Changing Cold Regions Network—the first two years

A briefing note for our Board of Directors and Government Partners

21 April, 2015

In February 2015, the Changing Cold Regions Network (CCRN; www.ccrnetwork.ca) completed its second full year as a research network. From its outset, the network has received strong support from a number of Canadian federal and provincial government agencies, and there has been much active cooperation in pursuit of common goals. This briefing highlights some key areas of progress and success, and our ambitions for the remainder of the 5-year programme, including how we are working to ensure our deliverables will meet our partners' needs. The briefing supplements our formal annual progress reports to our Board of Directors and to the Natural Sciences and Engineering Research Council of Canada (NSERC), available on our website at www.ccrnetwork.ca/outputs.

The overall aim of CCRN is to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological and climatic components of the changing Earth system at multiple scales. The geographical focus is on western Canada's rapidly changing cold interior. We use a network of 14 Water, Ecosystem, Cryosphere, and Climate (WECC) observatories (Figure 1) to study in detail the processes and their interactions in different environments, including the southern Arctic and sub-Arctic Tundra and Taiga, the Boreal Forest, the western Cordillera and the Prairies. At larger scales, we are addressing the changing regional climate, its effects on the region's major river basins: the Saskatchewan and Mackenzie, and potential feedbacks associated with large-scale Earth system change. Our main deliverables are improved understanding of these rapidly changing systems, including potential tipping points, and improved atmospheric, hydrological and hydro-ecological models for the diagnosis, prediction, and management of change.

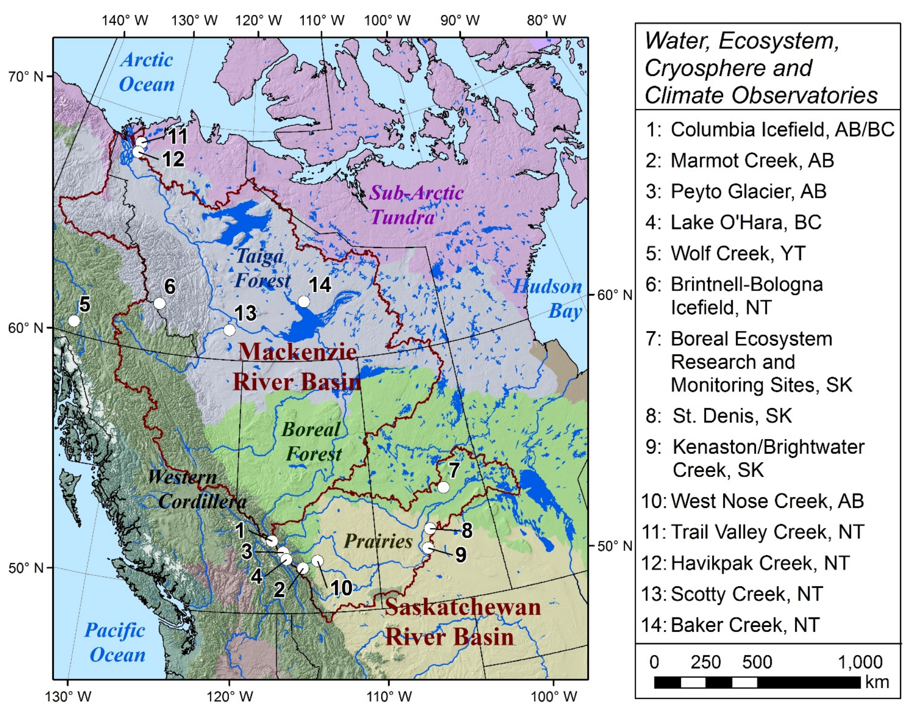

Figure 1: The CCRN's 14 WECC observatories across the interior of western Canada. These intensive research sites provide exemplary opportunities to study and understand process dynamics, observe environmental change, and develop and test numerical simulation models suited to cold region environments.

The programme and its objectives are divided into 5 Themes. These are:

- Theme A: Observed Earth System Change in Cold Regions—Inventory and Statistical Evaluation;
- Theme B: Improved Understanding and Diagnosis of Local-Scale Change;
- Theme C: Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction;
- Theme D: Analysis and Prediction of Regional and Large-Scale Variability and Change; and,
- Theme E: User Community Outreach and Engagement.

These Themes are inter-dependent and tightly integrated (see page 2 of our 2014 annual progress report).

Progress to Date

Network Development

As planned, CCRN has developed a large, multi-disciplinary network of researchers. This includes 40 investigators and 126 (past and present) student and post-doctoral researchers and support staff from 8 Canadian universities and 4 Canadian federal government agencies, with close linkage to the relevant provincial and territorial governments (www.ccrnetwork.ca/organization). International collaboration includes 18 scientists, from Germany, France, the U.S., U.K., and China; for example, work with the National Aeronautics and Space Administration (NASA) is supporting their Arctic Boreal Vulnerability Experiment (ABoVE) and the Soil Moisture Active Passive (SMAP) and Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) remote sensing soil moisture missions; work with the U.S. National Centre for Atmospheric Research (NCAR) includes high resolution modelling of past and future climates. In December 2014, the World Climate Research Programme (WCRP) endorsed CCRN as a Global Energy and Water Exchanges (GEWEX) Regional Hydroclimate Project (RHP), facilitating collaboration in, and leadership of, various relevant global initiatives (more on this in Box 5 below).

One key achievement over the first 2 years has been the integration of the CCRN team and its wide range of disciplinary expertise. In addition to regular teleconference management meetings, the network has held 3 full-network meetings, 7 specialist workshops, 5 training sessions, as well as developing a young researchers focus group to support training and personal development needs, and interdisciplinary thinking. This has facilitated effective collaboration between our members, spanning multiple disciplines and institutions.

Data Management

The network is committed to produce, document, and archive our results in an integrated, long-term repository, and to follow the principles of integrity, access, and stewardship in our approach to data management. Pages 3–4 of our 2014 annual report contain specific details on activities to date and progress towards populating our CCRN data archive. Our website contains other information and archive links: www.ccrnetwork.ca/outputs/data. Important activities in establishing a data management system and progress towards developing a legacy database have included:

- Creation of data access policies and a CCRN data management planning document;
- Setup of a data platform—the Water Information System, Kisters (WISKI) tool—to manage, process, and edit time series information;
- Provision of training and tutorials on WISKI to network investigators and students;
- Imports of recent observational records and metadata from the set of 14 WECC observatories;
- Ongoing dialogue with WECC observatory leaders and provision of support to facilitate transfer of archived data to WISKI system;
- Coordination with Environment Canada to provide access to regional data sets and archived WECC data;

- Coordination with Environment Canada to develop protocols for acquisition and archiving of Global Environmental Multiscale (GEM) model outputs over western Canada and the WECC observatories;
- Coordination with NCAR to archive 4km atmospheric model runs over the Saskatchewan Basin;
- Provision of access to selected real-time data streams.

We appreciate the strong level of commitment and cooperation that the network has so far received from many of our partners in regard to access to and sharing of long-term monitoring data and model outputs. This has been to our mutual benefit, and we are optimistic about maintaining this level of collaboration throughout the remainder of the network.

Theme A: Observed Earth System Change in Cold Regions—Inventory and Statistical Evaluation

Theme A synthesizes observed changes to the Earth system within the CCRN study domain and establishes a foundation for more detailed analysis and modelling in Themes B–E. Theme A objectives are now nearly complete. The network is preparing a set of products targeted towards specific user groups and stakeholders to highlight relevant Earth system changes and their implications. Activities have included:

- Completion of local-scale assessments and inventories of change at many WECC observatories, including changes in climate, vegetation, snow and glacier cover, permafrost, stream discharge, groundwater and pond levels, and surface water extent;
- Collection of tree core data from across the western Canadian Boreal and Taiga ecoregions to develop an extensive dendro-chronological record, which will provide unparalleled understanding of the connections between proxy record, ecosystem response, and climate variability;
- Regional-scale synthesis of Earth system change through an integrated literature review and analysis of federal climate and hydrometric datasets to contextualize changes over the CCRN domain (see Box 1);
- Development of conceptual models of drivers and mechanisms of change for WECC observatories and major ecoregions, which together with observations of change, will be diagnosed quantitatively in Theme B.

Although most of the work in this Theme does not have direct management application, it provides invaluable information on recent changes and context for all of the subsequent work being done in the network.

BOX 1: REGIONAL SYNTHESIS OF RECENT EARTH SYSTEM CHANGES OVER WESTERN CANADA

A wide range of Earth system changes have occurred over western Canada, including patterns of increasing air temperature, changing precipitation (exhibiting considerable seasonal and regional variability, with increases in some areas and declines in others), decreasing snow cover extent and duration, thawing permafrost and increasing active layer thickness, retreating glaciers, expanding shrub tundra in the north, 'browning' of the Boreal Forest in the south and collapse of forest covered permafrost plateaus in the Taiga Plains, earlier breakup of river and lake ice and a shorter freshwater ice cover period. Resulting changes in river discharge are complex and include increased winter and annual flow in much of the north, mixed trends elsewhere, and a shift to earlier timing of the spring freshet. A comprehensive evaluation of these changes is a critical first step toward diagnosing and predicting the mechanisms and interactions of the changing Earth system components, and to provide insight into the degree of adaptive management that is necessary.

CCRN has completed an extensive, integrated review of recent work describing changes in these various systems, highlighting conceptual linkages among them and the need for further diagnostic work. We have conducted broad-scale analyses of change using the Adjusted and Homogenized Canadian Climate Data (AHCCD), the associated gridded CANGRD product based on AHCCD (Figure 2), the Canadian Reference Hydrometric Basin Network (RHBN) and other RHBN-like stations maintained by the Water Survey of Canada. The results provide a consistent and up-to-date regional evaluation of hydro-climatic trends and identify systematic changes in climate and crysopheric regime. Mixed signals exist for runoff response—there is a clear need to better understand the underlying causes of this variability through process-based modelling. A manuscript has been prepared for submission to a scientific journal. The work will also be shaped into user-focused information brochures, presentations, and publicity materials as a deliverable for Theme E.

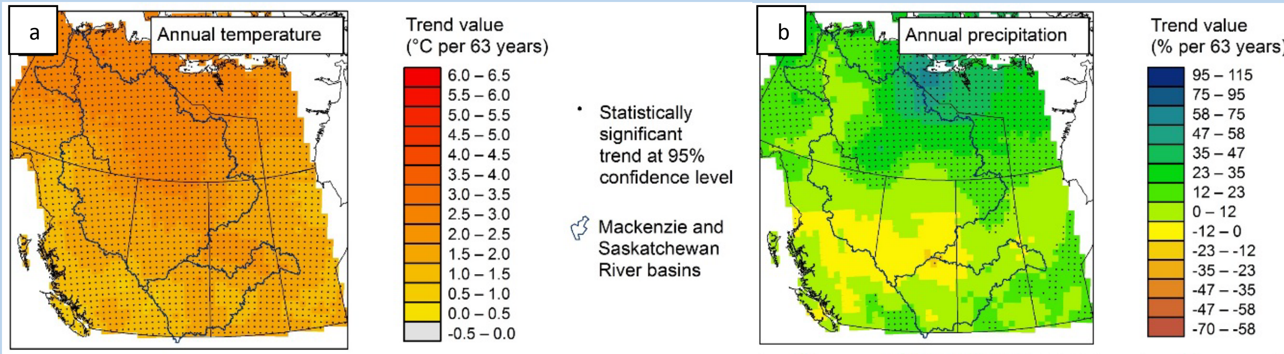

Figure 2: Trends in a) annual mean air temperature and b) total annual precipitation (1950–2012) over western Canada. Annual and seasonal trends have been computed from Environment Canada's CANGRD product; the patterns show statistically significant warming on average of about 2 °C, with the greatest increases (up to 5 °C) in the winter months, especially in the northern part of the domain, while precipitation has generally increased (~15% on average) but with strong regional and seasonal variability.

Theme B: Improved Understanding and Diagnosis of Local-Scale Change

Theme B addresses local-scale change by i) developing new integrative knowledge of Earth system processes, ii) incorporating these processes into a suite of integrative models, and iii) using the models to better understand Earth system change. Page 5 of our 2014 annual report includes detail on the progress. At the end of year-2, notable achievements in Theme B include:

- Targeted process studies in most WECC observatories, with a focus on understanding coupled cryosphere-hydrosphere-biosphere interactions and on comparing and contrasting processes amongst observatories;
- Continued operation and enhancement of WECC observatories, with the deployment of enhanced and new field instrumentation for a Special Observation and Analysis Period (SOAP) across all observatories (during the hydrological year October 2014–September 2015).
- Implementation of numerous improvements and new algorithms for physical processes within the Cold Regions Hydrological Model (CRHM) to calculate i) soil freezing-thawing, ii) frost table impacts on soil moisture storage and hydraulic conductivity, iii) surface runoff over organic terrain and through organic materials and snowpacks, iv) snow dynamics on glaciers and glacier hydrology, v) snow redistribution by avalanche, vi) representation of networks of depressional storage, vii) groundwater dynamics and surface interactions, and viii) snow–vegetation interaction in discontinuous canopies;

The work being done in this Theme has important practical applications for environmental management and decision making. Improvements to fine-scale models such as CRHM will greatly enhance predictive capability and diagnostic evaluation of past and potential future system change at the local scale, while new and improved algorithms and model parameterizations can be taken up in large-scale hydrological models and land surface schemes. These efforts are therefore helping to provide the scientific information and tools needed to manage Canada's response to climate change—a key challenge for many federal and provincial government departments.

BOX 2: CONTINUATION, MAINTENANCE, AND REVITALIZATION OF CCRN'S WECC OBSERVATORIES

CCRN's 14 WECC observatories (Figure 1)—most of which have a long history of research activities and extensive observational datasets—provide important insights into cold region Earth system processes and their interactions. Many of these observatories were originally established by our federal and provincial government partners, who continue to be invested in and closely involved with research and monitoring activities. In the face of rapid and dramatic environmental change, these observatories are of considerable importance, and collaboration between our government partners and CCRN to ensure their continued operation is of ever-increasing value towards documenting and understanding change. Since the network's inception, CCRN has played a key role in maintaining the sites and has leveraged investment in them to enhance their infrastructure and instrumentation, to the benefit of all of our partners.

Our 2014–2015 Special Observing and Analysis Period (SOAP) initiative involves coordinated scientific and monitoring activities across the domain, with special emphasis on the WECC observatories. SOAP is supported by enhanced instrumentation, and aims for consistent, high-quality observations, including a research focus on freeze and thaw processes in the shoulder seasons. Many WECC observatories have been upgraded with new and sophisticated soil, snowpack, surface energy flux, meteorological, and vegetation monitoring equipment. Through this initiative, the CCRN is well-positioned to provide a world-class comprehensive legacy dataset for examining process variability and responses across the domain, and for model development, application and evaluation.

Figure 3: Photographs of new or enhanced hydro-meteorological observation stations at some of the WECC observatories. Top row from left: meteorological station at Brightwater Creek, cosmic ray soil moisture and snowpack monitoring equipment at Trail Valley Creek, infrared thermometer and leaf wetness sensors at BERMS. Bottom row from left: meteorological stations at Fortress Mountain ridgetop (part of the Canadian Rockies Hydrological Observatory), Brintnell-Bologna Icefield, Trail Valley Creek tundra site, and Baker Creek (including a Campbell Scientific GMON3 snow water equivalent sensor). There are dozens of other new or enhanced stations at the various WECC observatories.

Theme C: Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction

Theme C builds on the insights from the WECC observations and fine-scale modelling (Themes A and B) to develop and test improved models for large scale application, both as land surface schemes within weather forecasting and climate models, and as large-scale hydrological models that can be used to analyze and predict change at large river basin scales. These activities are directly aligned with the needs of many of our partners, and will advance our predictive capacity over mid- and high-latitude regions. The work in this Theme also represents an important contribution at the international level (e.g., see Box 5 below). Important areas of progress have included:

- Completion of baseline simulations at most WECC observatories to evaluate performance of the Canadian Land Surface Scheme (CLASS), together with other international land surface schemes (e.g., Weather Research and Forecasting (WRF) model, a widely used U.S. modelling system and the Joint U.K. Land Environment Simulator (JULES), the U.K.'s community land surface scheme;
- Various improvements to CLASS for representing Prairie landscapes and cold region lakes;

- Setup and preliminary evaluation of Environment Canada's Modélisation Environmentale Communautaire – Surface and Hydrology (MESH) model over both the Mackenzie and Saskatchewan River basins, with several key focal issues identified for future work (see Box 3);
- Publication of key research reviews on the representation of water management in large scale models.

BOX 3: COLLABORATIVE DEVELOPMENT AND IMPROVEMENT OF LARGE-SCALE PREDICTIVE EARTH SYSTEM MODELS

Theme C involves close collaboration with Environment Canada (Water Science and Technology, Atmospheric Science and Technology, and Meteorological Service of Canada) to improve national capability for large-scale predictive water resources modelling, including hydrological, hydro-ecological and coupled atmospheric–land surface models. A working group of approximately 20 researchers has been established, including EC research scientists and various post-doctoral fellows and students supported by the network. The core group meets weekly; monthly conference calls are regularly attended by EC staff in Saskatoon, SK, Downsview, ON, and Dorval, QC. Two model development and application-focused workshops (in Dorval and Saskatoon) have focused the research and determined research priorities, with participation from our international collaborators; presentations and summary reports from each can be found on the CCRN webpage: www.ccrnetwork.ca/science/workshops. A follow-up workshop is planned for the fall of 2015, focused on the diagnosis of change. Training has been undertaken to familiarize GIWS researchers with the EC SPS coupled modelling system and the associated PEGASUS computing cluster.

Theme C activities have already yielded useful results and helped refine future priorities. Baseline runs of CLASS with standard parameterizations have established a benchmark for evaluating model performance; some improvements have been implemented. Setup and preliminary evaluation of MESH—EC's land surface and large-scale hydrological modelling system—over the region's major river systems has identified strengths

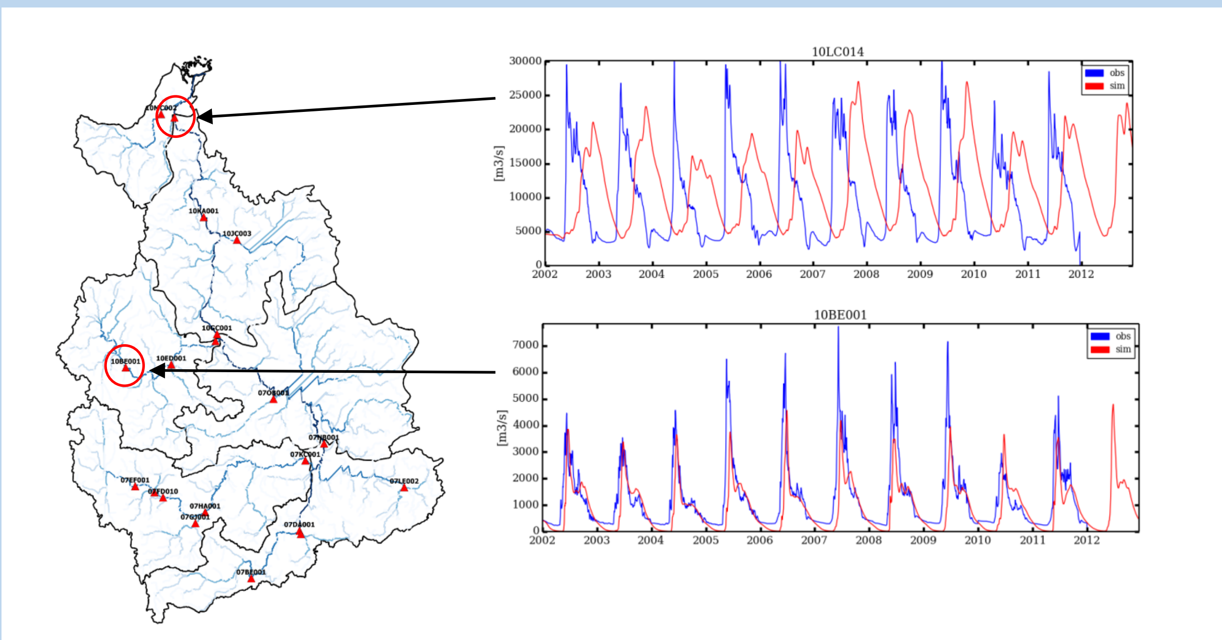

Figure 4: Preliminary hydrograph results from MESH over the Mackenzie River basin. Results show reasonably good performance at the smaller basin-scale, but poor performance at larger scales and the Mackenzie River basin overall. These results help to reveal model strengths as well as weaknesses/sources of uncertainty that require further attention. Important issues now being addressed include uncertainty in precipitation, initialization of state variables (including permafrost), model structure and process representation, and parameter scale-dependence and sensitivity.

and weaknesses, and hence prioritized future work. A new Prairie model incorporating the dynamics of non-contributing runoff areas has been implemented and published; a new cold region lake model is being developed and tested. In more northerly areas, the incorporation of a lateral wetland modelling component is being examined along with the representation of permafrost and its impacts on hydrology and land-atmosphere exchanges. Multi-objective parametrization and optimization is being used to explore performance trade-offs. Model intercomparison using other LSSs has engaged members of the international scientific community and will be used to identify the main strengths and limitations of cold regions process algorithms. We anticipate these important process improvements and insights being incorporated in CLASS and MESH will have a direct impact on operational models within EC and globally. Model improvements will be incorporated in Theme D model applications.

Theme D: Analysis and Prediction of Regional and Large-Scale Variability and Change

Theme D uses the comprehensive measures of regional change developed in Theme A and models developed in Theme C to assess the driving factors for the observed trends and variability in large-scale aspects of the Earth system, their representation in current models, and the projections of regional-scale effects of Earth system change on climate, ecology, land, and water resources. Although the activities in this Theme depend to a large extent on the activities and outcomes of other CCRN Themes, and many of the deliverables are slated for later in the programme pending model refinement, there have been significant early accomplishments, including:

- Individual research progress on atmospheric circulation patterns, instabilities for generating convection, precipitation phase changes, surface hydrologic changes, and runoff, with journal submissions based on these studies in preparation;
- Jointly with efforts under Theme B, a comprehensive focal investigation of the June 2013 extreme weather and flooding events that affected southwestern Alberta and downstream areas (see Box 4), and more recently an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations.

BOX 4: DIAGNOSTIC ANALYSIS OF THE JUNE 2013 EXTREME WEATHER AND FLOODING EVENTS IN WESTERN CANADA

In the late spring of 2013, a low pressure system bringing moisture from the Gulf of Mexico stalled over the foothills and front ranges of the southern Canadian Rocky Mountains, where very intense rainfall lasted for several days. This led to the most devastating and economically costly flooding event in the region's history, with numerous towns and the City of Calgary all significantly affected by floodwaters. CCRN recognized these

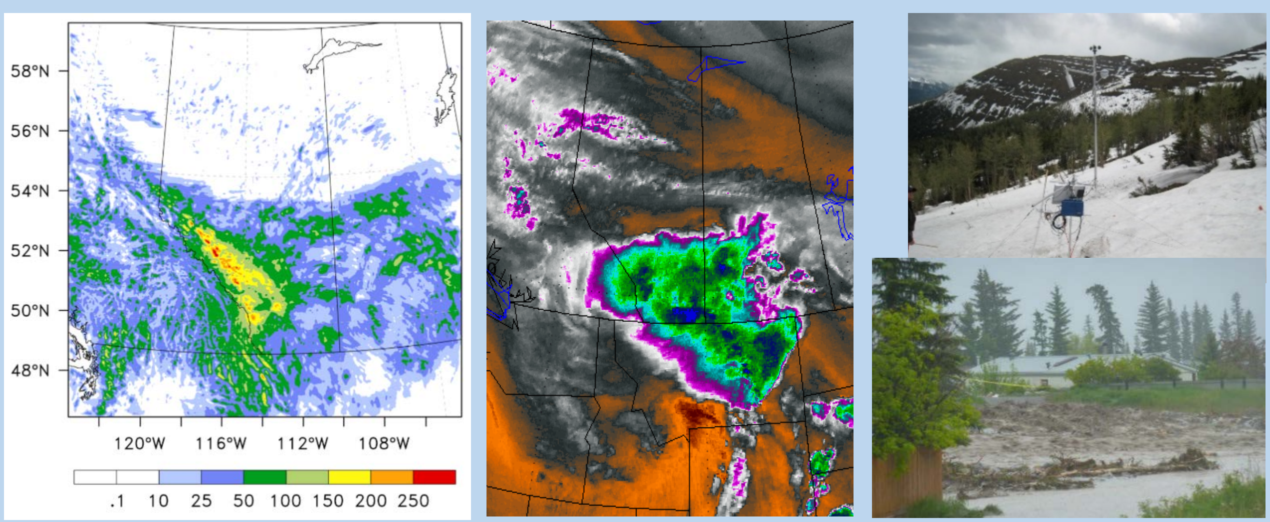

Figure 5: Extreme rainfall and flooding events in southwestern Alberta in late June 2013. These events were unprecedented in terms of the damage and economic costs. Left: simulation of the total rainfall between 19–22 June by the Weather Research and Forecasting (WRF) model; Center: observation of water vapour and cloud coverage on 20 June from NASA's GOES satellite; Top right: alpine snowpack prior to the event at the Marmot Creek Research Basin,

Kananaskis (the rain-on-snow event resulted in the complete melt of the snowpack, significantly increasing the volume of water input to soils and streams); Bottom right: flooding of a creek in the town of Canmore near the crest of the flood.

events as an important and timely case study to examine and diagnose in detail. The network combines expertise, observations, and modelling tools to provide an in-depth analysis of the events and the lessons learned. A workshop in Canmore, AB, in February 2014, brought together a wide range of scientists, water managers, and government officials to evaluate, synthesize, and discuss the events, including observations, diagnostic modelling, management decisions, and future mitigation. The workshop highlighted multiple perspectives, advanced scientific understanding, and identified challenges to overcome in future. Continuing analyses are leading to journal manuscripts focusing on the flood and its meteorology, hydrology, and water management aspects, and plans have come together to submit a collection of papers to an upcoming special issue of the journal *Hydrological Processes*. This will comprise an important Canadian scientific contribution on these types of events, which may be expected to occur more frequently in mountains areas across the world under climate change. The improved understanding of the factors leading to the flooding event also represents an important contribution to management and planning at many levels of government, and we will continue to work with our partners to ensure that the information and tools are effectively delivered.

Theme E: User Community Outreach and Engagement

Theme E engages a large community of partners and users, including local stakeholder groups, provincial and federal policy/decision makers, national and international research organizations, and other relevant groups, and disseminates the improved knowledge and tools within this extended community. Through our members, we are linked with 106 different partners, including 11 First Nations groups, 11 Canadian and U.S. federal departments, 2 regional water boards, 24 provincial and territorial agencies, 4 urban municipalities, 7 non-governmental organizations, 19 water and environmental stewardship societies, 26 industrial companies, 6 research and education centres, and 2 consultancies. CCRN has been actively involved in outreach and engagement since the network began, with various initiatives including:

- Grassroots level outreach and engagement with local and regional stakeholders and partners across our study domain of the western Canadian interior, ranging from training in the use of relevant models to engagement with the public and students in water management games and a theatre production;
- Extensive participation of CCRN members at major national and international science conferences, 60+ publications in leading scientific journals (www.ccrnetwork.ca/outputs/publications), and over 130 feature articles and interviews in the media (www.ccrnetwork.ca/outputs/media);
- 4 focused workshops to engage government partners across our study domain (model development and application workshops, 2013 extreme weather and flooding workshop, Northwest Territories summer 2014 fires workshop). Reports from these workshops are available at www.ccrnetwork.ca/science/workshops;
- Linkage with various national and international scientific organizations, including the World Climate Research Program (Climate and Crysophere, and Global Energy and Water Exchanges (GEWEX) projects, and the Integrated Land Ecosystem-Atmosphere Processes Study), the U.S. National Center for Atmospheric Research, NASA Arctic and Boreal Vulnerability Experiment, and the Canadian High Arctic Research Station initiative).

BOX 5: THE MACKENZIE AND SASKATCHEWAN RIVER BASINS—A GEWEX REGIONAL HYDROCLIMATE PROJECT

In December 2012, the GEWEX Hydroclimate Panel approved the Saskatchewan River Basin (SaskRB) Project as a Regional Hydroclimate Project (RHP), designed to support the GEWEX mission, imperatives and science questions. Subsequently, at the 7th International Scientific Conference on the Global Water and Energy Cycle held in The Hague in July 2014 it was suggested that there could be significant benefits from a broader RHP in western Canada that mirrored CCRN (SaskRB and Mackenzie River basin (MackRB)). Given its geographical focus (from the Canadian Rocky Mountains in the West to Lake Winnipeg in the East, and from the Canada–U.S. border in the South to the Arctic Ocean in the North), this project would complement well current proposals for a U.S. RHP focused on the Colorado River basin. A proposal focusing on the GEWEX themes of Global Water Resource Systems, Observations and Predictions of Precipitation, Changes in Extremes and Water and Energy Cycles and Processes was approved at the GEWEX Hydroclimate Panel meeting in Pasadena, CA in mid-December 2014. This extension will place CCRN in a position to more broadly engage the international scientific community and to contribute our results to this important global forum.

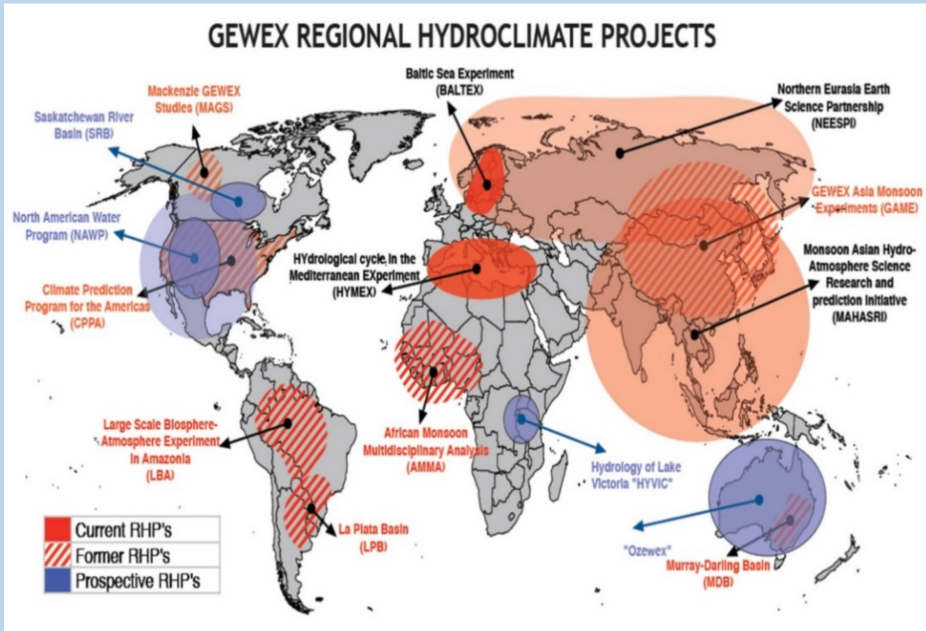

Figure 6: Existing, past, and prospective GEWEX RHPs. The approval of the Saskatchewan and Mackenzie River basins as a GEWEX RHP places the CCRN programme in an important international scientific context as the only current North American RHP. The CCRN builds on a number of previous initiatives in the interior of western Canada, including the Mackenzie GEWEX Study (MAGS), which ended in 2005.

Applications of CCRN Results to Management and Policy

It is important that our work meets the needs of our supporting partners, and as is clear from the above report on progress, we are working hard to ensure this. The close involvement of staff from various government departments within the network, and in particular on our Scientific Committee and Board of Directors, has greatly facilitated this. In other instances, focused workshops have been an effective mechanism for science transfer (i.e., bullet 3 under Theme E above). We are currently working on a refined strategy for engaging other relevant and interested government agencies in our study domain who would benefit from CCRN results, and developing targeted products for delivery that are aimed directly at their specific needs and interests.

Major areas where our work has important actual and potential applications to management and policy include:

- Input on trends and predictions to carry out new water-sharing and protection in the Mackenzie basin (i.e., a new Alberta-Northwest Territories agreement is now in force; a British Columbia and Northwest Territories agreement is nearing completion);
- High elevation snowpack and glacier hydrology sensitivity work to inform revisions to the Canada–U.S. Columbia River Treaty;
- Improvements to flood and drought prediction services and trend information for appropriate preparedness in both major basins;
- Improvements to forest fire understanding and predictions, and trend information for planning and deployment of fire-fighting resources;
- Improved understanding of the dynamics and sensitivity of permafrost and changing hydrology in the north, and associated impacts on wildlife habitat, infrastructure, and implications for resource development;

- Contributions internationally to improvements in global weather and climate modelling.

We must maintain close collaborations and a two-way dialogue with individual partners to continue to ensure that we achieve our original goals and that the value of these above contributions is maximized. With only 3 years remaining in our programme, our time is limited. We note that while the level of engagement with different partners has varied, we intend to broaden the interaction in the next year with further user-focused workshops and meetings, and more direct involvement with specific partners. We also invite our partners to send delegates to our CCRN annual general meetings (the next is 2–4 November, 2015 in Saskatoon) and are willing to include time here for presentations and discussion.