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The Changing Cold Regions Network: Observation, diagnosis and prediction of environmental change in the Saskatchewan and Mackenzie River Basins, Canada

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Climate change is causing rapid and severe changes to many Earth systems and processes, with widespread cryospheric, ecological, and hydrological impacts globally, and especially in high northern latitudes. This is of major societal concern and there is an urgent need for improved understanding and predictive tools for environmental management. The Changing Cold Regions Network (CCRN) is a Canadian research consortium with a focus to integrate existing and new experimental data with modelling and remote sensing products to understand, diagnose, and predict changing land, water, and climate, and their interactions and feedbacks over the geographic domain of the Mackenzie and Saskatchewan River Basins in Canada. The network operates a set of 14 unique and focused Water, Ecosystem, Cryosphere and Climate (WECC) observatories within this region, which provide opportunities to observe and understand processes and their interaction, as well as develop and test numerical simulation models, and provide validation data for remote sensing products. This paper describes this network and its observational, experimental, and modelling programme. An overview of many of the recent Earth system changes observed across the study region is provided, and some local insights from WECC observatories that may partly explain regional patterns and trends are described. Several of the model products being developed are discussed, and linkages with the local to international user community are reviewed—In particular, the use of WECC data towards model and remote sensing product calibration and validation is highlighted. Some future activities and prospects for the network are also presented at the end of the paper.

climate change, cryosphere, hydrology, atmospheric science, ecology, modelling, Canada

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Climate change as a result of the increasing atmospheric concentration of greenhouse gases is well established and is causing sustained, rapid and dramatic changes to Earth systems across the globe (IPCC, 2013). These changes include warming of the atmosphere, shrinking and diminishment of elements of the cryosphere such as snow, ice and permafrost, alterations of terrestrial ecosystems, and increasing occurrence of extreme events such as heat waves and heavy precipitation, among others. In general, the greatest increases in temperature are occurring at high latitudes. Consistent with these globally observed patterns, rapid changes have

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*Corresponding author (email: chris.debeer@usask.ca) been reported within the cold interior regions of western and northern Canada (Serreze et al., 2000; Hinzman et al., 2005; Prowse et al., 2009), where there is societal concern due to the impacts on water and other natural resources, agriculture, infrastructure, and risk associated with extreme events. These issues require both thorough understanding and diagnosis of recent past environmental changes, and improved prediction of future potential changes. There is therefore an urgent need to develop and improve the modelling tools through which this can be done. Given that these types of changes are impacting other similar cold region environments across the world, these scientific advancements will not only have local and regional value, but global importance as well.

The Changing Cold Regions Network (CCRN) is a Canadian research consortium dedicated 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. This network builds on a legacy of past Canadian and international research in this region that has focused on cold regions hydrology, glaciology, terrestrial ecology, atmospheric science, drought and modelling, including projects and networks such as the Mackenzie Global Energy and Water Exchanges (GEWEX) Study (MAGS; http://www.usask.ca/geography/MAGS/; Stewart et al., 1998; Woo et al., 2008), Boreal Ecosystem-Atmosphere Study (BOREAS; http://daac.ornl.gov/BOREAS/bhs/BOREAS_Home.html; Sellers et al., 1997; Hall, 1999), Drought Research Initiative (DRI; http://www.drinetwork.ca/; Stewart et al., 2011; Hanesiak et al., 2011), International Polar Year (IPY; http://www.api-ipy.gc.ca/), Western Canadian Cryopsheric Network (WC2N; http://wc2n.unbc.ca/) and Improved Processes and Parameterization for Prediction in Cold Regions Hydrology Network (IP3; http://www.usask.ca/ip3/). CCRN integrates and extends many aspects of these previous research projects, and will improve upon the understanding gained through these initiatives and further advance the state of model development and performance.

This paper provides an overview of this network and its observational, experimental and modelling programme. It fits within the scope of this special issue on watershed science, which addresses scientific advancements and multi-disciplinary aspects of water resource management, organized around six broad themes, including: 1) new theories in watershed science and catchment hydrology, 2) watershed observing systems, 3) cyber-infrastructure to support watershed science, 4) integrated watershed modelling, 5) watershed-scale hydrological data assimilation, and 6) new generation water resource management decision support systems. The paper is an invited contribution to the second of these themes, which deals with observational technologies and infrastructure for observing hydrological and ecological processes at the watershed scale. However, in general the paper contributes to all of the listed themes of this issue. The following section provides a synopsis of the network structure and its research programme, highlighting the suite of focal Water, Ecosystem, Cryosphere, and Climate (WECC) observatories, which provide the network with exceptional opportunities to observe change, investigate processes and their dynamics, and develop and test environmental models, from point to watershed scales. A brief examination of some of the recent Earth system changes occurring across the CCRN geographic domain follows in the next section, and insights into the changes are drawn from the detailed observations and process-level understanding developed at the WECC sites. Some of the modelling tools being developed and other experimental aspects of the network are then briefly described, and the linkages between CCRN, various stakeholder communities, and the international scientific community are discussed. The paper ends with concluding remarks and future prospects for this network.

1 Overview and description of the Changing Cold Regions Network

1.1 Network participants and structure

The CCRN includes over 40 Canadian researchers from eight universities and four federal government agencies (see Appendix, http://link.springer.com), as well as 14 prominent international collaborators from institutions across the world. As the programme develops, more researchers are continuing to join as collaborators. The network is funded for five years (2013–2018) through the Climate Change and Atmospheric Research (CCAR) Initiative of the Natural Sciences and Engineering Research Council of Canada (NSERC), and CCRN leverages significant in-kind support through its partner universities and government agencies. Management of the network is by a Scientific Committee, which directs the scientific progress of the network and plans all network activities. A Board of Directors oversees the organizational direction and financial accountability of the network, while an International Advisory Panel provides external advice and oversight, and facilitates liaison with the international research community. Further details on the structure and organization of the CCRN are available through the network's website at: http://www.ccrnetwork.ca.

1.2 Research programme

The CCRN's research programme brings together existing and new experimental data, utilizing ground-based observations and remotely sensed data products, together with improved modelling tools, to investigate changing Earth system processes and their interactions across a range of spatial scales. The geographic focus is the western and northern interior regions of Canada (see section 1.3). CCRN's research is divided into five major thematic components: (1) Theme A, Observed Earth System Change in Cold Regions—Inventory and Statistical Evaluation; (2) Theme B, Improved Understanding and Diagnosis of Local-Scale Change; (3) Theme C, Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction; (4) Theme D, Analysis and Prediction of Regional and Large-Scale Variability and Change; and (5) Theme E, User Community Outreach and Engagement.

Each of these themes is interlinked and the progression from A through to E represents an advancement from characterization of changes from local to regional scales, diagnosis and understanding of the changes, and ultimately prediction of future changes, with each theme's activities and deliverables strongly connected to the user community through E.

Theme A provides a synthesis of observed recent changes of the Earth system within the CCRN study domain and establishes the foundation of the project through the inventory, statistical evaluation, and synthesis of these changes. 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?

Theme B seeks to address the understanding, modelling, and diagnosis of change, focusing on local-scale interactions and effects. 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 (see section 1.3) 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?

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?

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?

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.

1.3 Study Area and Water, Ecosystem, Cryosphere, and Climate (WECC) observatories

The CCRN's research activities are focused geographically on the cold western and northern interior regions of Canada, which includes the 3.4×10^5 km^2 Saskatchewan and 1.8 million km^2 Mackenzie River Basins (Figure 1). Some activities and observations span a wider geographic range, however, consistent with a larger continental-scale focus for the climatic domain. The region covers a large diversity of climatic, physiographic, surface landcover, ecological, and hydrological conditions and characteristics, with steep gradients and sharp boundaries dividing many of the major eco-climatic sub-regions within. This vast area can be divided into four such major regions, including: 1) the western Cordillera, 2) the Boreal Forest, 3) the northern Prairies, and 4) the Sub-Arctic Lowlands, each with various spatial transitions and variations in their characteristics.

The western Cordillera generally forms the headwaters for both of these large river systems, and in the case of the Saskatchewan River, an overwhelming proportion of the total flow originates from runoff generated in this relatively small area (Comeau et al., 2009). Lower areas and valley are covered by forest of coniferous trees, while alpine areas above are covered in tundra shrubs, talus, and exposed bedrock. Elevations range from about 1500 m in the lower valleys to as much as 3500 m or more at the highest summits. At lower elevations, January temperatures range from about −10 to −15°C and July temperatures are between 15 to 20°C (Environment Canada, 2014), while temperatures at higher elevations are generally much cooler. The region is characterized by steep climatic gradients and a transition from maritime to continental conditions; precipitation ranges from several hundred mm annually at low elevations on the eastern slopes of the continental divide, to up to several thousand mm at high elevations along the divide, where significant snowfall occurs and large icefields exist (Moore et al., 2009; Marshall et al., 2011).

The Boreal Forest in western Canada occupies a vast

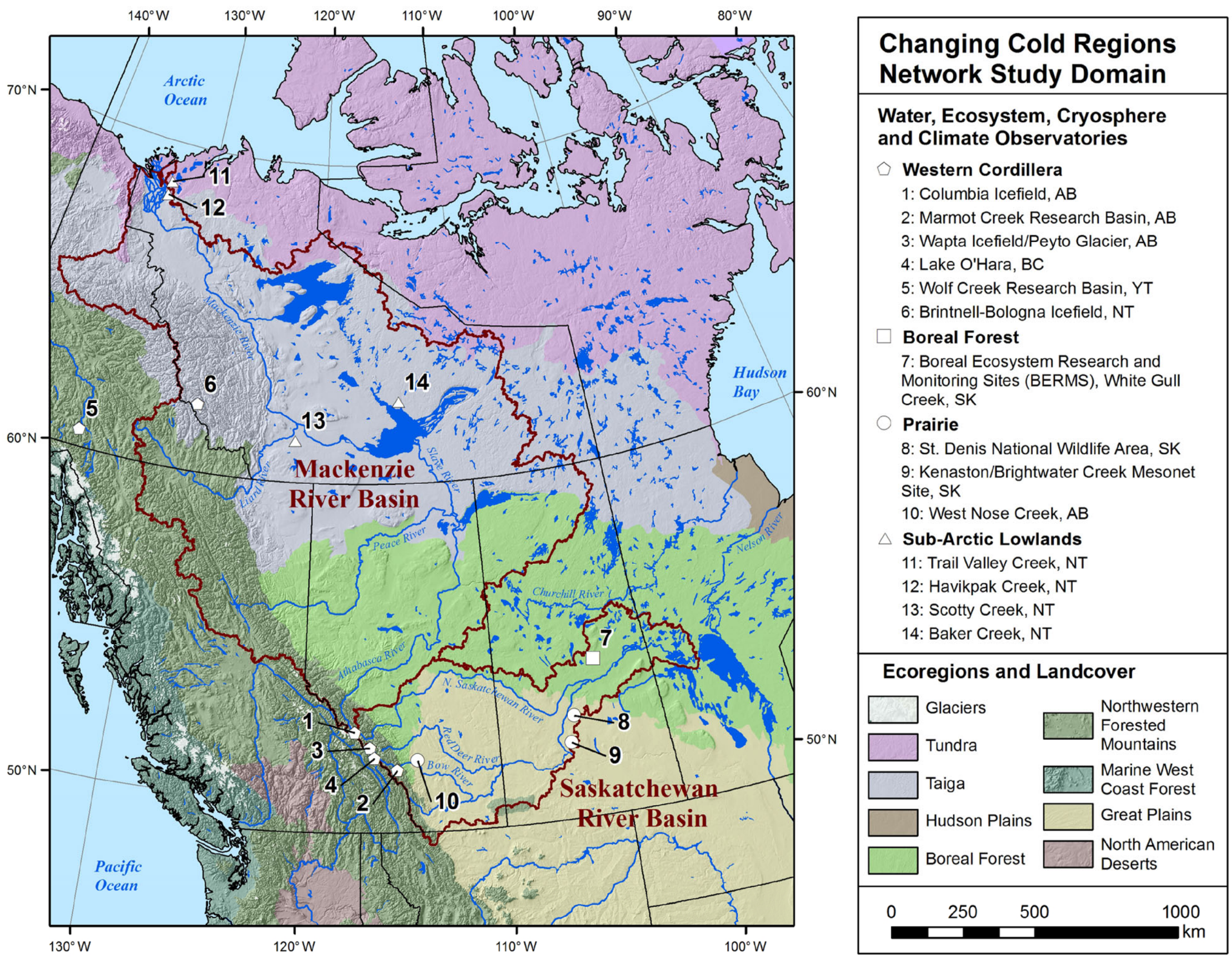

Figure 1 Map of the CCRN geographic study domain in western and northern Canada, showing major river systems, ecoregions, and landcover, as well as the location of WECC observatories. Source data is from the North American Environmental Atlas (http://www.cec.org/naatlas/) and the National Hydro Network (http://www.geobase.ca); the projection is UTM Zone 11 on the North American Datum of 1983.

region to the north of the Prairies, and gradually transitions to the Sub-Arctic Lowlands and Taiga Plains in the northern part of the Mackenzie River Basin. It is generally characterized by stands of coniferous trees such as black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and other species (Price et al., 2013). Annual precipitation ranges from about 300 mm just east of the Rocky Mountains to about 600 mm in northern Manitoba at the eastern edge of the CCRN study domain (Smith et al., 1999). The region is sub-humid with cool, short summers, where average July temperatures range from about 10 to 17°C (Price et al., 2013). Winter persists for about 6 months with average January temperatures between –17 to –23°C (Environment Canada, 2014).

The Prairie region occupies the southern part of the CCRN's domain, and is characterized by a relatively flat landscape with poorly developed stream networks and internally drained systems that do not connect with major rivers flowing through the region (which originate in the Rocky Mountains). Precipitation is low, ranging from about 300 to 400 mm per year (Sauchyn et al., 2009), with about 30% falling as snow. Conditions vary from semi-arid in the south-west to sub-humid with many wetlands and lakes in the north and east (Pomeroy et al., 2005). July average temperatures range from about 15 to 20°C, while January temperatures are typically between –15 to –20°C (Environment Canada, 2014).

The Sub-Arctic Taiga Plains Lowlands cover much of the northern part of the study domain, bounded by the Arctic Tundra to the north and east, the Boreal Plains to the south and the Cordillera to the west. The region contains vast areas of flat terrain with organic soils and coniferous forests, with a high density of open water and wetlands (Quinton et al., 2009). Discontinuous permafrost underlies most of the southern plains, transitioning to continuous permafrost in the northern parts of the region and the Mackenzie River delta. The climate is continental in nature with very cold winters (<–25°C in January) and summer temperatures that rise to about 15°C in July (Woo, 2012). Annual precipitation ranges from 200 to 400 mm, with a northward increase in aridity.

Nested within each of these major eco-climatic regions, CCRN operates a set of 14 unique long-term WECC observatories (Figures 1 and 2). All of these observatories have a history of research that pre-dates the CCRN, and most have long-term datasets including hydro-meteorological observations, remotely sensed data products, including Light detection and ranging (Lidar) topographic and vegetation structure mapping, and characterization of soils, geology, vegetation, permafrost, and glacial ice cover. Past and ongoing investigations by CCRN and other researchers at these sites has shed valuable insight on surface hydrology, sub-surface, cryospheric, terrestrial ecology, and atmospheric processes. Although each of these observatories had originally been established with a particular scientific emphasis, many of them are comprehensive and similar in terms of the data being collected and are useful for comparing process dynamics and variability across the spatial and climatic gradients of CCRN's study domain. In addition, these observatories help to supplement the regional federal and provincial government hydrometric and climatological monitoring station networks, which have observations going back as long as 50 to 100 years or more. The WECC sites generally provide a more detailed and comprehensive, albeit shorter, series of observational data that can be used to more closely examine and understand the processes behind patterns of change observed at the regional scale. Detailed information on each of the WECC observatories is available on CCRN's website at: http://www.ccrnetwork.ca/science-programme/research-sites.

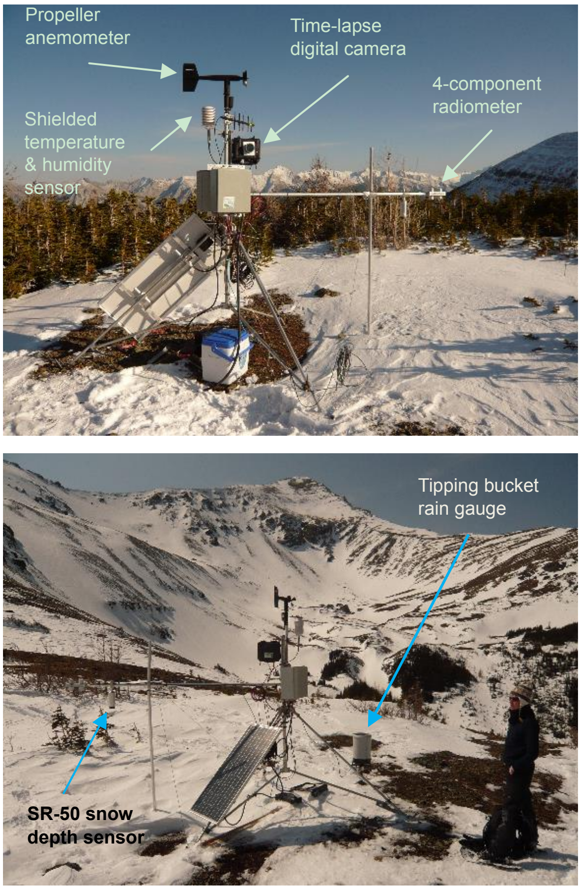

Figure 2 Example photographs of some of the hydro-meteorological observation infrastructure within a WECC observatory (i.e., Fisera Ridge station within the Marmot Creek Research Basin; http://www.ccrnetwork.ca/science-programme/research-sites/western-cordillera/marmot-creek.php). Instrumentation and measurements here include automatic datalogger and telemetry communications, incoming and outgoing shortwave and longwave radiation, air temperature and humidity, wind direction and speed, solid and liquid precipitation, snow depth, soil and snowpack temperature, and automatic time-lapse photography. The observations may be used, for instance, used to drive full energy balance simulations of snowmelt, while time-lapse photography provides a robust means of observing areal snowcover depletion patterns over an adjacent alpine cirque, as explained and demonstrated by DeBeer and Pomeroy (2009, 2010). Other novel and innovative observation approaches are used across the network of WECC observatories.

2 Observed recent earth system changes in western and northern Canada

A wide body of literature exists that documents ongoing, rapid, and dramatic Earth system changes across the study domain of the CCRN. The work of this network and its Theme A activities is also revealing further details of the recent changes. These include, but are not limited to, increasing air temperatures and changes in annual and seasonal precipitation, changes in streamflow and river discharge, warming of permafrost and thickening of the soil active layer, reductions in snow cover depth, spatial extent, and duration, declining glacier area and mass, earlier breakup of lake and river ice, and changes and shifts in vegetation communities of the Boreal Forest and Sub-Arctic Taiga and Tundra areas. Many of these observed changes are consistent with the changing regional and global climatic patterns. However, the complex and dynamic interactions and feedbacks between these various Earth system processes are not completely understood, and thus the work of the other CCRN themes is aimed at both diagnosing past changes and predicting future coupled responses to climatic variability. This section provides a brief synthesis of the recently observed changes in this region.

2.1 Air temperature

Air temperatures have been observed across a network of federal climate monitoring stations over the region, and the data has been rigorously checked and corrected for known sources of systematic error (e.g., Vincent et al., 2012). This dataset is known as the adjusted and homogenized Canadian climate data (AHCCD; http://www.ec.gc.ca/dccha-ahccd/), and using this, several studies have conducted annual and seasonal trend analyses and examined patterns of daily temperature extremes (Bonsal et al., 2001; Vincent and Mekis, 2006; Zhang et al., 2011; Vincent et al., 2012). The results over this region have shown that during the past 60 years, warming of about 2°C on average has occurred, with the strongest warming occurring during the winter months (i.e. greater than 3°C) and spring months (1.5 to 3°C). There is a strong spatial coherency to these trends. Barry et al. (2012) showed similar results using the Goddard Institute for Space Sciences gridded dataset of temperature over North America. Examination of daily extremes has shown that the trends are consistent with warming including fewer cold nights, cold days, and frost days, but more frequent warm nights and warm days (Bonsal et al., 2001; Zhang et al., 2011).

Figure 3 shows trends in annual average and seasonal air temperatures for the period 1970–2010, which are based on the AHCCD and were calculated using the non-parametric Mann-Kendall test. These are preliminary results from an ongoing and more in-depth analysis of climatic conditions over the region. Annual trends over this period average roughly 0.04°C/year (1.6°C/41 years) and range from about 0.01°C/year (0.41°C/41 years) to as much as 0.15°C/year (6.2°C/41 years). In winter, the average trends are higher at about 0.07°C/year (2.9°C/41 years), ranging from 0.02°C/year (0.8°C/41 years) to 0.14°C/year (5.7°C/41 years) in the north. These results, in comparison to those of previous studies covering a longer period of time, indicate that over the past several decades there has been an acceleration in the rates of warming across the region.

2.2 Precipitation

A number of studies have documented trends in precipitation and patterns of daily extreme precipitation indices using the AHCCD station time series (Vincent and Mekis, 2006; Zhang et al., 2001a, 2011; Mekis and Vincent, 2011). Their results have shown that precipitation has generally increased over the region since about 1950, ranging from about 5% to 35%, with the majority of stations with significant trends showing increases (Zhang et al., 2011). The patterns have not been as spatially coherent as for temperature, but in general the increasing trends have been most coherent over the northern part of the domain. Trends in the south have shown more variability, with many stations showing significant decreases in winter precipitation (Zhang et al., 2011). Vincent et al. (2006) reported that there has been an increase in the number of days with precipitation, especially days with rainfall, and that over most of the southern region, there has been a significant decrease in the ratio of snowfall to total precipitation. Analyses by Zhang et al. (2001a) and Vincent et al. (2006) did not reveal any clear and consistent patterns for indices characterizing extreme heavy precipitation events, and few stations had statistically significant long-term trends. It is likely that increases in total annual rainfall are due primarily to more days with measureable precipitation rather than increasingly intense events. This finding is somewhat in contrast to the statement by the Intergovernmental Panel on Climate Change (IPCC) in their most recent report that it is very likely there have been trends toward heavier precipitation events in central North America (IPCC, 2013).

The spatial patterns and trends in both rainfall and snowfall between 1970 and 2010 are shown in Figure 4. Again, these results are preliminary from part of a more in-depth

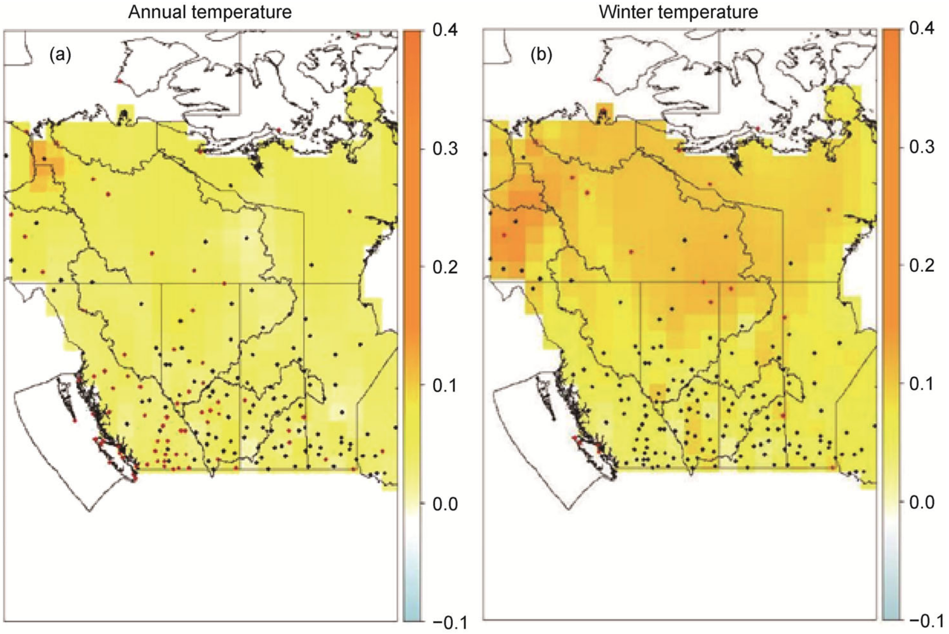

Figure 3 Temperature trends (°C/year) across the CCRN study domain over the period 1970–2010 based on the Environment Canada AHCCD: (a) annual trends; (b) winter trends. Dots indicate location of federal monitoring stations; red indicates a statistically significant trend at the 95% confidence level, while black dots indicates no statistically significant trend.

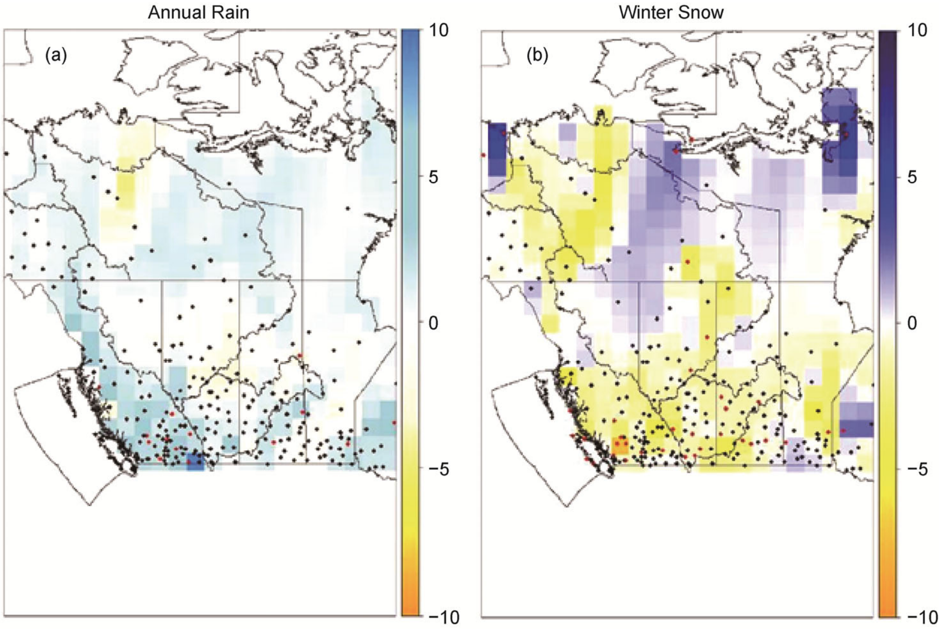

Figure 4 Spatial patterns of trends (mm/year) in annual (a) rainfall and (b) snowfall from 1970–2010 over the CCRN study domain. Data is from Environment Canada's AHCCD.

analysis using the AHCCD. The patterns are broadly consistent with the documented changes in the other studies above, and show that trends in rainfall are fairly similar with increases in general of between 1 mm/year (41 mm/41 years) and 3 mm/year (123 mm/41 years) over the region. Snowfall trends are much more varied, with an overall decline of between 0 mm/year and –4 mm/year (–164 mm/41 years) in the southern parts of the region, and an increase of up to as much as 5 mm/year (205 mm/41 years) or more in parts of the north. However, consider sub-regional variability in the patterns exists.

2.3 River and stream discharge

The observed trends in river discharge have been shown to vary across the region, with studies documenting both increasing and decreasing tendencies since about the mid-1960's (Prowse et al., 2009). Within the southern parts of western Canada, a general decreasing trend in annual flow has been observed, with the greatest declines occurring during the summer months but with increases during the winter (Zhang et al., 2001b; Rood et al., 2008; St. Jacques et al., 2010). There has been a shift towards earlier occurrence of spring runoff and peak flows, with reduced total discharge volumes, which in snowmelt dominated basins has been partly attributed to earlier spring snowmelt and decreasing snow water equivalent (SWE) (Burn et al., 2008; see changes in snow described below in section 2.5). Human impacts, such as flow regulation and water withdrawals, have had a major impact on the flow regime of many streams and rivers, but climatic drivers have also shown to be significant (St. Jacques et al., 2010). In the north, similar shifts in the timing of spring discharge have been observed (Burn et al., 2004), however, some studies have shown an increase in the volume of annual flow over the past several decades (St. Jacques and Sauchyn, 2009). It has been suggested that a possible explanation for increasing winter baseflow and annual flow in these northern streams is the thawing of permafrost (see below in section 2.4), which enhances infiltration and promotes deeper flowpaths and groundwater contributions, and also acts to expand the hydrological connectivity of surface flow pathways (Quinton et al., 2009).

Figure 5 presents a summary of the spatial patterns of long-term annual discharge trends over the region, based on a Mann-Kendall trend analysis of Water Survey of Canada (WSC; http://www.ec.gc.ca/rhc-wsc/) stations that have not been affected by upstream flow regulation. These results are preliminary and part of a more in-depth analysis as for air temperature and precipitation. A distinction is made between Reference Hydrometric Basin Network (RHBN; Harvey et al., 1999; Zhang et al., 2001b) stations and other unregulated stations in the region. RHBN stations comprise a network of natural rivers in Canada identified by Environment Canada as suitable for climate change research, while other stations require more caution when interpreting trends, as the effects of human land use change or water withdrawals may be contained within the records. Within the Mackenzie and Saskatchewan River Basins, the results show that the annual flow in a large number of streams and rivers has not changed significantly between 1970 and 2010. However, in parts of the southern and western Boreal Forest, there has been a significant decrease in annual flow at many stations, ranging from a few percent to as much as 30% of

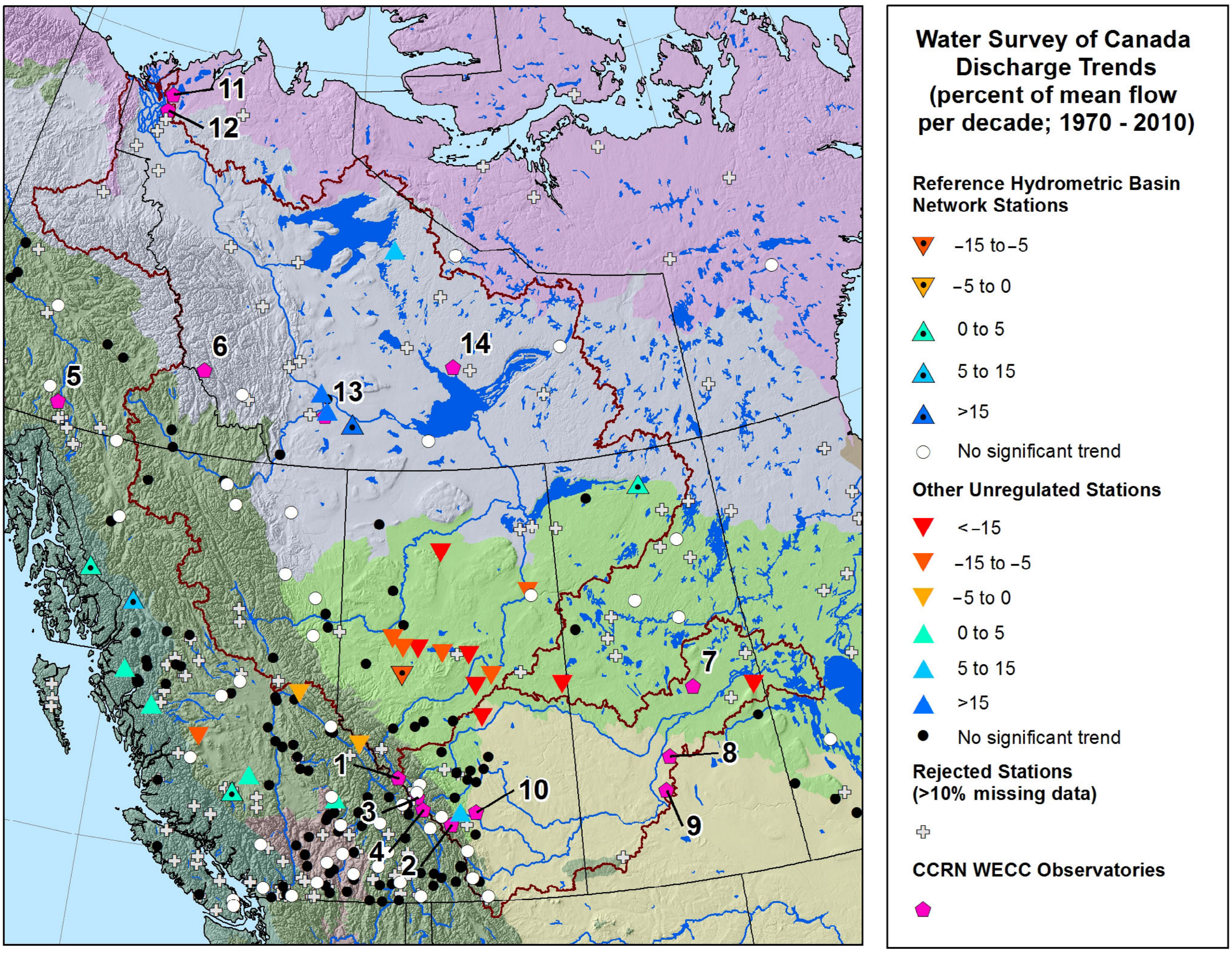

Figure 5 Variability in trends of annual discharge (% of mean flow per decade) of unregulated streams and rivers across the CCRN study domain during the period 1970–2010 (trends indicated are significant at the 95% confidence level). Discharge data is from the WSC archived hydrometric data; stations included are those that are 1) unregulated, 2) currently active, 3) continuous, year-round operation, and 4) have at least 35 years of record.

mean flow (–13% for one of the RHBN stations). In the southern and central Taiga Plains region within the Mackenzie River Basin, the annual flow of several streams and rivers has increased by as much as 15% to 20% over this period. It has been suggested that these increasing trends are likely due in part to thawing permafrost, and some local-scale process level insights are described in the following sub-section.

2.4 Permafrost

Changes in permafrost across the vast northern parts of Canada and the Arctic in general have shown a widespread pattern of rising ground temperatures, increasing soil active layer thickness, declining area of frozen ground, and degradation of areas of permafrost plateaus (see reviews by Smith, 2011; Burn, 2012). Over the past several decades, permafrost temperatures have been increasing across the Mackenzie Basin, but the magnitude and timing of this warming varies regionally (Smith et al., 2010; Smith, 2011). In the colder northern regions where continuous permafrost occurs, the temperature at the top of the permafrost has increased by 2°C or more since 1970, but there has been little thawing (Burn and Kokelj, 2009; Burn and Zhang, 2010). Farther south in the discontinuous zone of permafrost, the ground has warmed in many areas enough to bring ice to its melting point, and this has resulted in energy being used towards melting the ice rather than further increasing the temperature of the ground (Smith et al., 2010). In addition to this warming, deepening of the soil active layer has been widely shown (Mackay and Burn, 2002; Jorgenson et al., 2006; Smith et al., 2009; Burn and Zhang, 2010). Trends at long-term monitoring sites have shown considerable interannual variability, while there is also significant spatial variability resulting from the controls of local site factors. There has been significant degradation of permafrost in areas where it is thin or discontinuous in the Taiga Plains, as indicated by increasingly fragmented and an overall decline in the area of forest-covered permafrost plateaus (Beilman and Robinson, 2003; Burgess and Smith, 2003; Quinton et al., 2011; Chasmer et al., 2011; Baltzer et al., 2014).

As an example to highlight the patterns of this degradation, Figure 6 shows changes in permafrost plateau extent over time within the Scotty Creek Research Basin, which are from the analysis by Quinton et al. (2011) and described in more detail there. This illustrates not only the areal decline of permafrost (i.e. −10% between 1977 and 2008), but also the fragmentation of plateau areas and the widening and connection of previously isolated bog areas. The changes in connectivity of these areas, which facilitates more efficient drainage by linking the drainage network and increasing the effective contributing area for runoff generation, is likely a primary cause of the increasing discharge trends in the southern Taiga Plains shown above (Connon et al., 2014). Quinton et al. (2009) showed conceptually how preferential thaw around the edges of forest-covered permafrost plateaus and where canopy thinning occurs leads to permafrost thaw and can act as a feedback leading to further thawing. Thus, this has major implications for water management and predicting future flows in the context of widespread permafrost thaw (Quinton et al., 2011).

2.5 Snowcover

Over the past several decades there have been considerable changes in a number of aspects of the seasonal snowcover in this region, including its spatial extent, duration, maximum depth, and timing of melt onset. It has been observed that the extent of snowcover in the spring has been declining and that there has been an acceleration in the rate of this decline since about 1970, while snowcover in the fall has remained more-or-less consistent over the same period (Brown and Robinson, 2011; Kelly, 2012). There has been roughly an 11% decrease in April regional snowcover area relative to pre-1970 values (Brown and Robinson, 2011). This corresponds with a decrease in the duration of snowcover reported at ground observation stations and determined regionally through remote sensing analysis (Derksen et al., 2008; Zhang et al., 2011; Kelly, 2012). Decreases in annual snowcover duration have averaged more than 1 day/year over 1966–2007 (Brown and Mote, 2009), thus shortening the snowcover period from 1 to 2 months over much of the CCRN domain. A significant trend to earlier snowmelt has been observed at the observation stations (Brown and Braaten, 1998), and passive radar remote sensing analysis has shown that the onset of melt has shifted earlier each year by 0.2 to 0.6 days/year (5.8 to 17 days/29 years over the period 1979–2008), while snowmelt end dates have shifted earlier by 0.5 to 2.0 days/year (14 to 58 days/29 years; Tedesco et al., 2009). This is leading to a shorter period of melt in Canada, which would partly suggest that higher melt rates during the spring are accompanying these shifts in snow extent, timing, and seasonality.

Measurements of snow depth and SWE have shown that winter and early season depths have decreased in much of the region (Brown and Braaten, 1998), while peak depths

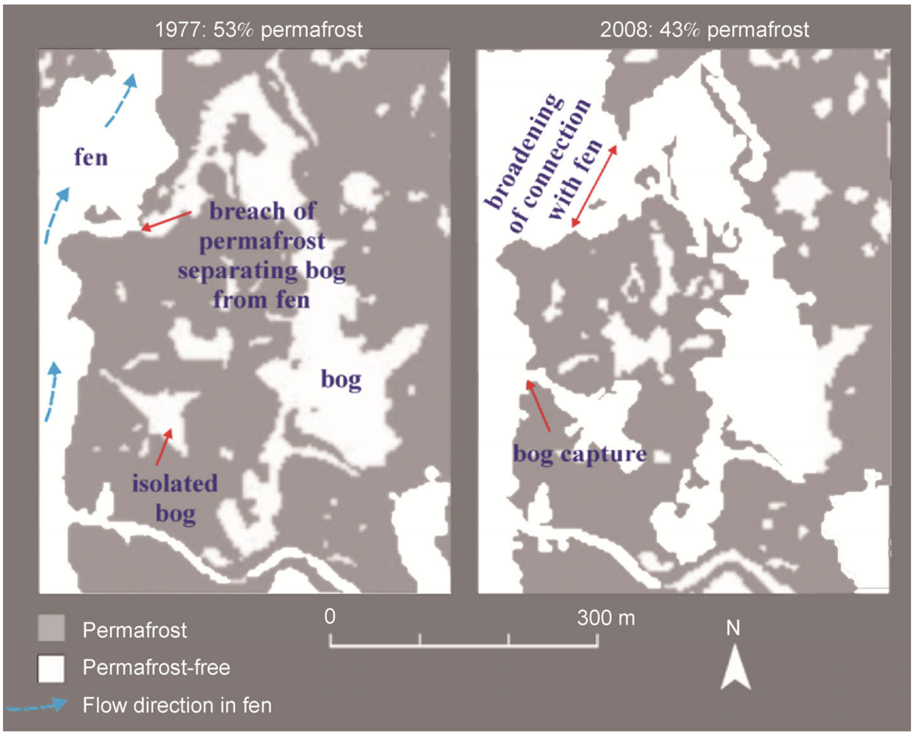

Figure 6 Map of small area within the Scotty Creek Research Basin, NT, showing areas underlain by permafrost in 1977 and 2008 and providing example of changes in hydrological connectivity, based on analysis by Quinton et al. (2011).

have also be declining (Zhang et al., 2011). In the southern parts of western Canada this is being driven mainly by less winter precipitation, as shown in Figure 4, and also by a greater percentage of precipitation falling as rain rather than as snow as the climate warms. The decreases reported at some stations in the northern region is more difficult to explain as the region as a whole generally experienced an increase in winter precipitation and snow (Figure 4; Zhang et al., 2011). SWE retrieval from passive microwave satellite data has made regional scale assessments possible and has provided insight on the local to regional scale variability (Derksen et al., 2003), but unfortunately, the satellite record is not mature enough to provide robust trend assessments in SWE for the overall region (Kelly, 2012).

2.6 Glaciers

Glaciers within the mountainous regions of the CCRN study domain have shown predominantly negative net annual mass balances, and have generally undergone decreases in their volume and areal extent, with widespread terminal retreat, glacier fragmentation and disappearance (Moore et al., 2009; Tenant et al., 2012). Observations at Peyto Glacier, a long-term reference mass balance site in the Canadian Rockies and one of the CCRN's focal WECC observatories, have indicated an average annual mass balance of about –0.75 m water equivalent in the last few decades of the 20th century, and the rate of ice loss has recently accelerated (Demuth and Keller, 2006). Between 1966 (when mass balance measurement began) and 2012, the glacier has had a cumulative net balance of about –27 m water equivalent (personal communication, Mike Demuth, April 2014). Annual ground based and remotely sensed Lidar observations here since 2000 have shown a rapid disintegration of its terminus. Regional glacier inventory work and analysis of change has shown that the area of glaciers has declined by as much as 25% over the last several decades in parts of the Rocky Mountains and the Mackenzie Mountains (DeBeer and Sharp, 2007; Demuth et al., 2008; Bolch et al., 2010; Demuth et al., in press). However, there is considerable variability in the amount of change documented by these studies, depending on the time period of analysis and the region of focus, and individual glaciers within different regions have exhibited a wide range of patterns. This attests to the strong control of local climatic and glacier morphological and dynamic features on glacier responses to climate forcing.

Although glacier meltwater contributes only a very small fraction of the total annual discharge of the major rivers in CCRN's domain, glacier contributions are relatively greater during late summer and can represent a significant component in some headwater areas (Comeau et al., 2009; Marshall et al., 2011; Naz et al., 2014). Observed declines in the late summer discharge of some rivers may be due, in part, to glacier recession and a reduction in the ice-covered area for surface meltwater generation (Moore et al. 2009). It has been suggested that an initial phase of warming-induced meltwater and runoff increases has already passed (Demuth and Pietroniro, 2003), but significant enhancement of meltwater production could resume if vast areas of ice at high elevations become subjected to increasing melt. There is still considerable uncertainty on the nature and sensitivity of glacial contributions under past and potential future climates, however, and further work needs to consider this in context with contributions from rainfall, snowmelt, and groundwater.

2.7 Lake and river ice

Over most of the study domain there has been a general reduction in the duration of winter ice cover on lakes and rivers since the mid-20th century, mainly due to earlier ice break-up in the spring (Prowse, 2012). Dates of freeze-up in fall and break-up in spring have tended to coincide with air temperature patterns, and the changes have widely been associated with a significant trend towards earlier spring 0°C temperatures (Duguay et al., 2006). The past ~60 year warming of 2–3°C in spring and fall temperatures has led to about a 15-day advance in the date of break-up and about a 10-day delay in the date of freeze-up (Prowse and Bonsal, 2004). Despite these changes in ice cover duration, there do not seem to be any clear trends or patterns in the thickness of lake and river ice during the latter part of the twentieth century (Lenormand et al., 2002).

2.8 Forest and tundra vegetation

Within the Boreal forest of northern and western Canada, changing climate is causing considerable changes in forest structure, composition, and density (MacDonald, 2012; Price et al., 2013). Across much of the northern Boreal Plains and the Taiga Plains ecoregions, the forest is underlain by permafrost. Recent warming here has produced rapid and widespread thaw of this permafrost and corresponding forest loss due to ground surface subsidence and waterlogging of soils at the forest margins (Baltzer et al., 2014). Rapid forest change is also occurring at both the northern and southern treeline limits. At the northern treeline, there has been vigorous recruitment and infilling of open crown stands, although the location of the northernmost tree stands has not shifted much (MacDonald et al., 1998). Olthof et al. (2010) found increases in conifer cover at the northernmost stands, but decreases along the southern edge of the Taiga treeline zone. Along the southern edges of the Boreal Forest there is accumulating evidence of declining tree growth and forest productivity in response to changing climate conditions and increasing drought stress (Lloyd and Bunn, 2007). This stress has led to widespread mortality of trees within the Aspen Parkland, which represents the transition from Boreal Forest to Prairies (Hogg et al., 2008).

Beyond the Boreal treeline, Sub-Arctic and Arctic tundra vegetation has increased in terms of both peak productivity and growing season length (Goetz et al., 2011). There have been changes in the composition and density of herbaceous vegetation, as well as expansion of areas of woody shrub vegetation (Sturm et al., 2001; Tape et al., 2006; Lantz et al., 2013). This is generally attributed to recent warming trends, although other natural and anthropogenic disturbances may be contributing to the spread of shrub tundra vegetation as well. The encroachment of tall shrubs across the northern landscape has the potential to alter many surface features, including the albedo, heat flux, soil moisture, snowpack characteristics, and ground thermal regime (Lantz et al., 2013), which are all interrelated and influenced by various feedbacks.

3 Model development for the diagnosis and prediction of change

The later research themes of the CCRN go beyond the evaluation of the environmental changes as described above, and are aimed at the diagnosis of past and prediction of future changes using a suite of hydrological, ecological, and atmospheric models. The broad aims and science questions of each of Themes B through D have been previously described in this paper. Here, we discuss some of the specific products currently being developed, tested, and improved within CCRN, along with some of the experimental modelling activities of the network.

A key tool for small to medium scale hydrological modelling being further developed in CCRN is the Cold Regions Hydrological Model (CRHM) platform (Pomeroy et al., 2007). This is a modular system in which the user can combine various process algorithms, based on several decades of hydrological research in western and northern Canada, into a functional model specific to the user's needs. The CRHM platform underwent significant advancement during the previous IP3 Network (http://www.usask.ca/ip3/), with the development and refinement of a number of process modules, and improvements to the model functionality and operation. This is being taken further in CCRN through the development, incorporation, and testing of new hydrological modules, including precipitation phase change, sparse forest structure, glacier hydrology, hillslope hydrology, groundwater, permafrost thaw, and vegetation dynamics. Simulations are driven by high spatial resolution field observations at a number of the WECC observatories (Figure 1). Recent CRHM development has been modified to include version control, community development via Dynamic-Link Library (DLL) module development capability, and a new interface for building and extracting information from complex models.

CCRN has been actively engaged in the development of several new algorithms within Environment Canada's Modélisation Environmentale Communautaire (MEC), MEC–Surface and Hydrology (MESH; Pietroniro et al., 2007) environment and the Canadian Land Surface Scheme (CLASS; Verseghy, 2000). The Prairies are a major challenge with respect to both hydrological and climate modelling. A recent addition to the MESH code includes the Probability Distribution Model based RunOFf generation (PDMROF) algorithm, which was developed to resolve the contributing vs. non-contributing area issue that causes difficulty in Prairie hydrological modelling (Mekonnen et al., 2014). PDMROF is based on a distribution function representation of pothole storage, and comparative testing with previous Prairie algorithms in MESH showed a time-varying contributing area that significantly improves river flow representation and is consistent with remote sensed imagery of time-varying pothole storage. Other areas of development include improved representation of cold region lake processes, including snow and ice cover within CLASS, and the development of new algorithms to represent anthropogenic effects of water management (e.g. reservoir operation). The need for realistic land surface complexity within land surface schemes, with all anthropogenic effects taken into account, has been recognized as key towards assessing changes in land surface hydrology and water availability by the World Climate Research Programme (WCRP).

The network is also engaged in the development and application of other hydrological and atmospheric models through collaborations with UK researchers and the US National Center for Atmospheric Research (NCAR). Some baseline model applications using the Joint UK Land Environment Simulator (JULES; Best et al., 2011; Clark et al., 2011) are underway at WECC sites, and algorithm testing and improvement is proceeding through point scale intercomparative analysis with CLASS to further improve algorithms in both systems. The Weather Research and Forecasting (WRF; http://www.wrf-model.org/index.php) model of NCAR has been applied to simulate and examine the June 2013 extreme weather and flooding events that occurred over western Canada. Modelling analyses of the events have also included synoptic meteorological conditions from the Global Environmental Multiscale Model (GEM; http:// collaboration.cmc.ec.gc.ca/science/rpn/gef_html_public/index.html), large-scale hydrology using MESH, and fine-scale process insights using CRHM. This coordinated focal analysis of the extreme weather and flooding represents a major effort of CCRN, and will make key contributions to the improved understanding and prediction of future similar extreme events, which are a concern worldwide. In particular, further model algorithm developments will focus on improving model capability of representing conditions under system change, extreme conditions, and climate non-stationarity.

4 Stakeholder and scientific community outreach and engagement

Theme E within CCRN serves to increase the application of knowledge and tools developed in Themes A to D, and build a community of users in this process. The network is engaged at three distinct levels: 1) A grassroots level in which individual co-investigators have long-standing relationships with various researchers and community groups in their study regions and disciplines. Engagement with local communities, environmental groups, First Nations, and other rights holders takes place via a two-way dialogue and interaction to increase the usefulness and benefits of the research to these stakeholders. 2) An intermediate level in which CCRN is linked with various municipal, provincial/territorial, and federal government agencies in Canada, as well as industry partners in relevant sectors. The connections here ensure that research activities are coordinated, aligned, and mutually beneficial, and that network outputs are integrated into practice and operational tools within the government agencies. CCRN is closely connected in this regard with Environment Canada (as discussed above), Natural Resources Canada, Agriculture and Agri-Food Canada, Parks Canada Agency, the Saskatchewan Water Security Agency, Alberta Environment and Sustainable Resource Development, and the Government of Northwest Territories. 3) An international level in which CCRN collaborates with prominent scientists across the globe and with major research groups and institutions beyond Canada. Linkage with NCAR is a prime example of this, but other connections include the WCRP through its GEWEX Global Land/Atmosphere System Study (GLASS) and Climate and Cryosphere (CliC) Programme, the Integrated land Ecosystem – Atmosphere process Study (ILEAPS), and NASA through several of its upcoming satellite missions and its Arctic–Boreal Vulnerability Experiment (ABoVE).

CCRN's WECC observatories will make a significant contribution to many of these international initiatives, with a number of future planned activities utilizing data collected here. Planned modelling activities include a cold region land surface scheme intercomparison project joint with GLASS and ILEAPS. Collaboration with ABoVE focuses on the use of WECC data towards their field monitoring and research activities, and which will also support their interpretation of regional satellite observations on ecosystem and environmental change in the circumpolar Arctic and Boreal regions. Many of the WECC sites provide validation data for current and future planned NASA airborne and satellite missions. In situ soil moisture measurements at certain sites in the Prairie, Boreal Forest, and Taiga Plains ecoregions will help with calibration and validation of remotely sensed soil moisture through passive and active microwave observations from the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) and Soil Moisture Active Passive (SMAP) missions. Prairie sites include geological lysimeters that provide a basis for measurement of integrated subsurface soil moisture and comparison with estimates from the satellite-based Gravity Recovery and Climate Experiment (GRACE) observing system. Evaluation of precipitation products from the 2014 Global Precipitation Measurement (GPM) mission will use some WECC data, while several WECC observatories will contribute directly to the World Meteorological Organization's (WMO) Solid Precipitation InterComparison Experiment (SPICE).

5 Summary and future directions

This paper has presented a brief overview of the CCRN, including its organizational structure and research programme, its study domain and WECC observatories, some recent environmental changes observed and local process insights being developed, key modelling tool developments and application, linkages with the user community, and international collaboration in a number of fields. In particular, it was highlighted how the observational system of WECC sites adds considerable value towards the observation, diagnosis, and prediction of atmospheric, ecological, hydrological, and cryospheric change at local scales, and can provide important insights into the nature of regional and continental scale change as well. The sites provide a testbed for model development, process understanding, and remotely sensed data validation.

To enhance the value of these sites, the CCRN is planning a special coordinated observation and analysis period at all of the WECC observatories and across the study domain. The focus period will be the hydrological year of October 1, 2014 to September 30, 2015. The aim is to develop a legacy dataset which can be used to enhance understanding of hydrological processes and for hydrological and atmospheric model input and validation purposes. Additional instrumentation will be deployed at the WECC observatories and other sites, existing instrumentation will remain operational and well-maintained, other special data sets will be collected (e.g., remotely sensed data, field-based observations, isotope and geochemical tracers, etc.), and CCRN will work with federal partners for rapid collection and processing of meteorological and hydrometric network data. Synergies with other planned initiatives will also be maximized (e.g. initial phases of SMAP, ABoVE, etc.). This special coordinated activity will provide comprehensive and comparable observations over the region with which to investigate process interactions, sensitivities, and responses across spatial and climatic gradients.

The aim is that the network will leave a legacy of both extensive datasets and improved modelling tools, in addition to its scientific advancements. Data generated from the WECC observatories, as well as from climate model outputs, reanalysis products, and remotely sensed observations will be inventoried and made publically available through a central repository and through links to other data holding centres. Special collections will include the focal analysis of the 2013 extreme events and the special coordinated observing and analysis period at the WECC sites. Some model products and code will be externally shared upon request, and may include open source code in some instances. Open source methodologies have the benefit of increasing the number of people contributing to further model development and testing, and improving speed and reliability of code (Whitfield et al., 2013).

As the Network continues throughout the remainder of its five-year programme, it will maintain a strong presence both nationally and internationally. Annual meetings will be held each year to bring the group together for a broad review of progress and discussion of activities and future plans. Regionally, CCRN will engage with the community through a series of topic- and theme-based workshops, which in some cases will lead to outputs such as special issue journal publications, for example. The CCRN will engage with the Canadian Geophysical Union (CGU) and Canadian Meteorological and Oceanographic Society (CMOS) at their annual meetings, while also connecting with international research communities, including the WCRP, WMO, American Geophysical Union (AGU), and European Geophysical Union (EGU) through their annual or other focused meetings. The network maintains an open stance toward developing further collaborative relationships with other partners, both nationally and internationally.

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