Changing Cold Regions Network

Final Progress Report to the CCRN Board of Directors and to the Natural Sciences and Engineering Research Council of Canada

Project Year-5 (Final Year)
23 February, 2018

Executive Summary

CCRN, which was funded through the Climate Change and Atmospheric Research (CCAR) initiative of NSERC, has reached the end of its five-year programme, with the network coming to a formal close in March 2018. A final meeting is planned for 5–6 March, 2018 to bring the network together for a last time and review achievements, future directions, and products and deliverables to be produced. The research team includes a large and diverse group (45 co-Investigators and government collaborators, 188 past and present students and post-doctoral fellows (PDFs), and 34 technical staff and other professional research support personnel) that has been well-integrated, productive, and has largely achieved the goals set out in our original proposal. As a network, we have made major advancements towards improving our understanding of recent Earth system change in the cold interior of western and northern Canada (CCAR Theme 3), advancing water, weather, climate and environmental prediction (CCAR Theme 2), and improving our understanding of Earth system processes and their representation in hydrological, atmospheric and ecological models (CCAR Theme 1). The network has produced invaluable scientific and technical advancements; the true value of the network will not be fully realized for many years, however, as the advancements continue to emerge beyond the end of the network. Our Board of Directors requested last year that we clearly articulate what we have achieved as a network in terms of model development and technical advancements, and so we have added this information to our webpage and as a supplementary report. CCRN has been closely engaged with federal, provincial, and territorial government partners to work collaboratively on common problems and issues. A number of extreme events that have occurred during the programme (flooding, fire, and droughts) have provided opportunities for focal and interdisciplinary analyses to gain improved understanding and predictability of such events in future, and have resulted in large numbers of publications and public communication pieces. We are closely connected with a number of international organizations. CCRN is recognized by the World Climate Research Programme as a Regional Hydroclimate Project and we are leading new international GEWEX (Global Energy and Water Exchanges Project) initiatives; for example the International Network for Alpine Research Catchment Hydrology (INARCH) is a GEWEX Hydroclimate Panel project that is an international spin-off from CCRN, while we also lead cross-cut topics on inclusion of water management in land surface schemes and on near 0°C precipitation. In addition to our collaboration with Environment and Climate Change Canada (ECCC) to enhance their CLASS/MESH modelling capability, our collaboration with NCAR has led to high resolution (4km) simulations of past and future climate using their WRF modelling system over the entire CCRN domain as a basis for comparative analysis. We have also been actively engaged in outreach with local communities, First Nations, other stakeholders, and the general public though meetings, interactions, the media, and newly developed information brochures. We have developed plans for the dissemination of our results, including two special issue journal publications, as well as plans for broader public engagement through the development of a documentary film. Our research expenditure has progressed according to plan; we expect to have a relatively small underspend on our budget this year, and plan to use this to support publication costs for submissions to our special issue journals in the coming months.

Contents

1. Introduction

CCRN's overall aims are to integrate existing and new experimental data with modelling and remote sensing products to understand, diagnose, and predict changing land, ecosystems, water, and climate, and their interactions and feedbacks over western Canada's cold interior. We use a network of 14 intensely instrumented Water, Ecosystem, Cryosphere, and Climate (WECC) observatories (Figure 1) to study these detailed processes and connections in the permafrost regions of the Sub-Arctic, the Boreal Forest, the Western Cordillera, and the Prairies, and we are working to better understand the changing regional climate and its effects on large-scale Earth system change and the region's major river basins: the Saskatchewan

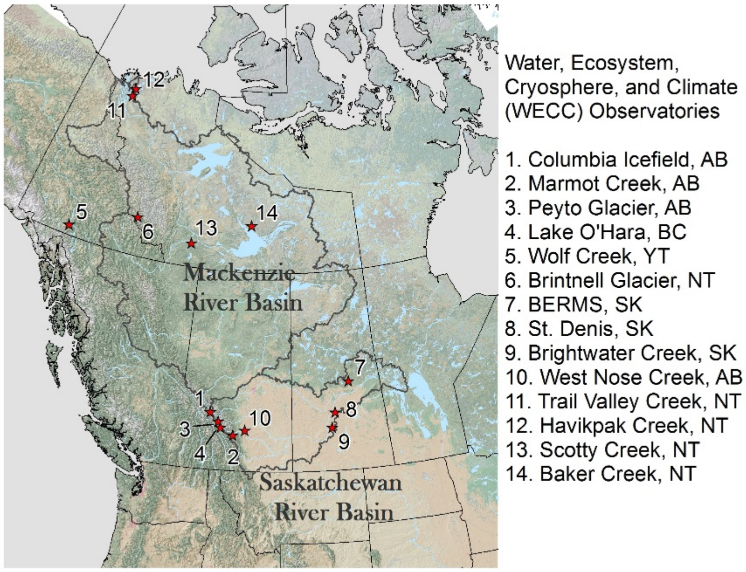

Figure 1. The CCRN's 14 WECC observatories across the interior of western Canada provide exemplary opportunities to study and understand process dynamics, observe environmental change, and develop and test numerical simulation models suited to cold region environments.

and Mackenzie. We are currently North America's only GEWEX Regional Hydroclimate Project, part of the World Climate Research Programme.

The CCRN programme and its objectives are organized based on five inter-related and inter-dependent Themes. Theme A, Observed Earth System Change in Cold Regions – Inventory and Statistical Evaluation, documents and evaluates observed change, including hydrological, ecological, cryospheric, and atmospheric components, in the cold regions of interior northwestern Canada over a range of scales. Theme B, Improved Under-standing and Diagnosis of Local-Scale Change, improves our knowledge of local-scale change by developing new and integrative knowledge of Earth system processes, incorporating these processes into a suite of process-based integrative models, and using the models to better understand Earth system change. Theme C, Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction, improves large-scale atmospheric and hydrological models for weather, climate, and river basin-scale modelling and prediction of the changing Earth system and its feedbacks. Theme D, Analysis and Prediction of Regional and Large-Scale Variability and Change, focusses on 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. Theme E, Outreach and Engagement, engages a 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.

Each of the Themes has a set of individual objective work plans and milestones, yet these are tightly integrated and inter-dependent. Theme A establishes a baseline inventory, statistical evaluation and synthesis of changes over a range of spatial scales. This is taken further in subsequent Themes, particularly B and D, where observations and conceptual models of change are further analyzed and diagnosed quantitatively. 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, while the application of these models, to address impacts of change on river flows and land-atmosphere feedbacks, is in Theme D. Theme E is integrated across all Themes to ensure that results are communicated in a relevant and useful manner, and that there is two-way engagement between the Network and its partners. The activities of all researchers in the Network cross multiple Themes and reinforce the linkages among them.

We have previously submitted annual progress reports to the Board of Directors and to NSERC for Project Years 1–4, and these can all be accessed on our website at www.ccrnetwork.ca/outputs/reports (financial sections are omitted in the versions available here). Other relevant documents can also be found there. This is the final scientific report for the network and it describes the achievements over the course of CCRN. In the following sections of the report we include an update on network management and activities in the past year, data management over the programme, scientific progress and achievements, collaborative activities, outreach and dissemination of results and findings, and HQP training.

Citations are provided throughout this report, and the references to papers and other published materials can be found on our website at http://www.ccrnetwork.ca/outputs/publications/index.php.

2. Network Management and Network Activities in the Past Year

2.1 Research Team Development and Management Structure

CCRN has developed a large, multi-disciplinary team of researchers, including 45 investigators and collaborators, and 222 current and past students, PDFs, research associates, technicians, and other HQP from eight Canadian universities and four federal government agencies. International collaboration includes 18 scientists from Germany, France, the U.S., U.K., and China, and we have actively engaged most of these people over the course of the network.

This past year, one of our investigators, Professor Jill Johnstone, stepped down from her position at the University of Saskatchewan to pursue other career opportunities. Her work within the network was mostly completed and remaining activities, funds, and supervisory responsibilities were transferred to Professor Colin Laroque at the University of Saskatchewan, who has worked collaboratively with Jill on the same projects for several years, thus ensuring continuity. NSERC was supportive of this transition. Jill has nonetheless remained committed to contributing to the network and collaborating with her colleagues in CCRN, and we thank her for her valuable contributions and service to the network.

Our management structure is described on our website at: www.ccrnetwork.ca/organization. There has been one change to the membership of our Board of Directors since our last report. Dr. Denis Petitclerc, Director General responsible for climate related activities under the National Agroclimate Information System, Agriculture and Agri-Food Canada, has retired and has been replaced in this role by Dr. Javier Gracia-Garza. We have invited Dr. Gracia-Garza to sit on the Board in place of Dr. Petitclerc.

2.2 Workshops and Meetings Held

We have held several key workshops in the past year to advance our science, plan future activities, and promote collaboration among the network. Summary reports for each and more detailed information are available on our website at www.ccrnetwork.ca/science/workshops. Smaller groups within the network hold regular meetings by phone to work on collaborative activities. The network's scientific steering committee meets approximately monthly by phone, and has held nine teleconference meetings over the past year.

Scenarios of Change Workshop (Saskatoon, SK, 20–21 March, 2017)

This workshop was held to gather multidisciplinary expert understanding on future Earth system change across western Canada and synthesize this into scenarios that could be applied within our large scale modelling framework. The meeting lead to a preliminary set of change scenarios for a number of different regions, clarity on driving data and modelling approaches, and a refined timeline for our activities to the end of the network. The insights from this workshop are being written up for a major review paper.

Modelling Workshop (Saskatoon, SK, 19–20 June, 2017)

This workshop was held to follow on from the scenarios of change workshop in March and review progress and further directions in our large- and fine-scale modelling. Preliminary model runs were examined and there were fruitful discussions that led to greater clarity on model refinements to pursue, driving datasets, further directions and timescales for completion of the work.

Wolf Creek Research Basin 25th Anniversary Science Summit (Whitehorse, YT, 28–29 September, 2017)

This event was held to mark the 25th anniversary of the setup and instrumentation of Wolf Creek as a research basin in the Yukon, and included scientific talks, discussions, a field visit, and social activities. The event drew significant media attention and helped to emphasize the importance of the research here in providing Yukoners with evidence-based science for decision making and water resource management. Detailed information can be found at http://www.ccrnetwork.ca/science/workshops/WC-Summit/wcrb-25-year.php.

Fall 2017 Modelling Workshop (Canmore, AB, 2–3 November, 2017)

This workshop was held to review progress and plans in our modelling of land and water futures over western Canada, and to plan products and publications as deliverables from the analyses of future change. The workshop highlighted the major advancements that had occurred over the previous six months, while significant progress was made in developing final plans to the end of the network in March and to address remaining problematic issues.

CCRN 5th Annual General Meeting (Saskatoon, SK, 5–6 March, 2018)

This event will be our final CCRN meeting—*The CCRN Finale*. It will include summary reports from our co-investigators and collaborators on their individual and collective achievements, as well as syntheses of overarching network and theme science advancements and next steps after CCRN. The meeting will include significant outreach, with the public premiere of a documentary film being produced about our research and findings. The meeting will be followed by the inaugural *Wheater Symposium*, meant to mark the retirement of Professor Wheater and his accomplishments, and which will include presentations from distinguished researchers and global leaders in a variety of disciplines. This will help shape the international activities and research priorities of the Global Water Futures Programme (GWF; www.globalwaterfutres.ca), which builds from CCRN.

2.3 Special Issue Journals

CCRN has opened two separate special issues in the EGU journals *Earth System Sciences Data (ESSD)* and *Hydrology and Earth System Sciences (HESS)*, which will stay open for submissions until after the formal end of the network, providing additional time to prepare submissions. These are open access journals, with published papers freely accessible to the public, and the two special issues are important initiatives that aim to pull together our datasets and make them available as a legacy for the network, and to synthesize the recent science advances contributing to CCRN's overall aims and objectives. The special issues are open to all submissions within their scope and welcome related datasets and studies from cold-region environments around the world.

ESSD is an international, interdisciplinary journal for the publication of articles on original research data, where data collection is well described and documented, and the data is readily accessible through a permanent repository and archived by a digital object identifier (DOI). HESS is a high profile international open-access journal for the publication of original research in hydrology and other Earth system sciences. Details are below and links to the issues are provided, where descriptions of the issue, submission information, and papers accepted or in discussion can be found.

- **ESSD Special Issue: *Water, ecosystem, cryosphere, and climate data from the interior of Western Canada and other cold regions***
    - Editors: C. DeBeer, W. D. Helgason, and P. Marsh
    - https://www.earth-syst-sci-data.net/special_issue901.html

    - Start date: 1 May, 2017; End date: 31 May, 2018
- **HESS Special Issue:** ***Understanding and predicting Earth system and hydrological change in cold regions***
    - Editors: S. Carey, C. DeBeer, J. Hanesiak, Y. Li, J. Pomeroy, B. Schaefli, M. Weiler, and H. Wheater
    - https://www.hydrol-earth-syst-sci.net/special_issue919.html
    - Start date: 1 June, 2017; End date: 1 September, 2018

3. Data Management

CCRN data management activities are overseen by Branko Zdravkovic who is the data manager for the Network and for the Global Institute for Water Security (GIWS) at the University of Saskatchewan. Information on Network data management activities is available to the public at www.ccrnetwork.ca/outputs/data. Guidelines, support, public data access, and data policy documents are also available at this location.

As identified in 2014 and in accordance to the CCRN Data Policy, observational records collected from the majority of WECC observatories have been captured in the central repository for the Network. These include metadata sets (2013) and collections that started at BERMS, St. Denis, Marmot Creek (2014), Fortress Mountain, Baker Creek, Brightwater Creek, West Nose Creek (2015), Scotty Creek, Trail Valley Creek, Havikpak Creek, Lake O'Hara (2016), Wolf Creek, and Ice Field observatories (2017). Most of the observatories contributed over 85% of their historical records to the CCRN central repository. Also, we were able to capture over 95% of records for many sites in the Western Cordillera, Prairies, and Boreal Forest observational areas. We are still expecting the more recent updates from some of the sites in Sub-Artic Lowlands. These records will be used to provide a better data coverage of the Mackenzie River Basin in the CCRN legacy archives. More information and statistics are available at giws.usask.ca/meta/reports/ccrn_stats.html, and charts showing the completeness of the records for various meteorological and hydrometric data during the CCRN study period are available at http://giws.usask.ca/meta/reports/ccrn2013_2017charts.html. Currently, data collection from eight CCRN observatories is automated. All of our time series records are controlled, processed, archived, and disseminated using the standardized data management protocols.

In 2017, we started the automated data collection and processing from Bologna Glacier Nunatak observatory in Nahanni National Park as well as Civic and Cougar Creek stations located in Canmore, AB area. Also, we improved the time series cleaning and filling procedures currently running on datasets from BERMS and Brightwater Creek observatories. In addition, we updated our mobile platform website to show the near real-time meteorological and soil data coming from 30 different stations in the Saskatchewan and Mackenzie River Basins (giws.usask.ca/telemetry). At the same time, we have been working on centralizing the access to modeling datasets for research conducted through CCRN as well as other programs that are organized by or in collaboration with the University of Saskatchewan. In 2018, our goal is to provide standardized access and support to our members for forcing data (GEM, CaPA, WFD, NARR, ANUSPLIN, CANGRD…), climate projection data (WRF, Can-RCM4, PCIC, NA_CORDEX) as well as Land Cover, Soil, DEM and other datasets from one location.

We have established a procedure for the official registration of observational datasets that will be included with the articles submitted to the special issue of ESSD (see section 2.3). This special issue will form a key legacy for the network where datasets are documented and readily accessible. The data management teams at GIWS and University of Saskatchewan outlined the procedures explaining how to document the metadata and obtain the Digital Object Identifiers (DOI) so that the information on our datasets is fully searchable through DataCite Canada organization. So far, three DOIs have been issued for the CCRN datasets. Finally, we are planning the format, scope, and dissemination methods for CCRN legacy datasets. Our goal is to have the subset of legacy data available to researchers and scientific community in early 2019, depending on the imposed academic embargo periods and conditions.

4. Scientific Progress and Achievements

4.1 Overarching Achievements and Network Statements

CCRN has the overarching goals to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological, and climatic components of the changing Earth system at multiple scales with a geographic focus on Western Canada's rapidly changing cold interior. Over our five-year programme the network has:

- Improved our understanding of recent Earth system change in the cold interior of western and northern Canada (CCAR Theme 3);
- Advanced water, weather, climate and environmental prediction (CCAR Theme 2); and,
- Improved our understanding of Earth system processes and their representation in hydrological, atmospheric and ecological models (CCAR Theme 1).

In doing so, CCRN has also:

- Enhanced our capability for water management in western Canada;
- Continued the long-term operation, and in some cases revitalized or expanded the infrastructure of a set of regionally important and representative WECC observatories;
- Trained the next generation of Earth System Scientists; and,
- Provided high quality datasets for change assessment and model verification.

Over the five years of this network, CCRN has worked with government, industry, water managers, First Nations communities and other stakeholders to deliver the improved hydrological, ecological and climate modelling tools needed to understand, predict and manage uncertain climate and water futures. CCRN has addressed issues of importance not only to Canada, but also the world, and has contributed to the work of Canada's Federal, Provincial and Territorial governments, NASA and the Canadian Space Agency, the US National Center for Atmospheric Research (NCAR), and the World Climate Research Program (WCRP).

CCRN Findings

Our climate has been undergoing rapid and significant change, and will continue to do so in the future. We have observed systematic warming and associated cryospheric responses over the past several decades, yet some of the ecological and hydrological responses have been complex and varied in both time and space, reflecting multiple processes and their interactions, sensitivities, and feedbacks. Through our field, theoretical, and modelling studies, we have gained new process-level insights and new diagnostic and predictive modelling tools that allow us to better understand the nature of these changes, and further to predict them in future under a changing climate. CCRN's multidisciplinary team has gathered together a collection of expert opinion and understanding on the trajectory of future Earth system change and landscape evolution in western Canada, allowing a conceptual and model-based assessment of the future atmospheric, ecological, hydrological, and crysopheric responses and interactions. We are confident that the future climate will be warmer, with an increased occurrence of both warm spells and heat waves, and increase in the occurrence of severe drought conditions, especially in the southern part of western Canada, and there will be an increase in the occurrence of heavy precipitation events, leading to more frequent flooding. Extreme events that have occurred during this network, such as the flooding in southern Alberta in 2013, the severe warm and dry conditions in 2014 and 2015, and the sequence of record setting severe wildfires in 2014, 2015, and 2016 in western Canada are likely to be seen more often and possibly with greater magnitude and cost to society in the coming decades. We are confident in the continued decline and loss of glaciers, diminishment of snowpacks, loss of permafrost, and reduction of ice-cover over western Canada. In association, we expect major forest and shrub vegetation shifts across the prairie, boreal, sub-arctic and southern arctic, and mountain ecoregions of western Canada, and we have developed quantitative projections as scenarios of future change for incorporation into our large-scale models based on our collective understanding of this change.

These future projections present some major challenges with respect to land and water management, societal decision making, and governance. The science we have developed and advanced in CCRN will help to inform policy and decision making, and can ultimately be used to help build a more resilient society in the face of an uncertain future and the threat of increasing risk. As the network draws to completion, there are still outstanding challenges and areas where understanding and predictive capability need to be improved, and the achievements made in CCRN will provide an important legacy to build upon.

Leadership and Contributions to the World Climate Research Programme

CCRN, both as a team and through our membership, has led major contributions to WCRP, including North America's contribution to the GEWEX Hydroclimate Panel (GHP) as a Regional Hydroclimate Project (RHP; https://www.gewex.org/panels/gewex-hydroclimatology-panel/regional-hydroclimate-projects-rhps/) over the past six years. This began following a workshop held in Saskatoon in March 2011, where the Saskatchewan River Basin (SaskRB) RHP was initiated. In December 2014, CCRN was endorsed as an RHP, expanding the focus to the Mackenzie and Saskatchewan Basins. Our past annual CCRN reports to GEWEX can be found at http://ccrnetwork.ca/outputs/reports/index.php. As CCRN is ending, we note a relatively new programme that is ramping up and in many respects following on from, and expanding upon, some of the activities and scientific issues being addressed in CCRN. The *Global Water Futures* (GWF; www.globalwaterfutures.ca) Project is a $143 Million, seven year (2016–2023), University of Saskatchewan-led research initiative that has an overall mission to improve disaster warning, predict water futures, and inform adaptation to change and risk management. GWF is the largest investment of its kind in university-led water research and aims to provide global leadership in water science for cold regions and to address the strategic needs of the Canadian economy in adapting to change and managing the risks of uncertain water futures and extreme events. Its geographic focus will include not only the Mackenzie and Saskatchewan River Basins, but a number of other major watersheds across all of Canada, while its science focus will expand to include water quality, social science, health, and water governance.

We envision our linkage to the GHP continuing through this major new initiative, under the leadership and direction of Distinguished Professor John Pomeroy, who was co-PI for CCRN. The CCRN secretariat staff has been expanded to manage this large and complex programme, and will benefit from including many of the same support and management staff, thus retaining continuity and experience. Most of the CCRN core team and collaborators are also actively involved in GWF and its activities.

CCRN members have also led or significantly contributed to other GHP and WCRP projects, including:

- The International Network for Alpine Research Catchment Hydrology (INARCH; http://www.usask.ca/inarch/index.php) is a GEWEX Cross-cut project that is an international spin-off from CCRN, led by Distinguished Professor John Pomeroy. CCRN and INARCH are closely linked and share many common research priorities and objectives.
- The Cold/Shoulder Season Precipitation Near 0ºC project is a GHP cross-cut project that addresses multiple aspects of precipitation phase transitions, and is led by CCRN investigators. There are many areas of overlap between these projects; in particular, CCRN is conducting a detailed assessment of changes in the 0°C isotherm, with objectives that are directly linked to this project.
- Another GHP cross-cut project is focused on Including water management in large scale models, and is led by several CCRN investigators, including the Principal Investigator. Considerable progress on this issue has been achieved through CCRN studies, and both initiatives have goals to include newly developed reservoir schemes into models, such as MESH.

4.2 Focal Activities and Special Cross-Cutting Topics

Several extreme events that have unfolded during this network provide key focal points for interdisciplinary investigation (spanning all Themes), including the destructive 2013 flooding in Alberta, the intense 2014 fire season in the Northwest Territories, and the severe 2015 drought across western North America.

The 2014–15 Special Observation and Analysis Period (SOAP) and Severe Drought Conditions in Western Canada

http://www.ccrnetwork.ca/science/SOAP/index.php

The SOAP initiative involved coordinated scientific and monitoring activities across the domain, with special emphasis on the WECC observatories during the 2014–15 hydrological year. SOAP was supported by enhanced instrumentation, and aimed for consistent, high-quality observations, including a research focus on freeze and thaw processes in the shoulder seasons. Many WECC observatories were 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. Datasets and papers describing them are being prepared for submission to our special issue of ESSD.

This period also provided an exemplary year where unusually warm and dry conditions were observed across most of the domain. The SOAP provided an opportunity for a focused examination of how this year was anomalous in terms of climate and hydrological response, and the factors that magnified or dampened the impact of the anomalies on the regional hydrology. The work was reviewed at a workshop in 2016 (http://www.ccrnetwork.ca/science/workshops/soap-2016/index.php) and the insights are being written into a synthesis paper for publication in our special issue of HESS.

Examination of the 2013 Severe Weather and Flooding in Southern Alberta

The heavy rainfall and associated flooding that occurred in southern Alberta in 2013 represented a first opportunity for the network to come together and conduct an in-depth assessment of a single, high-profile event. This began with a workshop where we reviewed various aspects of the meteorology, hydrology, and management decisions around the flood (http://www.ccrnetwork.ca/science/workshops/workshop-on-extreme-weather-and-hydrology/index.php). CCRN's focused work on understanding the event gained significant public media attention and led to the publication of a large set of papers in a special issue of the journal *Hydrological Processes*. A description of this effort and listing of all of the products from it is available at http://ccrnetwork.ca//science/2013-Alberta-flood/index.php.

Examination of the 2014 Severe Wildfire Season in the Northwest Territories and Other Major Wildfire Events

In 2014, the Northwest Territories experienced the largest fire season in its history, and this prompted a focused effort by a number of CCRN scientists, including ecologists, atmospheric scientists, and hydrologists, as well as many people from the territorial government, to come together and prioritize knowledge gaps and envision a research agenda to address those gaps with new research starting in 2015. This started with a workshop held in Yellowknife, NT (http://ccrnetwork.ca//science/workshops/nwt-fire-workshop/index.php), and continued as a focal topic of investigation and collaboration, leading to several key papers and outcomes (see reports by Baltzer, Johnstone, Turetsky, Kochtubajda; Kochtubajda et al. submitted).

Examination of Near-0°C Conditions and their Spatial–Temporal Changes

A special effort has examined the occurrence and features of near-0°C conditions. This complements other work on winter precipitation extremes and involves examining many stations across Canada to document near-0°C conditions. It is also examining a few location in more depth with Winnipeg being an initial focus. This work is being carried out by Ronald Stewart, Bob Kochtubajda, Eva Mekis, Barrie Bonsal, Kit Szeto, and Julie Thériault. One conference abstract has been submitted (Mekis et al., 2018), and the work will lead to one or more key papers on the topic.

4.3 Achievement of Individual CCRN Milestones and Deliverables

Work package descriptions for each of CCRN's Themes and specific details on the activities and milestones under each are provided on our website at http://www.ccrnetwork.ca/science/themes/index.php. Here we describe how these have each been achieved, list the deliverables that have been produced, and discuss further needs or research directions following on from CCRN. We also describe any difficulties that arose or changes in direction from our original plans; however, it is noted that in nearly every respect, CCRN is on track and has achieved what we set out to do as a network and more.

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

Lead: Sean Carey

A1 Assessing Change at the Local Scale

This work package contains the activities **A1.1 Inventory of observable local-scale change**, **A1.2 Statistical and meta-analysis of archived local data and environmental change**, and **A1.3 Dendrochronological examination of local change**.

Contributing to A1.1, a wide range of studies and analyses at the various WECC observatories and other local sites have been undertaken to inventory and assess Earth system changes, including vegetation, landcover, permafrost and soil conditions, and other characteristics. Relevant publications include: Baltzer et al. (2013), Bash and Marshall (2014), Connon et al. (2014), DeBeer et al. (2015, 2016), Demuth et al. (2014), Dumanski et al. (2015), Ehsansadeh et al. (2014), Harder et al. (2015), Hayashi and Farrow (2014), Ireson et al. (2015), Marshall (2014b), Patankar et al. (2015), Paznekas et al. (2015), Quinton and Baltzer (2013b), Shi et al. (2015), Shook and Pomeroy (2015), Spence et al. (2015), Yang et al. (2014b). The main limitation, which we identified in our inception report, is that the analyses did not include all WECC sites and that the specific variables and timescales being examined at individual sites differed. Nonetheless, this collective body of work represents an important deliverable of CCRN and we feel this milestone has been successfully achieved.

Milestone A1.2 was largely addressed through a focused effort lead by Sean Carey. Although we struggled early on to find resources to conduct the analyses and to decide on which specific data to use and what statistical tests to conduct, in the end the work was successful and shed new and important insights into the past behavior, sensitivities, and responses to hydro-climatic change amongst the different observatories. The work identified basins that are more-less sensitive to climate forcing, and in parallel, a toolkit was developed that can be used to quickly and efficiently evaluate rainfall-runoff patterns and to incorporate high-frequency water quality dynamics (Tang and Carey, 2017).

The dendrochronological analyses for A1.3 were led by the group of terrestrial ecologists within CCRN, including Jill Johnstone, Jennifer Baltzer, Merritt Turetsky, and Colin Laroque. Detailed information can be found in their individual progress summaries. Collection of tree core data and examination of local site conditions from across vast latitudinal transects over the western Canadian Boreal and Taiga ecoregions was undertaken to develop an extensive dendro-chronological record, which will provide unparalleled understanding of the connections between proxy record, ecosystem response, and climate variability. The ecological work went beyond this to examine detailed ecological responses to changing permafrost conditions, drivers and consequences of tundra shrubbing, gradients in boreal functional traits, soil and understory responses to established treeline gradients, treeline dynamics in alpine areas, and boreal forest sensitivity to changing climate and changing disturbance. In particular, a major effort was undertaken to study the post-fire vegetation and ecological responses to the severe wildfires in the Northwest Territories in 2014 and other fires using a vast network of plots across the Boreal and Taiga Forests of western Canada. Much of the work carried out in close collaboration with the NASA Arctic–Boreal Vulnerability Experiment (ABoVE). Tree-ring data has been contributed to the International Tree-Ring Data Bank (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring).

Relevant publications include: Anderson-Teixeira et al. (2015), Baltzer and Johnstone (2015), Baltzer et al. (2013, 2014, 2016), Chasmer et al. (2014), Chun et al. (2017), Day et al. (2016, 2017), Johnstone et al. (2016), Kiem et al. (2016), Mamet et al. (2016), Marshal and Baltzer (2015, 2016), Merchant et al (2016), McNickle et al. (2016), Pantankar et al. (2013, 2015), Pappas et al. (in press), Quinton and Baltzer (2013a, 2013b), Quinton et al. (2016), Sniderhan and Baltzer (2016), Sniderhan et al. (2018), Turetsky et al. (2017), Walker and Johnstone (2014, 2015), Walker et al. (2017, in press), and Williams et al. (2013).

A2 Assessing Change at the Biome and Regional Scales

This work package contains the activities **A2.1 Inventory of observable change - regional/domain scales**, and **A2.2 Documentation of extreme events**. Some of the activities blend with those contributing to work page A1, particularly the inventories and met-analyses of change, as the distinction in scale was sometimes difficult to define.

Work in A2.1 has been both at the local/biome scale (at WECC sites) and at the regional scale. Assessments of change have been largely completed, including changes in climate, vegetation, snow and glacier cover, permafrost, stream discharge, groundwater and pond levels, and surface water extent. From this, conceptual models of the mechanisms and drivers of change have been, and continue to be developed, which will be used towards quantitative diagnosis in Theme B. A key review paper has been published in Hydrology and Earth System Sciences that describes the recent Earth system changes observed in western Canada (DeBeer et al., 2016). Regional-scale synthesis of Earth system change has been undertaken through analysis of federal and provincial hydro-climatic datasets, remotely sensed data products, climate model reanalysis, and radar, rawinsonde, and lightning detection observations.

Documentation and analyses of recent extremes across our study domain have been carried out as part of the activities contributing to A2.2, and tie in strongly with the work in Theme D. This has included focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–16 with several papers published and others forthcoming. Relevant publications include: Brimelow et al. (2014, 2015), Fang et al. (2016), Kochtubajda et al. (2016), Liu et al. (2016), Pomeroy et al. (2016a, 2016b), Shook et al. (2015), Szeto et al. (2015), Whitfield and Pomeroy (2016).

Other Aspects of Theme A

We have conducted a multi-disciplinary expert synthesis of conceptual understanding and scenarios of future Earth system change across western Canada for the purposes of informing model setup, parameterization, and application under future climates. It is understood that most or all models do not adequately capture the process dynamics and interconnections and the integrated system responses, and thus it is unclear how useful the results are when these are run for future climate conditions. This synthesis is a major first step in overcoming some of these issues and in reducing uncertainty in model outputs. This was a key focus at our scenarios of change workshop in March 2017 (http://ccrnetwork.ca/science/workshops/scenarios-of-change) and the work is being written as a two-part manuscript for our special issue of HESS (see section 2.3 of this report). This has been pursued further in a quantitative diagnostics sense in Theme B. We are developing plain language science summaries and information products for public distribution, dealing with observed environmental change and documentation of extreme events—these are both key Theme A deliverables and these products will help a broad audience to better understand the changes taking place. Some of these are already on our website (www.ccrnetwork.ca/outputs/information-products).

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

Lead: John Pomeroy

B1 Targeted Process Studies

This work package contains the activities **B1.1 Deployment of enhanced field instrumentation**, **B1.2 Compilation of targeted process studies data**, and **B1.3 Development of enhanced local-scale process understanding**. Activities in Theme B use a unique legacy of process observations and modelling at long-term WECC observatories to address the overarching science questions in this Theme.

CCRN's 14 WECC observatories—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 and revitalizing the sites and has leveraged investment in them to enhance their infrastructure and instrumentation, to the benefit of all of our partners.

A workshop was held in Hamilton, ON to formulate plans for targeted process studies early on in CCRN (http://www.ccrnetwork.ca/science/workshops/targeted-process-studies/index.php). The workshop firstly dealt with existing instrumentation, data, and process understanding at the WECC sites to compile what was being done and what needed to be done for B1.1 and B1.2. Our website contains detailed information on each of the WECC sites (http://www.ccrnetwork.ca/science/WECC/index.php), including location and physical characteristics, research history, current science focus and instrument details, other resources and technical information, and contacts. Overviews of each basin presented at the targeted process studies workshop and data catalogues are provided as well.

To address the needs of B1, a SOAP year was planned at the targeted process studies workshop and carried out for the 2014–15 hydrological year (see section 4.2). The initiative was a major success, with participation from all 14 WECC observatories and a wide range of other supporting observations, modelling activities, and large scale analyses across the domain. A briefing note from April 2015 provides some highlights on the enhanced instrumentation and field campaigns undertaken during the SOAP initiative (http://www.ccrnetwork.ca/documents/CCRN_Progress_Briefing_for_BoD_and_Partners_April_2015.pdf).

As part of B1.3, numerous process studies have been carried out with an aim to better understand coupled cryosphere-hydrosphere-biosphere interactions, and compare and contrast processes amongst observatories. These have built upon novel and innovative measurement and observation strategies, and have been used primarily for the purposes of informing cold regions model and algorithm development and parameterization. This is described further in the next section.

B2 Development of Improved Local-Scale Models

This work package contains the activities **B2.1 Development of improved local-scale models** and **B2.2 Testing of improved local-scale models**. The main focus has been on development of the Cold Regions Hydrological Model (CRHM; www.usask.ca/hydrology/CRHM.php) platform, developed at the University of Saskatchewan's Centre for Hydrology, and deliverables are mostly new process modules within CRHM, subsequently applied in B3 for diagnosis of change. The goals have included a) a set of prioritized process improvements, b) model development at selected sites, c) comparative model application and evaluation across sites.

We have made major advancements towards the goals of B2, largely led by John Pomeroy and his research group. Development of CRHM has included implementation of numerous improvements and new algorithms of physical processes 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.

Focus has been given to development of the next generation Canadian Hydrological Model (CHM; http://ccrnetwork.ca/science/workshops/summer-2017-modelling-workshop/files/marsh_ccrn_modelling2017.pdf), also developed at the U of S Centre for Hydrology. CHM uses a variable resolution mesh to capture fine-scale variability where it exists, while reducing computational demands by reducing resolution in other parts of the domain. It has the design goals of i) multi-scale, multi-physics, variable complexity and domain, ii) assessment of model structural, parameter, and data uncertainty, iii) easily test multiple hypotheses, avoid rigid model structures, iv) incorporate existing code, and v) contribute to decision support systems. Many existing process algorithms have been ported into CHM, and given its flexibility and robustness, this model represents the next generation in cold regions hydrological modelling with the capability to bridge scales from local to regional to large basin-scale.

Relevant publications contributing to B1 and B2 include: Adams et al. (2015), Aksamit and Pomeroy (2016, 2017a, 2017b), Baltzer et al. (2016), Barr et al. (2013), Bartlett and Verseghy (2015), Brannen et al. (2015), Braverman and Quinton (2015), Burns et al. (2014), Chang et al. (2014), Chen et al. (2016), Connon et al. (2014, 2015, in press), Cordiero et al. (2017), Cosh et al. (2013), Costa et al. (2017), DeBeer and Pomeroy (2017), Dumanski et al. (2015), Ebrahimi and Marshall (2015), Fang and Pomeroy (2016), Garnaud et al. (2016), Harder and Pomeroy (2014), Harder et al. (2015, 2016), Helbig et al. (2016c), Hood and Hayashi (2015), Hopkinson et al. (2016), Kinar and Pomeroy (2015a, 2015b), Krogh et al. (2015, 2017), Kurylyk et al. (2015, 2016), Langston et al. (2013), Leroux and Pomeroy (2017), Lessels et al. (2015), López-Moreno et al. (2013, 2016, 2017), MacDonald et al., (2018), Mamet et al. (2016), Manns and Berg (2014), Marshall (2014), McClymont et al. (2013), Melaas et al. (2016), Ménard et al. (2014), Mohammed et al. (2013), Mohammed et al. (2014), Musselman and Pomeroy (2017), Musselman et al. (2015a, 2015b), Nagare et al. (2013), Pan et al. (2016), Patankar et al. (2015), Peterson et al. (2016), Pomeroy et al. (2016a, 2016b), Rahimzadeh-Bajgiran et al. (2013), Raleigh et al. (2013), Rasouli et al. (2014, 2015), Razavi and Gupta (2015a, 2015b), Reba et al. (2014), Rowlandson et al. (2015b), Sankaré and Thériault (2016), Shellito et al. (2016), Shook et al. (2013), Spence and Mengistu (2016), Spence et al. (2014), Steeves et al. (2016), Wake and Marshall (2015), Weber et al. (2016), Williams and Quinton (2013), Williams et al. (2015), Zhou et al. (2013, 2014).

B3 Diagnosis of Local Past Change

This work package contains the activities **B3.1 Methodology and toolkit development**, **B3.2 Application of existing models to diagnose change**, and **B3.3 Application of improved models to diagnose change**. The key deliverables include a toolkit for evaluation and diagnosis of change, a clearer understanding of model uncertainties and limitations for diagnosis of change, improved hydrological understanding of variability of hydrological processes and responses in light of climate variability and observed change, and understanding of system component sensitivity to changing air temperature and precipitation.

Work contributing to B3.1 was originally led by a post-doctoral fellow at the Global Institute for Water Security, University of Saskatchewan, who unfortunately had to move on leaving the work incomplete. However, this was subsequently picked up, albeit with a different focus, by Professor Saman Razavi, who led developments of the VARS-Tool (Variogram Analysis of Response Surfaces), which is a comprehensive, efficient, and robust toolbox for global sensitivity analysis (Razavi and Gupta, 2015, 2016a, 2016b).

Diagnosis of local-scale change in B3.2 and B3.3 has been pursued at multiple WECC observatories, including transects from north to south and mountains to lowlands across the domain. Historical analysis has involved an intercomparison using CRHM across as many basins as possible, including analyses of water budgets, timing of flows, and process mechanisms (e.g. rainfall vs. snowmelt runoff, timing and variability of flow, evapotranspiration losses across the areas), representing a synthesis of the hydrology of these regions. Models have been driven over the ERA-Interim period, providing a sufficient period of time to characterize the water budgets and historical change. Trends and teleconnection have begun to be analyzed to start to examine changes to evapotranspiration, snowmelt, sublimation, timing of various hydrological terms, shifts in runoff generation, etc. Some of this work has been recently published (Cordeiro et al., 2017; Mahmood et al., 2016; Krogh et al., 2017; Rasouli et al., 2014) and further papers are in development.

Models are also been applied in a prognostic manner to look at future projections and assessments of the associated hydrological change. We rely on North American Regional Climate Change Assessment Program (NARCCAP) and Weather Research and Forecasting (WRF) pseudo global warming (PGW) approaches. This is leading to a similar examination, comparing water budgets and trends, as in our historical analysis, comparing runs over a century of change and examining questions of what is different and why, what are the process mechanisms, and how are systems resilient or alternatively resistant to change? We are looking into transient changes due to glaciers, permafrost, vegetation, cultivation, and drainage, and explore the effects on hydrological systems. The plan will be to compile this into a synthesis paper, while transient changes will be addressed in a number of individual papers by members of CCRN.

Other Aspects of Theme B

Some activities of Theme B are ongoing in terms of applications on diagnosing change, and results from large-scale modelling efforts are being fed back to Theme B for more detailed examination of the meaning, implications, and process-level interactions. As we look at future scenarios, fine-scale models are being used to evaluate future impacts. This work will continue beyond the end of the network.

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

Lead: Howard Wheater

Our work in Theme C has involved close collaboration with partners at Environment and Climate Change Canada (ECCC), Natural Resource Canada (NRCan), and Agriculture and Agri-Food Canada (AAFC), as well as internationally with the US National Center for Atmospheric Research (NCAR). The aim is toward improving large-scale predictive models to better account for the changing Earth system and its atmospheric feedbacks, with their application to address impacts in Theme D. In particular, Theme C has focused on the development and application of the Canadian LAnd Surface Scheme (CLASS), Modélisation Environmentale Communautaire (MEC) – Surface and Hydrology (MESH), and Canadian Terrestrial Ecosystem Model (CTEM) models. A large joint modelling group of CCRN and ECCC researchers has been established with weekly/monthly meetings. (See our webpage for more detailed information on the models being developed and used in CCRN, and for a description of the specific advancements made during the course of the network; http://www.ccrnetwork.ca/science/models/index.php.)

C1 Algorithm Development for Weather and Large-Scale Hydrological Models

This work package includes the activities **C1.1 Testing of existing land surface schemes using WECC data** and **C1.2 Development and testing of improved algorithms at WECC and mesoscale**. Key deliverables include improved understanding of current model capabilities, identification of areas of need and opportunity for algorithm development, improved land surface scheme algorithms for a number of cold regions processes, and improved sub-grid process representation. This then feeds into C2 and subsequent Theme D work.

C1.1 work has largely been led by Andrew Ireson, in collaboration with a number of research scientists at ECCC. This work has involved a land surface scheme inter-comparison using CLASS as well as other well-known and widely used models, including the Joint UK Land Environment Simulator (JULES), the Weather Research and Forecasting Model–Hydrologic Processes (WRF-Hydro), the community Noah land surface model with multiparameterization options (Noah-MP), and the Common Land Model (CLM) Parallel Flow (PARFLOW). This showed various performance similarities and differences relating to soil parameterization and vegetation representations, while ongoing research is examining the effects of frozen and thawing soils in the models and tree-water relations.

To facilitate model testing and version inter-comparison, a point mode has been implemented in MESH. The same parameter file can be used to run any of the land surface schemes available in MESH, and outputs are written in a consistent format. (See the CCRN MESH summary report for further details; http://www.ccrnetwork.ca/science/models/ccrn_modelling_mesh_update_2018-02-12.pdf.)

In addition, an important contribution was led by Dr. Paul Bartlett and Dr. Murray MacKay of ECCC, which involved the provision of simulations from seven CCRN observatories, using CLASS with observed vegetation characteristics. This modelled data record contains a complete annual cycle at most sites in order to provide CCRN and other researchers with a set of baseline model input and benchmark output files for verifying initial simulations to ensure that proper model output is being produced. These can be obtained by contacting either Dr. Bartlett or Dr. MacKay (Paul.Bartlett@ec.gc.ca or Murray.MacKay@ec.gc.ca) and further information is on our website here:
http://www.ccrnetwork.ca/documents/2nd%20Annual%20Meeting/Bartlett%20Baseline%20CCRN-October-2014-C.pdf.

Under C1.2, analysis of large basin-scale performance led to the identification of priority areas for development. New or improved algorithms were developed for: Cold region lake modelling; Cold region wetlands; Snow process representation; Cold region vegetation processes (including snow–canopy interactions); Frozen soils; Prairie hydrology, including variable hydrological connectivity; Water management, including reservoirs and irrigation. Key areas of priority were defined for sub-grid process representation, which was and continues to be addressed with respect to a) Mountain discretization: issues of connectivity between grids (e.g. blowing snow) and discretization (slope/aspect, different forcing for elevation bands); b) Cold region wetlands subgrid representation, c) Spatial heterogeneity of soil moisture, d) Scale-dependence of process representation – scale dependence of parameters, Grouped Response Units versus spatially explicit location. Three major review papers were published on the representation of water management in large scale models and as a result this issue has been adopted by GEWEX as a cross-cut theme for an international collaborative project, with the CCRN PI as co-lead (Nazemi and Wheater 2015a, 2015b; Wada et al., 2017).

This work has progressed well and there are several notable successes as a legacy of the network. New and improved algorithms for MESH have included prairie wetland representations (PDMROF; Mekonnen et al., 2014), staged reservoir release (see Razavi et al., 2013), irrigation demand and abstraction, permafrost deep soil layer discretization, and new plant functional type representation for shrub tundra. A new 1D lake model has been developed and incorporated into MESH, and other existing elements (but not previously activated) have now been implemented, including glacier energy balance, and blowing snow sublimation, transport, and redistribution between tiles. Much of this was discussed and summarized at our previous two modelling workshops in Saskatoon and Canmore this past year (http://www.ccrnetwork.ca/science/workshops/index.php), and further details and presentations can be found there. One area we struggled with was the initialization of transient and non-stationary conditions for permafrost development, and its sensitivity under both past and future climate. However, we have been able to reasonably capture the extent and distribution of permafrost across our domain and it was agreed that what we have achieved is likely state of the art or better. This will need to be further pursued beyond CCRN.

Relevant publications include: Chen et al. (2016a, 2016b), Hassanzadeh et al. (2014, 2015), Li (2016), Mekonnen et al. (2014), Nazemi and Wheater (2014a, 2014b, 2015a, 2015b), and Wada et al. (2017).

C2 Large Basin-Scale Application and Testing of Weather, Climate and Large-Scale Hydrological Models, Including Verification and Assimilation of Ground-Based Observations and Remotely Sensed Data

This work package contains the activities **C2.1 Development of MESH modelling framework for major basins**, **C2.2 Development and testing of assimilation methods**, and **C2.3 Testing of improved land surface schemes at large basin-scale**. Deliverables under C1.1 include 10 km MESH models for the Mackenzie and Saskatchewan River systems, identification of key issues to address, and comparison of baseline simulations. For C2.2 these include improved assimilation schemes for the Soil Moisture – Active Passive (SMAP) mission, evaluation of potential for improved model performance using SMAP, AirMOSS (Airborne Microwave Observatory of Subcanopy and Subsurface), and GRACE (Gravity Recovery and Climate Experiment) datasets. Finally, for C2.3 this includes enhanced modelling capability for historical and projected future changes, including and – atmosphere interactions, integrating progress made in C1.2, C2.1, and C2.2, and feeding into Theme D.

The MESH framework has been developed for the two major basins under C2.1 and we have made major advancements in the modelling system, in terms of both basic operability and parallelization, ability to handle permafrost, irrigation, water management, and reservoirs. These are major achievements for the network, led primarily by Professor Wheater and Dr. Alain Pietroniro (ECCC), together with the joint CCRN–ECCC large-scale modelling team. The work has progressed over the course of CCRN to where we have fully working models for the two river systems and have been able to apply these for historical as well as future climate to examine scenarios of landscape and ecological change. This work was shown and discussed at our previous two modelling workshops in Saskatoon and Canmore this past year (http://www.ccrnetwork.ca/science/workshops/index.php), and further details and presentations can be found there. Technical information and descriptions of the specific model improvements and applications can be found in the individual progress report of Howard Wheater and the CCRN MESH summary report (http://www.ccrnetwork.ca/science/models/ccrn_modelling_mesh_update_2018-02-12.pdf).

Work contributing to C2.2 was primarily led by Aaron Berg and included use of soil moisture monitoring networks for improving observation of soil freeze-thaw processes and evaluation of soil moisture scaling properties at resolutions applicable to the NASA SMAP mission, upscaling of energy and water balance components from point- to field-scales, and evaluation of wetlands and soil moisture using RADARSAT-2 in prairie and taiga–tundra ecoregions. Relevant publications include: Adams et al. (2015), Bindlish et al. (in press), Burns et al. (2016), Champagne et al. (2016), Chan et al. (2018), Colliander et al. (2018), Djamai et al. (2015), Lyu et al. (in press), Kim et al. (2017), Manns et al. (2015), Ouellette et al. (2017), Reichle et al. (2017), Rowlandson and Berg (2015), Rowlandson et al. (2015), Roy et al. (2016, 2017a, 2017b), Williamson et al. (in press), Wrona et al. (2017). Although this was an important and productive endeavor, it was not possible in the end to link this to the other large-scale modelling activities. However, progress was made in the assimilation of other satellite products in the large scale hydrological models, in particular GRACE (in collaboration with NRCan; Yassin et al., 2017). The data provide a useful constraint on model performance and have reduced the uncertainty in (and hence improved the identifiability of) MESH model parameters.

Milestones for C2.3 have largely been achieved, as described above, with satisfactory performance of the large-scale models including permafrost representation, improved routing and simple lake processes, anthropogenic water management, irrigation schemes, blowing snow, and glaciers implemented and parameterized for the Mackenzie and Saskatchewan Basins.

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

Lead: Ronald Stewart

D1 Large/Regional-Scale Land Surface and Climate Controls

This work package includes the activities **D1.1 Large-scale controls over recent past climate**, **D1.2 Determination of past changes in all aspects of precipitation**, and **D1.3 Diagnosis of large-scale change and feedbacks**. Deliverables under D1.1 include characterization of large-scale conditions (sea surface temperature (SST) anomalies, large-scale oscillations) that have occurred, and variations in orographic-influenced circulations, and this links to the observed change in Theme A2. Under D1.2 this includes characterization of change in precipitation amount, phase and intensity, convection, droughts and heavy precipitation over the last few decades, relating to changes observed in D1.1. Finally, in D1.3, using basin-scale models developed in Theme C, deliverables include diagnosed causal effects of observed changes in river flows, and understanding of regional feedbacks between surface and atmospheric variables. Much of this work has been led by a group of atmospheric scientists, including Kit Szeto (ECCC), Barrie Bonsal (ECCC), Ronald Stewart (U of M), Yanping Li (U of S), Bob Kochtubajda (ECCC), Julie Thériault (UQAM), and John Hanesiak (U of M).

D1.1 has involved assessing the large to synoptic scale atmospheric controls on recent hydro-climatic extremes, and documenting trends and variability in key circulation patterns. This includes examination of large-scale controls of long-lived extreme rainstorms in southern Alberta, aspects of precipitation in the Prairies and temperature and precipitation over the west Coast. Examinations of coupled variability modes of Prairie precipitation with large-scale circulations and SST anomalies and their implications on the variability of continental storm tracks and Prairie precipitation have been completed. Relevant publications include: Bonsal et al. (2017), Brimelow et al. (2014, 2015, 2017), Nazemi et al. (2016), Szeto et al. (2015, 2016), and Yusa et al. (2015), with further manuscripts under preparation.

Work in D1.2 has examined changes in precipitation (mean and extremes) over western Canada and their implications for floods in southern Alberta, the Assiniboine Basin, and droughts in the area. Examinations of historical SPEI (Standardized Precipitation – Evaporation Index) for trends and variability of water availability at different scales over southern Canada have been completed. Other work has examined precipitation phase changes, winter precipitation extremes, surface hydrologic changes, and runoff. Assessments of various precipitation products and remotely sensed observations have been conducted, including NASA’s Global Precipitation Measurement (GPM), and characterization and regionalization of precipitation and drought characteristics over western Canada. Some of the papers above address this; others include: Asong et al. (2015, 2016), Dumanski et al. (2015), Khaliq et al. (2015), Kochtubajda et al. (2016), Liu et al. (2016), Masud et al. (2015), Pomeroy et al. (2016a, 2016b), Scaff et al. (2015), Schubert et al. (2016), Shook et al. (2015), Stewart et al. (2015), Szeto et al. (2015), and more are in preparation.

D1.3 has involved examinations of regional evapotranspiration, soil moisture, moisture flux convergence, etc., and large-scale (circulations) controls of Prairie precipitation. Examinations of trends of circulations, precipitation, air temperature, and their hydroclimatic impacts (e.g. snow water equivalent (SWE), SPEI) over northern Alberta and implications of the results for the Ft McMurray fire have occurred. Further contributions to D1.3 will come from the large-scale simulations currently underway for the Mackenzie and Saskatchewan River Basins.

D2 Changing Climate, Changing Land Surface Systems, and Large-Scale Hydrology

This work package contains the activities **D2.1 Assessment of large/regional circulation in models**, **D2.2 MESH/GEM sensitivity/feedback simulations using existing CLASS**, **D2.3 MESH development to include large-scale controls**, and **D2.4 GEM sensitivity/feedback simulations using improved CLASS**. Deliverables in D2.1 include establishment of the degree to which historic GEM, WRF, NARCCAP, CMIP5 models have simulated the circulations examined in D1, and understanding of any reasons for inadequate capabilities. For D2.2 this includes off-line MESH analyses of the sensitivity of land–atmosphere feedbacks to cryospheric, hydrologic, and terrestrial ecosystem change. For D2.3 this includes newly developed and tested MESH algorithms to represent: a) water management controls, b) land management change, and for D2.4 this includes analyses of sensitivity of land–atmosphere feedbacks to cryospheric, hydrologic, and terrestrial ecosystem changes and land/water management. This links to model developments in Theme C.

In D2.1, assessment of NARCCAP RCMs in ability to replicate key mid-tropospheric circulation patterns and examining future projections has been done, and the extent to which the circulation modes identified in D1.1 are reproduced in CMIP5 historical runs has been assessed. This work was led primarily by Barrie Bonsal and Kit Szeto. An important activity has been collaboration through Yanping Li with the US National Center for Atmospheric Research (NCAR) to produce 4 km resolution WRF climate simulations for the entire CCRN domain for 2001–2015 as well as pseudo-global warming simulations under RCP8.5 for 2086–2100. This provides unprecedented high resolution climate information for running surface hydrological models and gives important insights on precipitation extremes. More information is at www.ccrnetwork.ca/science/PGW. The historical simulations have shown good correspondence with observed circulation and other meteorological patterns. We are also collaborating with the Canadian Centre for Climate Modelling and Analysis (CCCMA) regarding the generation of 0.44 degree resolution continuous CanRCM4 regional climate model runs for western Canada under historical and future climate (RCP8.5) from 1950 to 2100. We have considered the ensemble projections and settled on the use of mid-range and outlier projections to capture a range of future climate possibilities, and have invested considerable effort in bias correction and downscaling of the results. This provides important driving data for future hydrological and land surface simulations in Theme B and Theme D.

Work in D2.2 and D2.4 has been ongoing and we are actively exploring the feedbacks and land–atmosphere interactions under future scenarios of change. This has involved offline simulations with the aim of one or more coupled simulations, and as the work warps up over the coming months we expect one or more papers to be produced on MESH results for the transient changes in vegetation, cryosphere, agriculture, and water management. In D2.4 we are also using WRF to examine the sensitivity of land–atmosphere feedbacks to Earth system change and land and water management.

D2.3 activities have been successful and there has been significant progress in development of models to represent land management change, as described above in Theme C. These are important achievements for the network.

D3 Atmospheric Circulations, Temperature and Precipitation

This work package contains the activities **D3.1 Establishment of large-scale controls in future climate**, **D3.2 Determination of role of regional circulations on future climate**, and **D3.3 Determination of future changes in precipitation and examination of future climate**. Deliverables for D3.1 include characterization of changes in large-scale conditions and regional circulations over next few decades in relation to projected temperature change (from GEM, WRF, NARCCAP, CMIP5). For D2.2 this includes establishment of future occurrence and variability of circulations linked with orography, and those affecting storm tracks, and determination of the role of such circulations in governing surface parameters, including temperature. Deliverables in D3.3 are establishment of future changes over region in precipitation quantity, phase and intensity including drought as well as instances of concurrent heavy precipitation, with special attention on heavy precipitation in lee of Rockies. This links with D4 on tipping points and the strategy for completing the work involves linking with other national and international activities.

Several different activities have contributed to these goals. Results from WRF PGW and the CanRCM4 future runs (see above) provide insights on future climate and key driving data for hydrological and land surface modelling efforts. Projected changes in large-scale circulation features that control precipitation and temperatures in Canadian regions have been assessed using CMIP5 results, and this has been used to examine the impacts on features such as cyclones, precipitation and temperature. Future changes in SPEI at various temporal scales have been assessed from several NARCCAP RCMs and from CMIP5 models. Work has also examined the changing hail threat and the convective storm environment in future over the CCRN domain using the HAILCAST model in combination with NARCCAP. Relevant publications include: Bonsal et al. (2017a, 2017b), Brimelow et al. (2017), with more publications forthcoming. In particular, all of the work is being synthesized into a major review and synthesis paper on future atmospheric and Earth system changes in western Canada

D4 Water Resources, Cryosphere and Ecosystems

This work package contains the activities **D4.1 Climate scenario selection for impacts assessment**, **D4.2 Determination of impacts on WECC observatories**, **D4.3 Determination of potential impacts on major river systems**, and **D4.4 Assessment of whether tipping points will occur**. Deliverables for D4.1 are selection of a sub-set of climate scenarios from GEM, WRF, NARCCAP and CMIP5 (impacts assessment, scope the full range of future scenarios, assigned associated levels of confidence), building on D2.1. For D4.2 this includes scenarios applied to WECC observatory and small/medium sized basins using fine- and meso-scale models, and assessment of potential impacts on cryospheric, ecological and hydrological systems. For D4.3 this includes assessment of river flow responses and impacts of management options in major basins through scenarios applied in MESH, and for D4.4, an assessment of the potential for tipping points to be reached in the coming decades, synthesizing results from D4.2 and D4.3.

Climate scenario selection has involved future runs of WRF and CanRCM4, as described above. A large amount of effort has gone into assessment of these products and downscaling and bias correction as required based on surface observations. This has been a key focus of our recent modelling workshops in Saskatoon and Canmore this past year (http://www.ccrnetwork.ca/science/workshops/index.php), and will be summarized at our upcoming CCRN Finale.

A significant amount of work has been done, with more underway, to examine the impacts at the local- to large-scales, using the models developed in Theme B and Theme C together with the climate runs selected in D4.1. This work is led primarily by John Pomeroy and Howard Wheater and specific details can be found in their individual reports. Future prognostic runs and sensitivity analyses have been initiated for a number of WECC observatories and will provide detailed insights and process-level understanding of future changes and interactions, informed by and expanding upon the results of our large-scale modelling. By the final months of CCRN, we have reached a point where we have our future scenarios of landscape, ecological, and land/water management change in hand and successfully incorporated within MESH models of the Saskatchewan and Mackenzie River Basins. Future runs are proceeding and will be largely completed by the end of the programme, providing new and unique insights into the future responses and impacts over multiple scales across our domain. A number of tipping points have already been identified, such as the loss of most mountain glaciers, dramatic changes to subarctic and arctic landscapes through the continued thaw of permafrost and collapse of forests, conversion of vast tracts of Boreal and Taiga forest due to the increase in extent, intensity, and occurrence of wildfires. We are highly confident in these changes over the coming decades given the current and projected climate. This work will be published as a collection of key papers that were identified at our last modelling workshop, and listed in the summary report (http://www.ccrnetwork.ca/science/workshops/Fall-2017-Modelling-Workshop/index.php).

5. Outreach, Communication, Promotion, and Publication of Research Results

5.1 Theme E: User Community Outreach and Engagement

Lead: Graham Strickert
Outreach Coordinator: Stacey Dumanski

Theme E's goals and strategy are described at www.ccrnetwork.ca/science/themes/E. It has a central goal to build a community of users including policy and decision makers, stakeholders and rights holders, and research scientists and organizations, both nationally and internationally. This aspect of the programme enhances the engagement and knowledge flow between the network and its partners and facilitates the transfer of improved scientific and decision making tools needed for water resource management and climate adaptation and mitigation strategies. Activities have taken place at a three-tiered level: 1) grassroots collaboration and engagement between network members and stakeholders, 2) an intermediate level linking the network with government and other partner organizations, and 3) an international level linking the network with major initiatives such as WCRP, GEWEX, NASA, NCAR, and others.

Some aspects of Theme E were slow to develop and were difficult to undertake in the early part of the network due to a lack of funding to support outreach and engagement. Additional funds were provided by NSERC through the CCAR Network Enhancement Initiative (NEI) during the final two years of the network, and this allowed the Theme E plan to come to fruition. More detail on the CCAR-NEI and our Theme E plan is provided in our report from year-4 (http://ccrnetwork.ca//outputs/reports/index.php), but we are pleased to report that these funds have supported the following key activities:

- **Canmore Coldwater Laboratory Grand Opening** (https://gwf.usask.ca/articles/grand-opening-gwf-coldwater-laboratory.php): this event was open to the public, mountain guides, outdoor recreational industry members, land and water managers and community planners and leaders. The event included tours of the Laboratory where HQP shared their research using plain language posters and an evening Science Town Hall with public science talks and a panel discussion. The event was well attended with over 130 people.
- **Wolf Creek 25th Anniversary Science Summit** (http://ccrnetwork.ca//science/workshops/WC-Summit/wcrb-25-year.php): This 2-day workshop celebrated 25 years of research at the Wolf Creek Research Basin, one of CCRN's WECC observatories. The event was well attended by past and current researchers, including members from Environment Canada, Yukon College, Yukon Government and the public. This event also included a public lecture and tour of the Wolf Creek Research Basin.
- **Travelling Engagement Tour:** Dr. Yanping Li and one of her PhD students travelled to the Canadian Centre for Climate Modelling and Analysis, University of Victoria and University of British Columbia and met with ECCC scientists, policy makers, university researchers and graduate students to introduce their work on the continental scale 4-km Weather Research Forecasting (WRF) simulation and Pseudo-Global Warming (PGW) run.
- **Cold Regions Ecohydrology Field Course:** CCRN helped fund 10 Dehcho high school students attend the cold regions ecohydrology field course at Scotty Creek from March 2017. Students learned from both elders and scientists about the local ecosystem and hydrological processes. They also used field instruments to collect ecological data and try out drones for imaging purposes. This course was led by Bill Quinton.
- **Delta Dialogue Network Travelling Display**: Funds were used to incorporate CCRN research results on observed changes in the central interior cold region into the Delta Dialogue Travelling Display (http://www.usask.ca/research-groups/ddn/). This display travelled to five communities across western Canada with over 1000 visitors. After this, it was set up at the Western Development Museum in Saskatoon for six weeks, where it was seen by approximately 4000 visitors.

- **CCRN Documentary – The Changing Climate and Environment of Western Canada**: CCRN developed a 3-part documentary film featuring major outcomes from the network. This included highlighting past environmental and climatic changes, scientific advancements made by the network, and future scenarios of change. The first screening of this documentary will occur during CCRN's 5th AGM – The Finale.
- The funds have also supported the hiring of a full-time outreach coordinator, development of plain language public outreach communications brochures (http://ccrnetwork.ca//outputs/information-products/index.php), travel support to engage with NCAR, NASA, and GEWEX, and data management assistance in archiving CCRN datasets.

We have continued to be active in outreach and engagement through direct interaction with partners and stakeholders, knowledge mobilization workshops, meeting and interactions with national and international organizations, media engagement and publicity of network activities and results, peer-reviewed literature contributions, and involvement in national and international conferences. Specific activities have included:

- Publication this year of 74 peer-reviewed articles appearing in a wide range of top-tier academic journals, with another 33 papers either in review, accepted, or in press (see www.ccrnetwork.ca/outputs/publications);
- Outreach to community-based stakeholders through involvement with water stewardship groups in SK, AB, and NT, interaction with First Nations communities in SK, AB and NT, and presentations and interactions with secondary schools in NT;
- Delivery of over 20 presentations to stakeholders such as government groups, First Nations and metis, NGOs, the United Nations, business groups, industry, the media, and universities;
- Development of four public outreach products: Observed Climatic and Environmental Change in Western Canada, Future Climate Conditions over Western Canada, The Changing Environment of Western Canada: Sub-Arctic Mountains, The Changing Environment of Western Canada: Canadian Rocky Mountains (see www.ccrnetwork.ca/outputs/information-products);
- Engagement of the media with over 65 interviews and feature articles written this year (see www.ccrnetwork.ca/outputs/media);
- Six Feature articles on student research;
- Dissemination of results and knowledge through major CCRN involvement at national and international conferences, including over 248 presentations (39 invited); and,
- Opening of two special issue journals (ESSD and HESS), which will form an important legacy for the network.

6. Recruitment and Training of Highly Qualified Personnel

One of the key aspects of the network, and of the NSERC CCAR Program in general, is the training of the next generation of scientists and professionals. The network has strongly supported this, with over 2/3 of our budget allocated to training of HQP training. Over the past year we have seen many students and PDFs graduate and/or move on in their careers, while we have also recruited some new personnel to continue the research in this and other follow-on activities. In total, CCRN has trained 188 students and post-doctoral fellows, who have have either completed their training or are currently involved with the research, including:

- 29 undergraduate research assistants and summer students, 65 Master's students, 41 Doctoral students, 53 post-doctoral fellows;
- We have also employed 34 technicians, research assistants and associates, and other professional staff.

Our network funding from NSERC has provided full or partial support to 128 students and post-doctoral fellows to this point in the network, with the others having been funded entirely through external sources. These HQP have been included in preparing research/funding proposals, developing research ideas/questions, developing research protocols/methods, data collection, interpreting research findings, undertaking knowledge mobilization activities (e.g. papers, reports, presentations, thesis, media, other), coordinating research resources (e.g. laboratory equipment, instruments, etc.), conducting multidisciplinary and/or multisectoral research, leading parts of the research project (e.g. human, financial, time management), understanding and applying the social, economic or ethical implications of research, transmitting results to federal partners, presenting results at national and international conferences, and coordinating with research partners and collaborators. It is pleasing to report that the level of involvement of these trainees and research assistants has been very high not only in terms of their contribution to the research itself, but also in presenting and discussing outcomes, implications, and future directions at our network workshops and at major national and international conferences. We have been actively encouraging the involvement of our HQP—for example we are holding a student poster competition at our CCRN Finale and requesting that PDFs also bring along posters, we have been posting their profiles on our website (http://ccrnetwork.ca//organization/hqp) and encourage them to contribute detailed research summaries for our newsletters and website, and we have engaged them on social media (Facebook and Twitter), with links via our homepage.