Changing Cold Regions Network (CCRN) Project Report for the GEWEX GHP Meeting
Reporting Period: November 2015 – October 2016
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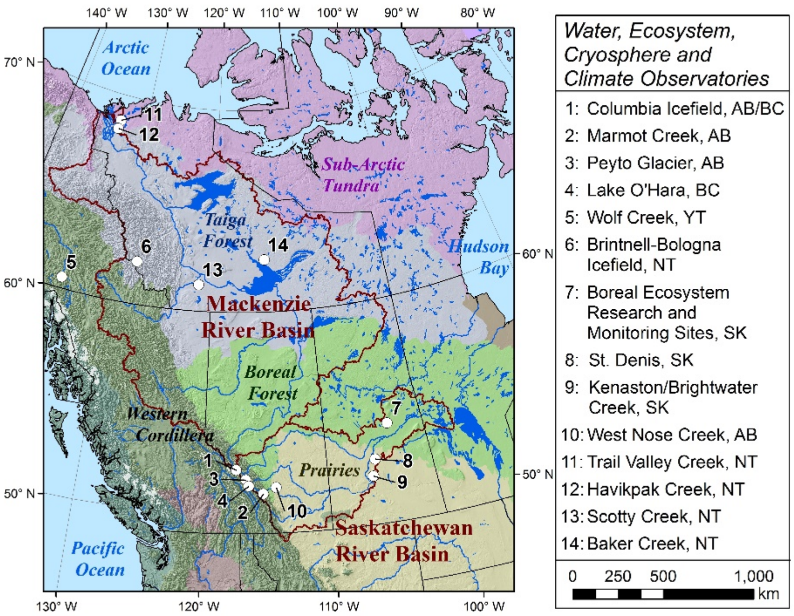
URL: www.ccrnetwork.ca
Chair(s) and term dates: Professor Howard Wheater (2013–2018)

1) Regional Hydroclimate Project (RHP) activities over the last year

As noted in our last report to the GHP, the Canadian RHP known as the Changing Cold Regions Network (CCRN) covers the interior of western Canada, including the Mackenzie and Saskatchewan River Basins (see www.ccrnetwork.ca/documents/Reports/CCRN_2015_GEWEX_Report.pdf). The overall aims of CCRN are to understand, diagnose, and predict changing land, ecosystems, water, and climate, and their interactions and feedbacks over western Canada's cold interior. This includes developing improved land surface and hydrological models for cold regions. We use a network of 14 intensely instrumented Water, Ecosystem, Cryosphere, and Climate (WECC) observatories representing the key biomes to study detailed processes and linkages, 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. Our science and outreach programme is divided into five major thematic components: Theme A, Observed Earth System Change in Cold Regions – Inventory and Statistical Evaluation; Theme B, Improved Under-standing and Diagnosis of Local-Scale Change; Theme C, Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction; Theme D, Analysis and Prediction of Regional and Large-Scale Variability and Change; and Theme E, Outreach and Engagement. Further details can be found at www.ccrnetwork.ca/science.



Key science highlights from the past year involve major progress and focal activities in our later thematic areas, dealing with model development and application in the diagnosis of change and large-scale analyses of variability and change, with particular emphasis on recent extreme events in our geographic region. We have continued to operate our set of WECC observatories, following a more intensive Special Observation and Analysis Period (SOAP) in 2014–15, and the data and process-level understanding that comes from these observatories contributes to each of our thematic areas.

Under **Theme A**, documentation and statistical analyses of Earth system change have been published (deBeer et al., 2016), providing a baseline for more detailed analyses and modelling work. We have continued to work on conceptual models of the mechanisms and drivers change and are using this towards the development of scenarios of landscape evolution and change to incorporate in our modelling of future climates. This work will come together more fully at our upcoming 4th annual general meeting (AGM) in Guelph, ON, in November, and will likely to lead to one or more key synthesis papers.

Under **Theme B**, we have made major progress in advancing process understanding, based on studies at the WECC sites, and parameterizing these processes in local-scale models, particularly the Cold Regions Hydrological Model (CRHM) platform, developed at the Centre for Hydrology, University of Saskatchewan. A coordinated effort has been initiated to apply CRHM in a systematic manner across most WECC observatories for 1) long-term historical runs to diagnose hydrological functioning and trends and cycling in this functioning over time, and 2) future runs to explore hydrological responses in relation to climate warming, focusing on geographic variability and the sensitivity to change in different environments. Progress on this and a clear path forward were established at a workshop held in

Saskatoon, SK, in June (see www.ccrnetwork.ca/science/workshops/crhm-workshop-2016). This will lead to two major group synthesis papers.

Work in **Theme C** has involved a wide range of activities toward the development of improved large-scale models and land surface schemes, along with the assimilation of remotely sensed data. This work has involved close collaboration and a strong partnership with Environment and Climate Change Canada (ECCC) to help them incorporate improvements into their research and operational models. Our main focus is the ECCC Canadian LAnd Surface Scheme (CLASS), Modélisation Environmentale Communautaire (MEC) – Surface and Hydrology (MESH), and Canadian Terrestrial Ecosystem Model (CTEM) models, but we are also working intensively with others such as 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)). The main effort has concentrated on developing and improving large-scale MESH models of the Mackenzie and Saskatchewan River systems, and within this, improving the representation of various processes such as permafrost, wetlands, hydrodynamics and large lakes, and snow processes, and also exploring ways of better handling spatial discretization (especially in mountainous terrain) and in particular, the effects of water management—CCRN is strongly linked to a GEWEX cross-cut project on including water management in large scale models. Various other activities have supported this work, which has progressed well to the point where we expect to have working models in place for both major basins this fall.

Our **Theme D** activities have expanded over the past year and we have made much progress through the collective work of a number of individual research scientists on many different aspects of large-scale hydro-climatic variability and change. In particular, a focus of this work has been on linking these conditions with some of the recent extreme events that have been observed in our geographic region (e.g. flooding in AB in 2013, drought in western Canada in 2015, and extreme wildfires across parts of the region in 2014, 2015, and most recently at Fort McMurray, AB, in 2016). This was reviewed in detail at a recent workshop in Winnipeg, MB, in May, where progress was made towards synthesizing the work and planning future activities (see www.ccrnetwork.ca/science/workshops/theme-d-workshop-2016). An important activity has been collaboration with the US National Center for Atmospheric Research (NCAR) to produce 4 km resolution WRF climate simulations for the entire CCRN domain (14-year historical simulations, 2000–14, plus pseudo-warming simulations of future climate), providing comparative data for Theme B, C, and D modelling and large-scale analysis.

Outreach efforts as part of **Theme E** have continued, ranging from grassroots level engagement among individual researchers and local stakeholders, to collaboration at senior management levels with our federal provincial, and territorial government partners, and linkage to international initiatives such as GEWEX and the World Climate Research Programme. This year we received additional support for the enhancement of CCRN outreach and have developed extensive plans for the final two years of our programme. Among the plans are to hold several major stakeholder-focused events to showcase our results and facilitate the transfer of knowledge and tools, supporting our investigators in enhancing their engagement with local communities and stakeholders, and developing professional products to communicate various science messages emerging from our work.

2) Planned panel activities for next year

Over the next year we plan to hold several key workshops and focus our science on a few priority areas. In the fall of 2016, we have three planned workshops: 1) a two-day SOAP workshop in early October, 2) our 4th AGM over three days in early November, and 3) a two-day modelling workshop in late November. We are also developing plans for an interdisciplinary workshop on wildfires in early 2017, including atmospheric, hydrological, and ecological perspectives, along with modelling community involvement.

Our SOAP initiative provided important observational data to form the basis of further scientific study. We will report on the observations and develop further plans for analysis at the upcoming SOAP workshop and AGM. Efforts will center on addressing several key topics, which were central to SOAP, such as the linkage between physical and ecological processes in fall and the responses the following spring, the interaction between vegetation and hydrology during and after snowmelt, and meltwater partitioning at the different WECC sites. The SOAP included an anomalously warm and dry spring across much of the region, and the intensive observations and modelling as part of SOAP could shed useful insight on the cause and effects of these conditions.

Work will continue in each of our thematic areas. In Theme A, and as a contribution to other Themes, we will continue our efforts towards the development of scenarios of change for our observatories and for our main ecoregions, based on conceptual and process understanding. Theme

B efforts will focus on CRHM historical diagnostic modelling at the observatories, with reporting at our upcoming AGM, and then on synthesizing results and developing individual and synthesis papers, representing the completion of Theme B. Future CRHM analyses will be based on the WRF pseudo-warming simulations (used as driving data) to diagnose future hydrological change and sensitivity, with reporting at our 2017 AGM, and papers to follow. This will represent completion of our last of the four work packages in Theme D. In Theme C we expect to have working models for both major basins ready for subsequent use in Theme D analyses by the fall. We plan to build on the discussions at the AGM regarding scenarios of change and will pull together all the large-scale modelling work and progress on the Theme B CRHM project at the upcoming fall modelling workshop. From here, we will decide on driving products and best approaches moving forward for the large-scale modelling analyses to be done in Theme D. Several focal topics have been added as areas of study in Theme D for the coming year, including a synthesis and examination of the three back-to-back extreme wildfire seasons in western Canada (2014–16), an examination of changes in the timing of the zero degree Celsius isotherm and associated impacts, a review of future projected changes (following review of past change, and linking with scenarios of change), and an examination of the chain-of-events around recent major disasters in our region.

3) Contributions to the GEWEX Science Questions

GSQ1: Observations and Predictions of Precipitation

- There has been much 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. This work was reviewed and discussed at a recent workshop (see http://www.ccrnetwork.ca/science/workshops/theme-d-workshop-2016/index.php for full details, including a summary report and presentations).
- Assessments of various precipitation products and remotely sensed observations, including GPM, and characterization and regionalization of precipitation and drought characteristics over western Canada, with several papers in draft.
    - Relevant publications include: Asong et al. (2015), Khaliq et al. (2015), Masud et al. (2015)
- A major CCRN effort was centered on a comprehensive focal examination of the extreme weather and flooding in southern Alberta in June 2013, focusing on meteorological, hydrological, and water management aspects of the flood. This has led to a collection papers being published in a special issue of *Hydrological Processes*. (See http://www.ccrnetwork.ca/news-events/news/2016/ccrn-special-issue-papers-on-the-2013-alberta-flood-coming-online.php for further details and links to all published papers.)
    - Relevant publications include: Fang et al. (2016), Harder et al. (2015), Kochtubajda et al. (2016), Liu et al. (2016), Pomeroy et al. (2016a, 2016b), Shook et al. (2015), Whitfield and Pomeroy (2016).
    - See outreach brochure summarizing our findings at www.ccrnetwork.ca/outputs/outreach/docs/CCRN_2013Flood_Poster.pdf
- Focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–16 with several papers published and others forthcoming
    - Relevant publications include those listed above and: Brimelow et al. (2014, 2015), Szeto et al. (2015)

GSQ2: Global Water Resource Systems

- Completion of inventories and assessments of Earth system change at many WECC observatories and across the CCRN domain.
    - Relevant publications include: Baltzer et al. (2013), Bash and Marshall (2014), Connon et al. (2014), DeBeer et al. (2015, 2016), Demuth et al. (2014), Dumanski et al. (2015), Ehsansadeh et al. (2014), Harder et al. (2015), Hayashi and Farrow (2014), Ireson et al. (2015), Marshall (2014b), Patankar et al. (2015), Paznekas et al. (2015), Quinton and Baltzer (2013b), Shi et al. (2015), Shook and Pomeroy (2015), Spence et al. (2015), Yang et al. (2014b).
- Analysis of large scale hydrological model performance for the Saskatchewan and Mackenzie basins. Identification of key challenges – input uncertainty, permafrost, cold region lakes and

wetlands, mountain hydrology, prairie hydrology, anthropogenic water management. Work initiated to address these with a number of draft papers underway and some recent publications. Much of this work (at various stages of development) had been reviewed and synthesized at a workshop last year (see www.ccrnetwork.ca/science/workshops/2015-modelling-workshop).
    - Relevant publications include: Hassanzadeh et al. (2014, 2015), Mekonnen et al. (2014), Nazemi and Wheater (2014a, 2014b, 2015a, 2015b).
- Progress with assimilation of remotely sensed data to constrain large scale hydrological models, and examination of scaling effects in the models.
- Extension of previous work on vulnerability analysis of water resource systems in the SaskRB – now includes risk-based hydro-economic analysis for Saskatchewan.
    - Relevant publications include: Hassanzadeh et al. (2015)

GSQ3: Changes in Extremes

- 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.
    - See http://www.ccrnetwork.ca/science/workshops/theme-d-workshop-2016/index.php for a summary of a recent workshop where this work was presented and discussed
- 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. See website link above.
- A major CCRN effort was centered on a comprehensive focal examination of the extreme weather and flooding in southern Alberta in June 2013, focusing on meteorological, hydrological, and water management aspects of the flood. This has led to a collection papers being published in a special issue of *Hydrological Processes*. (See http://www.ccrnetwork.ca/news-events/news/2016/ccrn-special-issue-papers-on-the-2013-alberta-flood-coming-online.php for further details and links to all published papers.)
    - Relevant publications include: Fang et al. (2016), Harder et al. (2015), Kochtubajda et al. (2016), Liu et al. (2016), Pomeroy et al. (2016a, 2016b), Shook et al. (2015), Whitfield and Pomeroy (2016).
    - See outreach brochure summarizing our findings at www.ccrnetwork.ca/outputs/outreach/docs/CCRN_2013Flood_Poster.pdf
- Focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–16 with several papers published and others forthcoming. Initial work towards an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations.
    - Relevant publications include those listed above and: Brimelow et al. (2014, 2015), Szeto et al. (2015)
- CCRN will continue to focus on conducting detailed analyses of recent extreme events (floods, droughts, wildfires) in our geographic domain, including the recent short but severe drought in 2015, the sequence of devastating wildfires in parts of the region from 2014–2016, local prairie flooding in several of the past years, hazardous winter precipitation and severe summer weather and hail that has affected several cities in the past year, and examination of the chain-of-events leading up to these events.

GSQ4: Water and Energy Cycles and Processes

- 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
    - Relevant publications: Adams et al. (2015), Burns et al. (2016), Champagne et al. (2016), Djamai et al. (2015), Manns et al. (2015), Rowlandson and Berg (2015), Rowlandson et al. (2015), Roy et al. (2016).
- 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.

  - Driving datasets and the progress of WRF runs were presented and discussed the two most recent CCRN workshops (http://www.ccrnetwork.ca/science/workshops/theme-d-workshop-2016/index.php, and http://www.ccrnetwork.ca/science/workshops/crhm-workshop-2016/index.php)

4) Activities contributing to the WCRP Grand Challenges as identified by the JSC

Clouds, Circulation, and Climate Sensitivity

- Theme/ work package D1
  - Specific scientific contributions will involve the assessment of large and synoptic scale atmospheric circulation patterns as they relate to observed temporal and spatial trends and variability (including extremes) in hydro-climate over the study region
  - In addition, studies will be undertaken to understand the mechanisms which link the regional water and energy response to large-scale forcings. This includes the role of the orographic barrier in amplifying the region's climate sensitivity to upstream large-scale forcings. Statistical techniques and diagnostic studies will be carried out to examine the coupled mode of variability between low-frequency forcings such as sea surface temperature anomalies, large-scale circulation patterns and warm-season synoptic activities
  - Relevant publications include: Armstrong et al. (2015), Asong et al. (2015), Brimelow et al. (2014, 2015), Khaliq et al. (2015), Kochtubajda et al. (2016), Liu et al. (2016), Masud et al. (2015), Szeto et al. (2015).
- Theme/ work package D3
  - Changes in the large-scale atmospheric circulation will be assessed from CMIP5 and other projections. Their subsequent effects on the continental synoptic activities and associated heat and moisture transports which affect critically regional temperature and precipitation responses will be assessed from the downscaled projections.

Melting Ice and Global Consequences

- Theme/ work package D4
  - Projection results will be used to address regional scale effects on land and water resources, using the large-scale models developed in Theme C. This includes the change in river flows for the Saskatchewan, Peace-Athabasca and Mackenzie River Basins, and effects of climate change for specific ecosystems.
  - We will determine whether future changes cross 'tipping points' in Earth system behaviour, leading to further extremes and dramatic system changes, such as deglaciation, permafrost disappearance and terrestrial ecosystem transition. Local scale assessments have begun in Theme B with several publications (Pomeroy et al. (2015b), Rasouli et al. (2014, 2015)), and planned CRHM historical and future diagnostic modelling (see http://www.ccrnetwork.ca/science/workshops/crhm-workshop-2016/index.php)
  - Outputs from this analysis will thus be used to identify global climatological controls on broad regional water resource response, and hence to enable specific design, operational or policy development problems under climate change to be addressed in Theme E. To address this issue, specific analyses will be carried out utilizing future conditions along with threshold guidance on conditions needed to trigger a fundamental shift.
- Glaciological studies, including mass and energy balance, glacier hydrology, and development of ice dynamic routines for local to regional-scale models are being conducted, crossing many of our thematic areas. See http://www.ccrnetwork.ca/science/WECC/index.php for information on the glaciological research at several of our WECC observatories.
  - Relevant publications include: Bash and Marshall (2014), DeBeer et al. (2016), Demuth et al. (2014), Ebrahimi and Marshall (2015), Marshall (2014a, 2014b).

Understanding and Predicting Weather and Climate Extremes

- A large amount of work is being pursued in CCRN that addresses recent extreme events in our geographic domain. See above under GSQ1 and GSQ3.
- Theme/ work package D1
    - Specific scientific contributions will involve the assessment of large and synoptic scale atmospheric circulation patterns as they relate to observed temporal and spatial trends and variability (including extremes) in hydro-climate over the study region
    - Another focus will be on precipitation. Studies include the occurrence of precipitation extremes from droughts to heavy precipitation including variability and simultaneous occurrence. The regional and larger scale factors leading to such events will be determined. The factors leading to the changing occurrence of winter precipitation will be examined. As well, changes in the occurrence of extreme precipitation rates will be determined over some areas and linked with the large and regional scales forcing factors
    - Relevant publications include: Asong et al. (2015), Brimelow et al. (2014, 2015), Dumanski et al. (2015), Khaliq et al. (2015), Kochtubajda et al. (2016), Liu et al. (2016),
    - Masud et al. (2015), Pomeroy et al. (2016a, 2016b), Scaff et al. (2015), Schubert et al. (2016), Shook et al. (2015), Stewart et al. (2015), Szeto et al. (2015).
- Theme/ work package D3
    - Key focal points will be on regional and local scale temperature changes and variations of prolonged summer hot periods, and extension of above freezing conditions. A focal examination of changes around the zero degree Celsius isotherm is planned. In terms of precipitation, the focus will be on the development of drought, heavy precipitation, extreme precipitation rates, as well as the changing phase of precipitation
- Theme/ work package D4
    - We will determine whether future changes cross ‘tipping points’ in Earth system behaviour, leading to further extremes and dramatic system changes, such as deglaciation, permafrost disappearance and terrestrial ecosystem transition. Local scale assessments have begun in Theme B with several publications (Pomeroy et al. (2015b), Rasouli et al. (2014, 2015)), and planned CRHM historical and future diagnostic modelling (see http://www.ccrnetwork.ca/science/workshops/crhm-workshop-2016/index.php)

Regional Sea-Level Change and Coastal Impacts

- We are not directly addressing global sea level change, but our modelling in Theme D will indirectly provide insights (e.g. through regional projections of ice volume change in western Canada, and through future runoff simulations and projections for the Mackenzie and Saskatchewan Rivers)

Changes in Water Availability

- Use of soil moisture monitoring networks for various objectives (see above under GSQ4)
- 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 NRCan)
- Various atmospheric research activities contribute to this Grand Challenge, described above under GSQ1 and GSQ2
- 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
- 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
- Theme/ work package D1 contributes to the Grand Challenge, as described above under the headings, *Clouds, Circulation, and Climate Sensitivity*, and *Understanding and Predicting Weather and Climate Extremes*

- Theme/ work package D2
    - Research on future conditions over the domain has given some indication of future states and interactions although with a great deal of uncertainty. In general, results predict continued increase in temperature – more in the cold season and at higher elevations. They also expect an overall increase in precipitation, but with considerable spatial and temporal variability. Northern regions are projected to see more increases in precipitation than southern regions of the study area, which has potentially huge implications for water resources. In parallel, there is a projected increase to in the frequency, intensity and duration of future droughts including more hot droughts. Overall, future water cycle related variability remains a huge knowledge gap.
    - Given the determination and understanding of changing conditions over the region, it is critical to assess how future conditions will evolve, in particular factors affecting water resources and ecosystems. Validated models from Theme C will be a critical basis for addressing this issue including our degree of uncertainty. Projections of future conditions over the region will be developed by CCRN (4 km WRF pseudo-warming) and others will be obtained (CanRCM5 projections, with improved CLASS algorithms and explicit representation of feedbacks).
    - Some relevant publications include: Asong et al. (2015), Khaliq et al. (2015), Masud et al. (2015).
- Theme/ work package D3
    - Changes in the large-scale atmospheric circulation will be assessed from CMIP5 and other projections. Their subsequent effects on the continental synoptic activities and associated heat and moisture transports which affect critically regional temperature and precipitation responses will be assessed from the downscaled projections. The initial focus will be on projections of temperature, precipitation, and their variation. Key focal points will be on regional and local scale temperature changes and variations of prolonged summer hot periods, and extension of above freezing conditions. In terms of precipitation, the focus will be on the development of drought, heavy precipitation, extreme precipitation rates, as well as the changing phase of precipitation.
    - Relevant publications include: Asong et al. (2015), Khaliq et al. (2015), Masud et al. (2015), Stewart et al. (2015).
- Theme/ work package D4 contributes to the Grand Challenge, as described above under the headings *Melting Ice and Global Consequences*, and *Understanding and Predicting Weather and Climate Extremes*

<u>Near-Term Climate Prediction</u>

- Our work on all future assessments of change is based on various climate model projections and forecasts, such as CMIP5, NARCCAP, CORDEX, but we are directly contributing to the development of climate forecasts. Our WECC observatories provide excellent validation datasets for model downscaling, bias correction, and other activities aimed at improving RCM performance and developing related products.

<u>Carbon Feedbacks in the Climate System</u>

- Activities at some of our WECC observatories, in particular the Boreal Ecosystem Research and Monitoring Sites (BERMS), focus on the spatial and temporal variability in the boreal forest's water and carbon balance, and their sensitivity to climate variability and change. Long-term, high-quality, and intensive observations of water, carbon, and energy fluxes at several towers in different forest stands provide exemplary opportunities to observe and understand the carbon balance and feedbacks with the climate system. Work has examined the net annual ecosystem carbon exchange from CO_2 flux measurements and partitioned it between gross ecosystem photosynthesis and ecosystem respiration.
- We have conducted preliminary analyses of the CTEM model, focusing on our BERMS sites, and will utilize the model to simulate different ecosystems, particularly around the boreal–prairie transition zone.

5) Cooperation with other GHP and WCRP Projects, outside bodies, and links to applications

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

6) List of key publications in the last year
(For complete CCRN list see www.ccrnetwork.ca/outputs/publications)

2016

- Blouin, K. D., Flannigan, M. D., Wang, X., & Kochtubajda, B. (2016). Ensemble lightning prediction models for the province of Alberta, Canada.*International Journal of Wildland Fire*, *25*(4), 421-432. DOI: 10.1071/WF15111
- Burns, T. T., Berg, A. A., Cockburn, J., & Tetlock, E. (2016). Regional scale spatial and temporal variability of soil moisture in a prairie region. *Hydrological Processes*. DOI: 10.1002/hyp.10954
- Buttle, J. M., Allen, D. M., Caissie, D., Davison, B., Hayashi, M., Peters, D. L., ... & Whitfield, P. H. (2016). Flood processes in Canada: Regional and special aspects. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, 1-24. DOI:10.1080/07011784.2015.1131629
- Champagne, C., Rowlandson, T., Berg, A., Burns, T., L'Heureux, J., Tetlock, E., ... & Itenfisu, D. (2016). Satellite surface soil moisture from SMOS and Aquarius: Assessment for applications in agricultural landscapes. *International Journal of Applied Earth Observation and Geoinformation*, 45, 143-154. doi:10.1016/j.jag.2015.09.004
- DeBeer, C. M., Wheater, H. S., Carey, S. K., & Chun, K. P. (2016). Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis. *Hydrology and Earth System Sciences*, 20, 1573-1598. DOI: 10.5194/hess-20-1573-2016
- Fang, X., & Pomeroy, J. W. (2016). Impact of antecedent conditions on simulations of a flood in a mountain headwater basin. *Hydrological Processes*. DOI: 10.1002/hyp.10910
- Garnaud, C., Bélair, S., Berg, A., & Rowlandson, T. (2016). Hyperresolution Land Surface Modeling in the Context of SMAP Cal–Val. *Journal of Hydrometeorology*, 17(1), 345-352. DOI: http://dx.doi.org/10.1175/JHM-D-15-0070.1
- Harder, P., Schirmer, M., Pomeroy, J., & Helgason, W. (2016). Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle. *The Cryosphere Discussions*. DOI: 10.5194/tc-2016-9
- Kochtubajda, B., Stewart, R. E., Boodoo, S., Thériault, J. M., Li, Y., Liu, A., ... & Szeto, K. (2016). The June 2013 Alberta Catastrophic Flooding Event–Part 2: Fine-scale precipitation and associated features. *Hydrological Processes*. DOI: 10.1002/hyp.10855
- Kurylyk, B. L., Hayashi, M., Quinton, W. L., McKenzie, J. M., & Voss, C. I. (2016). Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow. *Water Resources Research*. DOI: 10.1002/2015WR018057
- Liu, A., Mooney, C., Szeto, K., Thériault, J. M., Kochtubajda, B., Stewart, R. E., ... & Pomeroy, J. (2016). The June 2013 Alberta Catastrophic Flooding Event: Part 1–Climatological aspects and hydrometeorological features. *Hydrological Processes*. DOI: 10.1002/hyp.10906
- Pomeroy, J. W., Fang, X., & Marks, D. G. (2016a). The Cold Rain-on-Snow Event of June 2013 in the Canadian Rockies–Characteristics and Diagnosis.*Hydrological Processes*. DOI: 10.1002/hyp.10905
- Pomeroy, J. W., Stewart, R. E., & Whitfield, P. H. (2016b). The 2013 flood event in the South Saskatchewan and Elk River basins: Causes, assessment and damages. *Canadian Water*

Resources Journal/Revue canadienne des ressources hydriques, *41*(1-2), 105-117. DOI: 10.1080/07011784.2015.1089190

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