Changing Cold Regions Network

Progress Report to the Natural Sciences and Engineering Research Council of Canada (NSERC)
Project Year-3

1 December, 2015

Executive Summary

In August 2015, CCRN reached the midpoint of its 5-year research programme. After an initial start-up period in the first year, we have built a large research group (42 co-Investigators and government collaborators, 136 students and post-doctoral fellows (PDFs), and 25 technical staff and other professional research support personnel) that is now well integrated, active and productive, and has made major progress towards achieving the goals set out in our proposal. It is pleasing to note that important deliverables are emerging from all network Themes. People and plans are in place to successfully complete our remaining objectives by the end of the network in 2018. In particular our modelling strategy has been more closely defined, and now includes active collaboration with our sister CCAR project, the Canadian Network for Regional Climate and Weather Processes (CNRCWP). CCRN has been closely engaged with federal, provincial, and territorial government partners to work collaboratively on common problems and issues. Last year's workshop on the 2013 Calgary flood has led to joint research and a set of papers now submitted for publication. This year we have held two key workshops focused on sharing knowledge and shaping a research agenda on wildfires in the northern boreal and taiga forest, and on advancing the state of hydrological, ecological, and atmospheric model development. We are closely connected with a number of international organizations. CCRN is now recognized by the World Climate Research Programme as a Regional Hydroclimate Project and we are leading new international GEWEX 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. In addition to our collaboration with Environment Canada (EC) 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, and the media. The network has allowed the recruitment and professional development of 136 highly qualified personnel (HQP), helping to train the next generation of scientists, and while we are sorry to see them go, several of our post-docs have already moved on to faculty or research positions in Canada, USA, South America, Hong Kong, and Australia.

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 (www.ccrnetwork.ca/science/WECC) 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. (For a description of the network's science programme and Themes, see www.ccrnetwork.ca/science/themes.)

Annual progress reports have been submitted to our Board of Directors and to NSERC for Project Years 1 and 2, and a briefing on the first two years of CCRN was given to our Board in April 2015; these can be accessed at www.ccrnetwork.ca/outputs/reports. Here we focus on activities and progress during Year-3, and in some cases reference information from these previous reports and/or on our website. In the following sections of this report we include updates on the growth and development of the research team, workshops and meetings held in Year-3, data management activities, scientific progress and directions, outreach and publicity, HQP training, and the nature of collaborative relationships.

2. Growth and Development of Research Team, and Management Structure

CCRN has developed a large, multi-disciplinary team of researchers, including 42 investigators and 136 current and past students, PDFs, and other HQP from eight Canadian Universities and four federal government agencies. Integration of researchers is an important goal, and we believe that the network is functioning well in that respect. As discussed in Section 3 below, we have held numerous workshops and training events to promote network integration, and our researchers have actively collaborated on many important and timely matters (e.g. recent extreme events including the June 2013 floods in Alberta, the 2014 extreme fire season in the Northwest Territories, the 2015 drought in western Canada; the CCRN's Special Observation and Analysis Period (SOAP)). 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 past two and a half years. Our first progress report contains a description of the management structure, which is unchanged and working effectively; we note, however, that due to mobility restrictions, Jim Bruce has had to step down as Chair of the Board, but he continues to serve. He was replaced by Ming-ko (Hok) Woo, who previously chaired the IP3 Board of Directors. Further details on the team are available at www.ccrnetwork.ca/organization.

3. Workshops and Meetings

In Year-3, CCRN has held several key workshops to advance our science, plan future activities, and promote collaboration among network members, government partners, international collaborators, and various other stakeholders. These are briefly summarized below, while more detailed information is available on our website. In addition to these formal events, various smaller groups of collaborators within the network have been meeting on a regular basis throughout the year to advance specific research issues within the Themes or on a particular focal topic. This includes a core group of atmospheric scientists contributing primarily to Theme D, a team of ecologists whose work crosses many Themes, a group of modellers, including many EC staff, working on model development issues primarily in Themes C and D, and a small committee to advance outreach activities in Theme E. There have been seven meetings held to discuss the CCRN's modelling strategy, including separate meetings for each of Themes B, C, and D, which brought together most CCRN researchers contributing to these individual Themes. The network's Science Committee meets on a monthly basis and has held nine meetings so far in 2015.

Workshop on the 2014 Northwest Territories Fires – Developing a Research Framework *(12–13 January, 2015, Yellowknife NT)*

The 2014 fire season in the Northwest Territories involved record-setting area burned and major impacts to society as the fires were concentrated around the Great Slave Lake regions, thus affecting the majority of residents. This important and timely workshop brought together a large group of participants from the Government of the Northwest Territories, EC, researchers from within CCRN and others in the university community, and international collaborators to discuss the research needs arising from the 2014 fire season. Working groups identified a set of immediate priorities and critical next steps, and CCRN co-Is (Baltzer, Johnstone, Turetsky, Quinton) are leading the main research studies arising from this workshop, including the focus on predicting

wildfire-driven land cover changes and associated impacts on aquatic ecosystem function. (See report at www.ccrnetwork.ca/science/workshops/nwt-fire-workshop.)

Theme A workshop, Conceptual Models of Change *(22 January, 2015, Hamilton ON)*
This workshop brought together a small group of network investigators to discuss the development and advancement of conceptual models of change in the CCRN domain, particularly as applied to the WECC observatories. This led to hypotheses about the sensitivities and response to drivers of change, and following the workshop, a simple, yet comprehensive and robust meta-analysis of WECC data was carried out to synthesize observed patterns of hydrological, ecological, and climatic behavior in a comparative framework. This work will be used to develop improved conceptual understanding of change, which can then be diagnosed quantitatively in Theme B, and was followed up at our November annual meeting.

"Modelling Change in Cold Regions" Workshop *(28–30 September, 2015, Saskatoon SK)*
This three-day workshop included a large group of participants from within the network (with strong involvement from EC and representation of our Board by Michel Jean), as well as several key international collaborators (Clark, Lettenmaier, Wagener) and other Canadian university scientists, in particular Laxmi Sushama, PI for the CNRCWP. The workshop was aimed at evaluating progress across our Themes, including fine-scale and large-scale hydrological, hydro-ecological, and atmospheric modelling, and in particular addressing issues including the diagnosis and prediction of change. The event was highly successful as it demonstrated major progress in many areas, fostered important collaborative links, helped identify and prioritize future research directions, and resolved outstanding issues regarding our modelling strategy, in particular how we will proceed with the evaluation of interactions and feedbacks, simulation of future climate, and implications for feeding back to detail in large scale models. (See report at www.ccrnetwork.ca/science/workshops/2015-modelling-workshop.)

CCRN Third Annual General Meeting *(1–4 November, 2015, Saskatoon SK)*
The meeting provided an opportunity for the network to come together and synthesize activities and progress over the past year, and to plan future activities over the remainder of the programme. It included sessions on individual investigator updates, Theme syntheses, the 2014–15 SOAP initiative across all WECC sites, special cross-cutting topics (the 2015 drought and its manifestations; threshold behaviour and response to climate change), international collaboration, and network outreach. It also provided the opportunity for the early career researchers (students and PDFs) to get together, share their research, and take part in some special activities ahead of the AGM. The Board of Directors met over dinner on the second day of the meeting, and heard comments from the International Advisory Panel (IAP) members. (See further details at www.ccrnetwork.ca/science/workshops/ccrn-3rd-annual-meeting.)

4. Management of Data and Research Results, and Plans

Network data management activities are overseen by our database manager, Branko Zdravkovic, at the Global Institute for Water Security (GIWS), University of Saskatchewan. Many of the CCRN co-Investigators employ their own data management personnel and research technicians, and Branko liaises directly with them to coordinate data transfer. 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. Information is included on our website to make data management activities transparent (www.ccrnetwork.ca/outputs/data), including guidelines and support, public data access, and contact information.

Imports of WECC observatory time-series data (both historical and near real-time) into our central database have been progressing over the past year; we now have imports underway or completed for 12 of 14 WECC

observatories with time series observations at over 50 separate monitoring stations. Many of these are providing near real-time data straight into the database, while in other cases, updates are provided periodically. Our automated data collection includes the measurements from 11 new stations that are part of the Canadian Rockies Hydrological Observatory in the Rocky Mountains all managed by the Centre for Hydrology at the University of Saskatchewan. Also, we added records collected by EC from the prairie WECC sites. Our near real-time data now includes close to 1800 variables that are imported into the central repository on a daily basis. Most of our time series records are being processed in a uniform, standardized way ensuring that the same QA/QC procedures are applied at each observatory.

We have been working with EC to archive high-resolution GEM (Global Environmental Multiscale) model output over the CCRN domain as a contribution to the 2014–15 SOAP. Necessary variables have been identified and progress is being made on getting these from EC's Pegasus server to GIWS servers and making them available to the CCRN. Files will be provided in GRIB2 format, which is an international standard with documentation available. Through collaboration with Laxmi Sushama and the CNRCWP, we have begun acquiring multi-resolution forcing data for seven variables from the ERA-driven CanRCM5 simulation. These span from 1958–2014, and extend beyond the CCRN domain to cover all of Canada.

The Network database and data related resources have been attracting new users from the University of Saskatchewan and CCRN members. We continue to provide necessary training and tutorial sessions for all students and researchers that require WISKI database access. The data are available through the WISKI desktop clients, web interface, HTTP requests, and FTP clients. Many of our users employ MATLAB and R scripts to directly query the CCRN data.

At this stage in the network, we must focus on archiving of model datasets (including forcing data, model output and validation, model versions, etc.), spatial data and parameters other than time-series observations (e.g. snow and soil moisture surveys, etc.), and planning around our final legacy database, including its complete content, format, accessibility, and maintenance. This is especially important for activities as part of our SOAP year. We addressed some of these issues at our annual meeting in November, where it was agreed that SOAP data would be processed and submitted by March 2016.

5. Scientific Progress and Accomplishments to Date, and Future Directions

Theme A: Observed Earth System Change in Cold Regions—Inventory and Statistical Evaluation *(Lead: Carey)*

Theme A provides a synthesis of observed change to the Earth system within the CCRN study domain and establishes a foundation for more detailed analysis and modelling in Themes B–E. The key science questions are: 1) how have the hydrological, ecological, cryospheric and atmospheric components of the Earth system changed over the last several decades in response to climate warming, and 2) what are the collective large-scale trends and variability of the Earth system? Work in this Theme has addressed the local/biome scale (i.e. WECC sites), and the regional scale. Work at the local scale continues to deliver important insights into the nature of change in the different WECC observatories. Regional analyses have been ongoing using consistent approaches, datasets, and common analysis periods and are largely complete (a major synthesis paper has been published). Although Theme A objectives have largely been achieved, various ongoing network activities will continue to advance this science and generate deliverables. Accomplishments have included:

- Completion of local-scale assessments and inventories of change at many WECC observatories, including changes in climate, vegetation, snow and glacier cover, permafrost, stream discharge, groundwater and pond levels, and surface water extent (Baltzer, Berg, Carey, Hayashi, Helgason, Johnstone, Marshall, McDonnell, Quinton, Turetsky, Wheater);

- Collection of tree core data from across the western Canadian Boreal and Taiga ecoregions to develop an extensive dendro-chronological record, which will provide unparalleled understanding of the connections between proxy record, ecosystem response, and climate variability (Baltzer, Johnstone, Turetsky)
- Development of conceptual models of drivers and mechanisms of change for WECC observatories and major ecoregions, which together with observations of change, will be diagnosed quantitatively in Theme B (Carey, Ireson, Johnstone, Pomeroy, Quinton);
- Regional-scale synthesis of Earth system change through analysis of federal and provincial hydro-climatic datasets, remotely sensed data products, climate model reanalysis, and radar, rawinsonde, and lightning detection observations, as well as an integrated literature review of past change over the CCRN domain (Berg, Carey, Hanesiak, Hayashi, Helgason, Kochtubajda, Li, Pomeroy, Quinton, Stewart, Szeto, Wheater).

Theme B: Improved Understanding and Diagnosis of Local-Scale Change *(Lead: Pomeroy)*

Theme B 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. Regional-scale processes and interactions are addressed in Theme D. The work uses a unique legacy of process observations and modelling at long-term WECC observatories to answer the following science questions: 1) how have interacting Earth system processes changed in response to changing climate, 2) how can fine-scale process models be improved to better diagnose key factors governing change, and 3) what are the interactions amongst climatic, hydrological, ecological, and cryospheric drivers, processes and feedbacks, and thresholds leading to system changes at local scales? Several extreme events that have unfolded during this network provide key focal points for interdisciplinary investigation (spanning Themes B–E), 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. A major effort in Theme B is on developing and applying models developed using the Cold Regions Hydrological Modelling platform (CRHM) at all WECC observatories. Activities and deliverables are on track and an important success has been the coordination of efforts across nearly all WECC sites to achieve the following:

- Continued operation and enhancement of the observatories, with the deployment of enhanced and new field instrumentation for the 2014–15 SOAP across all observatories, which also included standardized ecological, hydro-meteorological, and isotopic data collection (Baltzer, Berg, Black, Demuth, Carey, Hayashi, Helgason, Howard, Ireson, Janowicz, Johnstone, Marsh, Marshall, McDonnell, Pomeroy, Quinton, Spence, Stewart, Thériault, Turetsky);
- Set-up and initial testing of CRHM, and for select basins, change detection and sensitivity analysis, with plans in place for extending this to all observatories (Carey, Hayashi, Helgason, Ireson, Marsh, Marshall, Pomeroy, Quinton, Spence).

Other activities have been progressing well and have produced various important deliverables, including:

- Targeted process studies with a focus on understanding coupled cryosphere-hydrosphere-biosphere interactions, comparing and contrasting processes amongst observatories, and developing improved cold regions model algorithms and parameterizations (Baltzer, Berg, Black, Carey, Hayashi, Helgason, Ireson, Johnstone, Marsh, Marshall, McDonnell, Pomeroy, Quinton, Spence, Stewart, Thériault, Turetsky);
- Implementation of numerous improvements and new algorithms of physical processes within the CRHM platform 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 (Pomeroy);
- Application of systems analysis methods to the analysis of model identifiability, parameter sensitivity, and model uncertainty (Wheater).

Theme C: Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction *(Lead: Wheater)*
Theme C builds on the insights from the WECC observations and fine-scale modelling (Themes A and B) to develop and test improved models for large scale application, both as land surface schemes within weather forecasting and climate models, and as large-scale hydrological models that can be used to analyze and predict change at large river basin scale. The application of these models, to address impacts of change on river flows and land-atmosphere feedbacks, is in Theme D. The key science question for this Theme is: how can our large-scale predictive models be improved to better account for the changing Earth system and its atmospheric feedbacks? There is a strong collaboration between the network and EC, particularly 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. Major progress has been achieved in the following areas:

- Completion of CLASS baseline simulations and performance evaluation at most WECC observatories, and initial intercomparative work using other models (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)), starting with sites in the southern boreal–prairie transition, with plans for extension to others in the domain (Bartlett, Ireson, Li, Razavi);
- Various improvements to CLASS and issues under development, including lakes, wetlands, snow/ mountain hydrology, frozen soils and infiltration, prairie hydrology, water management, coupled land-surface–groundwater, glacier dynamics, and linkage between hydrology, climate, and vegetation (Barr, Fortin, Ireson, Johnstone, MacKay, Marshall, Pietroniro, Pomeroy, Spence, Wheater);
- Setup and evaluation of MESH over both the Mackenzie and Saskatchewan River basins, with several key focal issues identified for future work, including input uncertainty, soil depth and permafrost initialization/representation, wetlands, and water management—channel hydraulics may be a major limiting factor for basin-scale modelling of the Mackenzie (Wheater);
- 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 Soil Moisture – Active Passive (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 (Berg, Helgason, Howard).
- Progress has also been made on the quantification of effects of uncertainty in driving variables, and new methods to accommodate this, and in the assimilation of other satellite products in the large scale hydrological models, in particular GRACE (in collaboration with Natural Resources Canada (NRCan)).
- An important development for the network is that Li, working with NCAR, is producing 4km WRF climate simulations for the entire CCRN domain (14 years historical simulations, plus pseudo warming simulations of future climate). This provides comparative data for Theme B, C and D modelling and large scale climate analysis. Similarly, collaboration with Sushama's CNRCWP provides access to the regional climate model CanRCM5, based on CLASS, which provides us with a platform for coupled modelling and additional simulations for large scale analysis.

Theme D: Analysis and Prediction of Regional and Large-Scale Variability and Change *(Lead: Stewart)*
Theme D uses the comprehensive measures of regional change developed in Theme A and models developed in Theme C to assess how, for example, changing large-scale atmospheric controls interact with regional Earth system processes in governing changes in climate variability and extremes. It addresses the key science questions: 1) what governs the observed trends and variability in large-scale aspects of the Earth system and how well are these factors and effects represented in current models, and 2) what are the projected regional scale effects of

Earth system change on climate, land and water resources? Many of the deliverables in this Theme are slated for late in the project; however, significant progress has been achieved, and going forward, a number of important issues have been resolved for the representation of land–atmosphere feedbacks and future climate scenarios. Personnel and plans are now largely in place to achieve the goals of this Theme. Progress up to this point has included:

- Individual research progress on atmospheric circulation patterns, instabilities for generating convection, large-scale forcing for drought, precipitation phase changes, winter precipitation extremes, surface hydrologic changes, and runoff, with a number of journal submissions and draft manuscripts based on these studies (Bonsal, Brimelow, Hanesiak, Kochtubajda, Li, Pomeroy, Stewart, Szeto, Thériault);
- A comprehensive focal investigation of the June 2013 extreme weather and flooding events that affected southwestern Alberta and downstream areas, including a number of submissions to a special issue of *Hydrological Processes* dealing with meteorological and hydrological aspects (Kochtubajda, Li, Pomeroy, Stewart, Szeto, Thériault; other important collaborators within EC include Boodoo, Goodson, Liu, Mooney);
- Focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–11 with publications forthcoming (Bonsal, Brimelow, Hanesiak, Kochtubajda, Stewart, Szeto);
- Initial work towards an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations (Baltzer, Bonsal, Johnstone, Kochtubajda, Quinton, Stewart, Turetsky);
- Collaborative agreement with Laxmi Sushama, PI for the Canadian Network for Climate and Weather Processes regarding CLASS algorithm development and testing (Themes C and D) and provision of CanRCM5 forcing data for MESH simulations (Wheater).

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

Theme E: User Community Outreach and Engagement *(Lead: Quinton)*

Theme E 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 the World Climate Research Programme (WCRP), GEWEX, and others. We have continued to be active in outreach and engagement through direct interaction with partners and stakeholders, knowledge mobilization workshops, short courses and training, 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 66 peer-reviewed articles appearing in a wide range of top-tier academic journals, with another 35 papers either in review, accepted, or in press (see www.ccrnetwork.ca/outputs/publications);
- Strong engagement with provincial, territorial, and federal government partners at two key workshops, including one in Yellowknife in January focused on the 2014 fire season in the North, and another in Saskatoon in September focused on various aspects of model development and application for the diagnosis of change (see Section 3);
- Outreach to community-based stakeholders through involvement with water stewardship groups in SK, AB, and NT, interaction with First Nations communities in SK and NT, and linkage to the Government of NT through the Laurier–GNT Partnership (Baltzer, Hayashi, Johnstone, Quinton, Strickert);
- Delivery of over 90 presentations to stakeholders such as government groups, First Nations and metis, NGOs, the United Nations, business groups, industry, the media, and universities;

- Engagement of the media with over 60 interviews and feature articles written this year (see www.ccrnetwork.ca/outputs/media);
- Delivery of a training course on CRHM in Waterloo, ON, and through CCRN and the Water Knowledge Application Network (WatKAN), establishment of and support to a community modeler within the Government of NT based in Yellowknife (Pomeroy, Quinton);
- Close linkages with groups such as NCAR, the NASA Arctic–Boreal Vulnerability Experiment (ABoVE), and GEWEX;
- Dissemination of results and knowledge through major involvement of the network at national and international conferences, including over 140 presentations and a special CCRN session at the 2015 Joint Assembly of the Canadian and American Geophysical Unions. CCRN will also have a strong presence at the upcoming 2015 Fall AGU Meeting, with 83 papers being authored or co-authored and 11 sessions co-convened by our Canadian membership.

7. Extent of Highly Qualified Personnel Recruitment and Training

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. Over the past year we have seen many students and PDFs graduate and/or move on in their careers, while we have also recruited a large number of new personnel to continue the research. We will soon be conducting a detailed survey on the training of HQP, their level of involvement, and their status following their involvement with the network as part of an evaluation of the CCAR programme in general. In the first three years of the CCRN programme, a total of 136 students and post-doctoral fellows have either completed their training or are currently involved with the research, including:

- 10 undergraduate research assistants and summer students, 56 Master's students, 29 Doctoral students, 41 post-doctoral fellows;
- We have also employed 25 technicians, research assistants and associates, and other professional staff;

Our network funding from NSERC has provided full or partial support to 66 students and post-doctoral fellows to this point in the network, with the others having been funded entirely through external sources.

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. For example, 25 of 41 presentations at our September modelling workshop were given by students and post-doctoral fellows, and nearly half of the 51 oral and poster presentations at our CCRN sessions at the 2015 Joint CGU–AGU Assembly in Montreal in May were by students and post-docs in the network. The linkage among the group of young/early career researchers has been fostered in other ways as well: they have set up a Twitter feed to share information (https://twitter.com/CCRN_ECRN), they have met several times by phone this past year to discuss training and professional development opportunities, and they held a half-day event ahead of our November annual meeting to share their research and hear from some professionals on topics including developing research brand identity and project management essentials.

8. Nature of Collaboration and Interaction with Government Scientists, Foreign Collaborators, and Other Partners

CCRN brings together a large and diverse group of researchers, government agencies, and foreign collaborators as noted in Section 2 and described in detail in our 2013 progress report to NSERC (www.ccrnetwork.ca/outputs/reports). During Year-3, we have had a high degree of engagement with many of our Canadian and international collaborators and partners, including scientific activities from the individual to

Theme levels, joint participation in key workshops, and collaborative activities at the international level (Sections 3, 5, 6). As briefly noted, we have worked with many of our listed foreign collaborators linking us with NCAR, GEWEX (and the new INARCH cross-cut project), NASA's ABoVE project and SMAP mission, the Chinese Academy of Sciences Cold and Arid Regions Environmental and Engineering Research Institute, and others. We co-convened an important set of sessions at the AGU–CGU Joint Assembly (*Changing Cold Regions: Climate, Cryosphere, Hydrology, Ecology*; with Marks) and brought in invited speakers (Clark, Lettenmaier), and we will be co-convening another session at the upcoming Fall AGU Meeting (*Recent Advances in Monitoring, Measuring, and Modeling Snow and Cryospheric Processes for the Detection and Diagnosis of Change*; with Marks). We included invited talks from several key collaborators at our September modelling workshop (Clark, Lettenmaier, Wagener), and brought in members of our IAP to our annual meeting (Harding, Hinzman, Kasischke) to hear their comments on the network and provide linkage to their respective organizations. Over the remainder of the programme we will continue to maintain and strengthen these various partnerships and collaborative relationships.