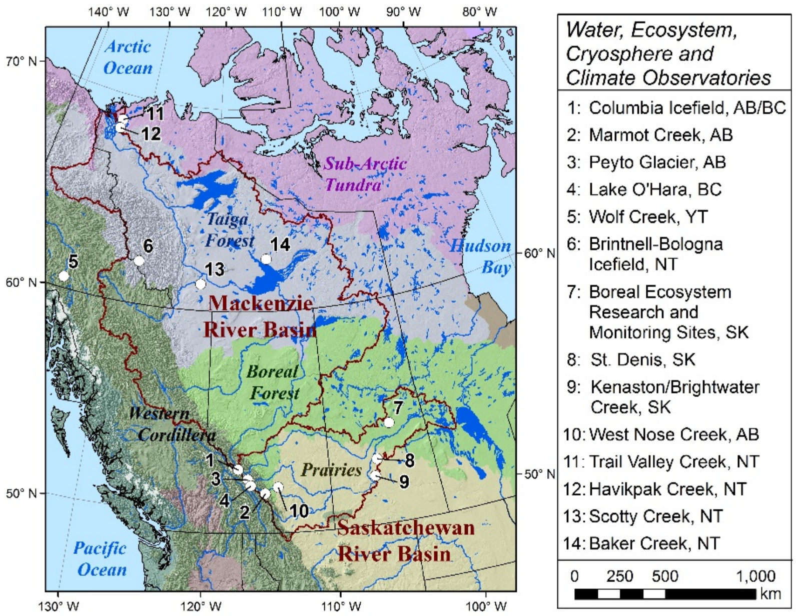
Changing Cold Regions Network (CCRN) Project Report for the GEWEX GHP Meeting
Reporting Period: November 2014 – October 2015
Starting Date: February 2013
End Date: March 2018
URL: www.ccrnetwork.ca
Chair(s) and term dates: Professor Howard Wheater (2013-2018)

1) Panel activities over the last year

As endorsed by GHP in 2014, the Canadian RHP has expanded in geographical scope from its previous (SaskRB) focus on the Saskatchewan River Basin (406,000 km^2) to include the 1.8 million km^2 Mackenzie River Basin, and now takes the name of the Changing Cold Regions Network (CCRN). CCRN covers the interior of western Canada, from the southern US border to the Arctic Ocean. 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 (www.ccrnetwork.ca/science/WECC) to study detailed processes and connections in the Boreal Forest, the Western Cordillera, the Prairies and the permafrost regions of the Sub-Arctic. 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. CCRN has a somewhat narrower disciplinary focus than the SaskRB, which also includes water quality, water resources management and socio-hydrology research.



CCRN is organized around 5 inter-dependent Themes (www.ccrnetwork.ca/science/themes). Theme A, Observed Earth System Change in Cold Regions – Inventory and Statistical Evaluation, documents and evaluates observed change, including hydrological, ecological, cryospheric, and atmospheric components, in the cold regions of interior northwestern Canada over a range of scales. Theme B, Improved Understanding and Diagnosis of Local-Scale Change, improves our knowledge of local-scale change by developing new and integrative knowledge of Earth system processes, incorporating these processes into a suite of process-based integrative models, and using the models to better understand Earth system change. Theme C, Upscaling for Improved Atmospheric Modelling and River Basin-Scale Prediction, improves large-scale atmospheric and hydrological models for weather, climate, and river basin-scale modelling and prediction of the changing Earth system and its feedbacks. Theme D, Analysis and Prediction of Regional and Large-Scale Variability and Change, focusses on the driving factors for the observed trends and variability in large-scale aspects of the Earth system, their representation in current models, and the projections of regional-scale effects of Earth system change on climate, ecology, land, and water resources. Theme E, Outreach and Engagement, engages a community of partners and users, including local stakeholder groups, provincial and federal policy/decision makers, national and international research organizations, and other relevant groups, and disseminates the improved knowledge and tools within this extended community.

Over the past year, important scientific progress has been made in each of Themes A–D. Work in Theme A has addressed both the local/biome scale (at WECC sites) and the regional scale. Assessments of change have been largely completed, including changes in climate, vegetation, snow and glacier cover, permafrost, stream discharge, groundwater and pond levels, and surface water extent. From this, conceptual models of the mechanisms and drivers of change have been, and continue to be developed. These will be used towards quantitative diagnosis in Theme B. A key review paper has been published in Hydrology and Earth System Sciences Discussions that describes the recent Earth system changes observed in western Canada[1]. Further, tree-core data have been collected from across the western Canadian Boreal and Taiga ecoregions to develop an extensive dendro-chronological record, to support analysis of the connections between proxy record, ecosystem response, and climate variability.

Theme B builds on a legacy of process observations and modelling at long-term WECC observatories. During the 2014–15 hydrological year, we have been coordinating a Special Observation and Analysis Period (SOAP) across these sites, which has included the deployment of enhanced and new field instrumentation, and standardized collection of ecological, hydro-meteorological, and isotopic data. This will provide an important legacy dataset and provide opportunities for model intercomparative analysis across the domain. Targeted process studies have been carried out with an aim to better understand coupled cryosphere-hydrosphere-biosphere interactions, compare and contrast processes amongst observatories, and develop improved cold regions model algorithms and parameterizations. A Theme B focus has been continued development of the Cold Regions Hydrological Model (CRHM) platform, with implementation of numerous improvements and new algorithms, e.g. to simulate 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.

Our work in Theme C has involved close collaboration with Environment Canada (EC) and the US National Center for Atmospheric Research (NCAR). A key aim is to improve large-scale predictive models to better account for changing cold region processes and atmospheric feedbacks. Applications are addressed in Theme D. Progress has been made on the development and testing of the Canadian LAnd Surface Scheme (CLASS), Modélisation Environmentale Communautaire (MEC) – Surface and Hydrology (MESH), and Canadian Terrestrial Ecosystem Model (CTEM) models, including baseline simulations and evaluation at most WECC sites and intercomparisons with the Joint UK Land Environment Simulator (JULES), the Weather Research and Forecasting Model – Hydrologic Processes (WRF-Hydro), the community Noah land surface model with multiparameterization options (Noah-MP), and the Common Land Model (CLM) Parallel Flow (PARFLOW)). Improvements to CLASS under development include cold region lakes and 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. Our water management research links to the GHP cross-cut and has included comparative analysis of alternative modelling schemes within MESH. Our soil moisture monitoring networks have provided 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. Large scale modelling has addressed input uncertainty, the representation of permafrost within land surface schemes and assimilation of NASA Gravity Recovery and Climate Experiment (GRACE) and other remote sensing data. In collaboration with NCAR, we are producing 4 km resolution WRF climate simulations for the entire CCRN domain (14 years historical simulations, plus pseudo warming simulations of future climate), which provide comparative data for Theme B, C and D modelling and large scale climate analysis.

Many of the deliverables in Theme D are slated for late in the project; however progress has been made on large-scale studies of 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. Several extreme events that have unfolded during this network provide key focal points for interdisciplinary investigation (spanning Themes B–E). We have completed a comprehensive

[1] DeBeer, C. M., Wheater, H. S., Carey, S. K., and Chun, K. P.: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a synthesis and review, Hydrol. Earth Syst. Sci. Discuss., 12, 8615-8674, doi:10.5194/hessd-12-8615-2015, 2015.

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. Initial work has started on an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations, and planning is underway on how to proceed with an examination of the 2015 prairie drought and its manifestations in terms of regional hydrology, agriculture, water management, and wildfire.

CCRN has held several important workshops over the past year to advance our science, plan future activities, and promote collaboration among network members, government partners, international collaborators, and other stakeholders. These have included: 1) Workshop on the 2014 Northwest Territories Fires – Developing a Research Framework (12–13 January, 2015, Yellowknife NT); 2) Theme A workshop, Conceptual Models of Change (22 January, 2015, Hamilton ON); 3) "Modelling Change in Cold Regions" Workshop (28–30 September, 2015, Saskatoon SK); and 4) CCRN Third Annual General Meeting (1–4 November, 2015, Saskatoon SK). Further details, including summary reports and presentations are available on our webpage at www.ccrnetwork.ca/science/workshops.

Other SaskRB deliverables include for example a special journal issue (14 papers) on the water quality of Lake Diefenbaker, detailed analysis of changing prairie flood hydrology and impacts of agricultural drainage, the first nutrient model of the South Saskatchewan river, further analysis of water resource vulnerability to economic development and climate change, and continued work with First Nations on changing ecosystems in the Saskatchewan Delta. Appendix A lists SaskRB publications.

2) Planned panel activities for next year

In Theme A we will continue to work on conceptual models of the mechanisms and drivers of change. To this end, we will hold a small workshop in March 2016 to synthesize results and prepare output products for both outreach purposes and for taking further quantitatively in Theme B.

Theme B goals include a) a set of prioritized process improvements, b) model development at selected sites, c) comparative model application and evaluation across sites. In the next year, we will continue with application of CRHM at all WECC observatories for comparative analysis and interrogation of observed change, supported by other detailed modelling activities (e.g., the USGS 3D SUTRA (Saturated-Unsaturated TRAnsport) groundwater model to include freeze-thaw thermodynamics). The plan is to apply CRHM to the WECC observatories to diagnose change, and this work is well in hand. Results from different sites were presented at the September 2015 CCRN modelling workshop, and will continue with setup and testing on all sites by winter 2015–16 with results forthcoming by the following spring and summer. These activities will be supported by a CHRM training workshop to be held in March 2016, and will lead to a more formal event in May 2016 (including MESH runs as well). The plan will be to take to take conceptual models and diagnose them using CRHM and MESH; this will be a last chance to review algorithm performance and needed changes before our CCRN 4th annual general meeting the following November. This will lead the direction for future scenarios of change, which is the next step in our science plans.

In Theme C, a plan has been prepared for a systematic comparative analysis of different land surface schemes, using common driving data and multi-criteria performance objectives, within a framework that incorporates parameter uncertainty. This is underway for the BERMS WECC observatory and will be extended to the other WECC sites over the next year. The CTEM model is being evaluated at selected WECC sites and discussions are ongoing towards developing this as a Canadian community model. The plan will be to include a special session at our next CCRN annual general meeting (2–4 November, 2016, Guelph, ON) on the land surface scheme intercomparison project, which will include exploring MESH, JULES, WRF-Hydro, and Noah-MP. Development and testing of algorithms for CLASS will continue over the next year, and will be delivered for use in Theme D by mid-2016. An important development since the inception report is the result of collaboration with the US NCAR. NCAR was planning high resolution (4km) runs of the WRF model for most of North America for both a 14 year historical sequence and a pseudo-warming future climate simulation. We have research staff embedded within NCAR who have been able to extend the planned domain to include the whole CCRN region. These simulations are currently partially complete, and will be carried on during the next several months or more. The main planned activity related to data assimilation was work with NASA in the development of soil moisture algorithms for the SMAP mission, and the validation of SMAP products using WECC observatory data. This work is proceeding as planned, although SMAP has recently experienced a failure of its active sensors, thus providing a limited window when both active and passive systems were functional. Additional work is underway to evaluate the use of GRACE gravity satellite products, which provide coarse-scale estimates of total water storage changes. In collaboration with NRCan, GRACE products have been assimilated within the MESH model of the Saskatchewan basin, with promising results. The data provide a useful constraint on model performance and have reduced the uncertainty in (and hence improved the identifiability of) MESH model parameters. New work is underway to investigate the utility of other satellite products.

In Theme D, activities continue to focus on characterization of change in precipitation amount, phase, and intensity, convection, droughts, and heavy precipitation over the last few decades. Recent extreme events, including the 2011 Assiniboine River flood, the 2013 southern Alberta flood, the 2014 Northwest Territories fire season, and the 2015 western Canadian drought, provide a focal point for interdisciplinary examination. Off-line MESH analyses of the sensitivity of land–atmosphere feedbacks to cryospheric, hydrologic, and terrestrial ecosystem change will be carried out, and newly developed MESH algorithms will be applied and tested to represent: a) water management controls, and b) land management change.

3) Contributions to the GEWEX Science Questions

GSQ1: Observations and Predictions of Precipitation

- 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
- A comprehensive 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 (see progress updates by Kochtubajda, Li, Pomeroy, Stewart, Szeto, Thériault in appendix);
- Focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–11 with publications forthcoming

GSQ2: Global Water Resource Systems

- Completion of assessments and inventories of change at many WECC observatories and across the CCRN domain.
- 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.
- Progress with assimilation of remotely sensed data to constrain large scale hydrological models.
- Extension of previous work on vulnerability analysis of water resource systems in the SaskRB – now includes risk-based hydro-economic analysis for Saskatchewan.

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
- 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
- A comprehensive 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;
- Initial work towards an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations

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
- 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

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

<u>Clouds, Circulation, and Climate Sensitivity</u>

- 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
- 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.

<u>Melting Ice and Global Consequences</u>

- 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.
  - 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.

<u>Understanding and Predicting Weather and Climate Extremes</u>

- 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
  - See progress updates by Kochtubajda, Li, Pomeroy, Stewart, Szeto, Thériault in appendix
- Focal examination of extreme events (floods, fires, droughts) affecting the CCRN region from 2009–11 with publications forthcoming

    - See progress updates by Hanesiak, Kochtubajda, Stewart, Szeto in appendix
- Initial work towards an interdisciplinary examination of the 2014 forest fires in the Northwest Territories, involving contributions from university and government organizations
    - See progress updates by Baltzer, Bonsal, Johnstone, Kochtubajda, Quinton, Stewart, Turetsky in appendix;
- 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
- 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. 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.

<u>Regional Sea-Level Change and Coastal Impacts</u>

- 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)

<u>Changes in Water Availability</u>

- 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
- 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)
- 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
- 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
- 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

- 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/ work package D1
    - 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 SST anomalies, large-scale circulation patterns and warm-season synoptic activities
    - 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
- 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).
- 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.
- Theme/ work package D4
    - The 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.
    - 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.

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

- The International Network for Alpine Research Catchment Hydrology (INARCH) is a GEWEX Hydroclimate Panel project that is an international spin-off from CCRN, led by Professor John Pomeroy. INARCH recently held an inaugural workshop in Kananaskis, Alberta, Canada, at which CCRN was represented by the PI, Professor Howard Wheater, and by several other network co-Investigators. A report on the INARCH workshop has been provided to GEWEX. CCRN and INARCH are closely linked and share many common research priorities and objectives. Wheater and Nazemi are contributing to the GHP cross-cut on representation of anthropogenic water management in large scale models.

6) List of key publications (CCRN members and HQP trainees underlined)

1. Ali, G, Tetzlaff, D, McDonnell, JJ, Soulsby, C, Carey, S, Laudon, H, McGuire, K, Buttle, J, Seibert, J, and Shanley, J (2015), Comparison of threshold hydrologic response across northern catchments. *Hydrol. Process.,* 29, 3575–3591. doi: 10.1002/hyp.10527.
2. Anderson-Teixeira, KJ, Davies, SJ, Bennett, AC, Gonzalez-Akre, EB, Muller-Landau, HC, Wright, SJ, Kamariah, AS, Zambrano, AMA, Alonso, A, Baltzer, JL et al. (2015) CTFS-ForestGEO: A worldwide network monitoring forests in an era of global change. *Global Change Biology*, 21: 528-549, doi: 10.1111/gcb.12712 .
3. Armstrong R.N, Pomeroy J.W. and Martz L.W. 2015. Variability in evaporation across the Canadian Prairie region during drought and non-drought periods. *Journal of Hydrology*: 521, 182-195. Doi: doi:10.1016/j.jhydrol.2014.11.070
4. Asong, Z.E., Khaliq, N. and H.S. Wheater. 2015. Regionalization of precipitation characteristics in the Canadian Prairie Provinces using large-scale atmospheric covariates and geophysical attributes. *Stochastic Environmental Research and Risk Assessment*, **29**: 875-892, doi: 10.1007/s00477-014-0918-z.
5. Baltzer, J and Johnstone, J (2015) The 2014 NWT Fires – Developing a Research Framework. Government of the Northwest Territories publication. https://forestecologyreseach.files.wordpress.com/2015/02/workshopreport_final.pdf
6. Bernhardt, M., Schulz, K. and Pomeroy, J.W. 2015. The International Network for Alpine Research Catchment Hydrology: a new GEWEX crosscutting project. *Hydrologie und Wasserbewirtschaftung*, 59(4), 190-191.
7. Black, T.A. and Jassal, R.S. 2015. Evapotranspiration (hydrometeorology). Chapter 12. In: *Ecosystems: a Bioscience Approach* (eds. E. Johnson and Y. Martin). Cambridge University Press. Final version of chapter submitted in July 2015. (Used data from OA and OBS for examples of evapotranspiration rates).
8. Brimelow, J., K. Szeto, B. Bonsal, B. Kochtubajda, J. Hanesiak, F. Evans and R. Stewart, 2015: Hydrometeorological aspects of the 2011 Assiniboine River Basin flood. *J. Hydrometeor*. 16, 1250-1272.
9. Chang, K-H., Price, D.T., Chen, J.M., Kurz, W.A, Boisvenue, C., Hogg, E.H., Black, T.A., Gonsamo, A., Wu, C., Hember, R. 2014. Simulating impacts of water stress on woody biomass in the southern boreal region of western Canada using a dynamic vegetation model. *Agricultural and Forest Meteorology* 198–199, 142–154. Data from OA used in model validation. TAB provided input on interpretation of agreement between OA measured and modelled fluxes, and discussion. doi:10.1016/j.agrformet.2014.07.013
10. Chun, K.P., Wheater, H.S. and Barr, A.G. 2014. A multivariate comparison of the BERMS flux tower observations and Canadian Coupled Global Climate Model (CGCM3) outputs. *Journal of Hydrology,* 519 Part B: 1537-1550, doi:10.1016/j.jhydrol.2014.08.059
11. Connon, R., W. Quinton, M. Hayashi and J. Craig, 2014. The effect of permafrost thaw on rising stream flows in the lower Liard River valley, NWT, Canada. *Hydrological Processes*. pp. 4163–4178. DOI: 10.1002/hyp.10206
12. Crasto, N., Hopkinson, C., Forbes, D. L., Lesack, L., Marsh, P., Spooner, I., & van der Sanden, J. J. (2015). A LiDAR-based decision-tree classification of open water surfaces in an Arctic delta. *Remote Sensing of Environment*, 164, 90–102. doi:10.1016/j.rse.2015.04.011

13. DeBeer, C.M., Wheater, H.S., Carey, S.K. and Chun, K.P. 2015. Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a synthesis and review. *Hydrology and Earth System Sciences Discussions*, 12, 8615-8674, doi:10.5194/hessd-12-8615-2015.
14. DeBeer, C.M., Wheater, H.S., Quinton, W.L., Carey, S.K., Stewart, R.E., Mackay, M.D. and Marsh, P. 2015. The Changing Cold Regions Network: Observation, diagnosis and prediction of environmental change in the Saskatchewan and Mackenzie River Basins, Canada. *Science China: Earth Sciences,* 58(1): 46-60, doi: 10.1007/s11430-014-5001-6.
15. Dumanski, S., Pomeroy, J.W. and Westbrook, C.J. 2015. Hydrological regime changes in a Canadian Prairie basin. *Hydrological Processes*, 29(18), 3893-3904. DOI: 10.1002/hyp.10567
16. Evaristo, J., S. Jasechko, and J.J. McDonnell. 2015. Global separation of plant transpiration from groundwater and streamflow, *Nature* doi: 10.1038/nature14983.
17. Falster, DS, Duursma, RA, Ishihara, MI, Barneche, DR, Fitzjohn, RG, Varhammar, A, Aiba, M, Ando, M, Anten, N, Aspinwall, MJ, Baltzer, JL, et al. (2015) BAAD: a Biomass And Allometry Database for woody plants. *Ecology*, 96(5): 1445. doi.org/10.1890/14-1889.1
18. Gober, P. and Wheater, H.S. 2014. Socio-hydrology and the science-policy interface: A case study of the Saskatchewan River Basin. *Hydrology and Earth System Sciences,* 18: 1413-1422. doi:10.5194/hess-18-1413-2014
19. Gober, P. and Wheater, H.S. 2015. Debates-Perspectives on Socio-Hydrology: Modeling Flood Risk as a Public Policy Problem. *Water Resour.Res.,* 51, doi:10.1002/2015WR016945.
20. Harder, P., Pomeroy, J.W. and Westbrook, CJ. 2015. Hydrological resilience of a Canadian Rockies headwaters basin subject to changing climate, extreme weather and forest management. *Hydrological Processes*, 29(18), 3905-3924. DOI: 10.1002/hyp.10596
21. Hassanzadeh, E., Elshorbagy, A., Wheater, H.S. and Gober, P. 2014. Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada. *Environmental Modelling & Software*, 58: 12-26, DOI: 10.1016/j.envsoft.2014.03.015.
22. Hassanzadeh, E., Elshorbagy, A., Wheater, H.S., Gober, P. and Nazemi, A. 2015. Integrating supply uncertainties from stochastic modelling into integrated water resource management: a case study of the Saskatchewan River Basin. *Journal of Water Resources Planning and Management*, doi:10.1061/(ASCE)WR.1943-5452.0000581.
23. Hayashi, M. and Farrow, C.R. 2014. Watershed-scale response of groundwater recharge to inter-annual and inter-decadal variability in precipitation. *Hydrogeology Journal*, 22: 1825-1839. DOI: 10/1007/s10040-014-1176-3 .
24. Hood, J.L. and Hayashi, M. 2015. Characterization of snowmelt flux and groundwater storage in an alpine headwater basin. *Journal of Hydrology*, 521: 482-497. doi:10.1016/j.jhydrol.2014.12.041
25. Ireson, A. M., A. G. Barr, J. F. Johnstone, S. D. Mamet, G. van der Kamp, C. J. Whitfield, N. L. Michel, R. L. North, C. J. Westbrook, C. DeBeer, K. P. Chun, A. Nazemi, and J. Sagin. 2015. The changing water cycle: the Boreal Plains ecozone of Western Canada. WIREs Water: doi 10.1002/wat2.1098.
26. Jasechko, S., Birks, S. J., Gleeson, T., Wada, Y., Fawcett, P. J., Sharp, Z. D., McDonnell, J. J., Welker, J. M. (2014), The pronounced seasonality of global groundwater recharge. *Water Resources Research.* 50: 8845-8867. DOI: 10.1002/2014WR015809
27. Khaliq, M.N., Sushama, L., Monette, A. and Wheater, H.S. 2015. Seasonal and extreme precipitation characteristics for the watersheds of the Canadian Prairie Provinces as simulated by the NARCCAP multi-RCM ensemble. *Climate Dynamics*, 44, 255-277, doi: 10.1007/s00382-014-2235-0.
28. Kinar N.J. and Pomeroy J.W. 2015. Measurement of the Physical Properties of the Snowpack. *Reviews of Geophysics*: 53, 481-544.
29. Kinar N.J. and Pomeroy J.W. 2015. SAS2: the system for acoustic sensing of snow. *Hydrological Processes*. DOI: 10.1002/hyp.10535.
30. Krogh S.A., Pomeroy J.W., and McPhee J. 2015. Physically Based Mountain Hydrological Modeling Using Reanalysis Data in Patagonia. *Journal of Hydrometeorology*: 16, 172-193. doi: http://dx.doi.org/10.1175/JHM-D-13-0178.1
31. Lesack, L., Marsh, P., Hicks, F., & Forbes, D. (2014). Local spring warming drives earlier river-ic breakup in a large arctic delta. *Geophysical Research Letters*, 7. doi:10.1002/213GL058761.
32. Lessels, J. S., Tetzlaff, D., Carey, S. K., Smith, P., and Soulsby, C. (2015) A coupled hydrology–biogeochemistry model to simulate dissolved organic carbon exports from a permafrost-influenced catchment. *Hydrol. Process.,* doi: 10.1002/hyp.10566.

33. Lucia Scaff, D. Yang, Yanping Li, E. Mekis, 2015: Inconsistency in precipitation measurements across Alaska and Yukon border, *The Cryosphere Discuss*., **9**, 3709-3739, doi:10.5194/tcd-9-3709-2015. *Journal Impact Factor = 5.52*
34. Mamet, S. D., K. P. Chun, J. M. Metsaranta, A. G. Barr, and J. F. Johnstone. 2015. Tree rings provide early warning signals of jack pine mortality across a moisture gradient in the southern boreal forest. *Environmental Research Letters* http://dx.doi.org/10.1088/1748-9326/10/8/084021
35. Marshall, KE and Baltzer, JL (2015) Decreased competitive interactions drive a reverse species richness latitudinal gradient in subarctic forests. *Ecology*, 96: 461-470.
36. Masud, M.B., Khaliq, M.N. and Wheater, H.S. 2015. Analysis of meteorological droughts for the Saskatchewan River Basin using univariate and bivariate approaches. *Journal of Hydrology*, **522**: 452-466, doi:10.1016/j.jhydrol.2014.12.058.
37. Mekonnen, M.A., Wheater, H.S., Ireson, A.M., Spence, C., Davison, B., and Pietroniro, A. 2014. Towards an improved land surface scheme for prairie landscapes. *Journal of Hydrology,* **511**: 105-116, doi: http://dx.doi.org/10.1016/j.jhydrol.2014.01.020.
38. Mohammed, A., R. Schincariol, R. Nagare and W. Quinton. Reproducing Field-Scale Active Layer Thaw in the Lab. Vadose Zone Journal. doi:10.2136/vzj 20 14.01.0008
39. Musselman K.N., Pomeroy J.W., and Link T.E. 2015. Variability in shortwave irradiance caused by forest gaps: Measurement, modelling, and implications for snow energetics. *Agriculture and Forest Meteorology*: 207, 69-82. doi:10.1016/j.agrformet.2015.03.014
40. Musselman, K.N., Pomeroy, J.W., Essery, R.L.H. and Leroux, N. 2015. Impact of windflow calculations on simulations of alpine snow accumulation, redistribution and ablation. *Hydrological Processes*, 29(18), 3983-3999. DOI: 10.1002/hyp.10595
41. Nachshon, U., Ireson, A., van der Kamp, G., Davies, S.R. and Wheater, H.S. 2014. Impacts of climate variability on wetland salinization in the North American Prairies. *Hydrology and Earth System Sciences*, **18**: 1251-1263, doi:10.5194/hess-18-1251-2014.
42. Nazemi, A. and Wheater, H.S. 2014. Assessing the Vulnerability of Water Supply to Changing Streamflow Conditions. *Eos – Transactions of the American Geophysical Union,* **95**(32): 288, doi: 10.1002/2014EO320007.
43. Nazemi, A. and Wheater, H.S. 2014. How can the uncertainty in the natural inflow regime propagate into the assessment of water resource systems? *Advances in Water Resources,* **63**: 131-142, http://dx.doi.org/10.1016/j.advwatres.2013.11.009.
44. Nazemi, A. and Wheater, H.S. 2015. On inclusion of water resource management in Earth System models – Part 1: Problem definition and representation on water demand. *Hydrology and Earth System Sciences,* **19**: 33-61, doi:10.5194/hess-19-33-2015.
45. Nazemi, A. and Wheater, H.S. 2015. On inclusion of water resource management in Earth System models – Part 2: Representation of water supply and allocation and opportunities for improved modeling. *Hydrology and Earth System Sciences*, **19**: 63-90, doi:10.5193/hess-19-63-2015.
46. Papale, D., T.A. Black, N. Carvalhais, A. Cescatti, J. Chen, M. Jung, G. Kiely, G. Lasslop, M. Mahecha, H. Margolis, L. Merbold, L. Montagnani, E. Moors, J. E. Olesen, M. Reichstein, G. Tramontana, E. van Gorsel, G. Wohlfahrt, B. Ráduly. 2015. Effect of spatial sampling from European flux-towers for estimating carbon and water fluxes with artificial neural network. *Journal of Geophysical Research – Biogeosciences* (accepted Sept 11 2015, in press). Used data from OA and OBS. TAB provided data interpretation and editorial input.
47. Patankar, R., W. Quinton, M. Hayashi, J. Baltzer, 2015. Sap flow responses to seasonal thaw and permafrost degradation in a subarctic boreal peatland, Trees, in press. Trees: Volume 29, Issue 1, 129-142. DOI 10.1007/s00468-014-1097-8.
48. Pomeroy J.W., Bernhardt M. and Marks D. 2015. Water resources: Research network to track alpine water. *Nature,* 521, 32-32. doi:10.1038/521032c
49. Pomeroy, J., R.E. Stewart and P.H. Whitfield, 2015: The 2013 flood event in the Bow and Oldman River basins: causes, assessment, and damages. Can. Water Res. J. (Accepted)
50. Rasavi, S., Elshorbagy, A., Wheater, H. and Sauchyn, D. 2015. Toward Understanding Non-stationarity in Climate and Hydrology through Tree-ring Proxy Records. *Water Resources Research,* **51:** doi:10.1002/2014WR015696.
51. Rasouli, K., Pomeroy, J.W. and Marks, D.G. 2015. Snowpack sensitivity to perturbed climate in a cool mid-latitude mountain catchment. *Hydrological Processes*, 29(18), 2925-2940.
52. Sagin, J., Sizo, A., Wheater, H.S., Jardine, T.D. and Lindenschmidt, K.-E. 2015. A water coverage extraction approach to track inundation in the Saskatchewan River Delta, Canada. *International Journal of Remote Sensing*, **36(3):** 764-781.

53. Shi, X., Marsh, P., & Yang, D. (2015). Warming spring air temperatures, but delayed spring streamflow in an Arctic headwater basin. Environmental Research Letters, 10(6), 064003. doi:10.1088/1748-9326/10/6/064003
54. Shook K., Pomeroy J.W., and van der Kamp G. 2015. The transformation of frequency distributions of winter precipitation to spring streamflow probabilities in cold regions; case studies from the Canadian Prairies. *Journal of Hydrology*: 521, 395-409. doi:10.1016/j.jhydrol.2014.12.014
55. Strickert, G.E., Chun, K.P., Bradford, L.E., Clark, D.A., Gober, P., Reed. M.G., Payton, D. (2015). Competing viewpoints about water security in a transboundary watershed. *Water Policy* doi:10.2166/wp.2015.195.
56. Walker, X., M. C. Mack and J. F. Johnstone. 2015. Stable carbon isotope analysis reveals widespread drought stress in boreal black spruce forests. Global Change Biology 21: 3102-3113. DOI: 10.1111/gcb.12893
57. Wang, S., Pan, M., Mu, Q., Shi, X., Mao, J., Brümmer, C., Jassal, R.S., Krishnan, P., Li, J., Black, T.A. 2015. Comparing evapotranspiration from eddy covariance measurements, water budgets, remote sensing, and land surface models over Canada. *Journal of Hydrometeorology* 16: 1540-1560 DOI: 10.1175/JHM-D-14-0189.1. (accepted March 2, 2015).
58. Wheater, H.S. and Gober, P. 2015. Water security and the science agenda. *Water Resour. Res*., 51, 5406–5424, doi:10.1002/2015WR016892.
59. Williams, T.J., Pomeroy, J.W., Janowicz, J.R., Carey, S.K., Rasouli, K. and Quinton, W.L. 2015. A radiative-conductive-convective approach to calculate thaw season ground surface temperature for modelling frost table dynamics. *Hydrological Processes,* 29(18), 3954-3965, doi: 10.1002/hyp.10573.
60. Yang, D., Marsh, P., & Ge, S. (2014). Heat Flux Calculations for Mackenzie and Yukon Rivers. Polar Science. doi:10.1016/j.polar.2014.05.001
61. Yang, D., Shi, X., & Marsh, P. (2014). Variability and extreme of Mackenzie River daily discharge during 1973–2011. Quaternary International, 1–10. doi:10.1016/j.quaint.2014.09.023
62. Yusa, A., P. Berry, J. Cheng, N. Ogden, B. Bonsal, R. Stewart and R. Waldick, 2015: Climate change, drought and human health in Canada. Intl. J. Environmental Research and Public Health, 12, 8359-8412.