Sensitivity of Dempster Highway Hydrological Response to Climate Warming

Interim Report

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March 2015

Executive Summary

Observations confirm that the climate of northern regions has become warmer and wetter over the last three decades resulting in degrading permafrost and changing vegetation. Studies have shown that climate change has already produced alterations to the hydrological cycle and hydrologic response with greater flooding and a general negative impact on transportation and community infrastructure. The proposed project components include a detailed sensitivity assessment of hydrological response to climate warming and associated permafrost thawing using the Cold Regions Hydrological Model (CRHM) along the Dempster Highway corridor. CRHM is a numerical modelling system created from recent process based research, including state of the art work carried out in Yukon's Wolf Creek Research Basin. The model contains a full suite of cold regions hydrological modules including, snow, frozen soils, permafrost thaw and runoff and is capable of assessing not only climate change but vegetation change and permafrost thaw impacts. CRHM has already been widely used for climate and land-use change studies in Yukon, NWT, Canadian Rockies, Prairies, Tibetan Plateau, Patagonia, Pyrenees and the Alps. Using a range of climate change scenarios, assessments will be carried out within the eight ecoregions which the Dempster Highway traverses. Since representative Dempster Highway climatological data is sparse, it will be necessary to establish one or two meteorological stations to supplement existing data. In addition the project will take advantage of weather reanalysis and climate model output datasets made available through participation in the Changing Cold Regions Network (CCRN). Study objectives include developing projected changes to magnitude, timing and interaction of water balance components (precipitation, evapotranspiration, runoff and storage). Projected changes to hydrological response (extreme and drought events, annual and seasonal flows) will be summarized and flood frequency curves based on annual peak flows will be developed for Dempster Highway stream crossings. These products will allow for the development of adaptation strategies and options which may include infrastructure design modification.

The multi-year study commenced November 1, 2013 and will end March 31, 2016. This report is the interim report for the 2014-15 fiscal year. Activities planned to be carried out during this period are summarized below.

<u>April 2014 – March 2015</u>

- Establish two meteorological stations within the Dempster Highway corridor, and develop climate change scenarios along the Dempster Highway

- Set up / calibrate CRHM to carry out focused experiments
- Drafting, writing and submission of interim report.

INTRODUCTION

The proposed project components include a detailed sensitivity assessment of hydrological response to climate warming and associated permafrost thawing using the Cold Regions Hydrological Model (CRHM) along the Dempster Highway corridor. CRHM is a numerical modelling system created from recent process based research, including state of the art work carried out in Yukon's Wolf Creek Research Basin. The model contains a full suite of cold regions hydrological modules including, snow, frozen soils, permafrost thaw and runoff and is capable of assessing not only climate change but vegetation change and permafrost thaw impacts. CRHM has already been widely used for climate and land-use change studies in Yukon, NWT, Canadian Rockies, Prairies, Tibetan Plateau, Patagonia, Pyrenees and the Alps. Using a range of climate change scenarios, assessments will be carried out within the ten ecoregions (Klondike Plateau, Yukon Plateau – North, Mackenzie Mountains, North Ogilvie Mountains, Eagle Plains, British-Richardson Mountains , Fort McPherson Plain, Peel River Plateau, Taiga Plains – Northern Plains, and Tundra Plains – Lowlands) which the Dempster Highway traverses between the Dempster Corner and Inuvik. Since representative Dempster Highway climatological data is sparse, it will be necessary to establish two meteorological stations to supplement existing data. In addition the project will take advantage of weather reanalysis and climate model output datasets made available through participation in the Changing Cold Regions Network (CCRN). Study objectives include developing projected changes to magnitude, timing and interaction of water balance components (precipitation, evapotranspiration, runoff and storage). Projected changes to hydrological response (extreme and drought events, annual and seasonal flows) will be summarized and flood frequency curves based on annual peak flows will be developed for Dempster Highway stream crossings. These products will allow for the development of adaptation strategies and options which may include infrastructure design modification.

ACTIVITY 1

a) Establish two meteorological stations within the Dempster Highway corridor

Two detailed weather stations have been installed in areas where not sufficient meteorological data are available. To install these stations, two field campaigns were carried out. The first campaign was in June, 2014, during which the two weather stations were installed: Windy Pass and Rio Roca station. Figure 1 shows the location of the available meteorological and hydrometric stations, snow survey sites and the two new weather stations.

These stations include the instrumentation detailed in Table . The characteristics of their locations are presented in Table 2, and photographs in Photograph 1and Photograph .

Table 1: New weather stations instrumentation

Measurement*	Manufacturer	Model	Quantity	Sensor Height [m]	
				Windy Pass	Rio Roca
Precipitation	Ott	Pluvio2	1	2.0	2.0
Air Temperature and Relative Humidity	Rotronic	HC-S3-XT	1	2.1	2.9
Outgoing and Incoming Shortwave Radiation	Apogee	SP-230	1 (each)	2.0 and 2.4, respectively	4.1 and 4.3, respectively
Wind Speed and Direction	RM Young	05108-10-L	1	4.3	5.0
Snow Depth	Campbell	CSI SR50A	1	2.2	2.5
Soil Heat Flux	Hukseflux	HFP01-L	1	-0.03	-0.03
Soil Moisture and Temperature	Campbell	CS655-L	4	-0.1, -0.23, -0.51, -0.91	-0.10, -0.30, -0.50, -0.76
Ground Surface Temperature	Omega	Type E Thermocouple	1	-0.01	-0.01
Snow Temperature	Omega	Type R Thermocouple	2	0.25, 0.40	0.10, 0.40

* The data logger is the CR1000 from Campbell

Table 2: New Weather Stations Location

Station	Geographic Coordinates	Elevation [masl]	Slope	Vegetation
Windy Pass	65° 4’ 0.8’’ N, 138° 14’ 46.1’’ W	1030	5°	Shrubs, moss and scattered spruce
Rio Roca	66° 50’ 1.0’’ N, 136° 20’ 0.0’’ W	660	4°	Grasses, moss, lichen and

				scattered spruce and shrub

The measurements frequency is 30 minutes except for the soil moisture and temperature, which will be every 6 hours.

During the second field campaign, in September, 2014, the weather stations were revised and fixed as necessary. Two soil pits were dug (one per station) to install the soil moisture and temperature sensors as can be seen in Photograph and Photograph . Qualitative analysis of the soil profiles from each soil pit is presented in Table 3. Also, snow temperature thermocouples at two heights were installed in each station.

These two new weather stations are expected to diminish the lack of detailed weather measurements, in particular the lack of precipitation records.

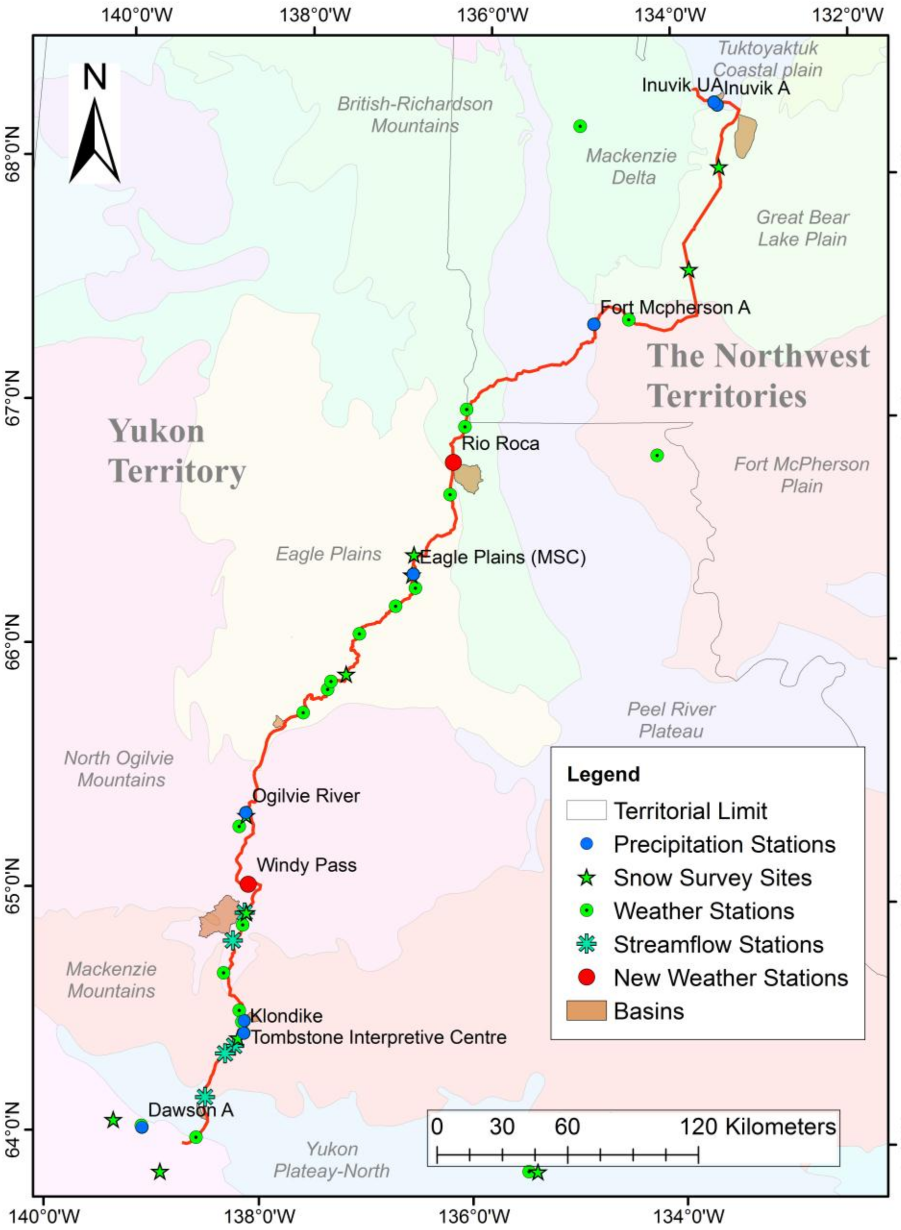

Figure 1: Weather and hydrometric stations along the Dempster Highway. Some stations with only temperature and wind speed measurements are presented as weather stations for the purpose of this figure.

Photograph 1: Windy Pass Station

Photograph 2: Rio Roca Station

Table 3: Soil profiles of each soil pit

Windy Pass		Rio Roca	
Depth [m]	**Description**	**Depth [cm]**	**Description**
0 – 0.23	Organic Layer (with roots)	0 – 0.18	Organic Layer (with roots)
0.23 – 0.38	Black Soil	0.18 – 0.81	Black Soil (permafrost was likely reached)
0.38 – 1.07	Grey Mineral Soil (permafrost not reached)	-	-

b) Develop climate change scenarios along the Dempster Highway

To generate potential future climate scenarios, data from the NARCCAP project (Mearns et al., 2009) will be used. The NARCCAP project provides daily high resolution (50 km) climate scenarios for North America (United Stated, Canada and northern Mexico) by using Regional Climate Models (RCMs) to dynamically downscale Global Climate Model (GCM) products. GCM products used in the NARCCAP project have been forced with the SRES A2 emission scenario (c.f. section **Error! Reference source not found.**), which is considered as a relatively high emission scenario. The driving GCMs and the RCMs used in NARCCAP are summarized in **Table 4**.

Table 4: Models combinations used in the NARCCAP project.

RCM	**NCEP**	**Driving GCM**			
		CCSM	**CGCM3**	**GFDL**	**HadCM3**
CRCM	X	X	X		
ECP2	X			X	X
HRM3	X			X	X
MM5I	X	X			X
RCM3	X		X	X	
WRFG	X	X	X		
ECPC	X				
WRFP	X				

Source: Modified from https://www.earthsystemgrid.org/project/NARCCAP.html

The historical period covered by the NCEP reanalysis is 1980 to 2004 (25 years), from 1971 to 2000 (30 years) for the GCM's historical period, and from 2041 to 2070 (30 years) for GCM's projections.

Although the data available from the NARCCAP project can be referred as high-resolution for regional studies, because of the local scope of this research (up to hundreds of kilometers for the largest basin) a downscaling approach is needed. Details of the downscaling approach proposed for this study are given in the next section.

Statistical Downscaling

A statistical downscaling will be applied to the daily and 50-km data from the NARCCAP project to obtain hourly and single point time series. Precipitation is the most important input to the hydrological cycle, and also the most difficult to properly downscale due to its great temporal variability. In this study, special attention is paid to the downscaling of precipitation data, whereas the other weather variable, such as temperature, relative humidity and wind speed, are downscaled separately but consistently with precipitation time series.

Precipitation

The approach to downscale precipitation follows what is presented by Sunyer et al. (2012) and Burton et al. (2010). First, the Change Factor method (CF) is used. The CF method assumes that GCM data do not realistically represent the absolute magnitude of future precipitation (or any other variable), but it better represents the changes in precipitation between the baseline (present period) and the future. Given this assumption, the CF approach can be also used to estimate changes in the statistical properties of precipitation, as is shown in Equation 1.

$$CF_i = \frac{St_i^{RCMfut}}{St_i^{RCMbas}};\ St_i^{Fut} = St_i^{Obs} * CF_i \qquad \text{Equation 1}$$

Where CF$_i$ is the Change Factor of the “i” calendar month, St_i^{RCMfut} is the statistical property associated with the RCM’s precipitation (in this case, this is the data from NARCCAP) for the future scenario and the month “i”, St_i^{RCMbas} is the statistical property associated with the RCM’s precipitation for the baseline and the month “i”, St_i^{Obs} is the observed statistical property for the month “i”, and St_i^{Fut} is the corrected statistical property for the future scenario.

In this study, five moments or statistical properties will be used to characterize the precipitation regime; these are the mean, standard deviation, skewness and changes in the length of wet and dry spells. The use of high order moments have shown to provide a better fit on extreme events (Cowpertwait, 1998).

The second step of the downscaling is the generation of precipitation using the previously calculated statistical properties of the precipitation. For this aim, the weather generator Neyman-Scott Rectangular Pulse (NSRP; Cowpertwait et al., 1996) will be used. The NSRP model simulates precipitation in a four steps process according to Burton et al. (2008):

a) Storms origins occur as a uniform Poisson process with the occurrence rate represented by a λ [1/hr] parameter;

b) Each storm origin generates a Poisson random number, C with parameter ν [], of rain cells that each follows the storm origin after a time interval that is independent and exponentially distributed with parameter β [1/hr];

c) Each raincell produces a uniform rainfall rate throughout its lifetime. The duration and intensity, X, if each raincell are independent and are exponentially distributed with parameter η [1/hr] and ξ [hr/mm], respectively;

d) The rainfall intensity is equal to the sum of the intensities of all the active cells at the instant in time.

A schematic representation of these four steps is presented in . The five parameters (λ, ν, β, η and ξ) are calibrated separately for each calendar month using hourly precipitation, in order to obtain the same statistical properties of the precipitation simulated by the corrected NARCCAP data.

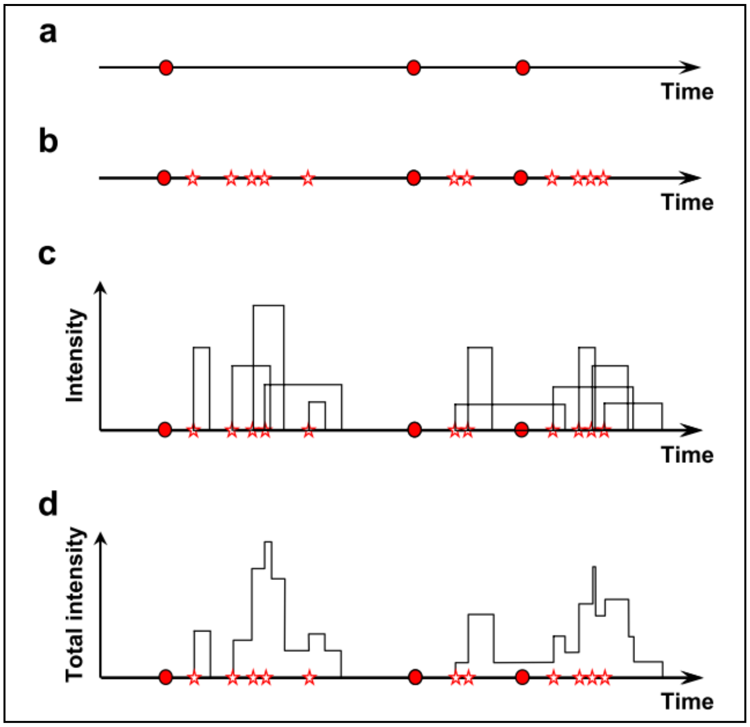

Figure 2: NSRP model representation. Taken from Burton et al. (2008)

Other Meteorological Variables

Once the precipitation series are generated (i.e. the wet or dry state of each day is determined), the other variables: mean temperature, temperature range, vapour pressure and wind speed are generated using the autoregressive model presented by Kilsby et al. (2007). This procedure was developed for daily variables; however, here it will be adapted to generate hourly time series.

For the mean temperature and the temperature range, the four transitions states: current day dry and previous day dry (DD), current day wet and previous day wet (WW), current day wet and previous day dry (DW) and current day dry and previous day wet (WD), are associated with four equations, with associated regression and correlation coefficients, as shown in Equation 2 to Equation .

DD transition:

$$T_i = a_1 T_{i-1} + b_1 + e \qquad \text{Equation 2}$$

$$R_i = a_2 R_{i-1} + b_2 + e \qquad \text{Equation 3}$$

WW transition:

$$T_i = a_3 T_{i-1} + b_3 + e \qquad \text{Equation 4}$$

$$R_i = a_4 R_{i-1} + b_4 + e \qquad \text{Equation 5}$$

DW transition:

$$T_i = a_5 T_{i-1} + a_6 P_i + b_5 + e$$ Equation 6

$$R_i = a_7 R_{i-1} + a_8 P_i + b_6 + e$$ Equation 7

WD transition:

$$T_i = a_9 T_{i-1} + a_{10} P_i + b_7 + e$$ Equation 8

$$R_i = a_{11} R_{i-1} + a_{12} P_i + b_8 + e$$ Equation 9

T_i, R_i and P_i are the mean temperature, temperature range and mean daily precipitation, respectively, for the day “i”. The regression coefficients (a_1 to a_{12} and b_1 to b_8) are determined by regression analysis using observed data, and e’s are independent standard normal (Gaussian) variables.

The rest of the variable are generates using the expression presented in Equation 1.

$$X_{i,j} = c_j + d_j P_i + e_j T_i + f_j R_i + g_j X_{i-1,j} + e$$ Equation 1

Where j=1, 2 correspond to vapour pressure and wind speed, and coefficients c_j, d_j, e_j, f_j and g_j are determined by correlations with observed data. Thirty years is a standard period to calibrate all the regression coefficients. This autoregressive procedure ensures that generated time series are robust between variables.

Preliminary climate change scenarios for air temperature and precipitation have been developed; however, further work is required to refine these.

ACTIVITY 2

Set up / calibrate CRHM to carry out focused experiments

The hydrological model selected for the simulations is the Cold Regions Hydrological Model (CRHM; Pomeroy et al., 2007). This model is preferred among other models because it has a set of modules that represent hydrological processes suitable for cold regions environments, including key processes of the arctic and subarctic regions, such as blowing snow transport and sublimation and canopy interception of snow and radiation.

The basic spatial units or control volumes, in which CRHM performs the energy and mass balances are called Hydrological Response Units (HRU), which are defined as spatial areas with similar biophysical, pedologic, geomorphic, hydrometeorological and hydraulic properties, which may not be spatially join. In this study, HRU’s will be defined based on landcover characteristics (e.g. forest, river and peatland), elevation and aspect, all features that have been acknowledged to be critical on cold regions (Carey and Woo, 2001; Pohl and Marsh, 2006;

Pomeroy et al., 2006, 2004) and have been previously used in other studies (Krogh et al., 2015; Rasouli et al., 2014). The number of HRUs will be the minimum possible (parsimonious model) without compromising relevant heterogeneities characteristics of each basin, as fully aggregated models cannot successfully represent cold regions hydrology (Dornes et al., 2008). CRHM will be run in a hourly time step to capture critical sub daily variations, such as melting and refreezing of snow (Pohl and Marsh, 2006) and flash flood that can occurs in a couple of hours. The period of simulation will be of 30 years, in order to capture a diverse quantity of hydrological conditions and to estimate long term statistical trends. The model will simulate most key hydrological processes of the arctic and subarctic basins. These processes and the proposed models to their simulation are presented in Table 5, and a flowchart with their interactions within CRHM is presented in Figure 3.

Although CRHM incorporates most cold regions physical processes, there are other small-scale physical processes that occur in the Arctic region, which have shown to play a significant role. Such is the case of shrubs, which may not only affect blowing snow accumulation by increasing surface roughness (Essery and Pomeroy, 2004), but also affect the surface radiation balances between the atmosphere, subcanopy and ground surface, by rapid changes in surface albedo and the ground fraction covered by shrubs, which are associated with bending and/or burial during winter and their spring-up in early spring (Bewley et al., 2007; Sturm et al., 2005). Ménard et al. (2012) present a first approximation to the modelling of shrubs bending and its impact in albedo calculations. This model appears as a potential tool to be incorporated into CRHM’s modules library, which is expected to improve the modelling performance in arctic and subarctic regions. If shrubs radiative transfer estimations are inadequate without including such a model in CRHM’s simulations, the model presented by Ménard et al. (2012) could be incorporated and evaluated with recent observations of buckbrush from the Wolf Creek Research Basin (WCRB) in Yukon.

Table 5: Selected methods to construct the hydrological model with CRHM

Physical Process	**Method**
Global Radiation	Calculates theoretical direct and diffuse global radiation, and maximum sunshine hours (Garnier and Ohmura, 1970).
Shortwave Radiation	The model presented by Annandale et al. (2002).
Longwave Radiation	The model presented by Sicart et al. (2006).
Albedo	An albedo model developed by Gray and Landine (1987).
Net Radiation	A model developed by Brunt (1932) to estimate all-wave radiation to snow-free surfaces.
Blowing Snow Transport and Sublimation	The Prairie Blowing Snow Model (PBSM; Pomeroy and Li, 2000).
Evapotranspiration	Penman Monteith (Monteith, 1981).
Runoff Routing	Muskingum (Chow et al., 1994, p. 312).
Soil Moisture	A Three-Layers Soil Model with depression and detention storage (Pomeroy et al., 2007).

Canopy Interception	The Rutter Interception Model (Valente et al., 1997) for the summer. A Canopy Interception model for the winter (Hedstrom and Pomeroy, 1998; Parviainen and Pomeroy, 2000; Pomeroy et al., 1998).
Frost Table Thaw	The XG-algorithm based on Stefan’s equation (Changwei and Gough, 2013).
Snow Accumulation and Melt	A Two-Layer Energy Balance Model (SNOBAL; Marks et al., 1998).
Soil Infiltration	The Ayers model for unfrozen soils (Ayers, 1959). Infiltration into frozen soils using the method described in Gray et al. (2001).

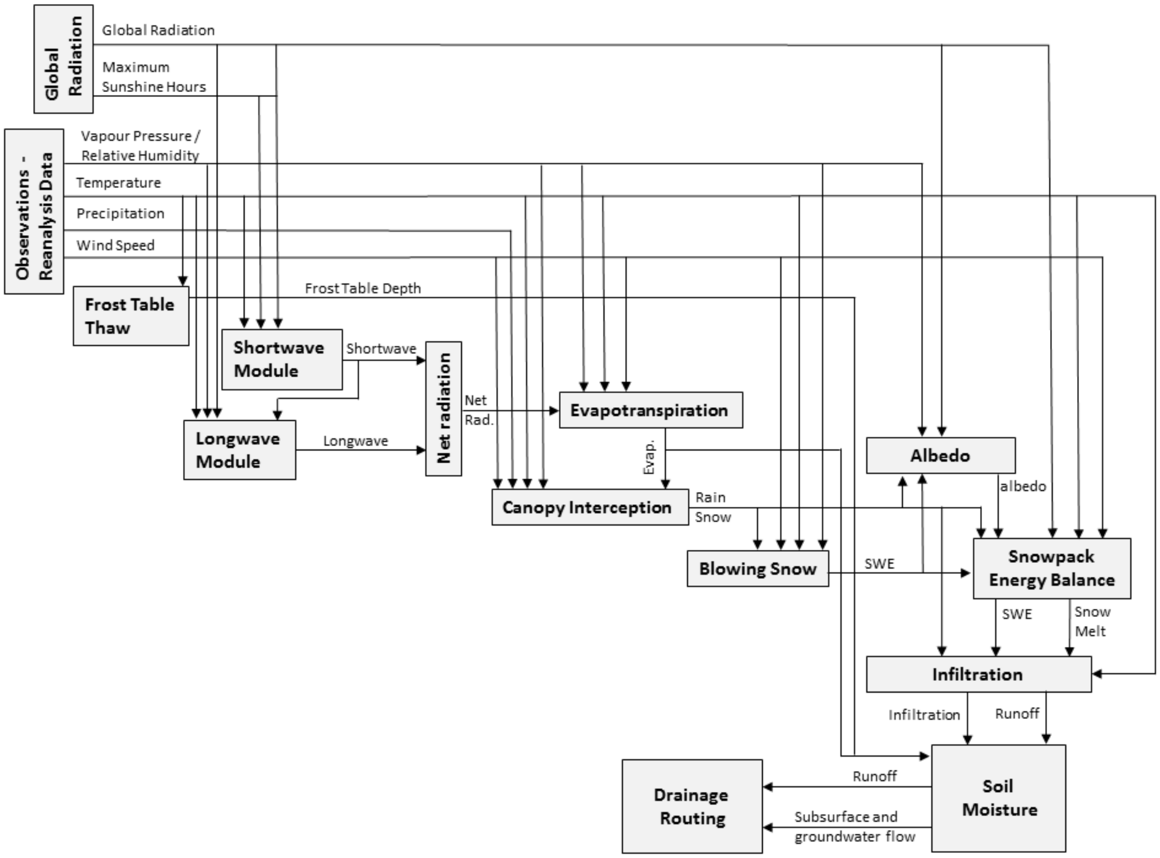

Figure 3: Modules interactions in CRHM

The modelling of the seven basins will be accomplished as follows: CRHM will be first tested with the gauged basins to evaluate its performance, and to calibrate any required parameter; however, because of the physically based nature of the model, most of the parameters will be either obtained from field work observations or transferred from similar regions, leading to a minimum requirement for parameter calibration, which is mostly associated with subsurface and surface flow routing and water storage. Model performance will be compared against daily streamflow records and snow survey when available. Second, once the model's parameters are set, CRHM will be implemented to model the ungauged basins.

Precipitation and Temperature Spatial Distribution

Single point data needs to be spatially distributed within each basin, to account for topographic effects. A temperature lapse rate needs to be estimated, as well as an orographic precipitation gradient. Because of the lack of weather stations, these gradients cannot be obtained from direct observations; therefore, they need to be estimated. For this aim, the Weather Research Forecast model (Michalakes et al., 2004) will be run for an average precipitation year and for each of the seven basin. The model will be run in a 1 (km) spatial grid, which is expected to capture most spatial heterogeneities.

Sources of Uncertainties

There are different sources of uncertainties associated with any hydrological model, which can be grouped in (1) observational data, (2) initial conditions, (3) parameters (4) model structure (Liu and Gupta, 2007; Wagener and Gupta, 2005; Walker et al., 2003). Each source of uncertainty, associated with the proposed model, is detailed bellow.

1) Observational Data: It is related to all the uncertainty in the measurements and how this are used to extrapolate data within the basin. In this particular study, it is also associated with the uncertainty in reanalysis products and the downscaling approach. Uncertainty associated with the downscaling of reanalysis data is usually tackled by creating a set weather data ensembles to run the hydrological model. Data used to evaluate the performance of the model (e.g. streamflow and snow depth) also falls into this category.
2) Initial Conditions: Initial conditions are usually hard, if not impossible, to accurately determine, particularly for soil moisture conditions, which can widely vary within a basin. However, initial conditions for other variables, such as snow cover area or snow depth, can be more easily determined if a well-stablished snow-free period can be found for the basin. In this study most areas in most basins are typically complete snow-free by the end of the summer. To set initial conditions, a spin-up period is typically used. For this study a period of two years is expected to provide an adequate spin-up period.
3) Parameters: In this study parameters will be set from four different sources, each with different levels of uncertainties. (i) physiographic characteristics: DEMs accuracy is not perfect, but given the basin-scale of the research, is that a 20-km DEM (ASTER-GDEM) is expected to provide an adequate representation of the main topographic variations, resulting in negligible uncertainty added to the model; (ii) field work observations: field work observations are usually very accurate; however, they only represent the specific monitored area, and therefore, any extrapolation beyond that particular point is subject to uncertainties; (iii) other studies from the WCRB: information from other basins is also subject to uncertainties produced by the local extent of measurements (same as (ii)) and the fact that both basins do not have exactly the same characteristics; and (iv) calibration: when none of the previous approaches for parameterization is possible, calibration is the only alternative. Calibrations uncertainty can be reduced by setting realistic ranges for

parameters; however, problems such as equifinality (Beven, 2006) may also arise. A common approach to estimate calibration uncertainty is through a sensitivity analysis, which can be also performed to parameters from (ii) and (iii).

4) Model Structure: Model structure is related to the set of approaches used to represent the hydrological cycle, as well as its spatial-temporal resolution. Model structure is typically determined by previous knowledge of the basin, available data modeling objective and the modeller preference (Wagener and Gupta, 2005). Whatever the model structure is, its uncertainty will be associated with the degree of understanding of the processes simulated; in fact, some authors have stated that model structure uncertainty estimation might never be achieved (Liu and Gupta, 2007), primarily due to the lack of a "perfect" model to represent the reality. In this sense, CRHM incorporates some of the state-of-the-art models to represent cold regions processes; however, these models are by no mean perfect representations of the system, leading to unknown uncertainties. Also, the lack of models to represent certain hydrological processes in CRHM, such as shrubs bending or icings, adds another source of uncertainty to the model structure.

Summary

- Seven arctic and subarctic basins, each from different ecoregions, will be modelled.
- Because of the remoteness of the area and the lack of detailed weather stations, the climate of the area will be characterized by using data from two new weather stations, available weather stations and atmospheric reanalyses products.
- Reanalysis data will be spatially downscaled using a well-known statistical downscaling model (SDSM), to obtain daily records of precipitation, temperature, relative humidity and wind speed, which will be used to either complement stations with records shorter than 30 years or to obtain weather time series for basins without observations.
- Temporal disaggregation of daily precipitation will be performed by a simple multiplicative (microcanonical) random cascade model to obtain hourly records of precipitation.
- Precipitation and temperature from single point stations will be distributed by estimating a topographic gradient from a WRF run for an average precipitation year.
- A hydrological model will be constructed using the Cold Regions Hydrological Model Platform (CRHM) in an hourly time step for 30 years.

The model will be tested in gauged basins using daily streamflow and snow surveys (when available) records, and then applied to ungauged basins to reconstruct the hydrology of the basins.

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