

Changing Climate, Uncertain Futures, and Evolving Practices

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There is now consensus among climate scientists that the Earth's climate is changing and that human-induced greenhouse gas emissions are playing a driving role. Environmental practitioners are facing an ever-increasing demand from clients to incorporate climate change into future development plans and design criteria. However, there remains a large gap between the longer-term, global-scale climate predictions typically provided by the climate modelling community and the local-scale (and often synoptic) climate predictions needed by practitioners. This knowledge gap has often forced engineering design studies and environmental impact assessments to either make crude assumptions about climate change or avoid addressing it at all.

On April 21–23, 2008, the Air and Waste Management Association and Canadian Water Resources Association jointly held a three-day symposium in Vancouver, BC, to explore the gap between scientists and practitioners. The symposium brought together leading experts on the current state of climate change science and professionals who use future climate predictions in engineering and environmental studies. Twenty invited speakers addressed a wide range of climate change topics and presented an informative afternoon workshop session on climate downscaling. Links to symposium presentations can be found at www.climatesymposium.com.¹

This *Streamline* article presents a synthesis of the symposium and highlights key findings on the current state of climate change science and projected impacts for British Columbia. The article concludes with

¹Presentations will be available online for up to 1 year following the symposium.

recommendations on guidelines for including climate change into practice.

Current State of Climate Change Science

There has been tremendous effort over the past three decades to develop global climate models (GCMs; also known as general circulation models) to simulate the Earth's climate system with its complex interactions and feedback among components. Continuing research has led to ongoing improvements to model resolution, computational methods, and parameterizations, as well as better representation of greenhouse gas emissions and their impact on radiative forcings. These models have led the Intergovernmental Panel on Climate Change to conclude with 90% certainty that human activities are having a measurable effect on the Earth's climate.

The current generation of GCMs resolves a horizontal (grid cell) resolution on the order of 300–500 km and 10–20 vertical levels in the atmosphere. At this scale, British Columbia is represented by approximately 10 grid cells. Regional climate models (RCMs) offer higher resolution (about 50 km) over a limited domain of the Earth's surface, but are nested within a GCM and forced at the boundaries by the GCM results. Despite their higher resolution, RCMs rely on the same physics-based equations as GCMs and still require parameterization to address sub-grid processes (e.g., convection). Output from both GCMs and RCMs is widely available; however, the computational resources and technical expertise required to run the climate models limit their development and execution to large organizations or

government agencies such as OURANOS (www.ouranos.ca) or the Canadian Climate Centre for Modelling and Analysis (www.cccma.ec.gc.ca).

While GCM and RCM climate simulations are becoming increasingly realistic, they include many calibrated parameters. As with all calibrated models, good model performance under nominal conditions does not necessarily mean that they can accurately predict climatic response to natural or anthropogenic perturbations (e.g., rising greenhouse gas concentrations, volcanoes). In fact, many of the available GCMs do not agree with each other in the direction of change of a particular hydroclimate variable for a particular region.

Typically, climate modellers illustrate model performance using predictions of global mean temperature over recent history and the ability of the model to predict changes in the global mean resulting from major events such as volcanic eruptions. Unfortunately, these results offer little assistance to the practitioner trying to objectively determine whether a particular GCM or RCM is reliably resolving the climate system over a given spatial domain of interest. The accuracy of a GCM to reproduce synoptic-scale features is critical to the success of any downscaling technique applied to derive local-scale predictions. Alex Cannon (Environment Canada) presented recent work by Ian McKendry and others at UBC, who compared predictions from the Canadian Global Climate Model (CGCM2) with the National Centers for Environmental Prediction (NCEP) weather re-analysis product, which provides a reasonable representation of the "true" state of the atmosphere (see McKendry *et al.* 2006). For the Pacific Northwest, the authors found systematic errors in the frequency of CGCM2's prediction of Arctic outflow and Pineapple Express atmospheric circulation patterns for the historical period 1961–1989.

While practitioners will find that objective evaluations such as McKendry *et al.*'s are rare at present, the climate modelling community is looking to develop a standard set of validation

Continued on page 40

data sets so that climate models can be evaluated both spatially and temporally (Reichler and Kim 2008). This will make the evaluation of climate model predictions for a particular region more digestible for practitioners.

Future anthropogenic emissions scenarios — the alternative ways in which society might adapt and evolve over the next 100 years — are an important source of uncertainty in future climate predictions. The scenarios range from pessimistic “business-as-usual” approaches to fossil fuel consumption and population growth (“A1” and “A2” scenarios, respectively), to rapid technological change and introduction of clean and resource efficient technologies (“B1” and “B2” scenarios, respectively). Climate predictions for the first half of the 21st century are relatively insensitive to the different emissions scenarios due to the residence time of greenhouse gas and momentum of the global climate system; regardless of the choices that society makes today, the climate is predicted to warm over the next several decades. However, the choice of emissions scenario significantly influences climate predictions for the latter half of the 21st century.

The number of future climate realizations that can be derived by combining different climate models and emission scenarios can be overwhelming to a practitioner. There is no guidance from the climate modelling community on how to best integrate the model runs. The de facto approach seems to involve considering all combinations of models and emissions scenarios to estimate uncertainty for a given climatic variable, time period, and location of interest (e.g., Rodenhuis *et al.* 2007).

Most water resource assessments focus on catchment scales of about 10 to 1000 km². Global and regional climate models do not realistically represent the atmospheric forcings at these catchment scales. As a result, climate models require some downscaling to appropriately transfer information to the local scale.

A number of established methods are available to downscale climate change

projections from GCMs to the local scale. Available methods vary from simplistic approaches based on observed climatology (e.g., the “delta” method) to complex “dynamical” downscaling methods that nest climate models at ever-increasing resolutions. The practitioner chooses a downscaling technique most appropriate to the task at hand. Environment Canada’s Canadian Climate Change Scenarios Network (www.cccsn.ca) provides an excellent source of information on models, downscaling tools, and analyses for practitioners. Table 1 summarizes the strengths and weaknesses of various classes of downscaling methods based on Wilby *et al.* (2004).

Projected Impacts of Climate Change in British Columbia

In general, global climate models predict warmer conditions for British Columbia over the next century. However, prediction of future precipitation conditions are mixed and within the range of variability currently observed. Watershed managers should be prepared to manage the impacts associated with both “warm and wet” and “warm and dry” years.

While science can currently predict general climate change trends for temperature (and to a lesser extent, precipitation), numerical predictions retain a high degree of uncertainty. Some guidance is offered in the summary of historical trends and projected climate impacts conducted by the Pacific Climate Impacts Consortium (PCIC) and presented by Dave Rodenhuis (Rodenhuis *et al.* 2007; available free from the Pacific Climate Impacts Consortium Web site at www.pacificclimate.org). The PCIC report summarizes predictions for a number of hydroclimatic variables and currently represents the most significant analysis of its kind for British Columbia.

Both weather (daily to decadal) and climate (multi-decadal to centuries) in British Columbia are strongly affected by naturally occurring multi-year climate cycles such as the ENSO (El Niño–Southern Oscillation) and PDO

(Pacific Decadal Oscillation). Although analysis has determined that underlying climate change is occurring, these climate anomalies will continue to cyclically moderate or exacerbate expected climate change effects. The current generation of global climate models represents these modes of climate variability imperfectly, and practitioners should use model predictions of these low-frequency climate oscillations cautiously. In addition, the natural variability associated with these cycles should be carefully considered when assessing prediction uncertainty.

The consensus GCM prediction of warming in British Columbia is expected to impact nival and glacial hydrologic regimes most severely. This warming will reduce winter snow accumulation and lead to earlier spring freshets followed by longer, more pronounced summer low flows (Leith and Whitfield 1998). Alan Hamlet (University of Washington) showed how hydrologic models can be used to identify landscapes that may be susceptible under a changing climate. He also presented a study demonstrating that April 1 snowpacks in the US portion of the Columbia Basin will be much more sensitive to predicted climate warming than the Canadian side.

In glacier-fed basins, reduced winter accumulation and enhanced summer ablation will lead to a reduction in glacier mass and area through time. Dan Moore (University of British Columbia) presented a hypothesis representing four distinct stages of response of glacierized basins to a warming climate, as indicated by changes in late summer streamflow. In the first stage, glaciers maintain a quasi-equilibrium with the contemporary climate. In the second stage, glaciers respond to a climate warming by entering a negative mass balance and late summer streamflow increases. As glacier area shrinks in response to continued warming, continued recession no longer enhances late summer streamflow. At this third stage, late summer streamflow begins to decrease until it reaches a new and lower state of quasi-equilibrium (Stage 4) or until the



glacier disappears altogether. Stahl and Moore (2006) analyzed trends in late summer (August - September) streamflow from several hydrometric gauges in British Columbia. They found that basins with glaciers exhibited a negative trend in late summer streamflow whereas no apparent trend was evident in basins that had no glaciers present. This suggests that many glacier basins in the Western Cordillera may already be in the "third stage" of response to climate warming. A decrease in glacier meltwater contribution during late summer will have important consequences upon power generation, stream thermal regimes, and ecological assemblages.

Groundwater also plays an important role in moderating streamflow and thermal regimes. The interaction between climate, surface water, and groundwater in British Columbia is complex. Aquifer response is not only a function of the climate signal but also the interaction of surface water, recharge, aquifer properties, and anthropogenic effects (e.g., drawdown). In many parts of British

Columbia, groundwater systems are closely connected with the surface water system. Diana Allen (Simon Fraser University) used a groundwater model to illustrate the close connection between the timing and magnitude of surface water of the Kettle River with groundwater levels near Grand Forks, BC. Despite a predicted increase in annual recharge to the Grand Forks aquifer under future climate scenarios, groundwater levels are predicted to be much lower in late summer as the spring freshet on the Kettle River occurs earlier in the year. With declining summer streamflows, agricultural water demand could increase utilization of groundwater resources even at current levels. However, agricultural demand is not expected to remain constant. Projected increases in temperatures will increase agricultural water demand, especially in water-limited regions such as the Okanagan Valley. This could impact growing season length, timing of bud burst, and evaporative demand, which may favour certain crop types or varieties. Denise Neilsen

(Agriculture and Agri-Food Canada) illustrated how wineries in the Okanagan have adapted to growing more tender varieties of grapes in response to less severe winter conditions since the 1990s. Arguably of greater interest was her illustration of how continued change will move the climate beyond the region of productivity now being enjoyed, such that some varieties will become much more difficult to support.

The Intergovernmental Panel on Climate Change estimates global sea level will rise from 18 to 59 cm per century primarily due to thermal expansion of the oceans and melt contribution from major ice caps such as Greenland and Antarctica. However, if the rate of glacier melt observed on these ice caps in the past decade persists, sea level may rise a further 17 cm by the end of the 21st century. The direction of increasing sea levels is conclusive but local-scale predictions are again confounded by external factors, in this case subsidence and local tectonic movement. Bill Crawford (Department of Fisheries and Oceans)

Table 1. Strengths and weaknesses of various downscaling techniques (adapted from Wilby *et al.* 2004)

Class	Sub-class ^a	Strengths	Weaknesses
Climatological	Delta Method (e.g., ClimateBCb)	<ul style="list-style-type: none"> • Straightforward to apply • Easily accessible 	<ul style="list-style-type: none"> • Climate variables considered mutually independent • Poor representation of extremes • Temporal disaggregation of monthly values to finer time scales may not be appropriate
	Regression Methods (e.g., SDSM, ^c ASD ^d)	<ul style="list-style-type: none"> • Straightforward to apply • Wide range of predictor variables can be incorporated 	<ul style="list-style-type: none"> • Poor representation of observed variance and extreme events • May assume linearity and/or normality of data
	Weather Generators (e.g., LARS-WG ^e)	<ul style="list-style-type: none"> • Production of large ensembles for uncertainty analysis • Production of long simulations for extremes 	<ul style="list-style-type: none"> • Arbitrary adjustment of model parameters for future climate • Unanticipated effects to secondary variables of changing precipitation parameters
	Weather Typing (e.g., Synoptic Typer ^f)	<ul style="list-style-type: none"> • Yields physically interpretable linkages to surface climate 	<ul style="list-style-type: none"> • Requires additional task of weather classification • Circulation-based schemes can be insensitive to future climate forcings • May not capture intra-type variations in surface climate
Dynamical	Regional Climate Models (e.g., CRCM, ^g RegCM3 ^h)	<ul style="list-style-type: none"> • Physically consistent simulation of all atmospheric variables for all layers of the atmosphere 	<ul style="list-style-type: none"> • Considerable training and expertise in climate modelling required

^a Several of the statistically based downscaling techniques incorporate a hybrid of methods (e.g., regression + weather generator).

^b See <http://www.genetics.forestry.ubc.ca/cfg/climate-models.html>

^c Statistical Downscaling Model (SDSM) – see <https://co-public.lboro.ac.uk/cocwd/SDSM/>

^d Automated Statistical Downscaling (ASD) – see http://gaia.ouranos.ca/DAI/downscaling_tools-e.html

^e Long Ashton Research Station Weather Generator – see <http://www.rothamsted.bbsrc.ac.uk/mas-models/larswg.php>

^f See www.bom.gov.au/inside/ccsb/mss/projects/synoptictyper/

^g Canadian Regional Climate Model – see www.cma.ec.gc.ca/models/crcm.shtml

^h Regional Climate Model version 3 – see <http://users.ictp.it/RegCNET/model.html>

showed how even coastal communities located relatively close together can have rates of sea level rise that differ by 0.4–0.6 cm/yr. The main impact of local tectonic movement on sea-level rise is a function of energy being stored in the deforming plates during the inter-seismic period. It is difficult to consider how a major earthquake may affect the rate of sea-level rise; however, all coastal communities of British Columbia must be prepared to adapt to long-term increasing sea levels.

Guidance for the Practitioner

The state of climate modelling science is continually improving, and is expected to eventually improve hydroclimate predictions at scales directly relevant to practitioners. The climate modelling community is striving to deliver regional climate model projections at a horizontal grid scale of 10 km within the next 5 years, a considerable advancement over the status quo. Given the speed at which the science is evolving, practitioners must become and stay familiar with the most current climate change predictions. Summary reports like the one recently produced by PCIC offer practitioners an excellent overview of up-to-date projected climate changes in British Columbia. There is a near-term need for partnership organizations (perhaps similar in nature to PCIC) that can effectively transfer information between modelers and practitioners. Regardless of the advances in climate modelling over the next 5–10 years, the results from such models need to be downscaled to conduct local impact studies. Practitioners are encouraged to learn more about various downscaling techniques and their advantages/disadvantages in a particular application. Tools such as

ClimateBC (Wang *et al.* 2006) are an excellent source of information, but can be misleading if not applied with an understanding of the limits and uncertainties that accompany its predictions.

A healthy, long-term hydroclimate network representative of hydroclimatic conditions experienced throughout British Columbia is necessary to enable usage of state-of-the-art downscaling techniques, track and validate trends in hydroclimatic variables, validate models, and improve predictive capability at unmonitored locations.

Except for dynamical downscaling, all other downscaling techniques are conditioned somewhat upon observational data networks. A healthy, long-term hydroclimate network representative of hydroclimatic conditions experienced throughout British Columbia is necessary to enable usage of state-of-the-art downscaling techniques, track and

validate trends in hydroclimatic variables, validate models, and improve predictive capability at unmonitored locations. In particular, high elevations and northern regions where the effects of climate change are likely to be the most dramatic need to be monitored more closely.

Conclusions

The state of climate change science is evolving rapidly and tools and techniques for assessing local and regional impact are becoming increasingly available to the practitioner. The climate symposium offered an opportunity for interchange between scientists and professionals dealing with climate change in their everyday practice. While there remains a significant gap between the states of science and practice, events such as the climate symposium should be conducted regularly to ensure that practitioners are well equipped and informed of advances in science, tools, and techniques for incorporating climate change impacts in local and regional scale assessments. ~

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