Annual Science & Progress Report – Project Year-2

1 December, 2014

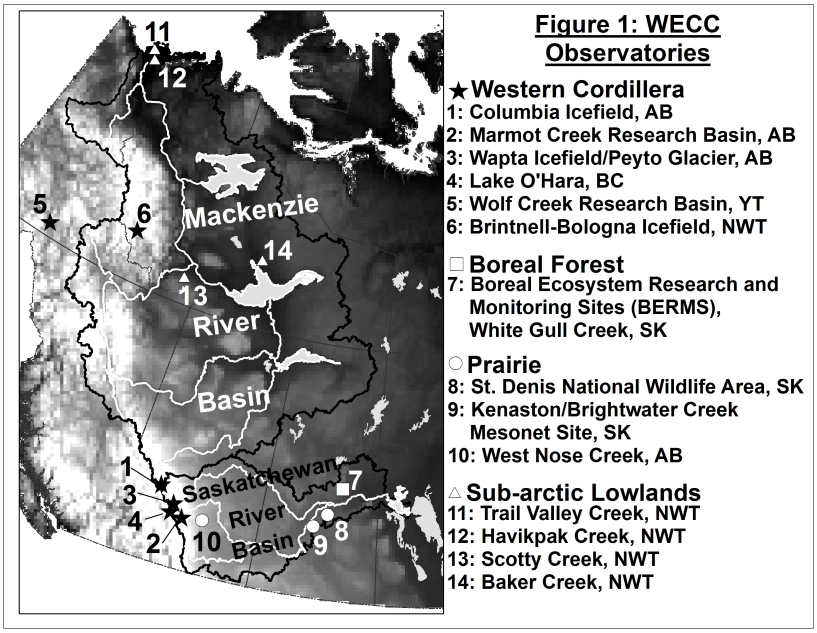
Executive Summary

The Changing Cold Regions Network (CCRN) formally commenced on 1 February, 2013, and was officially announced in May 2013. CCRN is now approaching the end of the second year of its 5-year programme, and its first full year of activity. We are pleased to report that significant progress and achievements have been made in many areas, and that the Network is on course to deliver new science and modelling tools as proposed. In particular, during year-2 we have:

- Held several important workshops that have advanced our science, strengthened plans for model development and application, and engaged some key partners and stakeholders;
- Recruited numerous students and post-doctoral fellows and established a network of Early Career Researchers within CCRN;
- Made significant progress towards developing a network data management system, including archive data from our Water, Ecosystem, Cryosphere, and Climate (WECC) observatories;
- Built and strengthened collaborative relationships with several prominent national and international research organizations, including the World Climate Research Programme (WCRP), the Canadian High Arctic Research Station initiative (CHARS), NASA (ABOVE, SMAP and AirMOSS projects), NCAR, among others;
- Submitted a proposal to the WCRP to advance CCRN as a GEWEX Regional Hydro-Climate Project;
- Engaged local stakeholders and community groups across the CCRN study domain;
- Implemented a Special Observation and Analysis Period (SOAP) involving enhanced instrumentation and coordinated science and monitoring activities at our WECC observatories;
- Conducted an integrated study of the June 2013 extreme weather and flooding in Alberta, and made plans to publish a collection of papers on this in a special issue of *Hydrological Processes*;
- Produced a quantitative assessment of recent climatic and hydrometric trends over the CCRN domain;
- Collected and analyzed extensive tree core data from across the CCRN domain for dendro-chronological studies;
- Carried out targeted process studies and developed many new and improved process algorithms for implementation within the CRHM platform;
- Completed baseline simulations using EC's Canadian Land Surface Scheme (CLASS) and other international LSSs at most WECC observatories, and hence made various CLASS improvements;
- Set up large scale baseline simulations over the Saskatchewan and Mackenzie River Basins using EC's CLASS and MESH (large-scale hydrological) models to identify priorities for development;
- Assembled large *in situ* soil moisture datasets at WECC observatories for evaluation and calibration of remote sensing products (AirMOSS and SMAP), and for development of data assimilation methods;
- Conducted diagnostic studies on various atmospheric phenomena using CMIP5 and NARCCAP datasets, and collaborated with researchers at NCAR in the U.S. on 4-km WRF regional climate modeling covering both continental U.S. and Canada; and,
- Actively disseminated our research results in the peer-reviewed literature and through conference presentations, media engagement, and other means.

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 world class WECC observatories (Fig. 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 and Mackenzie.



The programme and its objectives are organized based on 5 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 Understanding 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 analysed 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. As the Network

nears the end of its second year and progress is made in all Themes, the strong connectivity of the overall Network science and outreach programmes is emerging.

Progress made during the first year of the CCRN programme is described in our first annual report to NSERC (1 December, 2013). In that report, we describe how the Network's management structure had been implemented and we note here that this has been working well and remains unchanged. Other areas of initial year-1 Network progress are not repeated here and we focus primarily on our activities during year-2 of the programme. We first describe workshops and meetings held before discussing specific progress with data management and other Theme activities. The report then provides information on the recruitment and training of highly qualified personnel.

2. Workshops and Meetings

In year-2 CCRN has held several important workshops to advance the scientific programme and to engage with key stakeholders and our government partners and international collaborators. These are listed below and more detailed information, including agendas, workshop summary reports, and presentations are provided on the CCRN website (www.ccrnetwork.ca). In addition, in year-2 so far there have been 29 teleconference, web-based, and in-person meetings among various groups within the CCRN as well as connecting us with outside groups (8 Science Committee, 5 SOAP planning, 5 CHARS and NASA ABoVE, 5 ECRN, 3 CCRN Themes, 2 CanSISE Network, and 1 CCRN Board of Directors meetings).

Major Year-2 CCRN Meetings and Workshops (see CCRN website for details)

- *CCRN Theme C and Environment Canada Modelling Workshop (22–23 January, 2014):*
- *Workshop on "Extreme Weather and Hydrology – Lessons Learned from the Western Canadian Floods of 2013 and Others" (11–12 February, 2014)*
- *CCRN Modelling Workshop (15–16 September, 2014)*
- *CCRN 2nd Annual General Meeting (19–22 October, 2014)*

3. Progress in Data Management, Scientific Activities, and Outreach

We have made major progress in all thematic areas this year, and since our Network originally commenced in February 2013. An Inception Report was developed that describes on-going and planned CCRN activities and deliverables, from the broad Theme level down to the detail of individual activities. This report provides a basis to assess progress and guide future planning, and will continue to be periodically reviewed and updated as the Network evolves. The scientific objectives are on course to being achieved as originally proposed, and engagement with partners and stakeholders has been productive, with new opportunities continuing to emerge. Major areas of progress in data management and within each of CCRN's science and engagement Themes are described below.

While significant modelling progress is being made in Themes B, C and D, a concern was expressed by members of our International Advisory Panel that we should more clearly articulate our goals and plans for model development, and refine our modelling strategy to a point of greater specificity. This was reiterated by our Board at their annual meeting in October 2014. In response, we have developed a working document to flag issues requiring attention and have convened a meeting of modelling Theme leaders and other key participants to take this forward. A strategy document is now being synthesized.

Data Management

Data Management Team: Branko Zdravkovic (U of S, database manager), Alan Barr (EC), Bob Kochtubajda (EC), Phil Marsh (WLU)), Jay Sagin (U of S), Ron Stewart (U of M), Julie Thériault (U QC), Daqing Yang (EC).

As a Network, we are committed to produce, document, and archive our results in an integrated, long-term repository, and our Network inception report contains a description of the data management strategy

we are employing to achieve this. CCRN uses the Water Information System Kisters (WISKI) platform, which supports features to import, analyze, and visualize large quantities of data with the option to use Kisters' or external modelling and scripting tools for further data processing. Over the past year we have been importing data collected at our WECC observatories into the WISKI repository. Imports have been completed or are underway for 10 of the 14 observatories, including time series observations from 31 separate meteorological stations, hydrometric gauges, and other monitoring stations. We are in the process of completing a meta-data catalogue that details the existing data at each observatory and station, and the portion of it archived in our repository (e.g. variable, observation frequency, period of record, etc.). Scripts have been created and a procedure established for external users to export data from the archive and upload summary files to the server. To facilitate access to the database and ease of use within CCRN, we have been providing WISKI training and tutorial sessions covering graphical user interface, standards used when importing and processing the data (flags for cleaning, etc.), data editing, and the WISKI modelling tool. There has been a need identified within the Network for archiving of high temporal resolution GEM Model outputs over our WECC observatories during the SOAP, and we are working with partners in the Canadian Meteorological Centre to discuss needs and solutions. We will also be working to ensure the proper archiving of all targeted process data collected during the SOAP so that it can be easily accessed and used for intercomparative analysis and modelling studies, and thereby form an important legacy of the CCRN.

A concern expressed in a reviewers' comments on last year's progress report was that data management activities need to be more visible and transparent. We recognize the importance of this and are working to improve the visibility of data management and sharing on our website, where a new tab has been added to provide such information along with links to products and outputs (e.g. datasets, models, publications, etc.). We will also ensure that those intending to use large, composite datasets available through CCRN work in close collaboration with those responsible for gathering the data to ensure proper recognition and the prior development of good scientific questions to which the data are suited.

Theme A

Theme A Management: Sean Carey (MU, Theme A lead), Chris Spence (EC, A.1 lead), Merritt Turetsky (U of G, A.2 lead), Bill Quinton (WLU), John Pomeroy (U of S), Ron Stewart (U of M).

Considerable progress has been made in satisfying Theme A objectives, which are focused on assessing change in the CCRN domain from local to regional scales. Inventories of local scale change at the WECC observatories are largely complete through the collation of historical hydrometric and supporting remote sensing information archived on the centralized CCRN database. In addition, several focused studies are utilizing remote sensing platforms to assess changes in landcover and other indices (e.g. Normalized Difference Vegetation Index) over the past several decades. For example Moderate Resolution Imaging Spectroradiometer (MODIS) is being used in Scotty Creek to assess vegetation loss due to permafrost thaw and regrowth from fire, while in the Columbia Icefield, images are being used to quantify the rate of glacial retreat over the past several decades. Similar work is occurring elsewhere.

Large advances have been made in the meta-analysis of change in the CCRN domain. The Network has utilized the Adjusted and Homogenized Canadian Climate Data (AHCCD) derived from federal monitoring stations, and the gridded temperature and precipitation anomalies (CANGRD) to assess change with the CCRN domain. A meta-analysis of annual and seasonal temperature and precipitation trends identified that warming and wetting were most pronounced in the Mackenzie River Basin. Most notably, warming in the spring is influencing the timing of melt and precipitation phase change, whereas increasing precipitation is resulting in a greater winter snow accumulation in recent years. These results were mapped onto the WECC observatories to provide co-investigators (co-Is) comparable data sets for analysis activities.

For streamflow, trends were assessed in annual and monthly records for over 500 Water Survey of Canada stations over a range of time periods. Changes in peak flows, low flows, frequency of floods and timing of other hydrometric indices are being assessed at present. In addition, analysis of streamflow at the WECC observatories is also being undertaken, and a common framework for analysis is being established.

Dendro-chronological examination of local change is well underway. Tree-rings from most WECC observatories have been sampled in 2014 and analysis has begun. Across the northern CCRN domain, there

are divergent trends in tree ring / climate relations, as permafrost thaw and other factors complicate the relationship. Linkages between tree-rings and long-term biometeorological records (particularly at the BERMS sites) will provide unparalleled understanding on the connections between proxy record, ecosystem response, and variability in climate.

An inventory of observable change has been completed and forms the basis of a paper in the final stages of preparation by DeBeer and co-authors. This is an integrated review of previous work, and insights from the WECC observatories, to contextualize regional change in the CCRN domain and target gaps that have not been previously identified.

Finally, extreme events in the WECC domain are also being documented. A multi-year analysis of warm season precipitation and thunderstorms was completed, along with an assessment of recent large precipitation extremes in the Saskatchewan River Basin. In addition, research on intense weather systems that triggered severe flooding in southern Alberta provided an opportunity to understand the meteorology and hydrology of this event and place it in a historical context.

Theme B

Theme B Management: John Pomeroy (U of S, Theme B lead), Jeff McDonnell (U of S, B.1 lead), Sean Carey (MU, B.2 lead), Howard Wheater (U of S, B.3 lead), Bill Quinton (WLU), Phil Marsh (WLU).

Theme B focuses on local scale interactions and effects to aid in our understanding, modeling and diagnosis of change. At the end of year-2, considerable progress has been made. A number of targeted processes studies have occurred in all the WECC basins, with a number of cross-cutting activities that begin on 1 October, 2014 with the beginning of the Special Observation and Analysis Period (SOAP), which has resulted in the deployment of enhanced and new field instrumentation across all observatories including for example Eddy Covariance instruments in Wolf Creek, SODAR/windRASS at Brightwater Creek, ground based LiDAR and COSMOS soil moisture at Trail Valley Creek, etc. CCRN is well positioned to provide a world-class comprehensive and comparable data set during the SOAP period.

Targeted process studies are being undertaken in each of the WECC observatories, with a focus on understanding coupled cryosphere-hydrosphere-biosphere interactions and on comparing and contrasting processes amongst observatories. Isotope analysis to identify vegetation water use and catchment storage is being implemented. Recent wet conditions are being used to study hillslope water flow and wetland interconnection in the Prairies where previous concepts have been developed for predominantly dry climate phases. In the western Cordillera, surface-groundwater interactions are receiving additional attention, as mountain basins appear to exhibit resilient behavior in response to climate variability. A renewed focus on linking energy, carbon and water balances is being undertaken with a network of eddy-flux stations, with an objective of the SOAP period being to understand timing of photosynthesis and sources of water for evapotranspiration. Cryospheric processes are being intensively studied across the observatories, with snow redistribution, melt and coupled heat-and mass transfer in soils receiving particular attention along with glacier energetics observations. In addition, biological feedbacks on permafrost thaw is a new area of study.

Development of improved local scale models through improved process representation has advanced considerably in year-2. In the Cold Regions Hydrological Model (CRHM), new modules have been developed to calculate i) soil freezing-thawing, ii) frost table impacts on soil moisture storage and hydraulic conductivity, iii) flow through organic materials, iv) snow dynamics on glaciers, v) snow redistribution by avalanche, and vi) wetland fill and spill. New multiscale algorithms have been developed for fine scale modelling of radiative transfer to snow under forests and in forest gaps. Other platforms are being used to explore the capillary bundle approach for movement of water in frozen soil and coupled runoff-dissolved organic carbon algorithms to improve our understanding of coupling between the carbon and water balance.

An integrated focus of Theme B is to explore methodologies and develop toolkits to assess Earth system change. Work has advanced on the application of systems analysis methods to the analysis of model identifiability, parameter sensitivity and model uncertainty and are being linked with existing model structures. Models are also being used to assess hydrological sensitivity to temperature and precipitation change – initial results show that snow hydrology sensitivity to warming is very strong and increases as latitude decreases. This sensitivity can be compensated for by an increase in precipitation at northern sites

but not at southern sites. CRHM simulations over 50 years in Marmot Creek show further elevation specific responses to climate variability. Theme B is poised for strong advances in year-3 based on the work done to date and the results of SOAP.

Theme C

Theme C Management: Howard Wheater (U of S, Theme C lead), Andrew Ireson (U of S, C.1 lead), Aaron Berg (U of G, C.2 lead), Murray MacKay (EC), Al Pietroniro (EC).

Theme C aims to improve the capability of land surface schemes for weather and climate modelling, and large scale hydrological models.

In year-2, a significant CCRN large scale modelling team has been built (7 Post-docs, 3 graduate students, 1 research assistant, various EC staff), funded by CCRN, EC and the Global Institute for Water Security (GIWS). While the core group is based in Saskatoon, monthly conference calls are regularly attended by key EC staff from Ontario and Quebec. A CCRN modelling workshop was also held (15-16 September), attended by 40 people, which was helpful in reporting progress and identifying strategic needs and opportunities. Presentations are available on the CCRN web-site.

Development and testing of land surface schemes for weather forecasting and large scale hydrological models is underway. The current EC Canadian LAnd Surface Scheme (CLASS) has been run for multiple WECC sites to provide a baseline overview of strengths and weaknesses. The BERMS boreal forest sites have a particularly rich dataset and have been the focus of more extensive analysis. The CLASS model sits within EC's MESH hydrological model. MESH has been run in a Monte-Carlo framework for the BERMS catchment to analyse parameter sensitivity and trade-offs in performance between evaporation and streamflow. We envisage intercomparison between 3 land surface schemes: CLASS, WRF (a widely used U.S. modelling system), and JULES, the UK's community land surface scheme. This will be initially at the BERMS sites, but once protocols have been developed, will be rolled out across the various WECC observatory sites. Discussions are also underway for an international model intercomparison of cold region processes based on WECC and other sites to inform the next IPCC assessment, in collaboration with the GEWEX and iLEAPS international programmes.

Various CLASS model improvements are being tested based on the WECC baseline analysis. In addition a new Prairie land surface scheme has been developed to represent variable contributing areas to runoff, now published. This gives a significant improvement in Prairie streamflow simulation capability. Work has begun to evaluate coupled land surface and groundwater modelling, applied for the first time for the prairie environment, at St. Denis. Work is also proceeding with the further development of a 1D EC cold region lake model, initially based on data from Baker Creek. While the above work focusses on water and energy fluxes, we have now recruited a post-doc to work on modelling the linkage between hydrology, climate and vegetation dynamics, using the EC CTEM model (which links to CLASS), for research based initially on the BERMS sites.

Large scale hydrological modelling has similarly proceeded with the set-up of baseline CLASS/MESH models for the Mackenzie (1.8 million km^2) and Saskatchewan (400,000 km^2) Basins. This has requires a considerable amount of work on DEMs and land surface classification, but 10 km resolution models are now in place. As expected, results are mixed and are guiding various model developments. We aim to focus on subgrid resolution and snow processes for the Rocky Mountain headwaters, on the representation of lakes and wetlands for the Mackenzie, and in general model parameter estimation and regionalisation. A particular issue for the Mackenzie is the initialisation of permafrost (current climate does not give current permafrost). For the Saskatchewan we will do further work on headwater and prairie response, and in particular the representation of water management (reservoirs and irrigation). In that respect CCRN is part of an international working group addressing the representation of water management in large scale models. We have produced 2 major review papers (on-line in the journal HESS) and are testing alternative algorithms on the South Saskatchewan River prior to their incorporation in MESH.

A further element of Theme C is the development and testing of data assimilation methods to enhance model performance. A key focus is the use of remotely-sensed soil moisture. We note that 2 WECC observatories are currently being used by NASA for testing of the SMAP and AirMOSS missions. CCRN

work to date has focussed on the development of datasets within Themes A and B to support future model application. We are also expecting to pursue the use of new precipitation data products (the NASA GPM remote sensing mission and high resolution atmospheric model outputs) and snow products, with support to GIWS from EC.

Overall Theme C is on track to deliver improved models that can be used to explore effects of environmental change under future climates, supporting the objectives of Theme D.

Theme D

Theme D Management: Ron Stewart (U of M, Theme D lead, D.3 lead), Kit Szeto (EC, D.1 lead), Al Pietroniro (EC, D.2 lead), John Pomeroy (U of S, D.4 lead), Howard Wheater (U of S).

The overall objectives of Theme D are to understand the factors driving observed trends and variability in large-scale aspects of the Earth system, to assess how well these factors and effects are represented in large scale models, and to determine projected regional scale effects of Earth system change on climate, land and water resources.

A substantial effort was undertaken directly on Theme D in year-2 and other activities are carrying out work on Themes A–C in preparation for later Theme D involvement. The team directly involved in Theme D in year-2 includes 4 CCRN-funded researchers (Hanesiak, Pomeroy, Stewart, Wheater), 1 non-CCRN funded university researcher (Li), and at least 4 government researchers (Bonsal, Brimelow, Kochtubajda, Szeto). Students and PDFs are in addition. As CCRN moves forward, it is expected that almost all of its researchers will eventually be contributing to Theme D in some manner.

Individual progress has been made on a range of topics, as outlined in the original CCRN proposal. These include atmospheric circulation patterns, instabilities for generating convection, precipitation phase changes, surface hydrologic changes and runoff. Studies have relied on diagnostic studies using CMIP5, NARCCAP or other projection datasets, have analyzed datasets of past conditions over the CCRN region to understand their trends and infer their possible change, have carried out process model studies of surface and hydrologic conditions under current and future conditions, and have contributed to setting up WRF for future projections. Several journal articles have already been completed or are in preparation based on these studies.

Much of the progress in Theme D has been through research by its individual researchers although a team has been focusing on the 2013 Alberta flood. This latter research actually touches all Themes and it is essential for Theme D to utilize this collective knowledge to assess the future likelihood of such events. As planned, Theme D activities thus far have largely focussed on data analysis, with some supporting atmospheric modelling. As deliverables from Theme C become available, the models will be used to evaluate land-atmosphere feedbacks, and ultimately to project scenarios of change.

We are pragmatically examining our Theme D plans for the remainder of CCRN. While maintaining our overall goals and general path, we are now in a better position to deal with practicalities. This includes assessing modelling platforms and their utilization, more detailed planning of linkage between individual and Network-scale activities, defining scope for coupled land-atmospheric modelling, and identifying final products such as synthesis articles. This effort was facilitated through a breakout session at the CCRN October workshop, and will be further developed through conference calls and interactions afterwards, including a focussed winter/spring 2015 workshop.

Overall, Theme D progress has progressed as planned. Some important deliverables depend on Theme C modelling, but this work continues to progress on schedule.

Theme E

Theme E Management: Bill Quinton (WLU, Theme E lead), Graham Strickert (U of S, outreach coordinator), Howard Wheater (U of S).

Theme E is focused on enhancing the engagement and knowledge flow between the Network and its partners and other stakeholders, and facilitates the transfer of improved scientific and decision making tools. In year-2 we have been highly active in numerous ways, including direct collaboration and interaction with partners and stakeholders, knowledge mobilization workshops, short courses and training, meetings 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 scientific conferences.

Since the inception of the Network, CCRN co-Is have published 38 manuscripts in peer-reviewed journals, with an additional 13 papers accepted and in press. These manuscripts feature in a range of top tier academic journals such as Global Change Biology, Hydrological Processes, Water Resources Research, Soil Science Society of America Journal, Hydrogeology Journal, Journal of Hydrometeorology, and Hydrology and Earth System Sciences. A publication list is available on our Network website. Co-Is have provided 79 presentations at workshops and scientific conferences, and 23 presentations given to stakeholders that include various local, regional, national, and international groups and organizations. CCRN's research has been extensively covered in the media with over 130 feature articles and interviews with co-Is. To profile this media engagement and make it readily accessible to those interested, we have included a listing on our webpage in the section on *Theme E*, and included links to the online sources.

CCRN has been actively engaged with our federal and provincial partners. First, our Science Committee and Board of Directors include senior managers and directors from various government agencies, including Environment Canada (EC), Natural Resources Canada (NRCan), Agriculture and Agri-Food Canada (AAFC), Alberta Environment and Sustainable Resources Development (AESRD), and the Saskatchewan Water Security Agency (SK WSA). This provides direct linkage to facilitate productive and mutually beneficial interaction between the Network and these agencies. Other linkages with federal and provincial partners have been developing through the involvement of government scientists and collaborations on specific projects and at CCRN WECC observatories. For example, collaborative activities between CCRN and AAFC have included complementary field monitoring and research at the Kenaston/Brightwater Creek observatory, and those between CCRN and NRCan have included joint participation in field activities and instrument deployment at the 3 glacier and icefield observatories. Work at these glacier sites and at the Lake O'Hara observatory also involves Parks Canada Agency who provide logistical support, while the research benefits their mandate for environmental conservation and education within the Parks system. Linkages with Environment Canada have been strongly developed (see description of *Theme C* and *Theme D* activities). These have been facilitated through the joint modelling group that has been formed and through 2 key modelling workshops and the extreme weather and hydrology workshop all held this past year (see *Workshops and Meetings*). The extreme weather and hydrology workshop was also a very productive and informative event that brought together a wide range of other local, provincial, national, and international stakeholders and collaborators, including a public forum for outreach to the local community.

Nationally and internationally, CCRN has been linking with a number of major scientific and government organizations across the world, and we have been actively engaging our international collaborators in workshops and various other projects. Our Network was well-represented at the WCRP's GEWEX Forum in the Netherlands this summer, and the GEWEX Hydro-Climate Panel (GHP) has requested that CCRN apply to become a Regional Hydroclimate Project (i.e. including the Mackenzie Basin, as the Saskatchewan Basin is already), to which we have responded with a formal proposal. There are various other connections between GEWEX and CCRN that are planned or underway, including model intercomparison studies and cross-cut activities on water resources modelling, and mountain hydrology. We are linked with the U.S. National Center for Atmospheric Research (NCAR) through collaborations among some of our Network co-I's and international colleagues, who are jointly participating in atmospheric and hydrological modelling studies over the North American Rocky Mountains to examine the Colorado and Alberta floods of 2013, and over the larger CCRN domain. This work is using the NCAR Weather Research and Forecasting (WRF) model, a key model being tested and applied within Theme C, as well as an associated hydrological modelling system (WRF-Hydro). These activities fit within our proposed GEWEX crosscut activity, the International Network for Alpine Research in Catchment Hydrology (INARCH) for intercomparing and modelling the hydrometeorology of high mountain regions around the world. As a Network, we have actively pursued linkages with the both the Canadian High Arctic Research Stations (CHARS) and the NASA Arctic and Boreal Vulnerability Experiment (ABoVE). Discussions have dealt with collaborative activities and opportunities at our northern WECC observatories

and across the sub-arctic and arctic parts of the Mackenzie River Basin in general. Both organizations, along with representatives of the Government of Northwest Territories, were represented at our annual meeting, where we held special sessions to further explore and develop formal collaborative relationships.

The Wilfrid Laurier University – Government of Northwest Territories (Laurier–GNWT) Partnership Agreement and the GIWS Socio-Hydrology Programme have continued to represent important and effective outreach mechanisms for CCRN in both the northern and southern parts of our study domain. The Laurier–GNWT Partnership continues to contribute significantly to the CCRN's research, capacity building and engagement initiatives in the North. Researchers based at Laurier Centre for Cold Regions and Water Science and their GNWT collaborators submitted a $7M application to the Canada Foundation for Innovation. If funded, the Changing Arctic Network (CANet) will provide new state of the research infrastructure to the existing CCRN research sites in the NWT. The Water Application Network (WatKAN) funded by the Canadian Water Network is supporting CRHM interface development to meet specific needs of GNWT. New research sites (e.g. Fort Liard, Wrigley, Yellowknife regions) were established by Partnership researchers to address specific CCRN-Theme B questions and to test if processes and modelling methods developed at existing CCRN sites are transposable to other sites. The 2014 fire season was one of the most severe on record. CCRN researchers in the NWT have mobilised into interdisciplinary teams and have begun instrumenting burn sites to explore the impact of different burn severity and site characteristics on snow cover accumulation, ecology, ground thaw, and runoff.

Activities of the GIWS Socio-Hydrology Programme have supported CCRN through several key projects that have used social science methodologies to capture, represent, compare and contrast, and convey divergent perspectives from a wide range of stakeholders and decision makers in the Saskatchewan River Basin. The objectives have included building relationships, developing common understanding, studying societal responses, and informing water management decisions. CCRN science results will be incorporated into these projects, which will be expanded to cover a more diverse range of stakeholder groups over a larger geographic region. The Network outreach coordinator has recently met with a range of northern stakeholders and decision makers, in connection with the Laurier–GNWT Partnership, and is developing a strategy to facilitate similar projects for CCRN outreach across the Territories.

4. Recruitment and Training of Highly Qualified Personnel

One of the most important aspects of the Network is the training of the next generation of scientists, and CCRN has continued to be committed to ensuring that this activity is well-supported. Roughly 2/3 of the overall project budget is allocated to the development of highly qualified personnel (HQP). During year-2 of the CCRN programme, we have significantly expanded the recruitment and training of HQP, and we are now largely on track with meeting our recruitment goals for this stage of the Network. There are presently 105 personnel that are all making important contributions to the Network's scientific objectives, while gaining practical experience in field research, data analysis, modeling, presenting research results, and publishing research papers. This includes:

- 16 professional researchers, 24 postdoctoral fellows, 22 PhD candidates, 32 MSc Candidates, 6 technicians, and 5 undergraduate research assistants.
- Of these, 16 are entirely funded and 41 are partially funded by the Network, while 48 are funded entirely through external sources.

A concern was expressed by our Board at the last annual meeting that the students and post-doctoral fellows were not highly engaged in the meeting (and possibly the Network), and a suggestion was made to form a network among them and to explore ways to enhance their involvement in CCRN. In response we have set up an Early Career Researcher Network (ECRN) within CCRN that is being managed and directed internally with oversight from the CCRN Science Committee. This nested network has already provided opportunities for peer-to-peer collaboration among HQP within CCRN and web-based training/professional development activities. In combination with the CCRN's 2nd annual meeting, a 1-day ECRN meeting and workshop was held, providing an opportunity for students and post-doctoral fellows to meet and present their research, receive training on the WISKI data management platform, and discuss possible and desired

future training, networking, and professional development opportunities. This was a highly successful and engaging event for the early career scientists, and we will continue to hold similar events to keep them closely involved.

Appendix: Abbreviations

AAFC: Agriculture and Agri-Food Canada
ABoVE: Arctic–Boreal Vulnerability Experiment
AESRD: Alberta Environment and Sustainable Resources Development
AHCCD: Adjusted and Homogenized Canadian Climate Data
AirMOSS: Airborne Microwave Observatory of Subcanopy and Subsurface
BERMS: Boreal Ecosystem Research and Monitoring Sites
CANet: Changing Arctic Network
CANGRD: Canadian Gridded Temperature and Precipitation Anomalies
CanSISE: Canadian Sea Ice and Snow Evolution
CCAR: Climate Change and Atmospheric Research
CCRN: Changing Cold Regions Network
CHARS: Canadian High Arctic Research Station
CLASS: Canadian Land Surface Scheme
CMIP5: Coupled Model Intercomparison Project Phase 5
Co-I (Co-Investigator)
COSMOS: COsmic-ray Soil Moisture Observing System
CRHM: Cold Regions Hydrological Model
CTEM: Canadian Terrestrial Ecosystem Model
DEM: Digital Elevation Model
EC: Environment Canada
ECRN: Early Career Researcher Network
GEM: Global Environmental Multiscale
GEWEX: Global Energy and Water Exchanges Project
GHP: GEWEX Hydro-Climate Panel
GIWS: Global Institute for Water Security
GNWT: Government of Northwest Territories
GPM: Global Precipitation Measurement
HQP: highly qualified personnel
iLEAPS: Integrated land Ecosystem – Atmosphere process Study
INARCH: International Network for Alpine Research in Catchment Hydrology
IPCC: Intergovernmental Panel on Climate Change
JULES: Joint UK Land Environment Simulator
Lidar: Light detection and ranging
MEC: Modélisation Environmentale Communautaire
MESH: MEC – Surface and Hydrology
MODIS: Moderate Resolution Imaging Spectroradiometer
MU: McMaster University
NARCCAP: North American Regional Climate Change Assessment Program
NASA: National Aeronautics and Space Administration
NCAR: National Center for Atmospheric Research
NRCan: Natural Resources Canada
NSERC: Natural Sciences and Engineering Research Council of Canada
SK WSA: Saskatchewan Water Security Agency
SMAP: and Soil Moisture Active Passive
SOAP: Special Observation and Analysis Period
SODAR: SOnic Detection And Ranging
U of G University of Guelph
U of M: University of Manitoba
U of S: University of Saskatchewan
U QC: Université du Québec à Montréal
WatKAN: Water Application Network
WCRP: World Climate Research Programme
WECC: Water, Ecosystem, Cryosphere, and Climate
windRASS: wind Radio-Acoustic Sounding System
WISKI: Water Information System Kisters
WLU: Wilfrid Laurier University
WRF: Weather Research and Forecasting