loss of water from irrigation reservoirs and open-channel delivery systems due to evaporation, leakage and other factors indicates the need for further improvement in the management of limited water resources.

Forestry

Generally, net primary forest productivity is expected to increase under warmer temperatures and longer growing seasons, if water and nutrients are not limiting (Norby *et al.*, 2005). Increased photosynthetic activity for much of Canada during the period 1981–1991 has been attributed to a longer growing season (Myneni *et al.*, 1997).

Free-air CO_2 enrichment experiments found trees respond to increased CO_2 concentrations more than other vegetation, with biomass production increasing an average of about 20 to 25% (Long *et al.*, 2004; Norby *et al.*, 2005). Higher levels of atmospheric CO_2 improve water-use efficiency (WUE); that is, less water is lost for a given unit of CO_2 uptake (Long *et al.*, 2004) – particularly important for water-limited sites. Johnston and Williamson (2005) found that, even under severe drought conditions, increased WUE under a high CO_2 future would result in an increase in productivity relative to current conditions. Simulated future drought reduced productivity of white spruce in Saskatchewan by about 20% on sites with low available water-holding capacity (Johnston and Williamson, 2005).

Insect outbreaks are expected to be more frequent and severe (Volney and Fleming, 2000). Of particular concern is the mountain pine beetle, currently in a major outbreak phase in the interior of British Columbia. It is now beginning to spread east, with approximately 2.8 million trees affected in Alberta as of spring 2007 (Alberta Sustainable Resource Development, 2007). The beetle is limited by the occurrence of –40°C winter temperatures; with warming, this limiting temperature is likely to occur farther to the north and east, allowing the beetle to spread into jack pine in the Prairie Provinces.

Forest fires are expected to be more frequent (Bergeron *et al.*, 2004), of higher intensity (Parisien *et al.*, 2004), and to burn over larger areas (Flannigan *et al.*, 2005). Increased forest fire activity will likely favour hardwood species (e.g. aspen) over some conifers (e.g. white spruce), as aspen recovers quickly after fire. Increased tree mortality in the southern margin of the boreal forest is projected as a result of the interaction of insects, drought and fire (Hogg and Bernier, 2005; Volney and Hirsch, 2005).

In areas where winter operations are important, a shorter period of frozen ground conditions will limit operations and affect scheduling of harvesting equipment. Potential adaptation measures for dealing with climate change impacts include managing forests to reduce fuel loads and fire loss potential; assisting the migration of commercial tree species; thinning forests to enhance growth and insect / disease resistance; and maintaining connectivity (Spittlehouse and Stewart, 2003). Forest loss could be irreversible if adaptation is slow or only reactive.

Transportation

Increased frequencies of extreme precipitation events (Kharin and Zwiers, 2000) and increased inter-annual climate variability are likely to result in increased damage to roads, railways and other structures as a result of flooding, erosion and landslides. Asphalt surfaces, particularly those with significant heavy truck traffic, are especially susceptible to damage during heat waves, which are expected to increase in frequency.

Winter roads, that is, those that use frozen lakes and muskeg, have experienced significant negative impacts. Manitoba Transportation and Government Services has reported decreased ice thickness, poor ice texture and density, delayed winter road seasons, problematic muskeg areas and decreased load limits. The average length of the winter road season in Manitoba is expected to decrease by 8 days in the 2020s, 15 days in the 2050s and 21 days in the 2080s (Prentice and Thomson, 2003).

The longer ice-free season in Hudson Bay and northern channels resulting from continued climate warming (Arctic Climate Impact Assessment, 2005) will increase opportunities for ocean-going vessels to use the Port of Churchill terminus for grain and other bulk commodities. But northern railways passing through areas of permafrost, as does the rail line serving Churchill, will require frequent repair, if not replacement, as a result of continued permafrost degradation (Nelson *et al.*, 2002). Additionally, some paved roads in northern areas are stabilized by frozen substrates during winter and may be compromised by warmer winter temperatures.

Communities

Prairie cities may find existing water storage and drainage systems inadequate to handle projected changes in precipitation intensity and snowmelt. Increasing drought frequency and severity will require water efficiency initiatives. The City of Regina has developed drought contingency plans, including water conservation programs and expansion of water treatment and delivery capacity (Cecil *et al.*, 2005). Other Prairie cities do not have such contingency plans in place (Wittrock *et al.*, 2001). More frequent heat and drought events can place urban vegetation and wildlife under extreme stress. For example, the City of Edmonton (2007) estimated the loss of approximately 23,000 trees to drought since 2002.

In general, rural communities are more sensitive to climate change impacts than cities, due to their more direct natural-resource dependency and lack of economic diversification. Drought is of particular concern, as small communities are largely dependent on well water or smaller reservoirs. Of greatest concern for agricultural communities are extreme weather events, droughts and ecosystem shifts. Rural residents may be more skeptical than urbanites about climate change (Neudoerffer, 2005), which may hinder adaptation initiatives.

Many Aboriginal communities are partly dependent on subsistence for their livelihood. Declines or uncertainties in the availability of moose, caribou, deer, fish and wild rice will increase dependence on imported foods. Unsuitable snow and ground conditions greatly hamper travel to trap lines, hunting grounds and fishing areas. At the February 2004 Prince Albert Grand Council Elders' Forum, elders reported more frequent extreme weather events, deterioration in water quantity and quality, changes in species distributions, changes in plant life, and decreasing quality of animal pelts. Traditional knowledge and land management systems served as a source of resiliency in the past, and could play an important role in strengthening adaptive capacity in the future.

Health

Prairies residents may experience increasing negative health burdens from air pollution, food-borne pathogens, heat-related illnesses, particulate matter, water-borne pathogens and vector-borne diseases (Seguin, 2008). Subpopulations most at risk are children, the elderly, Aboriginal peoples, the poor, the homeless, and people with underlying health conditions.

An increased frequency of wildfires may result in increases in respiratory ailments, hospital visits and mortality (Bowman and Johnston, 2005). Warmer temperatures decrease the number of cold-related deaths, but also enhance the production of secondary pollutants, including ground level ozone (Last *et al.*, 1998; Bernard *et al.*, 2001). Drought may increase concentrations of pathogens and toxins in domestic water supplies (Charron *et al.*, 2003; World Health Organization, 2003). Outbreaks of water-borne disease have been linked to intense precipitation, flooding and runoff from agricultural livestock areas (Millson *et al.,* 1991; Bridgeman *et al.*, 1995; Charron *et al.*, 2003, 2004; Schuster *et al.*, 2005). Hantaviruses may increase, as well as West Nile virus. Other potential health threats are western equine encephalitis, rabies, influenza, brucellosis, tuberculosis and plague (Charron *et al.*, 2003).

Energy

Increasing water scarcity and water supply variability are the major climate change risks to energy industries. Production of oil, and even some natural gas, relies on significant quantities of water (Bruce, 2006). Tar sands production is already putting pressure on Athabasca River water; climate change and expanding production will worsen this problem (Bruce, 2006). Drought periods will reduce the supply of cooling water to power plants.

Approximately 95% of the electricity generated in Manitoba comes from renewable water energy (Manitoba Science, Technology, Energy and Mines, 2007). Future hydro generation will be impacted by decreasing water flows from the western portion of the Prairies due to glacial ice decline (Demuth and Pietroniro, 2003) and lower snow accumulations (Leung and Ghan, 1999; Lapp *et al.*, 2005).

Warming is already causing substantial permafrost degradation in many parts of the north (Majorowicz *et al.*, 2005; Pearce, 2005), which will lead to land instability, soil collapse and slope failures. Together with an increased frequency of extreme climate events, this will create problems for foundations and roads. There will be pipeline ruptures and costs to reroute existing pipelines to more stable locales (Huang *et al.*, 2005).

Tourism and Recreation

Lower lake and stream levels, particularly in mid- to late summer, may reduce opportunities for water-based recreation: swimming, fishing, boating, canoe-tripping and whitewater activities. Hunting and fishing could decline with decreasing waterfowl and game fish populations. The island forest parks (Henderson *et al.*, 2002) and small recreation areas of the southern Prairies, where water and trees draw visitors, are particularly sensitive to changing climate. Banff's ski industry may be negatively affected by less snowfall (Scott and Jones, 2005). Less snow cover and a shorter season will also impact cross-country skiing, snowshoeing and snowmobiling (Nicholls and Scott, in press).

2. Other Key Research Reports

Climate Scenarios for Saskatchewan

In 2009 PARC published a new set of climate scenarios (Barrow, 2009) for Saskatchewan based on the latest available GCM outputs. Since changes to moisture balance represent the most serious impact to both Saskatchewan's forest and grassland regions, scenarios were selected on the basis of an annual moisture index, i.e. on the combined effect of both temperature and precipitation changes. Moisture balance is a key issue in the health of Saskatchewan ecosystems and in the success of key industries such as agriculture. It also affects water supply to industry, cities and towns, and hydropower generation. The results for specific Saskatchewan towns are summarised in Figure 1, and show a future of increased aridity for Saskatchewan, even under the most optimistic of scenarios.

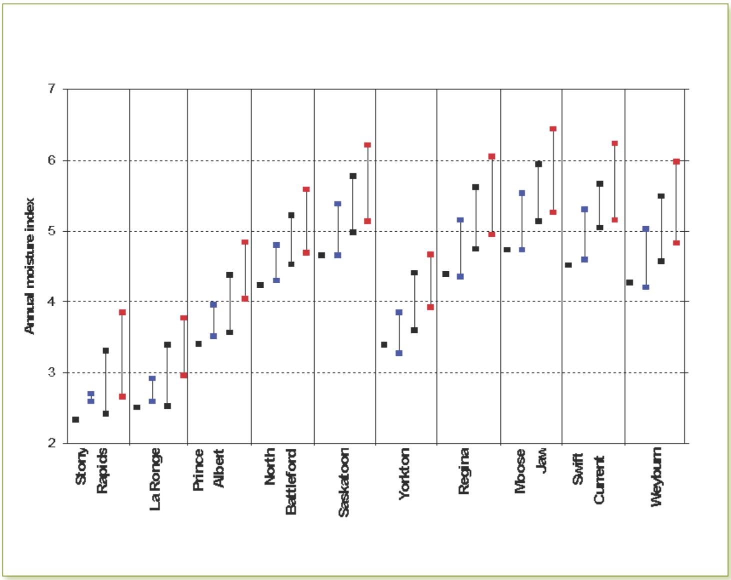

Figure 1 | Annual moisture index for the forest and grassland sites in Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). Higher numbers indicate more arid conditions.

Across a range of global climate models and greenhouse gas emission scenarios, there is a consistently-predicted increase in future annual temperature and precipitation throughout Saskatchewan. These climate changes impact many activities, especially agriculture. When, within the year, extra heat and water will be available is an important question. Most of the warming is occurring in winter. The frost-free growing season is getting longer. However, some of the advantages of a cold winter are being lost that enables transportation over ice and frozen ground in northern Saskatchewan, prevents many pests and diseases, and stores water as snow – the most abundant, reliable and predictable source of water. Most of the extra precipitation is expected in winter and spring and increasingly in the form of rain as the climate warms. Scenarios of summer precipitation are less consistent but many include decreased summer precipitation falling in fewer and more intense storms. Thus, on average, the mid to later stages of longer warmer summers will tend be drier, possibly much drier.

The report (Barrow, 2009) notes that while most scenarios generate information on projected changes to mean climate, in Saskatchewan it is climate variability that is the key concern. Variability is the degree and frequency of variations from the mean climate, the climate normals. It is changes in variability which are likely to have the largest effect on the frequency and magnitude of extreme climate events. Extreme events on the Prairies include tornadoes, plow winds, hail, severe thunderstorms, blizzards, droughts, rain-flood events, and ice events. These extreme events in turn tend to have a large impact on our environment, economy and infrastructure. Understanding or defining changes in climate variability as well as changes in mean climate is not a trivial task. Statistical techniques (such as stochastic weather generators) exist which allow the perturbation of observed time series by both changes in means and variability. These techniques are best applied at the site scale, so one option would be to focus on specific locations, such as those in Figure 1.

Saskatchewan's Natural Capital in a Changing Climate

In 2009 PARC published a major report (Sauchyn *et al.,* 2009) identifying the main impacts and adaptation options for Saskatchewan's natural systems, based on the latest climate scenarios. The report draws on the expertise of top climate change researchers and a large body of previous work to create a state-of-knowledge synthesis of key biophysical impacts and adaptation options. The focus is on Saskatchewan's ecosystems and water resources and the sectors of the economy, agriculture and forestry, which are most dependent on these natural resources. The report documents the expected impacts of climate change on Saskatchewan's natural resources and dependent industries, and outlines options for adaptation of resource management practices, policies and infrastructure to minimize the risks associated with the impacts of climate change and to take advantage of opportunities provided by a warming climate. Key conclusions include:

- The major biophysical impacts of climate change in Saskatchewan are seasonal, annual and geographic shifts in the distribution of water resources and plant and animal species.
- One of the most certain projections is that extra water will be available in winter and spring but summers generally will be drier as the result of earlier spring runoff, and a longer warmer summer season of water loss by evapotranspiration. Much of the observed and projected warming in Saskatchewan is during winter and spring, such that the frost-free growing season is getting longer and expected to get significantly longer as the climate warms.

- A longer warmer growing season will favour diversification of prairie agriculture and higher crop, pasture and forest productivity. However, higher productivity will be limited by the availability of soil moisture.
- The impacts of climate change tend to be adverse because Saskatchewan communities and resource economies are sensitive to fluctuations in the quantity and quality of natural capital and they are not adapted to the projected larger range of climate conditions.
- The net impacts of climate change depend heavily on rates of climate change and the effectiveness of adaptation measures. South of the Churchill River, nearly all of Saskatchewan's ecosystems and water resources are managed. Most impact assessment has assumed no adaptation or made simple assumptions about adaptation. This reflects a lack of understanding of adaptation processes and the difficulty of predicting changes in public policy and socio-economic factors.
- Planned adaptation is a component of adaptive resource management and sustainable economic development. There is a gap in our understanding of the extent to which existing management practices and public policies either encourage or discourage the implementation of adaptive strategies. There is also a need to determine the relative importance of adaptive responses versus other priorities, and to develop approaches that incorporate climate change considerations into existing policy instruments.
- The major threats are understood with the least certainty. The recurring impacts of drought in Saskatchewan suggest that the severity and duration of future droughts will determine much of the impact of climate change. Droughts, and to a lesser extent flooding, could limit opportunities provided by a warmer climate and will challenge capacity to adapt to changing conditions. Nearly all climate change assessments are based on climate change scenarios that give shifts in mean conditions between decades.
- A key finding of this impact assessment, therefore, is that the gap in our knowledge of climate variability is problematic for evaluating impacts and developing appropriate adaptation strategies.

3. PARC's Future Priorities

Water issues and climate change are the key challenge to the Prairie Provinces and PARC will continue to engage in research and collaboration in this area. Climate variability, in particular the risk of drought, is the key risk, and efforts are under way to try and model and understand variability under climate change. Tree species range mapping and policy development and general ecosystems protection policy under climate change will continue to be foci, as will development of a web-based tool to help stakeholders understand and adapt to the climate change impacts challenge on the Prairies. PARC will continue to train new researchers and support scholarship in the impacts and adaptation field, and will continue with an active program of media engagement and information dissemination. Prominent amongst these efforts is the June 2010 launch of **www.SaskAdapt.ca**. This new website summarises key PARC research in an accessible way for a wide range of stakeholders.

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9

Climate Impacts Science for Adaptation

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Abstract: The difficulty of translating scientific results on climate change into useful information defines the abyss that is addressed by a relatively new Pacific Climate Impacts Consortium of academics-government-industry at the University of Victoria. The scope of the consortium is applications of research on climate variability and change to decision-making. In particular, adaptation requires planning and decision making at local and regional scales. Historical hydroclimatology provides context and scenarios based on projections from Global Climate Models indicate a range of future outcomes. Information at ever higher spatial and temporal scales are attained from Regional Climate Models and from empirical downscaling. Investigating the link between adaptation and mitigation with the UVic Earth System Climate Model shows that adaptation will be required in British Columbia even with best case mitigation, but that reducing greenhouse gas emissions will have a considerable effect on the magnitude of climate change in British Columbia. These sources of future climate change projections are being used in projects where active collaboration between the Pacific Climate Impacts Consortium, researchers, and stakeholders results in moving beyond projections of climate itself into projections of impacts that inform adaptation.

Keywords: climate impacts, adaptation, Pacific Climate Impacts Consortium, British Columbia

1. Introduction

This paper is a summary of a presentation given on 11 March 2009 at the National Science Meeting on Planned Adaptation to Climate Change hosted by Environment Canada in Victoria, British Columbia. The text describes most of the topics presented, but only selected results are shown in figures. See "Climate Overview 2007: Hydro-climatology and Future Climate Impacts in British Columbia," available online at **www.PacificClimate.org\publications** (Rodenhuis *et al.,* 2007 for more detail). Following a description of the history and mandate of the Pacific Climate Impacts Consortium, three sections are presented: historical hydroclimatology, future climate change, and future climate change impacts.

2. Bridging the Gap with the Pacific Climate Impacts Consortium

In May 2005, a group of scientists and stakeholders concluded that there was a need to focus resources to build regional capacity to adapt to a changing climate. As a result, the Pacific Climate Impacts Consortium was formed by the BC Ministry of Environment and BC Hydro at the University of Victoria.

> *A vision emerged from the workshop to "stimulate the collaboration of government, academia, and industry to reduce vulnerability to extreme weather events, climate variability, and the threat of global change. The consortium for climate impacts will bridge the gap between climate research and climate applications, and will make practical information available to government, industry, and the public."*

The Pacific Climate Impacts Consortium partners with climate researchers, impacts researchers, and stakeholders in order to assist users to apply research results to management, planning, and decision-making. The Pacific Climate Impacts Consortium carries out its mission by organizing projects into four themes, with most activity currently in the first two: Regional Climate Impacts, Hydrological Impacts, Ocean Influences, and Climate Analysis. The Pacific Climate Impacts Consortium staff with resident expertise in these themes work with stakeholders in order to progress from climate change to bio-physical impacts to inform socio-economic impacts and adaptation (Pacific Climate Impacts Consortium, 2009).

3. Hydroclimatology

Due to its complex topography, British Columbia has considerable diversity in terms of past temperature, precipitation, and streamflow (Figure 1). The effects of short term climate variability such as El Niño and La Niña are considerable, as is the Pacific Decadal Oscillation (PDO) (Figure 2).

A comparison of trends computed from the global CRU TS2.1 dataset (Mitchell and Jones, 2005) over three different time periods (Figure 3) illustrates several features of historical temperature trends in British Columbia: night-time lows have been increasing more rapidly than daytime highs, the difference between these rates has been narrowing, temperatures have been increasing more rapidly towards the end of the century (largely due to the influences of both global warming and of the positive phase of the PDO). In contrast, precipitation trends are within the magnitude of historical variability, as demonstrated by the switch from positive 100- and 50-year trends to strong negative recent (30-year) trends in winter. Differences in trends depending on time period also underscore the importance of using future climate projections from models rather than simply extending past trends.

4. Future climate change

Several sources of future projections were presented. First, Global Climate Models provide the most comprehensive range of uncertainty. A set of 30 GCM projections prepared for the IPCC Fourth Assessment Report projects changes from the 1961-1990 baseline by the 2050s of +1.2°C to +2.5°C (annual temperature), +3% to +11% (annual precipitation), and -9% to +2% (summer precipitation) for the British Columbia region. Second, a comparison of the Canadian Regional Climate Model (version 4.1.1) to the GCM projection that drives it showed that additional regional detail resulting from dynamical modelling of land surface-atmosphere feedbacks provided important additional regional detail (Figure 4). Finally, draping future climate projections over high resolution historical PRISM climatology (Daly, 2006) allows for illustration of how the projected climate changes look when imposed on the fine scale climatology that results from British Columbia's complex topography (Figure 5).

The three sources of climate projections described above are all based on the IPCC SRES emissions scenarios (Nakicenovic *et al.*, 2000). The three emissions scenarios considered (B1, A1B, and A2) have CO_2-equivalent greenhouse gas (GHG) concentrations that differ widely (600, 850, and 1250 ppm) by the end of the century. None of the scenarios include intentional efforts to reduce GHG emissions, such as those proposed and committed to by many jurisdictions. In order to determine whether adaptation will be required in British Columbia even if aggressive GHG reductions are attained, results from the UVic Earth System Climate Model (ESCM) were averaged over British Columbia and compared to the SRES scenarios (Figure 6). ESCM emissions are reduced linearly until 2050 to the indicated percentage below 2006 levels, then held constant afterwards (Weaver *et al.,* 2007).

The changes for British Columbia by the end of the century (2081-2100) for the B1, A1B, and A2 emissions scenarios according to the median of all IPCC AR4 projections are 3.8°C, 3.2°C, and 2.2°C, respectively. In general, model uncertainty results in roughly 1°C of uncertainty about these median lines over British Columbia (not shown) that is fairly constant throughout the 21st century. Also, these results are averaged over the Province but differences between the scenarios are less in some

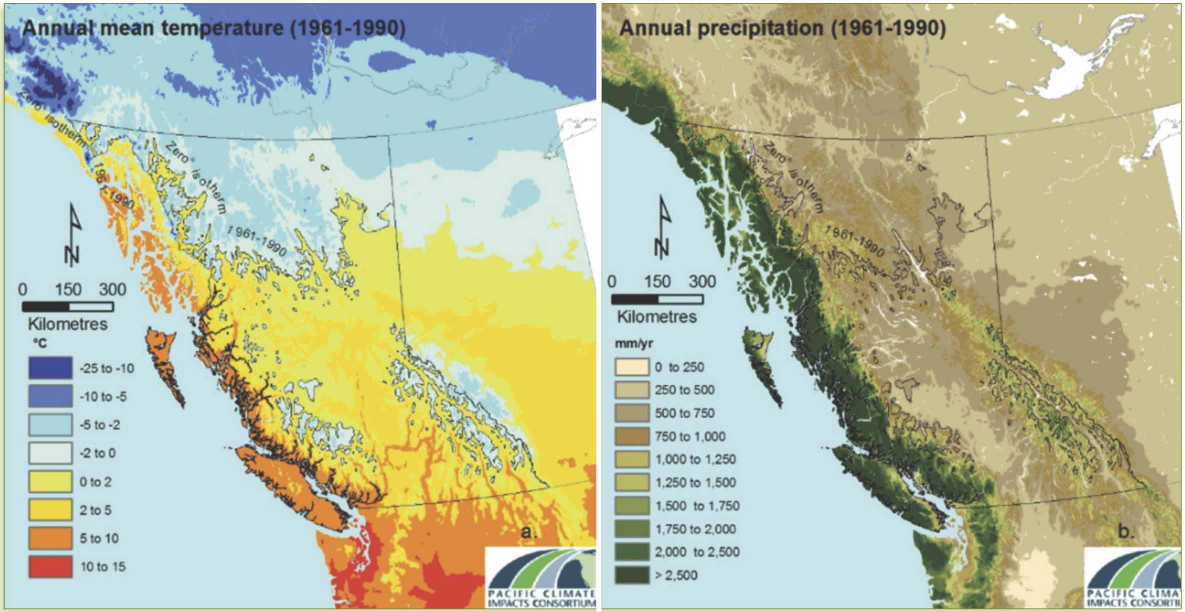

Figure 1 | Historical climatology (1961-1990) for annual average temperature and annual precipitation. Data source: PRISM (Oregon State University).

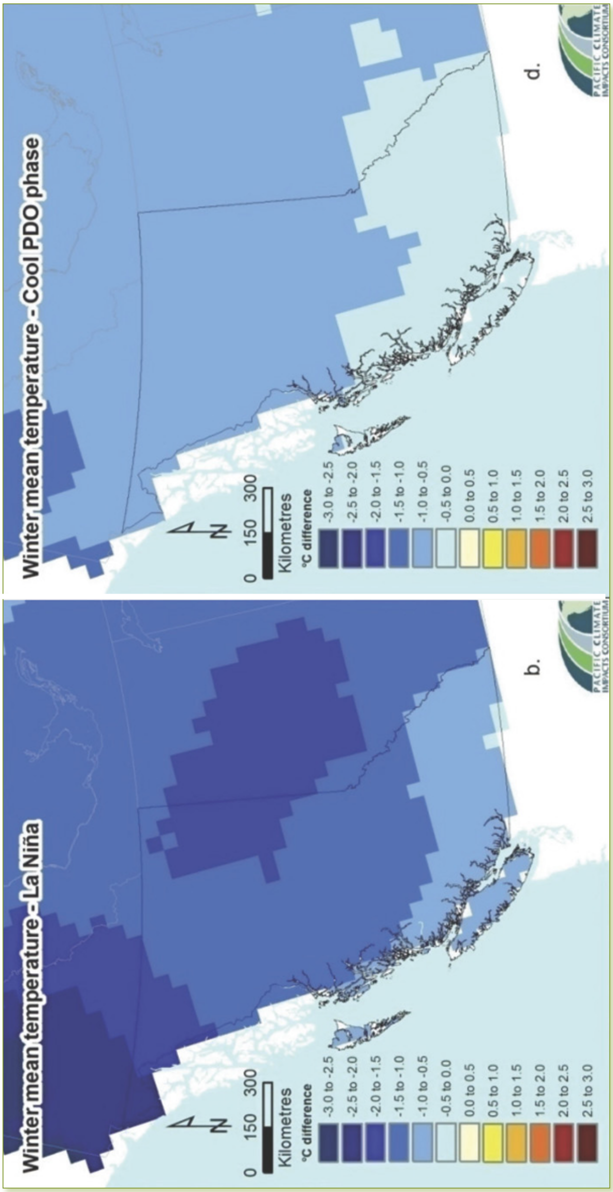

Figure 2 | Winter mean temperature difference between the average of all La Niña years during the 20th century and the average of all years (left). Winter mean temperature difference between average of all the Cool phase PDO years during the 20th century and average of all years (right). Data source: CANGRID (Environment Canada).

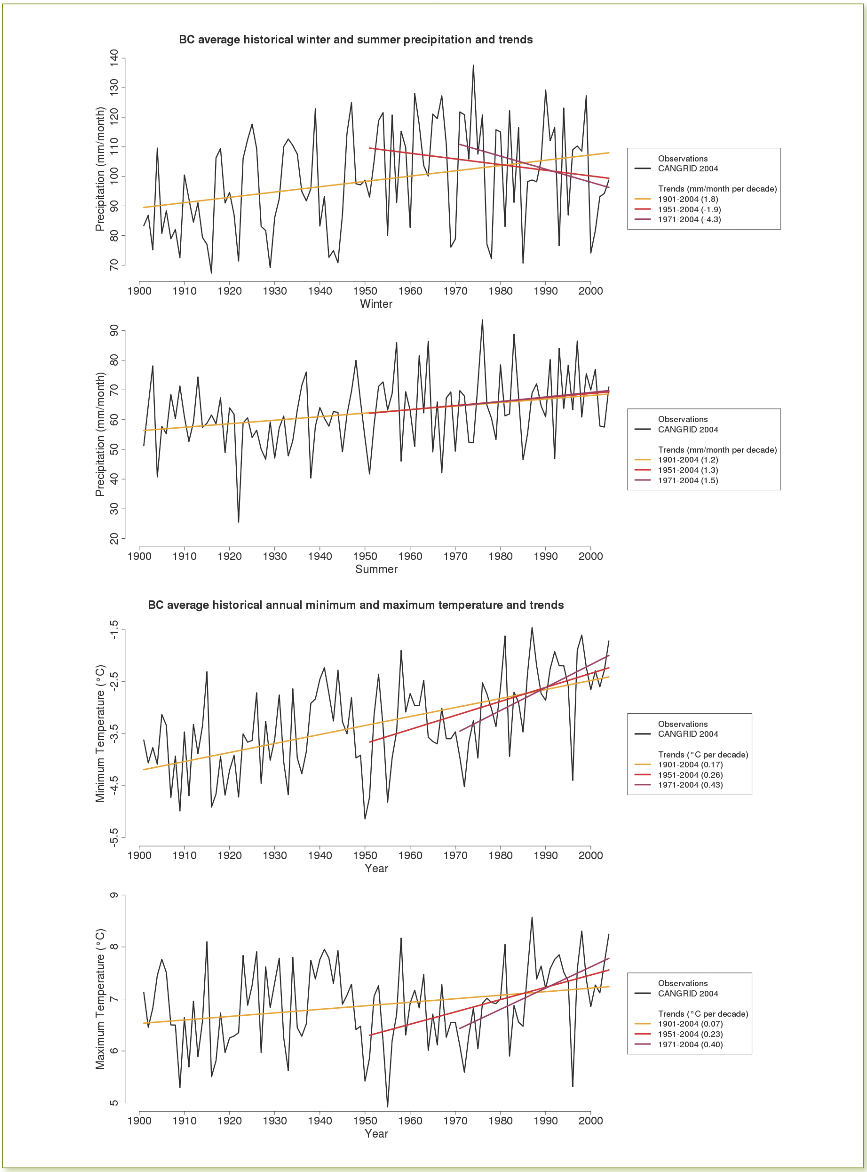

Figure 3 | Median of all trends across British Columbia for minimum temperature (night-time low), maximum temperature (day-time high), winter precipitation and summer precipitation based on CRU TS2.1 gridded time series of historical climate.

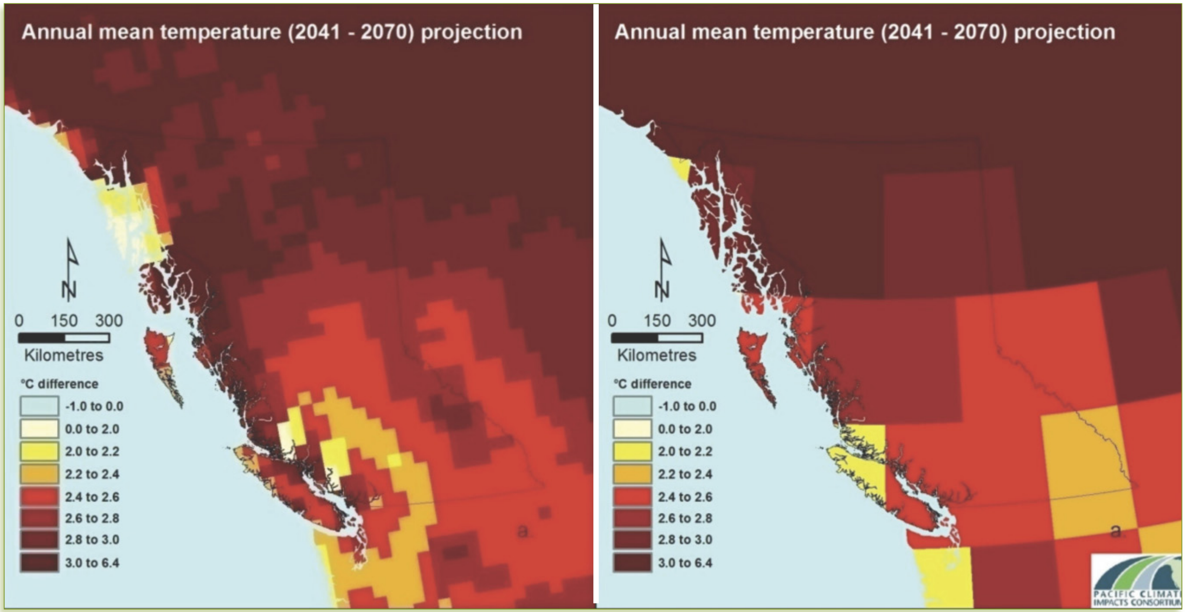

Figure 4 | Comparison of RCM Canadian Regional Climate Model version 4.1.1 (runs acs and act) to its driving GCM (CGCM3 following emissions scenario A2, run 4). Data sources: Ouranos Consortium and Coupled Model Intercomparison Project 4 (Lawrence Livermore National Laboratory).

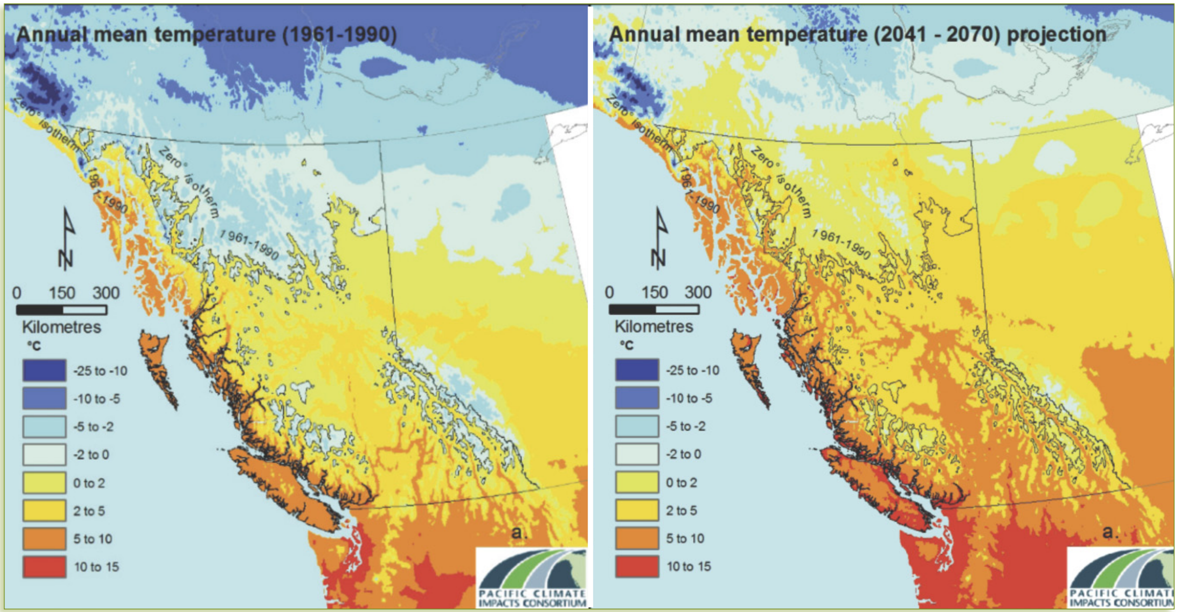

Figure 5 | Historical climatology (1961-1990) for annual average temperature and future projected temperature by draping the GCM projection from CGCM3 following emissions scenario A2 (run 4) over the high resolution (4 km) climatology. Data sources: PRISM (Oregon State University), Coupled Model Intercomparison Project 4 (Lawrence Livermore National Laboratory).

regions (e.g., coast) and larger in others (e.g., north). The amount of climate change associated with the 0% and 25% reductions, 2.3°C and 2.1°C, respectively, are comparable to the B1 scenario. This suggests that the UVic ESCM response is comparable to the median of IPCC models as the 0% to 25% reductions result in similar greenhouse gas concentrations by the end of the century to the B1 emissions scenario. More aggressive reductions result in less warming: 1.8°C and 1.5°C for 50% and 75%, respectively. Overall, there is a considerable difference in magnitude of climate change (and thus in expected impacts on ecosystems and infrastructure) between the highest (A2) emissions (3.8°C) and the very aggressive 75% reduction target (1.5°C). These results imply then that adaptation will be required even with an extremely high level of success in GHG reduction efforts (mitigation) and also that success at mitigation will result in considerably less change to adapt to.

5. Future impacts

The ultimate goal of the analysis of historical climatology and projections of future climate is to facilitate adaptation. Resident expertise of the Pacific Climate Impacts Consortium staff in physical sciences including hydrology, climate scenarios, and downscaling has been applied through collaborative projects with stakeholders. Three examples in particular are: (1) hydrological modelling (BC Hydro, BC Ministry of Environment), (2) forest impacts (BC Ministry of Forests and Range), and (3) community assessments (several stakeholders).

The hydrological modelling for BC Hydro and BC Ministry of Environment applies the Variable Infiltration Capacity (VIC) model, originally developed for use in Global Climate Models (Liang *et al.,* 1994; Liang *et al.,* 1996). The model has been widely applied in basins throughout North America, including the Columbia River Basin (Hamlet and Lettenmaier, 1999). The Pacific Climate Impacts Consortium (in collaboration with the BC River Forecast Centre and BC Hydro) has set up VIC to run in major British Columbia watersheds, including the Peace, the Canadian portion of the Columbia and the Fraser River basins. Future climate change scenarios have been developed for these watersheds, and in the Fraser additional analysis has been done to determine the effects of change in forest cover as a result of the Mountain Pine Beetle outbreak. Subsequently, the Peace and Campbell River basins will be investigated (Figure 7). In addition to the VIC model, the Pacific Climate Impacts Consortium will explore the effectiveness of applying the Canadian Regional Climate Model to determine changes to future streamflow. Results will be compared between the hydrologic modelling and the Regional Climate Model.

Impacts on forestry have been investigated in collaboration with the BC Ministry of Forests and Range, Pacific Forestry Centre, University of Victoria, and University of British Columbia researchers. In particular future tree species suitability and pest outbreak risk were investigated using bioclimatic envelope modelling (Flower and Murdock, in prep.). This approach shows only where the currently suitable climate moves to and does not consider the effects of interactions with soil, water availability, forest genetics, and other considerations. Suitable climates are projected to move much more rapidly than trees can migrate. These projections are useful for adaptation in order to inform the decision as to which species to plant in which location (assisted migration). This is an example of a decision in which adaptation and mitigation are linked, as the planting of trees to act as carbon sinks in order to reduce GHG emissions relies upon the survival to maturity of the species planted. Survival will depend in part upon the changing climate over the next century, as well as changes to pest outbreak risks that will accompany climate change.

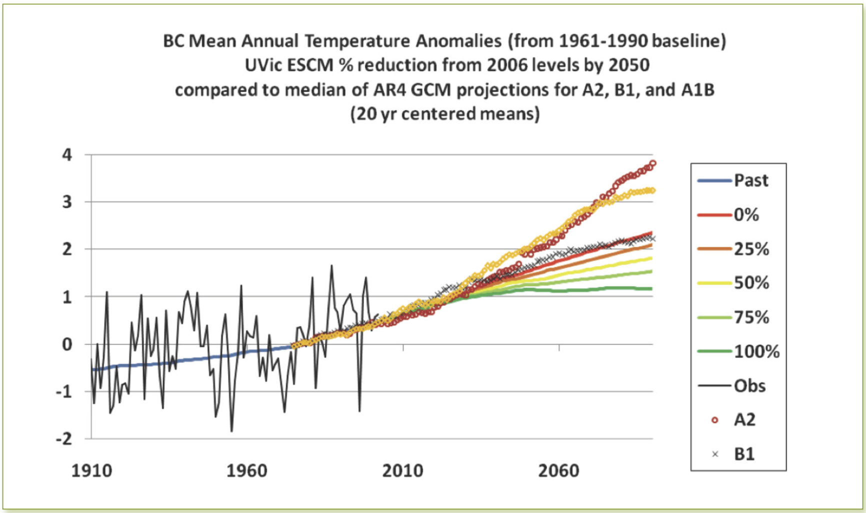

Figure 6 | British Columbia Mean Annual Temperature Anomalies from 1961-1990 baseline from the UVic ESCM by 2050 for five emissions scenarios (% reduction from 2006 levels) compared to median of AR4 GCM projections for A2, B1, and A1B displayed as 20-yr centered means to remove annual and decadal variability. The 100% reduction (green line) indicates carbon-neutrality (i.e. net zero global emissions) by 2050 – this may be considered a best case scenario for mitigation. ESCM projections provided by Ed Wiebe and Mike Eby of the UVic Climate Modelling Lab.

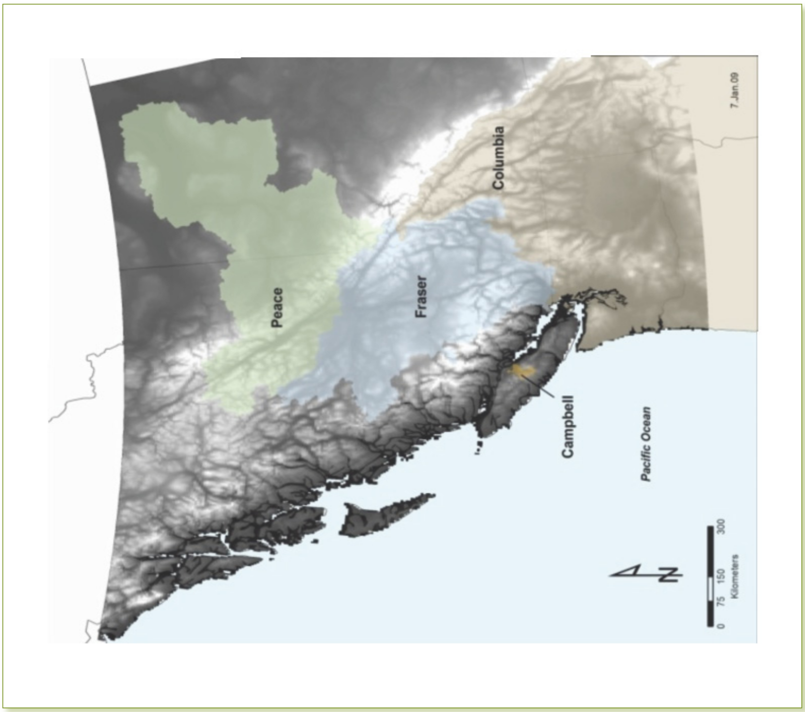

Figure 7 | Watersheds under investigation within the scope of the VIC hydrologic impacts project.

Figure 8 shows the change in the climate envelope for spruce in British Columbia by the end of the century based on a principal components analysis of three species of spruce combined (Engelmann, white, and their hybrid) according to current tree locations in British Columbia, Alberta, Washington state, Yukon, and Northwest Territories. The figure on the left shows a significant contraction of the range of climatic suitability for spruce by the end of the century, with some gains at elevation and in the north based on an average of 10 GCM projections. The results from individual projections vary considerably from each other and this uncertainty can be paralyzing to adaptation decision-making. The agreement between GCM results is also shown in the figure on the right so that a risk management approach can be taken. The darker shades of green and brown show increasing agreement between GCMs on suitability and unsuitability of the climatic envelope for spruce, respectively.

Finally, community assessments have been undertaken in collaboration with several stakeholders (e.g. Werner and Murdock, 2008). In each case the Pacific Climate Impacts Consortium staff provides analysis of past and future climate conditions along with interpretation, in order to facilitate adaptation by stakeholders. Each project requires a stakeholder partner, results in a climate impacts assessment report, and in each case different regional priorities are investigated. In addition to presenting analysis centred over smaller regions of British Columbia and the Yukon, a common feature to each project has been an attempt to go beyond annual average temperature and precipitation into parameters that will be more meaningful for adaptation. One example of this is shown in Figure 9: changes to frost free period in the Cariboo-Chilcotin region from one GCM.

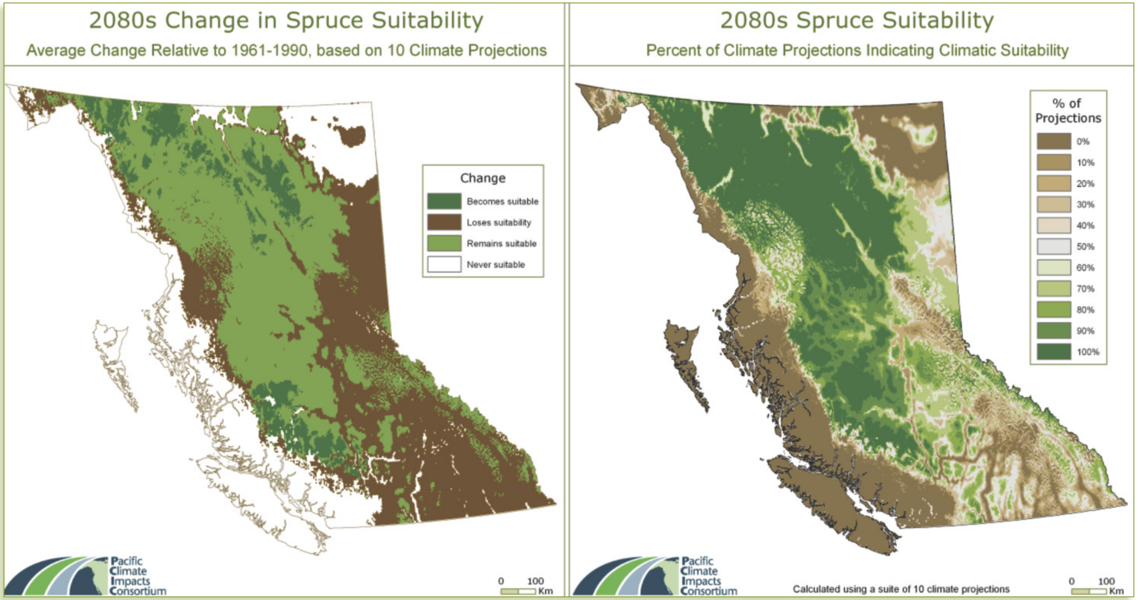

Figure 8 | Change in climatic suitability for Spruce by the 2080s based on an average of 10 Global Climate Models. The figure on the left shows areas that become suitable that were not previously (dark green) and areas that lose suitability that were suitable previously (dark brown). The figure on the right shows the percentage of the 10 projections that showed suitability: darker green indicates more agreement on suitability, darker brown indicates more agreement on unsuitability.

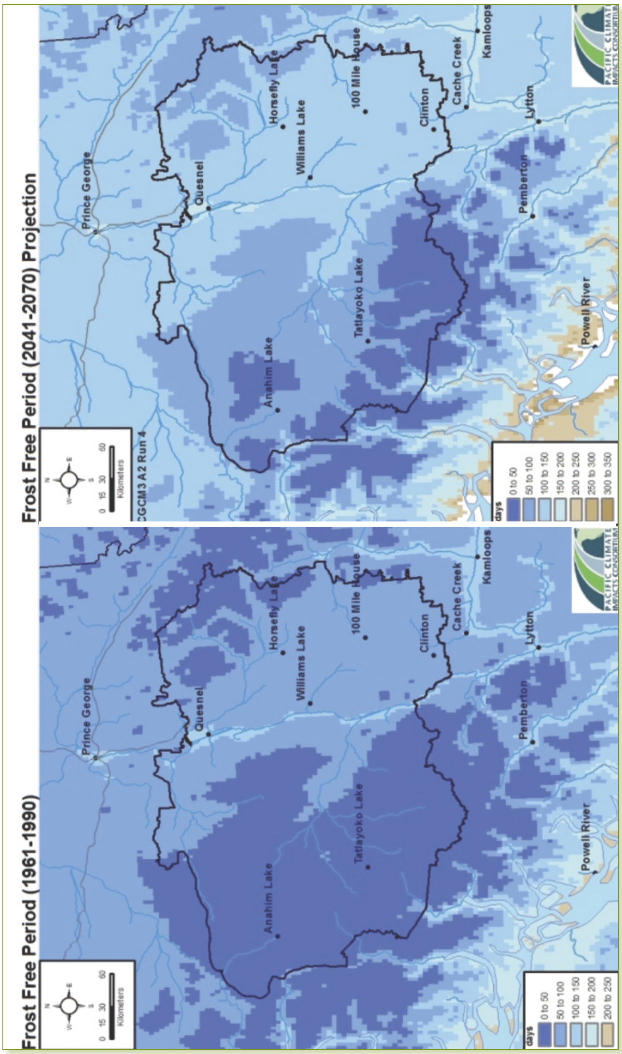

Figure 9 | Historical and future projected frost free period. Data sources: ClimateBC (University of British Columbia), PRISM (Oregon State University), and Coupled Model Intercomparison Project 4 (Lawrence Livermore National Laboratory).

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10

Atlantic Region Adaptation Science Activities

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Abstract: On the Atlantic coast of Canada, the predicted effects of climate change, such as sea-level rise and the increased occurrence and intensity of extreme weather events, are compounded in many areas by post-glacial crustal subsidence, leading to increased coastal erosion and flooding. This places dykelands, coastal populations and their infrastructure and industries at risk. Trends in hydrologic data are already beginning to appear in New Brunswick hydrometric records to support the predictions of local climate scenarios developed using statistical downscaling from global models. Ice on lakes, rivers and along the coast is forming later, mid-winter break ups are occurring more often and the dates of spring floods have advanced to earlier in the year. Saltwater intrusion into freshwater aquifers is a growing concern as coastal municipalities and industries work to achieve a balance between changing demands and availability. Impacts to municipal water supplies, agriculture, forestry, fisheries, tourism and energy are also expected as water resources come under increased pressure. The predicted regional impacts of climate change assembled from the general scientific literature and the work presented at jurisdictional expert conferences and workshops held in New Brunswick are summarized. Recognizing the importance and benefits of working collaboratively on regional adaptation issues, the Atlantic Provinces have adopted a Climate Change Adaptation Strategy. Within the framework of this Atlantic Adaptation Strategy, and as part of the Natural Resources Canada Regional Adaptation Collaboration Program, a number of projects, informed by science, are being proposed by the Atlantic Provinces. These projects are intended to develop tools and approaches that will support appropriate adaptation planning and decision making for coastal areas, inland waterways and for related infrastructure. between Environment Canada and various universities across Canada.

Keywords: adaptation, climate change, infrastructure, statistical downscaling, Atlantic Canada, sea-level rise, flooding, regional collaboration

1. Introduction

The scientific consensus is that climate change due to human activities is occurring now, and will become more pronounced in the future. The Intergovernmental Panel on Climate Change (IPCC Working Group I, 2007) have deemed the evidence of climate change as "unequivocal" as levels are observed increasing global air and ocean temperatures, widespread melting of snow and ice and rising sea level. Computer models, used to simulate the changes to the global climate induced by human activities, predict that the climate will become warmer, as global average surface temperatures are predicted to rise between 1.1°C and 6.4 °C over the next hundred years (IPCC Working Group I, 2007). Such changes in the earth's temperature are unprecedented in the last 10,000 years.

Efforts to decrease greenhouse gas emissions are required, but these efforts will not stop further climate change from occurring. Climate changes have already begun and will continue throughout the 21st century, thereby affecting our natural environment and resources significantly. What may appear to be relatively small changes in temperature are linked to substantial changes in the physical environment. Changes in weather and climate have numerous ancillary effects on other vital aspects of the total environment such as the water cycle, vegetation, pests, diseases, fire risk, floods and droughts, food production, and human health. Therefore, changes induced by climatic change will have a significant effect on the health and economic well-being of all Atlantic Canadians. Adaptation to changing environmental conditions is necessary to lessen the effects of climate change.

In the Atlantic region, unlike other parts of Canada, the predicted effects of climate change, such as sea-level rise and the increased occurrence and intensity of extreme weather events, are compounded in many coastal areas by post-glacial crustal subsidence. This will increase coastal erosion and flooding, placing dykelands, coastal populations and their infrastructure and industries at risk.

Scientific work (including monitoring, research, special investigations, and a review of scientific literature) provides an understanding of the many risks posed by climate change, which natural and human systems are likely to be most vulnerable, and what might be achieved by adaptive responses. This scientific work, commonly referred to as adaptation science, is required in the immediate future to provide a sound basis for policy, planning, and program delivery aimed at offsetting the impacts of climate change.

This report focuses on adaptation science activities conducted previously in Atlantic Canada (the provinces of New Brunswick, Newfoundland and Labrador, Nova Scotia, and Prince Edward Island) and identifies areas in need of future research to identify the consequences of climate change and potential adaptation responses. The following section summarizes climate projections to the end of this century for Atlantic Canada, and more specifically New Brunswick, based on the results of statistical downscaling of global climate models. The subsequent section provides an overview of the changes already being observed in Atlantic Canada based on an examination of historical climate records. This is followed by a summary of the predicted regional impacts of climate change assembled from the general scientific literature and the work presented at jurisdictional expert conferences and workshops. The last two sections of the report present an overview of the Atlantic Canada Climate Change Adaptation Strategy and the project areas being addressed as part of the Natural Resources Canada Regional Adaptation Collaboration Program.

2. Climate Projections for Atlantic Canada

Although future climates cannot be predicted with certainty, confidence in many aspects of climatic prediction is growing as global climate models become more advanced.

At present, the prediction of future climates is largely based on coarsely gridded global climate models that are being developed by researchers around the world for various greenhouse gas emissions scenarios (IPCC Working Group I, 2007). In order for these models to be of use at a regional and local scale, statistical downscaling techniques based on historical climate observations are commonly used. This method enables more detailed local-scale predictions to be elaborated on from relatively coarse global climate models outputs [i.e., the reliability of predictions improve as "predictions" of past climate improve].

Swansburg *et al.* (2004) and Lines *et al.* (2006) developed statistical downscaling model outputs of the first version of the Canadian Global Climate Model (CGCM1) in order to generate local climatic scenarios for New Brunswick and the Atlantic region respectively. While their work was based on the first generation of climate change scenarios, these efforts have been major contributions to climate change prediction in Atlantic Canada and have provided some of the most detailed predictions of future climatic conditions for the region to date.

Local climate scenarios for New Brunswick

Swansburg *et al.* (2004) generated local hydro-climatic scenarios for seven meteorological stations in New Brunswick for the period of 2010 to 2099. Using the

CGCM1 with, what was hoped to be a worst-case scenario of tripling of carbon dioxide concentrations over pre-industrial levels by 2100, They predicted that annual and seasonal maximum and minimum air temperature would increase significantly across New Brunswick throughout the 2020's, 2050's and 2080's compared to conditions during the period 1961 to 1990. They estimated that the annual minimum air temperature would increase by approximately 4 to 5°C, while maximum air temperature would increase by approximately 4°C, with larger increases in air temperature at central New Brunswick stations than in northern or southern regions of the Province. Seasonally, increases up to 6°C were estimated in maximum spring air temperature and minimum winter air temperature.

The authors predicted that, compared to current climate conditions, total annual precipitation would increase from 2010 to 2099 by 25 to 50% by the 2080's at northern and central stations and by 9 to 14% at southern stations. Throughout most of the province, winter precipitation would increase, and, given the warmer temperatures, some of this increase may be in the form of rain rather than snow.

In addition to temperature and precipitation, they performed downscaling of New Brunswick hydrometric records. Using this approach, they projected that average annual discharge would increase by 16 to 45% in New Brunswick by the 2080's compared to average discharge conditions from 1961 to 1990. Winter and spring discharge will increase significantly at all hydrometric stations, with the largest increases likely towards the end of the 21st century. Summer discharge will decrease significantly at all stations, while autumn discharge was predicted to decrease significantly in all rivers except the upper Saint John and Restigouche. An increase in flood magnitude and frequency was predicted for New Brunswick (Swansburg *et al.*, 2004).

Local climate scenarios for the Atlantic region

Statistical downscaling was used by Lines *et al.* (2006) to generate local climatic scenarios for 14 meteorological stations located across all four Atlantic Provinces. Using the CGCM1, with a less extreme emissions scenario (GHG+A1) than that used by Swansburg *et al.* (2004), they also developed seasonal and annual projections for the 2020's, 2050's and 2080's. Their projections indicated a consistent rise in maximum and minimum air temperatures across the region, with the exception of Labrador, where temperatures were predicted to decrease slightly. They estimated that in Atlantic Canada the mean annual minimum air temperature would increase by 5°C, while the mean annual maximum air temperature would increase by approximately 4°C.

They projected that by the 2080's, winters will become 4 to 6 % wetter and summers will become 8 to 18 % wetter than the base climate of 1961 to 1990.

Average annual precipitation was projected to rise by 8 to 20% in Atlantic Canada, except over northern Nova Scotia and eastern New Brunswick, where decreases of approximately 5% were projected (Lines *et al.*, 2006).

Recent work

As part of the recent Canada-wide study, From Impacts to Adaptation: Canada in a Changing Climate 2007, a summary of climate projections based on a suite of seven global climate models was presented in the chapter on Atlantic Canada by Vasseur and Catto (2008). Largely due to the work of the Canadian Climate Change Scenarios Network (CCCSN), the outputs of various global climate models developed by researchers around the world are now accessible on-line for use in the development of climate change scenarios for impacts studies of user specified sites (Barrow *et al.*, 2004). The work presented by Vasseur and Catto (2008) illustrates a recent shift towards looking at suites of several climate models rather than focusing on more detailed downscaled projections from just one model (e.g. Swansburg *et al.*, 2004; Lines *et al.*, 2006).

By examining the projections for the 2080's from a suite of global climate models, Vasseur and Catto (2008) were able to project a change in the average annual temperature of approximately 4°C and an increase in annual precipitation of approximately 7 to 8% above 1961 to 1990 levels for Atlantic Canada. Seasonally, New Brunswick, Nova Scotia and Prince Edward Island are predicted to experience an increase in mean annual temperature of 2 to 4°C in summer and 1.5 to 6°C in winter during the next 50 years compared to observed conditions from 1961 to 1990 (Vasseur and Catto, 2007). Newfoundland and Labrador are also predicted to experience smaller increases than in the other Atlantic Provinces due to the influence of the Labrador Current and the North American Oscillation on climate patterns (Vasseur and Catto, 2007).

3. Observed Impacts of Climatic Changes in Atlantic Canada

At present, we know temperatures have increased over the past century by an average of 1.3°C across Canada (Environment Canada, 2009), extreme precipitation events have become more frequent, and the ice regime on lakes and rivers has changed and will likely continue to change.

Trends are beginning to appear in hydrometric records that support the predictions of local climate scenarios developed using statistical downscaling. Flooding and ice jamming of inland waterways, and sea level rise and storm surges along coastlines, are two key areas where impacts are occurring in Atlantic Canada and where the observed trends are consistent with climate change.

Inland Waters

Climatic change was given serious consideration following the major 1987 ice jam floods along the Saint John River (Beltaos, 1999; Hare *et al*., 1997). Although no overall trends in mean annual precipitation or stream flow were detected at the time, both appeared to have become more variable since 1950. Freshets had generally started earlier since 1972. There were also several years with high flow, when compared with periods earlier in the century. Only a small rise of spring temperatures was detectable, but snowy or wet winters, coupled with greater variability in temperature, caused earlier thaws and several major flooding and ice-jam events.

Hare *et al*. (1997) stated that one-day heavy rain or snowfall events had increased in intensity over the Saint John River Basin since 1872. Major precipitation events, not always associated with tropical disturbances crossing the region, occasionally occurred in late summer and fall. A further conclusion was that large amounts of precipitation might also occur during the period of spring ice breakup and flooding in New Brunswick, dramatically exacerbating the resulting flood (Hare *et al*., 1997), as demonstrated by the flooding of the Saint John River Basin in the spring of 2008.

In 2008, R.V. Anderson Associates Limited examined the records of 13 hydrometric stations in New Brunswick over the period of 1969 to 2006 to ascertain if significant trends in selected hydrologic parameters attributable to climate change could be detected. They found that trends in hydrologic data are beginning to appear in the hydrometric records, with the most significant changes occurring during the past few decades; climate change was surmised to be a plausible explanation for this observation. Statistical analyses confirmed previous observations that the dates of spring flooding had advanced to earlier in the year. Trends in the data also indicated that the number of mid-winter ice breakup events had increased over the period of record, and that ice regimes in New Brunswick are less stable, leading to more uncertainty about ice jamming conditions.

From an engineering perspective, an increased frequency and severity of river ice movement and jamming could increase the possibility of infrastructure being damaged or destroyed by the erosive power of the ice (Beltaos and Burrell, 2003). The apparent increasing instability of ice regimes in New Brunswick, combined with the potential for major storms to occur simultaneously with the spring thaw and the onset of the freshet, confirms a need for adaptation along inland waters to lessen the likelihood and severity of future flood damages.

Further work should be undertaken to compare the hydrometric records in the other Atlantic Provinces to see if similar trends are also occurring there.

Coastal Areas

As detailed in Vasseur and Catto (2008) and Daigle *et al.* (2006), storm surges have resulted in property destruction and erosion along coastal areas in all four Atlantic Provinces in the past 15 years. The most notable of these was the benchmark Atlantic storm event of January 21, 2000, declared a disaster by the Federal Government of Canada.

Atlantic Canada (with the exception of northern Labrador) is undergoing isostatic subsidence and tilting as a result of glacial loading and unloading at the end of the last glaciation (Daigle *et al.*, 2006). The observed rate of relative sea-level rise is therefore a result of the combined effects of global sea-level rise and subsidence, and is greater for Atlantic Canada than the current global rate of 17 cm per century (Daigle *et al.*, 2006).

Based on current estimates, a relative sea-level rise on the order of 60 cm is expected for Atlantic Canada over the coming century (Daigle *et al.*, 2006; IPCC, 2007). This will result in more frequent flooding of low-lying areas, currently prone to flooding, but also in flooding of higher, previously immune areas that currently host critical infrastructure (Daigle *et al.*, 2006; Vasseur and Catto, 2008).

Currently, a water level in excess of 3.6 m above Chart Datum (CD), similar to the January 21, 2000 event, occurs approximately once every 100 years in the southern Gulf of St. Lawrence (Daigle *et al.*, 2006). Based on climatic predictions, researchers surmise that the frequency and severity of these events will increase with global warming and the associated sea level rise. At the present rate of relative sea level rise, Daigle *et al.* (2006) predict that by 2100 a storm-induced water level of 3.6 m above CD could occur statistically every 10 years in the Southern Gulf of St. Lawrence.

Sea level rise threatens not only coastal infrastructure, but also fragile ecosystems and natural resources such as wetlands and freshwater aquifers. Saltwater intrusion of freshwater aquifers is a growing concern as municipalities and industries work to achieve a balance between changing demands and water availability in coastal areas. The impact of sea level rise and a changing hydrology regime on the saltwater/freshwater interface in coastal areas is poorly understood at this time and is an area in need of future research.

4. Summary of Expert Meetings on Climate Change

Since 2003 New Brunswick has hosted a number of meetings and workshops attended by jurisdictional experts from New Brunswick and other Atlantic Provinces dealing with climate change adaptation. These meetings and workshops have increased our understanding of the anticipated impacts of climate change in the region and have helped to identify regional adaptation priorities.

In November 2003, a two-day meeting was held in Fredericton to discuss adaptation to climatic change as it applies to New Brunswick water resources. Attended by more than 30 water resource managers, environmental specialists and experts on climate change, the meeting concluded that New Brunswick (and also Atlantic Canada) faces many challenges to adapt to climate change. This meeting began the process of quantifying the possible impacts of the changing climate on the region.

The principal recommendations from this meeting (Riley Environment Limited, 2004) follow:

- Continuation of monitoring river, groundwater, and climate-related parameters;
- Development of an accurate inventory of water resources (including supply and usage) to enable effective management;

- Development of provincial water use policies and resource management programs that recognize the value of water;
- Development, as a high priority, of an adaptation strategy, to enable the province to plan for the inevitable and substantial impacts expected from climate change;
- Revision of infrastructure design criteria to reflect changes in climate;
- Coordination of efforts of various federal and provincial government agencies;
- Public education on the expected effects of climate change on water resources; and
- Encouragement of better use and conservation of water resources.

A further technical meeting of experts in the areas of water and natural resource management, fisheries, climatology, civil engineering and ecology took place at the Université de Moncton, New Brunswick in 2004. The title of the event was: "Climate Change Impacts and Adaptation: Water Resources and Fisheries in New Brunswick".

The scientists at this meeting reconfirmed the conclusions and recommendations made at the November 2003 conference. Presentations on science and policy, in particular the reality of having to "plan for uncertainty", made it clear that decisions have to be made now, bearing in mind what is already known. This was summed up as: "It's happening, what are we going to do about it?" Integrated planning, taking a whole ecosystem approach, and making decisions on a basis of sound science, were all emphasized.

Based on the information assembled by drawing on the general scientific literature, and the work presented at the New Brunswick expert conferences and workshops held from 2003 to 2008, the sectors predicted to be most affected by climate change in Atlantic Canada are precipitation and water resources; ecosystems and biodiversity; fisheries and aquaculture; coastal zones; agriculture and horticulture; forestry; air quality; health; and sustainable development. Tables detailing the predicted effects of climatic change in each of these sectors, along with an indication of the relative degree of confidence, are given in Appendix I. Major areas that were not dealt with explicitly included energy production, transportation, manufacturing, and the retail and service industries (including insurance).

During the development of the chapter on Atlantic Canada (Vasseur and Catto, 2008) for the Natural Resources Canada report, From Impacts to Adaptation: Canada in a Changing Climate 2007, coastal areas, inland waters and related infrastructure were identified as priority areas for adaptation to climate change in Atlantic Canada. In May 2008 the New Brunswick Department of Environment in collaboration with the three other Atlantic Provinces and in partnership with Natural Resources Canada hosted a Climate Change Adaptation Workshop in Saint John, New Brunswick. The workshop was attended by climate change and adaptation scientists and researchers from the four Atlantic Provinces and all levels of government. The presentations and discussions focused on three priority areas, summarized below.

Coastal Areas

Sea-level rise is expected to increase coastal flooding, storm surge effects, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of our coastal communities. Coastal zone impacts are expected to affect local resources, for example through erosion of beaches and salt water intrusion of drinking water wells.

Inland Waters

Later arrival of freeze-up and more mid-winter break-ups of river ice will occur. Spring break-up has advanced to earlier in the year and the number of ice-free days has increased. Inland water resource impacts include fluctuating groundwater recharge and lower summer groundwater levels, plus surface and groundwater quantity and quality changes. Water availability is an example of a critical component which will be impacted by climate change. It is predicted that the Atlantic region will receive more total precipitation; however it is expected to arrive in the form of more intense storm events. The ability to adapt to flood and drought conditions must be developed.

Infrastructure

Infrastructure-based components of our economies and social networks (transportation, wellness and culture, public services) will be altered by changes to climate. The understanding of how predicted changes to climate will affect these infrastructure resources, and therefore, our economy is a critical part of planning the future.

5. Atlantic Climate Change Adaptation Strategy

Coming out of the 2008 workshop, the Council of Atlantic Environment Ministers (CAEM) identified climate change, and especially climate change adaptation, as a key environmental issue for Atlantic Canada. Recognizing the importance and benefits of working collaboratively on regional adaptation issues, and based on the recommendations from previous expert meetings on climate change, the CAEM agreed to collaborate on a Climate Change Adaptation Strategy for Atlantic Canada in June 2008.

Principles and Goals

1. To enhance the resilience and adaptive capacity of Atlantic Canada communities to climate change.
2. To integrate climate change adaptation measures through climate proofing in existing and development activities.
3. To promote meaningful regional collaboration, co-ordination and sharing of good practices on the integration of climate change adaptation in development decisions.

Key Result Areas

Recognizing the complex inter-relationships and linkages among the principles and goals of the strategy, three key result areas for action were identified under the Atlantic Climate Change Adaptation Strategy.

1 - Indentifying Climate Risks

An important first step in adaptation to climate change is the identification and quantification of the risks associated with climate change. Once quantified, it is then possible to begin to build tools to ensure the resilience of both natural and man-made environments to these risks.

2 - Climate Proofing Decisions

Climate proofing decisions in Atlantic Canada refers to assisting partners in their efforts to reduce their risks and vulnerability to climate change. Seeking opportunities from climate variability where they exist is also a component of climate proofing decisions.

3 - Regional Collaboration
Establishing a Regional Adaptation Collaborative with an organizational body to oversee its implementation, and focusing on the common priority Atlantic region issues of: coastal areas, inland waters and infrastructure.

6. Atlantic Regional Adaptation Collaborative Program

In June, 2008 all four Atlantic Ministers of the Environment formally agreed to work collaboratively on adaptation to climate change. The provinces have assembled a team of professionals, scientists and partners in engineering, land use planning and municipal administration interested in helping communities incorporate adaptation to climate change into decision making. Within the framework of the Atlantic Adaptation Strategy, and as part of the Natural Resources Canada Regional Adaptation Collaborative Program (RAC), this collaborative will aid in building on the existing and well-functioning networks that exist in the Atlantic region, as well as in identifying opportunities, filling gaps and removing barriers to adaptation. As part of the RAC, a number of projects have been proposed that would develop tools and approaches to enable appropriate adaptation planning and decision making in the three previously identified priority areas of inland waterways, coastal areas and their related infrastructures.

As proposed, the Atlantic RAC will extend collaboration beyond the four Atlantic Departments of Environment to include the Atlantic Planners Institute, the four Atlantic Engineering Associations, the Atlantic Municipal Associations, the Insurance Bureau of Canada and Natural Resources Canada. The aim of the Atlantic RAC is to foster collaborative work that will produce applied solutions to existing problems that relate to environmental change.

The New Brunswick Department of the Environment is the lead agency for climate change adaptation in New Brunswick and has taken on the lead role in the development of the Atlantic RAC. In this capacity the Department has been leading the development of an Atlantic Canada proposal to the Natural Resources Canada Regional Adaptation Collaborative Program.

7. Conclusions

Uncertainties exist about the magnitude and consequences of climatic change, especially at the local scale. However, Atlantic Canada is being, and will continue to be impacted by a changing climate. Coastal communities and habitats, inland water resources in terms of quality and quantity issues, and infrastructure such as transportation and communications networks and water and wastewater infrastructure will be stressed increasingly by climate change impacts.

Approaches to risk and vulnerability management must be developed to protect current and future development, communities, our economy and critical natural features from impacts associated with climate change. Development should be based on principles that consider weather extremes, environmental conditions, and matters of public safety. Decision making at all levels of government and support mechanisms to those processes (e.g. regulation and policy) should seek to guide development to appropriate locations that reduce or remove public risk and increase their resilience to a changing climate.

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APPENDIX I

Predicted Impacts of Climate Change in Atlantic Canada

A list of the effects of climatic change that are expected in Atlantic Canada is given in the following tables. This information has been assembled by drawing on the general scientific literature, and takes into account the work presented at the expert conferences held in New Brunswick from 2003 to 2008. The level of confidence varies considerably between predictions, so where possible, an indication is given of the degree of confidence for each item. This involves professional judgment but is still useful when interpreting the information.

The categories "high", "medium" and "low" can be equated with "very likely", "likely" and "possible" probabilities of occurrence.

Table 1 | Predicted effects and implications of climatic change on weather and climate in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

WEATHER AND CLIMATE	
Predicted Effects	**Implications**
Temperatures will continue to increase on average, with a more pronounced upward trend in inland districts and in summer. **H**	Sustained or increased need for public advisories of heat-stress conditions.
The ice-free season will lengthen in most areas. **M**	Examine implications for recreation, public safety and flood risk.
The frost-free season will lengthen. **H-M**	Potential benefit, but plan for associated increased risk of new/exotic diseases affecting plants, wildlife, domestic animals and humans. Basic climatological monitoring at key trend sites must continue, and be protected for the long-term.
Snowfall and duration of snow cover likely to decrease, affecting winter recreation including skiing and snowmobiling **M**	Build climate change considerations into planning for future winter sporting developments.
"Surprise" changes **H**	A need exists for more detailed studies by federal climatic specialists to refine predictions of climatic change in eastern Canada. This is especially true for New Brunswick where competing continental and marine influences complicate predictions.

Table 2 | Predicted effects and implications of climatic change on precipitation and water resources in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

PRECIPITATION AND WATER RESOURCES	
Predicted Effects	**Implications**
The precipitation distribution through the year will change. Water supply will diminish, especially in inland districts, due to higher temperatures. **M-H**	Assess groundwater and surface water reserves in terms of sustainable yields. Promote water conservation in all use sectors, especially industry and agriculture.
Hydrological processes / water cycle will change. **H**	Ensure adequate data collection and evaluation on all components of the hydrologic cycle, including evaporation and infiltration.
The duration of dry spells between rainfall events is expected to increase, with an associated increase in drought frequency, duration, and severity. **M-H**	Carry out studies that may lead to better techniques for prediction of atmospheric or hydrologic drought.
Precipitation patterns will become more erratic, with an increased frequency of intense storm events, such as summer convective storms (thunderstorms, hailstorms and tornadoes). Associated impacts from erosion and siltation. **M-H**	Ensure appropriate agencies maintain adequate forecasting capability and emergency preparedness.
River flows will become more variable. Spring peak flows will occur earlier and be reduced in duration. Summer minimum flows will be lower. Periods of very low or zero flow are expected to become more frequent. **H**	Carry out updated hydrological modelling for NB, to examine the details of the altered hydrological regime.
Flooding may become more frequent and more severe. Mid-winter thaws and ice breakups, with the potential for ice-jam flooding, will become more widespread and frequent, resulting in more ice jam floods during the winter months. If the mid-winter jams re-consolidate, then spring ice breakup is likely to have more severe impacts. **M-H**	Using an updated hydrological analysis, produce updated flood hazard mapping for the province to assess critical areas at risk. **Note:** existing hydrologic relationships based largely upon the assumption of a homogeneous period of record may underestimate peak flows used for bridge and culvert design. A safety factor may have to be added during design to take into account the hydrologic uncertainties caused by climatic change.
Aquatic ecosystems will change as water levels become lower and water temperatures become higher during the summer months. Algal blooms and eutrophication expected to increase. **M-H**	Ensure continued monitoring; identify critical habitats; continuously evaluate effectiveness of nutrient management activities.

Table 3 | Predicted effects and implications of climatic change on ecosystems and biodiversity in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

ECOSYSTEMS AND BIODIVERSITY	
Predicted Effects	**Implications**
Altered ecosystem characteristics and productivity. Some species and ecosystems may be reduced or disappear altogether, causing a loss of biodiversity. **H**	Critical species and habitats need to be identified and plans put in place for protection.
Cold-water species such as salmonids will become increasingly stressed as water levels become lower and water temperatures become higher during the summer months. Suitable freshwater habitat for some aquatic species, such as salmonids, may be lost. Increased water temperatures and reduced dissolved oxygen is expected to harm cold water fish species. **M-H**	Ensure continued monitoring; identify critical habitats.
Shrinkage of boreal/alpine zones with reduction in associated habitat, threats to survival of associated biota. **H**	
Invasion of new (”exotic”) plants and animals extending their ranges into NB. **H**	Plan for appropriate surveillance and management.
Increased fire hazard expected to threaten key habitats and associated species. **M-H**	Examine options for enhanced protection of critical habitats.
Low river flows in summer and increased water temperatures will threaten cold water aquatic life. **H**	Consider greater management efforts on species that can better tolerate warmer water.
Increased frequency of extreme weather events (especially windstorms, droughts, and increased winter freeze-thaw activity) expected to pose significantly increased stress on forest and other ecosystems. **M-H**	Examine options for enhanced protection of critical habitats (also, see under forests).

Table 4 | Predicted effects and implications of climatic change on coastal zones in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

COASTAL ZONES	
Predicted Effects	**Implications**
Mean sea level will continue to rise, increasing the likelihood of (a) coastal flooding, (b) drainage problems with urban infrastructure draining to tidal estuaries. **H**	Ensure coastal development proceeds taking into consideration projected environmental changes.
Increased rates of coastal flooding and erosion due to more extreme weather events, higher water levels (including storm surges), and less protection against waves being provided by sea ice. Associated effects on coastal infrastructure. **M-H**	Consider planning for managed retreat or engineered protection of critical areas prone to erosion.
Sea-level rise and changes in precipitation could alter coastal marshes and cause detrimental changes to coastal ecosystems. **M**	Evaluate coastal areas of potential risk based on projected sea level rise, topographical information (e.g., existing mapping), and ecological assessments.
Increased risk of salt intrusion and contamination of coastal aquifers, due to increasing sea levels and increased pumping from inland aquifers for irrigation. **H**	Evaluate sustainability of coastal drinking water aquifers and plan for future new supplies as required.

Table 5 | Predicted effects and implications of climatic change on fisheries and aquaculture in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

FISHERIES AND AQUACULTURE	
Predicted Effects	**Implications**
Inland aquaculture may suffer from reduced water quantity and quality due to lower summer flows, reduced water availability and higher water temperatures. **M-H**	Evaluate water resource availability using updated hydrological analyses. Develop a strategy for reducing water use in aquaculture.
Increased pest and disease problems, affecting inland and coastal fisheries (including shellfish). **M**	Plan and operate operations to minimise potential effects of new or increased pests/diseases. Improve fish/shellfish health monitoring programs.

Table 5 cont. | Predicted effects and implications of climatic change on fisheries and aquaculture in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

FISHERIES AND AQUACULTURE	
Predicted Effects	**Implications**
Recreational angling likely to be affected by low summer river flows, changes in the ice season and changes in species abundance. Fishing seasons may change (timing, duration). **M-H**	Plan additional protection measures as required to maximise the potential for the survival of desired species. Develop alternative recreation and tourism strategies (e.g. to account for reduction of recreational fishery).
Salmonids increasingly vulnerable due to higher water temperatures and lower summer flows. **M-H**	Identify critical salmonid habitat for protection, emphasizing stream vegetation buffers and protection of water resources.

Table 6 | Predicted effects and implications of climatic change on forestry in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

FORESTRY	
Predicted Effects	**Implications**
Increased fire hazard. **H**	Promote appropriate forest fire risk prevention and mitigation measures.
Increased risk of wind damage. **M-L**	Strategic planning to anticipate and mitigate effects of wind damage.
Increased risk of destructive pests and diseases. **M-H**	Ongoing monitoring and scientific studies of destructive pests and diseases. Development of forest management practices to lessen or adapt to higher pest damages.
Longer growing season and higher CO_2 may stimulate growth, but limited overall benefit due to poor soils and increased drought stress. **H**	Ongoing trials required of species or varieties with potentially improved adaptation to drought, higher temperatures, or higher CO_2.
Changes in regeneration, reproduction, and fitness for some species, and a potentially changing species mix. **M-H**	Ongoing scientific studies required to assess the probable impact of changing atmospheric conditions on regeneration, growth, reproduction, and survival.
Increased incidence of freeze-thaw winter injury. **M**	Ongoing scientific studies required to assess the probable impact of freeze-thaw winter injury on tree survival and associated forest decline.

Table 7 | Predicted effects and implications of climatic change on agriculture and horticulture in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

AGRICULTURE AND HORTICULTURE	
Predicted Effects	**Implications**
Probability of summer water shortages will increase, creating a greater need for irrigation in New Brunswick's potato belt and possibly in other areas. **H**	Evaluate groundwater resources in agricultural areas and the potential impacts of long-term irrigation.
Increased irrigation may be problematic in some areas due to local water chemistry.	Plan for additional water testing for irrigation suitability (e.g. sodium absorption ratio testing).
More summer rainfall is expected to fall in high intensity rainfall events. This means an increased probability of soil erosion. **H**	Promote conservation practices in agriculture, forestry and horticulture that protect against soil erosion.
Longer frost-free season and higher mean temperatures (most likely in inland districts, less certain in coastal areas) may allow new crops to be grown or increased productivity of some existing crops. **M-L**	Evaluate options for trial or introductions of new crop species or varieties.
Potential for increases in pests and diseases, including novel or exotic varieties. **M-H**	Planning required to anticipate and mitigate the impacts of new pests, diseases.
Increased heat stress for livestock, especially in intensive operations. **M**	Anticipate and mitigate the impacts of higher heat stress.

Table 8 | Predicted effects and implications of climatic change on air quality in Atlantic Canada (degree of confidence: **H** = highest, M = intermediate, **L** = least).

AIR QUALITY	
Predicted Effects	**Implications**
Hotter summers are expected, with an increased frequency of smog episodes. **H**	Maintain focus on NO_X and VOC controls, plus public advisories of poor air quality episodes.
Increasing temperatures will lead to an increased flux of VOCs in to the atmosphere from natural and other sources (approx 20% increase per degree Celsius). **H**	Maintain priority on effective VOC controls (industries and transportation) and promote cleaner energy sources.

Table 8 cont... | Predicted effects and implications of climatic change on air quality in Atlantic Canada (degree of confidence: **H** = highest, M = intermediate, **L** = least).

AIR QUALITY	
Predicted Effects	**Implications**
Changes may occur in atmospheric circulation that influence the long-range transport of air pollutants. **M-L**	Maintain monitoring programs to detect and understand changes.
The emission of air pollutants associated with electrical generation may change as heating and cooling demands change (increased demand in summer, lessening demand in winter). **M-H**	Additional potential for exacerbation of summertime smog episodes: maintain monitoring and assessment networks, promote energy smart buildings to offset increased summer demands.
Forest fires expected to be more frequent and larger, increasing the associated emissions of VOCs and particulate matter. **M-H**	Maintain air quality tracking and advisory programs; need for health studies to understand the significance of additional risks and their effects.
Changes in the nature of pollen, dust and spore concentrations are expected in response to warmer weather, possibly synergised by higher CO_2 and humidity. **M**	Maintain monitoring of key indicators to track and understand the nature of changes, and provide input to health management.

Table 9 | Predicted effects and implications of climatic change on human health in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

HUMAN HEALTH	
Predicted Effects	**Implications**
Increase in conditions relating to heat stress, possible exacerbation of air pollution related stresses. **M-H**	Provide adequate advisories and mitigation.
Increase in probability of bacteriological contamination of food and water. **M**	Increased need for surveillance and inspection programs.
Increase of vector-borne diseases. **M**	Increased surveillance and testing of swimming areas and wildlife vectors.
Possible decrease in cold-related conditions, frostbite, hypothermia (complicated by changes in activities and behaviour). **M-L**	Uncertain; anticipate shifts in recreational activity patterns.

Table 10 | Predicted effects and implications of climatic change on sustainable development in Atlantic Canada (degree of confidence: **H** = highest, **M** = intermediate, **L** = least).

SUSTAINABLE DEVELOPMENT	
Predicted Effects	**Implications**
Changes in climatic conditions (such as rainfall intensity, duration and frequency) might make some land (e.g. flood plains, steep sites) unsuitable for some types of development, and might require changes in development patterns and the types of development. **M-H**	Carry out the studies necessary to identify and evaluate potential hazards. Use community planning and landscape design tools to lessen the exposure and susceptibility of future development to potential natural hazards created or enhanced by climatic change. Promote land stewardship for critical areas and areas subject to erosion. Place special attention in terms of land use planning on appropriate development in areas prone to riverine or river ice flooding.
Drinking water quality will likely be affected by the change in the quantity and quality of water at the source, as well as from the problems of old water infrastructure. **H**	Examine the adequacy of drinking water supplies and supply systems in terms of quantity and quality. Review source water protection programs for effectiveness.
Urban drainage infrastructure will be overloaded more often. Associated risk of contamination from sewage. **M**	Review basic municipal drainage infrastructure. Assess the risk of urban flooding, and associated water contamination, due to urban drainage infrastructure becoming over-loaded more often. Promote design of urban development that minimizes runoff and maximizes natural infiltration so as to replenish aquifers.
Due to changing climatic conditions, municipal or coastal infrastructure designed to have long life spans might be damaged or become incapable of functioning properly **M**	Assess existing infrastructure with remaining long service lives and renovate/ repair if necessary. Design new infrastructure considering potential hydroclimatic changes. Develop and promote design criteria to minimize susceptibility of future. Priority should be given be given to areas such as major municipal or coastal infrastructure or other areas where the planning horizons are long and structures are designed to have long life spans.
Increased temperatures may change requirements for heating and air conditioning. **M**	Promote site layouts and building materials, designs and technologies that lessen indoor extremes of temperature.
Resource availability might change as commodity supplies and markets respond to changing environmental conditions. **L**	Carry out basic studies of the energy and material (resource) inputs and outputs to define the economic footprints of the province's urban areas, and develop appropriate conservation measures as needed.