Changing Cold Regions Network Modelling Strategy

Report to Board of Directors October 2015

1. Scope and Context

This report is produced at the request of CCRN's Board of Directors, in response to 2014 advice from the International Advisory Panel that the scope, objectives and deliverables of the modelling components of CCRN should be more clearly defined and articulated.

Modelling is central to delivering the science objectives of CCRN and in particular is a core activity in Themes B, C and D, as well as contributing in various ways to E. The modelling activities are strongly connected across the Themes. Modelling in B leads into C, which leads into D, which feeds back to B, and each have modelling contributions to E.

Theme B focusses on Improved Understanding and Diagnosis of Local-scale Change, building on the availability of high quality data from the CCRN WECC observatories. Aims are to: 1) develop new fundamental and integrative knowledge of critical Earth system processes; 2) incorporate these processes into a suite of process-based integrative models for the diagnosis and prediction of change at the local level; and 3) use these integrative models to better understand the interactions among climatic, hydrological, ecological and cryospheric drivers, processes and feedbacks, and thresholds leading to system changes. Hence sub-theme B2 focusses on development of improved local-scale models and B3 applies the models to diagnose past changes at the local scale.

Theme C, Upscaling for Improved Atmospheric Modelling and River Basin-scale Prediction, aims to develop and test improved models for large-scale application, i.e. land surface schemes within weather forecasting and climate models, and 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 of this theme is: How can our *large-scale* predictive models be improved to better account for the changing Earth system and its atmospheric feedbacks? C1 addresses algorithm development for weather and large-scale hydrological models, C2 focusses on large basin-scale application and testing of weather, climate and large-scale hydrological models, including verification and assimilation of ground-based observations and remotely sensed data.

Theme D concerns Analysis and Prediction of Regional and Large-Scale Variability and Change. It addresses the 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? D1 considers controls on large/regional-scale climate, ecosystems and hydrology and includes both the assessment of atmospheric circulation patterns and the use of large basin-scale models to diagnose the causes of changes in river flows and evaluate land-atmosphere feedbacks. D2 addresses changing climate, changing land surface systems and large-scale hydrology. It includes assessment of the ability of climate models to capture regional climate features, preliminary off-line analysis of sensitivity of land-atmosphere feedbacks using current Environment Canada (EC) models MESH/CLASS, development of MESH to include water management and land management, and revised sensitivity analysis of feedbacks using improved MESH/CLASS (we noted in the Inception Report that we expect to have the capability to make some coupled runs, but the mechanisms and modelling systems were unclear). D3 concerns assessment of atmospheric changes, including heavy precipitation, from climate model projections. D4 will use climate projections to assess impacts, for basin-scale river flows and selected ecosystems, including for WECC observatory sites. A specific deliverable is to look at tipping points.

Theme E concerns Outreach and Engagement; CCRN modelling work has not been formally defined, but has a range of contributions to make. It is important to link CCRN research with practitioner needs. This includes working with partners such as Environment Canada to improve their ability to model weather, climate and large-scale hydrology, and working with Provincial and Territorial governments to provide training in the use of models such as CRHM. However models are being used more widely as tools to build public awareness of the challenges of water management – simple models can be used in 'games', more realistic models can be used to evaluate policy options for water futures.

2. Theme B

B 2.1 and 2.2 - development and testing of improved local-scale models.

Since the development of our inception report we have identified clear goals for Theme B and gone a long way to achieve these. These goals include a) a set of prioritized process improvements, b) model development at selected sites, c) comparative model application and evaluation across sites.

Much of the work in Theme B has focused on the development and application of the Cold Regions Hydrological Modelling Platform (CRHM), a modular modelling system for cold regions hydrology developed by Pomeroy and others at the University of Saskatchewan with CCRN colleagues at Environment Canada (Pietroniro), Natural Resources Canada (Demuth), USDA-ARS (Marks), Yukon Environment (Janowicz), Univ. of Calgary (Hayashi), Edinburgh Univ. (Essery), Wilfred Laurier University (Quinton) and McMaster University (Carey). Process improvements to date within CRHM include: glacier hydrology; frozen ground dynamics; representation of networks of depressional storage; groundwater dynamics and surface interactions; surface runoff over organic terrain and through snowpacks; and snow vegetation interaction in discontinuous canopies. Detailed comparative evaluation of alternative snow model components is currently being finalized. CRHM is being applied at all WECC sites for comparative analysis of model performance and the interrogation of observed change. Additional detailed modelling includes application of a new release of the USGS 3D SUTRA (saturated-unsaturated transport) groundwater model to include freeze-thaw thermodynamics, developed by McKenzie (McGill). SUTRA has been applied to the Scotty Creek WECC to investigate long term permafrost dynamics. In addition a wholly new physics-based conceptualization of freeze-thaw processes in unsaturated soils is under development (by Ireson, UofS) to meet some deficiencies in current three-phase modelling.

B3- Diagnosis of change

Three elements were defined – B3.1 Methodology and toolkit development, B3.2 Application of existing models to diagnose change, B3.3 Application of improved models to diagnose change.

B3.1. The original plan for B3.1 was to develop a set of tools for sensitivity and uncertainty analysis that could be used to explore model and parameter non-stationarity. Progress was made and a toolkit developed, since applied to a 1D lake model developed by Mackay (EC) within the CLASS framework. The post-doc who developed these left prematurely due to family reasons, but the recent appointment of Dr Saman Razavi to a Faculty position at UofS has provided a continuity of expertise in this area and some additional new tools, in particular for meta-modelling, optimisation for large models and sensitivity analysis. However, preliminary results of CRHM model application to the diagnosis of change have demonstrated that response to change can be subtle. For example significant changes to sub-basin scale processes can occur, with compensating effects leading to little change in observed flows at small catchment-scale. Hence the emphasis on diagnosis has moved to process-based modelling and exploration of component process sensitivities.

B3.2 and B3.3, application of existing and improved models for detection of change have merged - improved algorithms are being used as they become available. 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. This work should be substantially complete by the end of 2015.

3. Theme C

C1.1 Testing of existing land surface schemes using WECC data/ C1.2 development and testing of improved algorithms at WECC scale.

A major focus of Theme C is joint work with EC to enhance the capability of the CLASS/MESH modelling system and a large joint modelling group has been established with weekly/monthly meetings. In addition we are working with the UK JULES and the US WRF-CLM land surface models to evaluate the relative performance advantages of different models and algorithms. Significant progress has been made with C1.1. Bartlett (EC) completed single year baseline CLASS runs for representative WECC sites, identified some weaknesses, and has made some model improvements. Work has been ongoing at individual WECC sites using EC's CLASS/MESH, the UK JULES model, and the US WRF-CLM. 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 sites and will be extended to the other WECC sites in due course. The CTEM model is being evaluated at selected WECC sites and discussions are ongoing towards developing this as a Canadian community model.

Under C1.2, development and testing of improved algorithms at WECC scale, analysis of large basin scale performance led to the identification of priority areas for development. New or improved algorithms are being developed for: Cold region lake modelling; Cold region wetlands; Snow process representation; Cold region vegetation processes (including snow-canopy interactions); Frozen soils; Prairie hydrology, including variable hydrological connectivity; Water management, including reservoirs and irrigation. Key areas of priority have been defined for sub-grid process representation, which is being addressed with respect to a) Mountain discretization: issues of connectivity between grids (e.g. blowing snow) and discretization (slope/aspect, different forcing for elevation bands); b) Cold region wetlands sub-grid representation, c) Spatial heterogeneity of soil moisture , d) Scale-dependence of process representation – scale dependence of parameters, Grouped Response Units versus spatially-explicit location. Two major review papers were published on the representation of water management in large scale models and as a result this issue has been adopted by GEWEX as a cross-cut theme for an international collaborative project, with the CCRN PI as co-lead.

C2.1 development of MESH framework for major basins

10km CLASS/MESH frameworks have been developed for the Saskatchewan and Mackenzie basins, sensitivity to driving inputs has been explored and analysis of sensitivity to grid resolution is underway for the SaskRB. Preliminary results allowed prioritization of research issues to be addressed, which include uncertainty in driving variables, representation of permafrost, representation of lakes/wetlands, and the representation of water management in large scale models. Work on each of these issues is underway. An important development since the Inception Report is the result of collaboration with the US National Centre for Atmospheric Research (NCAR). NCAR was planning high resolution (4km) runs of the WRF model for most of N 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.

C2.2 Development and testing of assimilation methods

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.

C2.3 testing of improved LSSs at large basin-scale

This work is planned for 2016-2017. C1.2 has delivered some new products already, notable an improved prairie hydrology scheme for CLASS. There is time pressure to complete other planned developments, and progress is being monitored. In any event a cut off has been defined (Fall 2016) to allow C2.3 to proceed on schedule.

4. Theme D

Theme D concerns Analysis and Prediction of Regional and Large-Scale Variability and Change, and combines analysis of climate controls with various modelling activities. At the time of the Inception report, the modelling was not well specified, mainly due to uncertainty in the availability of EC models and products, in particular with respect to coupled modelling of land-atmosphere interactions. However, following discussions at the September 2015 modelling workshop and agreed collaboration with our sister CCAR project, the Canadian Network for Regional Climate and Weather Processes (CNRCWP), clear plans have been developed. CNRCWP is primarily working with CanRCM5, based on the CLASS land surface scheme. Collaboration with

CNRCWP provides a platform for incorporating CLASS improvements in the RCM and for access to coupled CLASS simulations. In addition, the collaboration with NCAR through Li provides a capability to run WRF in coupled mode.

D1 addresses Large/regional scale land surface and climate controls: D1.1 addresses large-scale controls over recent past climate, D1.2 determination of past changes in all aspects of precipitation, D1.3 diagnosis of large-scale change and feedbacks. D1.3 will use the large basin-scale models developed in C to diagnose causal effects of the observed changes in river flows, and to investigate through off-line simulations and sensitivity analysis the feedbacks that occur on the regional scale between the many surface and atmospheric variables. Driving data are being provided by CNRCWP.

D2 Changing climate, changing land surface systems, and large-scale hydrology
D2.1 is an assessment of whether large scale/regional circulations are captured in existing models. CanRCM5 and high resolution WRF runs will now be available to support these analyses, in addition to CMIP5 models.
D2.2 MESH/GEM sensitivity/feedback simulations using existing CLASS will use *existing* CLASS land surface schemes in a preliminary off-line analysis of the sensitivity of land-atmosphere feedbacks to cryospheric, hydrologic and terrestrial ecosystem change.
D2.3 – MESH Development to Include Large-Scale Controls will develop and test new MESH algorithms to represent a) water management controls on river flows, including reservoir and irrigation management, and b) land management change, for the Saskatchewan, Peace-Athabasca and Mackenzie River basins.
D2.4 – GEM sensitivity/feedback simulations using improved CLASS will undertake regional scale simulations including off-line and coupled simulations using improved CLASS/MESH and WRF schemes to analyze the sensitivity of land-atmosphere feedbacks to cryospheric, hydrologic and terrestrial ecosystem changes and land/water management.

D3 Atmospheric circulations, temperature and precipitation
No modelling required other than access to simulation results as specified above.

D4 Water resources, cryosphere and ecosystems

D4.1 – Climate Scenario Selection for Impacts Assessment
Selection of future scenarios will be harmonized with CNRCWP for CanRCM5 runs; pseudo-warning results will be available for 4km WRF simulations.
D4.2 – Determination of Impacts on WECC Observatories
Scenarios developed in 4.1 will be applied to the WECC observatory and small/medium sized basins using fine- and meso-scale models and assess potential impacts on cryospheric, ecological

and hydrological systems. Initial tests using NARCCAP simulations to drive CRHM at Wolf Creek, Yukon suggest significant downscaling uncertainties to using these products for impact assessments in northern mountain environments. A NCAR physically based downscaling method is being assessed in Canadian mountain environments to determine its suitability for reducing this uncertainty.

D4.3 – Determination of Potential Impacts on Major River Systems

Scenarios will be applied to the MESH models of the Saskatchewan, Peace-Athabasca and Mackenzie River basins to explore future river flow responses, including preliminary assessment of impacts of management options.

D4.4 – Assessment of Whether Tipping Points will Occur

Results of D4.2 and D4.3 will be synthesized in conjunction with expert elicitation to undertake assessment of potential for tipping points to be reached in the next 10-30 years.