The IP3 Research Network:
Improved Processes and Parameterisation for Prediction in Cold Regions

A Primer on IP3 Science:
Enhancing Understanding of Water Resources in Canada's Cold Regions

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1. Overview of IP3

IP3 is a research Network funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) for 2006-2010 and strongly supported by partners in federal, provincial, and territorial governments, communities, and the private sector. CFCAS enhances Canada's scientific capacity in the climate and atmospheric sciences by funding the generation and dissemination of knowledge in areas of national importance and policy relevance, through focussed support for excellent university-based research**.** The IP3 Network is comprised of several dozen Investigators and Collaborators from across Canada, the US, and Europe. IP3 is a component of the 2007-2008 International Polar Year (IPY), the 2002-2012 International Decade for Prediction in Ungauged Basins (PUB), and the Climate and Cryosphere project (CliC) of the World Climate Research Programme. The network is headquartered at the University of Saskatchewan's Centre for Hydrology.

IP3 is undertaking fundamental research on processes and parameterisations in Canada's cold regions that remain poorly understood but are critical for developing a predictive capability for weather and water resources. This research is being accomplished through specialized observations in a set of research basins where the key components of the natural water and energy cycles and the flows of these cycles can be observed and used to develop and test water cycle and related energy flow concepts and equations. It is expected that these concepts and equations can form the basis for the development of physically-based hydrological models and integrated atmospheric water cycle models for small basin to large area water resource assessments.

IP3 is devoted to an improved understanding of hydrology and weather systems in cold regions, particularly Canada's Rocky Mountains and western Arctic. Cold regions hydrology and weather are of key importance to applied water management and policy development for agriculture, communities, recreation, sustainable industrial development, and environmental conservation in western and northern Canada. Through field investigations, Network scientists are studying snowpacks, glaciers, forests, lakes, wetlands, permafrost, and runoff generation in cold environments where frozen ground, snow, and glaciers dominate the hydrology and climate. IP3 is incorporating recent advances in the understanding of snow hydrology, frozen ground dynamics, evaporation, remote sensing, and glaciers into Canadian coupled atmospheric-hydrological models and physically-based hydrological models in order to improve the predictive capacity for small headwater streams and rivers in cold regions. IP3 will make contributions to better weather and climate prediction, estimation of streamflow from ungauged basins, prediction of changes in Rocky Mountain snow and water supplies, calculation of freshwater inputs to the Arctic Ocean, and sustainable management of mountain and northern water resources. IP3's ultimate goal is to make an effective contribution to multi-scale assessments of the coupled climate/weather/ hydrological system in cold regions. End points of such assessments include improved understanding and predictability of snow accumulation and melt, glacier dynamics, soil moisture, evaporation, frozen soil thaw, lake level and streamflow.

2. Scientific Objectives and the IP3 Themes: Processes, Parameterisation, and Prediction

IP3 is focussed on three Scientific Objectives:

1. Understanding key cold regions hydrometeorological **processes**[1]. This requires intensive **field observations**[2] and development of improved mathematical **process algorithms**[3].
2. Improving the mathematical **parameterisation**[4] of land surface cold regions hydrological processes and incorporating the new parameterisations into coupled land surface–hydrology models.
3. Validating and improving hydrological and atmospheric models for better **prediction** and **simulation** of water resources, atmospheric fluxes, and surface climates in cold regions.

2.a. Theme 1 - Processes

The objective of Theme 1 is to assess and improve our understanding of key climate system **processes** related to the hydrometeorology of cold regions and their interactions with the atmosphere, hydrological system, and biophysical aspects of the land surface. Multiple-scale near-surface **field observations** are being carried out along a transect of eight high latitude and high altitude instrumented research sites that are representative of the cryosphere of Western Canada. Intense field observations are made to characterize mass and energy fluxes to and from snow and ice, water bodies, frozen soil, and permafrost. **Process algorithms** that mathematically describe these fluxes and other hydrometeorolgical processes are being developed and improved for small to medium scales (10's to 100's of km) and are evaluated using data from the IP3 research basins.

Field Observations: The eight IP3 research basins (Figure 1), each 10 to 200 km^2 in area, range from high altitude cordilleran sites in the south (Rocky Mountains) and west (Coast Ranges) to low elevation basins in the north and east. These basins provide a great variety of vegetation, topography, climate, and precipitation regimes for developing and testing new ideas. Field observations include sub-hourly measurements of air temperature, humidity, wind speed, rainfall, snowfall, snow depth, surface temperature, solar and longwave radiation, soil moisture, soil temperature, and turbulent fluxes of heat and water vapour. Winter and summer mass balance, streamflow, snow depth, groundwater, and glacier surface meteorology are also recorded during monthly or annual field campaigns. Descriptions of each of the basins are included in Appendix A.

Process Algorithms: These describe snow and glacier ice, open water, and runoff generation, and are being developed using coupled mass and energy observations in the eight research basins. Processes include sensible heat exchange, evaporation, radiation exchange, snow accumulation and loss, blowing snow transport rate, precipitation, snowmelt, ground heat flux, advection, soil thaw, overland flow, sub-surface flow, soil moisture change, runoff and streamflow. Issues of spatial variability in processes are being addressed by multiple observations within basins, comparison of basins and employment of new remote sensing technology. Because the basins cover significantly different topography and climate, algorithms are evaluated with data from multiple basins to ensure robustness and transferability to a variety of different environments.

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[1] A hydrological process is a physical process in the water cycle such as evaporation, snowmelt, infiltration, runoff, etc.

[2] Field observations entail the measurement of meteorology, solar radiation, snow depth and density, soil moisture and temperature, streamflow, ice thickness, vegetation, topography and other natural features in a basin. This involves manual observations in remote locations and use of computer-controlled weather and hydrological stations.

[3] An algorithm is a set of equations and logical rules used as part of a computer program. In hydrology, these tend to describe a hydrological or weather process and form part of computer-based numerical predictive models.

[4] A parameterisation is a method of describing a complex physical phenomenon in relatively simple mathematical form so that it can be used in a computer simulation. For instance, while snowmelt is an exceedingly complex physical process, snowmelt parameterisations can be simple linear equations.

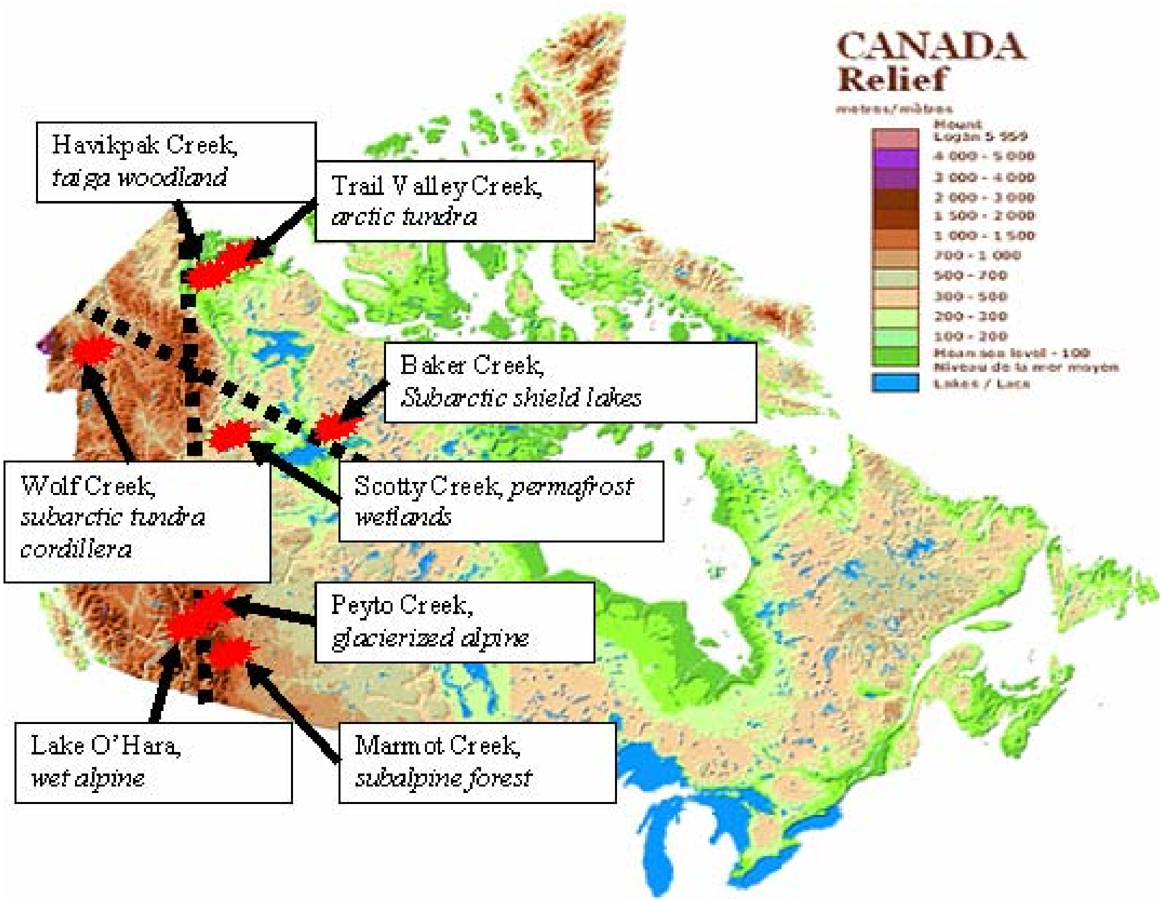


Figure 1. IP3 Research Basins cover cold regions transects from high altitudes (Wolf, O'Hara, Peyto, Marmot) to low altitudes (Scotty, Baker, Havikpak, Trail Valley), and high latitudes (Trail Valley, Havikpak, Scotty, Baker, Wolf) to low latitudes (Peyto, Marmot, O'Hara).

Theme 1 Activities:

2007: All research sites fully instrumented and experiments set up

2008: All field sites fully operational with personnel on-site for intensive data collection, implementation of new and developing numerical process descriptions into the Cold Regions Hydrological Model, CRHM (see 2.b. below)

2009: Final year of full-scale field measurements

2010: Incorporation of all new numerical process descriptions into CRHM, and continued refinement of numerical process descriptions as they are tested across all research catchments

2.b. Theme 2 - Parameterisation

The objective of Theme 2 is to improve the basin-scale mathematical **Parameterisation** of cold regions hydrological processes that control the coupled atmospheric-hydrological system. New parameterisations are being incorporated into coupled land surface/atmosphere-hydrology models for small- to medium-scale prediction. The parameterisation strategy takes into account the spatial heterogeneity of land surface hydrology processes: Process behaviour is hierarchically described at different length scales, from small hillslopes or landscape units (called "tiles" or "HRUs", hydrological response units) to sub-basins, small basins, and large basins. This strategy recognizes the drainage basin, or watershed, as a basic land surface parameterisation unit and allows for testing the transferability of parameterisations developed at the point scale, which is the scale at which observations are made, to small and large basins which are the scales at which predictions are required (Figure 2).

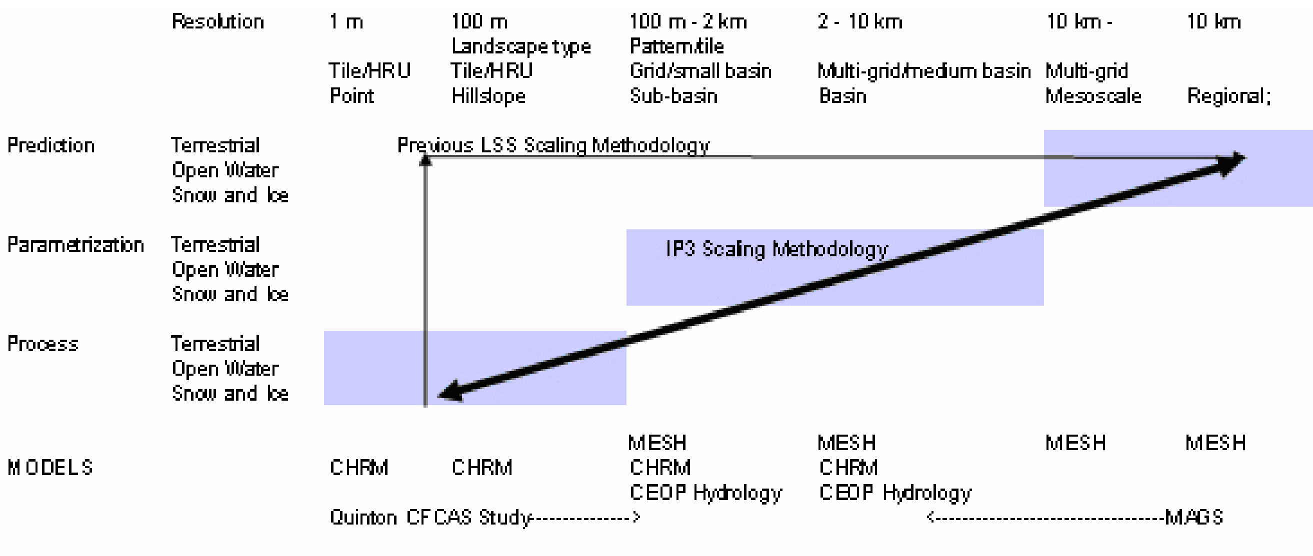


Figure 2. The IP3 parameterisation and modelling approach: Bottom-up deductive reasoning from point-scale process relationships is combined with top-down inductive reasoning from large-scale basin behaviour to cover the range of spatial resolutions needed in predictive hydrological and meteorological modelling.

The scaling hierarchy is as follows: Processes are scaled up to the tile or HRU **(**example: forest stand, hillside, or wetland**)** with accommodation for small-scale variability. Tiles or HRUs are aggregated according to observed interactions in the research basins. For example, in some basins there is horizontal exchange between tiles as water and snow move from one landscape unit to the next, while others have tiles or HRUs that only generate vertical fluxes of radiation, water vapour, and sensible heat. These differences in hydrological behaviour have great implications for the basin or landscape-type aggregation strategy. Generally, forests, tundra, wetlands, and lakes all require distinctive strategies that describe the unique water and energy flow in each ecosystem.

One of the modelling tools being used to develop and test new process algorithms and parameterisations is the **Cold Regions Hydrological Model (CRHM)**. CRHM is being developed in-house by IP3 for incorporating and connecting physically-based hydrological process algorithms. Since CRHM is a physically-based "process model," it can be used as a first-step in developing and testing mathematical descriptions of the natural world - it is a kind of proving ground where parameterisations can be tested alone and then together with others to find out whether the numerical process descriptions are complete and accommodate various landscape and environmental possibilities. CRHM also is a user-friendly tool to assemble hydrological models for prediction of snowpacks, soil water, lake level, and streamflow in headwater and small basins. CRHM is described in more detail in Section 3.

Once the parameterisations are evaluated successfully in CRHM, they are incorporated into a coupled hydrological-atmospheric model. Environment Canada is currently developing this model in conjunction with their new community environmental modelling system (**Modélisation Environmentale Communautaire - MEC**) which is intended to produce operational forecasts. MEC can be configured in various ways and is designed to facilitate coupling between models focusing on different components of the earth system. The configuration which IP3 is using, **MEC - Surface and Hydrology (MESH)**, couples independent hydrological and atmospheric models. This allows the land surface hydrological behaviour to influence and react to the atmosphere just as weather and water co-exist as in the natural world. To test new model elements (including new parameterisations) which are to be incorporated into MESH and the other predictive models, simulation results are compared to as many other data as possible. These other data may consist of field measurements or the results of smaller scale models such as very fine scale finite element models or CRHM. Comparison to these data sources will add confidence that the processes are being represented properly within the predictive models. Further information on MESH is included in Section 3.

Theme 2 Activities:
2007: Set up CRHM at selected test basins (representing arctic, alpine, wetland, and Precambrian shield) and assess existing parameterizations over complex terrain
2008: Test CRHM and MESH against field data and modelling outputs and against each other, characterize surface parameter distributions, and develop certain parameterisations
2009: Incorporate new parameterisations into CRHM and MESH and scale-up/regionally average mass and energy balance equations for cold regions hydrological processes in complex vegetated terrain
2010: Implement parameterisations in coupled models and evaluate CRHM, MESH, and CLASS with the new algorithms (see 2.c. below for information on CLASS, the Canadian Land Surface Scheme)

2.c. Theme 3 - Prediction

The objective of Theme 3 is to test and improve weather, water, and climate models leading to better **Prediction** and **Simulation** of related atmospheric impacts on water resources, atmospheric fluxes, and surface climates in cold regions. The program is designed to achieve this goal through a combination of observational, experimental, theoretical, and modelling studies at a range of appropriate spatial and temporal scales developed in Themes 1 and 2. Combined use of land surface hydrology models, regional atmospheric models, numerical weather prediction models, and coupled environmental models permits examination of the influence of varying land cover and boundary atmospheric conditions at multiple scales, from local to regional (10's of km to 1000's of km). This approach is resulting in direct improvement to water resource modelling capability, such as better modelling structure, physics, and parameterisation via improved physical understanding. This includes improved schemes for the interaction of soil moisture and evaporation, optimization of land surface parameters using streamflow hydrographs, and the parameterisation of cold region processes including permafrost, frozen soil, snow sublimation, and snow redistribution by wind and vegetation.

The IP3 approach combines the strength of bottom-up (deductive reasoning from point-scale process relationships) and top-down (inductive reasoning from large-scale basin behaviour) modelling methods (Figure 2). These two methods meet in the middle through definition of a set of basic Hydrological Response Units (HRUs), typically but not limited to topographically-based hillslopes with aspect defined (i.e., north-facing slope, southeast-facing hill with 15° slope, etc.) or to vegetation and soil combinations such as are found in individual forest stands or patches of tundra, wetlands, or shrublands. Basins are described by a network of grid cells that are connected by the stream network. Each grid cell in the models is composed of a number of HRUs and is thus characterized by the representative landscape units that form the basis for the water and energy budget calculations. The HRU is treated as a control volume for application of mass and energy budgeting and is represented by state variables such as soil moisture and temperature averaged over the entire HRU. These variables are then linked to differing HRUs in the grid cell and are used to generate boundary conditions to determine the transfer of water and energy between grid cells. HRUs can be grouped to have the same parameter set for a variety of grids – this improves the ability to calibrate parameters from limited streamflow or snow observations. The HRU provides the link between microscale studies and mesoscale modelling. For example, slope and aspect can be explicitly related to relevant variables such as soil moisture and temperature profiles and the position of the wetting front and of liquid/ice interfaces. Spatially-distributed observations from the eight IP3 research basins as well as from existing federal and provincial observation networks are required for such modelling. Combination of observations with multi-scale modelling provides improved knowledge of fundamental cold regions hydrological processes as well as a scale-dependent understanding of the interactions of snow and ice, hydrology, atmosphere, and climate.

Modelling domains have been established at three different scales for western Canada (Figure 3). Each scale is modelled by a different predictive model. Large-scale modelling is being accomplished with the Canadian Regional Climate Model (CRCM) over western Canada. The CRCM is a numerical integration scheme for computing atmospheric flow and is generally used at large spatial scales and coarse resolution. It is very useful for examining the regional impacts of climate change and variability. Higher-resolution modelling is being accomplished with the Global Environmental Multi-scale (GEM) model which is currently used at Environment Canada for numerical weather prediction (NWP) such as weather forecasting. The GEM is being run as a Limited Area Model (GEM-LAM) and is set up for 2 domains, GEM-North and GEM-South. The GEM-LAM operates at intermediate resolution and thus bridges regional simulations (CRCM) and basin-scale simulations which are being made with MESH. As described above, MESH combines atmospheric modelling with land-surface and hydrological modelling. MESH has been established and is being run over all eight IP3 basins at increasingly higher resolutions. These predictive models are designed to be used in both hind-casting and forecasting modes.

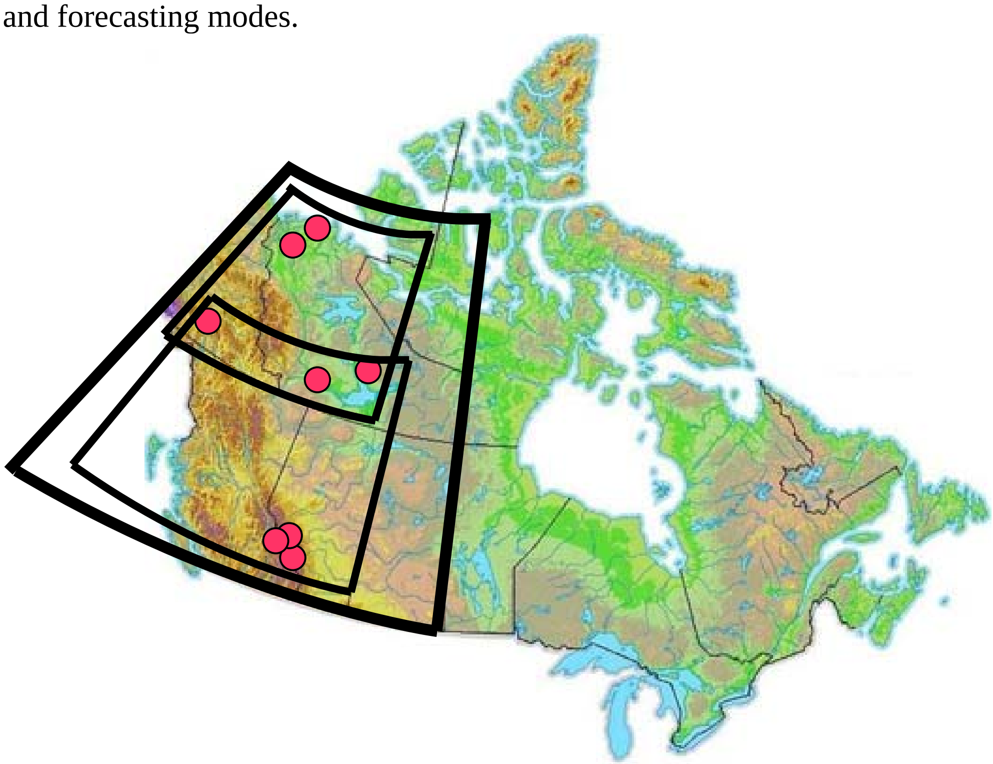


Figure 3. IP3 modelling domains. The CRCM domain is established over all of western Canada (thick black line), two GEM domains (GEM-north and GEM-south) are established over northern and southern portions of the CRCM domain (thin black lines), and MESH domains focus on the eight research basins (red circles).

There are two other models in the IP3 modelling hierarchy: CRHM and CLASS. CRHM is being used as a method to test parameterisations which can be improved and incorporated into the larger-scale predictive models, namely GEM and MESH, and is a predictive tool in its own right. The simple user interface of CRHM makes it useful for training and for development of purpose-built physically-based basin models that rely on no or minimal calibration. CRHM is being distributed to all interested users as a technology transfer component to IP3. The Canadian Land Surface Scheme (CLASS) is used as either a stand-alone land surface scheme or as part of the MESH, GEM, and CRCM models. The current versions of CLASS and MESH have not been widely tested in complex topography or cold regions, so it is IP3's mandate to evaluate and improve these models for operational applications in Canada.

IP3 anticipates three major accomplishments in Theme 3:

1. Production of an integrated hydrology-land surface model (MESH),
2. Improved hydrologic prediction in ungauged regions, and
3. Improved weather prediction.

For the first of these goals, the IP3 program is assessing the feasibility and scientific and technical considerations required for implementation of MESH within the GEM numerical weather prediction (NWP) modelling framework of Environment Canada. NWP is "the forecasting of weather elements through the use of numerical models" (from the Environment Canada NWP products webpage, http://www.weatheroffice.gc.ca/model_forecast/about_these_products_e.html). NWP is also "the cornerstone of the Environment Canada Weather Environmental Prediction (WEP) System and the...operational program that provides the fundamental guidance for the weather warning program" (from the Environment Canada NWP research and development page, http://collaboration.cmc.ec.gc.ca/science/rpn/general/en/index.html).

Environment Canada's NWP system currently relies on the Global Environmental Multiscale (GEM) model. IP3 has hired a GEM Modeller to help improve the representation of atmospheric feedbacks in the GEM model through improved parameterisation of snow, ice, and soil frost processes on the land surface. The GEM Modeller is also examining scaling relationships and problems associated with running large-scale atmospheric models over complex terrain to drive hydrological models. Improved GEM and MESH code and linkages between them is an important product of IP3 for Environment Canada. Because IP3 researchers will be developing MESH and GEM within the existing Environment Canada modelling framework, all IP3 work can be easily transferable to operational model runs for improved weather and water supply forecasting.

The second goal, improved prediction in ungauged regions, is necessary to extend IP3's modelling results from its research basins to the rest of Canada. Most of Canada's high latitude and high altitude regions are not monitored by hydrological or meteorological instrumentation. Uncertainty in hydrological prediction in these "ungauged" regions is largely due to the impossibility of parameterising models using measured streamflow. IP3 is improving understanding in cold regions by using landscape-based parameters resulting from detailed field studies rather than traditional top-down (inductive) approaches. The eight IP3 research basins have been chosen to represent the various landscape types in Canada's cold regions so that process algorithms and parameterisations are quantified for nearly all Canadian cold landscapes (except large icefields). Landscape-based parameterisation allows parameter selection and transferability from the research basins to ungauged locations. This understanding and transferability have been previously unattainable in most hydrological modelling systems, particularly those for cold regions.

Improved weather prediction is the third goal. Feedback from the land surface to the atmosphere is understood to be a critical driver of local weather, but assessing the magnitude and importance of land-surface feedbacks has been poorly understood. IP3 is providing the first systematic quantification of the importance of land surface feedbacks in cold regions.

Theme 3 Activities:
2007: Establish operational version of MESH for all 8 research basins
2008: Incorporate new process parameterisations into MESH, test MESH and perform sensitivity analyses, and compare results with observed hydrographs and other data
2009: Continue to improve and evaluate MESH with new algorithms and additional basin observations
2010: Incorporate numerical snow and ice hydrology and cold regions process descriptions into a coupled land surface scheme-hydrological model, and simulate terrestrial water and energy cycles for selected cold regions environments

3. Modelling Tools

While the CRCM, GEM, MESH, and CLASS are being developed jointly by IP3 and other institutions, CRHM is an IP3-only modelling project. This section contains additional detail on CRHM, MESH, and CLASS as they are the most pertinent to water resources applications.

3.a. The Cold Regions Hydrological Model (CRHM)

The Cold Regions Hydrological Model (CRHM) is a software platform for building physically-based hydrological models over small to medium sized basins. CRHM,

- can segment a basin or a landscape type such that the water balance for selected surface areas (HRUs) can be computed;
- is sensitive to the impacts of land use and climate change;
- does not require the presence of a stream in each HRU as do most hydrological models (not all cold regions HRUs have streams);
- is suitable for testing individual process algorithms; and
- does not require calibration.

CRHM uses physically-based algorithms to model the hydrological cycle and hydrological processes, including those of considerable uncertainty such as blowing snow, snow interception in forest canopies, sublimation, snowmelt, infiltration into frozen soils, hillslope water movement over permafrost, actual evaporation, and radiation exchange to complex surfaces. CRHM was first developed as an experiment in model construction and has evolved into a research and predictive tool that can rapidly incorporate new process algorithms (parameterisations) and connect them over a basin for simulating the cold regions hydrological cycle.

The CRHM interface consists of a native Microsoft Windows application written in C++. It can be run in XP, Vista, Linux, and the Macintosh environment. Field data or other model output data are placed into observation files from which variables can be graphed or linked into the model. Similar to an electronic circuit, various object oriented modules can be linked together in CRHM to form a larger, more complicated model. This can be done in a simple fashion, and does not require re-writing or re-compiling code. Thus, various groups of researchers can place their models or algorithms into the program. The data are moved successively between each of the modules. In addition, more advanced users can write macros in an interpreted language that is similar to C++, from within the model, and these macros can be used to extend the model and even change its structure. The data are plotted as the model runs, and the results can either be exported to a text file, ArcGIS, or an EXCEL spreadsheet. The exported data can then be taken into other programs which are used for post-processing of the data, or the data can be used to drive other models such as CLASS. CRHM can be run in either spatially-distributed or aggregated modes to show the effect of differing model resolution. The basic unit of calculation in the model is the HRU (Hydrologic Response Unit).

CRHM is a flexible modelling system. Landscape elements in CRHM can be linked episodically to mimic natural process sequences via blowing snow transport, overland flow, organic layer subsurface flow, mineral interflow, groundwater flow, and streamflow. CRHM has a simple user interface but no internal provision for calibration: parameters, observations, and model structure (modules) are selected to reproduce the fundamental behaviour of the particular hydrological system being studied. Accordingly, the model can be used both for prediction and for diagnosis of the adequacy of hydrological understanding.

CRHM Modules and Structure: The complete set of CRHM modules can be classified into the following categories. For many categories there is a choice of modules ranging from basic to strongly physically-based, so as to permit the most appropriate algorithms to be used for the available data, information reliability, basin characteristics, scale, intended output, etc:

1. **Basin**: Basin and HRU physical, soil, and vegetation characteristics;
2. **Observation**: Interpolates meteorological data to HRU using adiabatic relationships, and saturation vapour pressure calculations;
3. **Snow Transport**: Blowing snow transport and sublimation;
4. **Interception**: Rainfall interception, snowfall interception, snow interception in forest canopies, and sublimation;
5. **Radiation**: Shortwave direct and diffuse algorithms, slope corrections, snow albedo decay, longwave radiation, canopy transmissivity, and net radiation;
6. **Evaporation;** several physically based methods for unsaturated and saturated surfaces including transpiration;
7. **Snowmelt**: energy balance snowmelt, radiation index, temperature index, snow cover depletion, and simple land surface scheme melt methods;
8. **Infiltration**: Basic and parametric infiltration routines for frozen soils, frost depth calculation, Green-Ampt infiltration and redistribution for unfrozen soils;
9. **Soil Moisture Balance**: Multiple flowpath 2-layer "bucket" model with sub-surface flow, groundwater, depressional storage and "pond" options; and
10. **Flow**: Organic layer flow, timing and storage control of overland, mineral interflow, and streamflow using the lag and route hydrograph and Muskingum routing methods.

Comparison to other models: CRHM participated in a blind test of snow models in several forested and open environments, the Snow Model Intercomparison Project II (SnowMIP2). The results of a comparison of model output to measurements at sites in Switzerland, Canada, and USA specific to CRHM suggest that there is reasonable predictive capability in uncalibrated runs with minimal parameter requirements.

For more information or for a downloadable version of CRHM, please see http://www.usask.ca/hydrology/crhm.htm or contact the IP3 Network Manager, Julie Friddell, at ip3.network@usask.ca or 306-966-4907.

3.b. Modélisation Environmentale Communautaire (MEC), MEC - Surface and Hydrology (MESH)

Environment Canada has been developing a community environmental modelling system (Modélisation Environmentale Communautaire – MEC) to facilitate coupling between models focusing on different components of the earth system. The ultimate objective of MEC is to use the coupled models to produce operational forecasts. MESH (MEC – Surface and Hydrology), a configuration of MEC used in IP3, is specialized for coupling land-surface and hydrological models. This system is the Canadian result of an intensive global research effort to couple atmospheric and hydrological models to improve hydrological flow simulations and atmospheric predictions in both climate and weather prediction models.

To link the land surface and the atmosphere through the movement of water, sophisticated land surface schemes (LSS) have been implemented in global climate models, regional climate models, and operational forecasting numerical weather prediction (NWP) models. A Canadian example of a LSS is CLASS. Recently, LSS are also being incorporated into hydrological models, and atmospheric and hydrological models are being linked (as in MEC/MESH) with LSS as the common link. Combination of a LSS and a hydrological streamflow model provides a stand-alone hydrology-land-surface scheme (HLSS). When a HLSS is incorporated into an atmospheric model, the result is a fully coupled system.

These efforts have led to the development of research modelling tools, but the use of these models in hydrometeorological forecasting systems has been limited largely due to the technical hurdles involved in testing changes to an operational NWP system. MEC is being developed to overcome this obstacle. The MEC system allows different surface models to coexist within the same modelling framework so they can easily be compared for the same experiment using exactly the same forcings, interpolation procedures, grid, time period, time step, and output specifications. The model coupler can be used to couple models running on different grids, and potentially, on different time steps. An important feature of MEC is its ability to read atmospheric forcings from files instead of obtaining them from an atmospheric model through the coupler. This makes it possible to test changes to the surface schemes offline (i.e., without the complication of the atmospheric model having to always run concurrently). The land-surface scheme is thus independent of the atmospheric model. As such, it is possible to increase the spatial resolution of the land-surface scheme without changing the resolution of the atmospheric model. It is possible to run MEC in an offline mode (de-coupled from the atmosphere) to allow the land-surface to develop unconstrained (Figure 4).

The current versions of MEC and MESH include three land-surface schemes: (1) a simple force-restore scheme; (2) a version of the ISBA LSS (Interaction Soil-Biosphere-Atmosphere); and (3) version 3.0 of the Canadian Land Surface Scheme (CLASS). In MESH, CLASS can run on a number of different tiles on each grid cell, which allows subgrid variability in the landscape to be taken into account. Using the HRU approach, a parameter set is identified for each landscape class so that the calibration of the model is not done at the grid cell level nor at the sub-basin level, but on the whole domain at once.

One of the primary goals with respect to the MESH modelling system is the proper description and quantification of the importance of sub-grid variability. The current version of MESH is based largely on landscape-derived tiles, but the flexibility of the MESH system allows for transfer of water and energy between tiles (within a grid) and between grids. Water must be routed between tiles, and account must be taken of bank and stream flow with variable roughness and linking of streamflow routing to groundwater, unsaturated zone, and sub-surface flows.

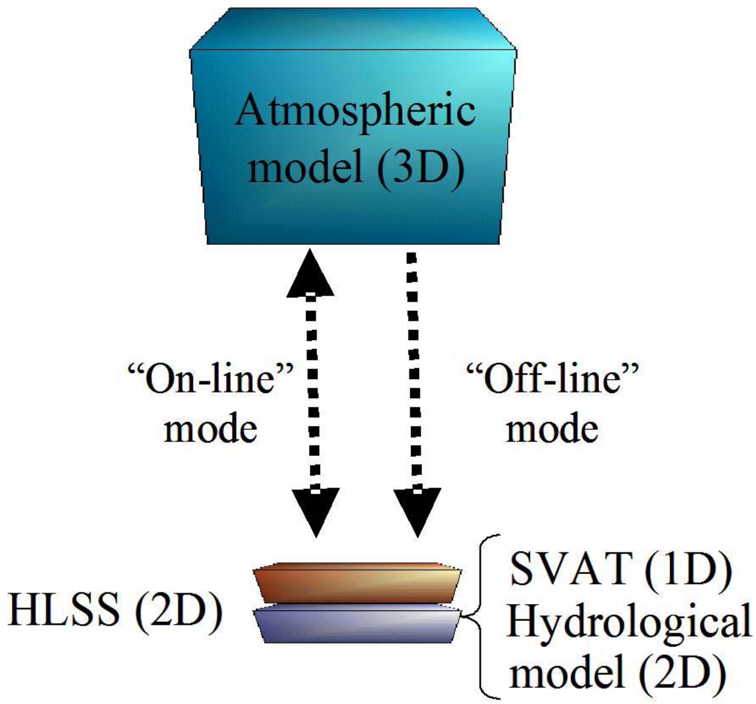


Figure 4. A strategy for coupled atmosphere, land and hydrology models. The atmospheric model can be run along with the hydrological/land surface model(s) ("on-line" mode), or the atmospheric model can be run first and then its output used to drive the hydrological/land surface model(s) ("off-line" mode). Note that CLASS is the SVAT 1D model and MESH is the coupled HLSS (hydrological land surface scheme).

MESH has two main components: a tile connector and a grid connector. The tile connector currently consists of a very simple aggregation of results from the tile process algorithm. This system does not allow for transfer of water between tiles, but runoff between tiles will be accommodated by the "fill and spill" method (where lake or pond tiles fill to a defined volume and then spill downstream) or by the transfer of blowing snow between tiles. The grid connector in MESH routes flow volumes to and from successive grids.

The two main advantages of the MESH modelling system are that

1. It is a community system, and
2. It is part of an operational forecasting system in use at Environment Canada.

This not only means that researchers and end-users can use it and modify it freely, but also that MESH should continue to improve over the years, benefiting from improvements made to the modelling system for both research and operation purposes. The development of MESH ties directly into a series of existing projects and programs in Canada including the Drought Research Initiative (DRI, another CFCAS Network), the National Agri-Environmental Standards Initiative (NAESI), the International Polar Year (IPY), and IP3.

3.c. The Canadian Land Surface Scheme (CLASS)

The Canadian Land Surface Scheme "CLASS" was developed in the late 1980s for the Canadian Global Climate Model (GCM), in response to the perceived need for a "second-generation" land surface model which would adequately treat the effects of vegetation, snow, and soil on exchanges of heat and moisture with the atmosphere. CLASS is an important addition for atmospheric models, necessary to better characterize lower boundary sinks/sources of moisture, energy, and momentum. CLASS uses physically-based equations to simulate the energy and water balances of vegetation, snow, and soil. Environment Canada is developing CLASS by sifting proposed modifications to the model and testing them at operational scales to ensure their applicability to regional climate modelling, numerical weather forecasting, and environmental prediction implementations. CLASS has likely the most sophisticated and physically realistic treatment of snow processes in any operational land surface scheme. Recent upgrades include interaction of snow with vegetation canopies and modification to the treatment of evapotranspiration. Expected upgrades from IP3 include incorporation of blowing snow redistribution, surface radiation balance on slopes, snow-covered area depletion based on variability of snow accumulation, and calculation of infiltration rates into frozen soils. All of these improvements directly affect the vertical energy and water flux calculations done within CLASS. Other steps in CLASS development include scaling studies, sensitivity tests of parameterisations, and investigations of the optimum partitioning of tiles among landscape types.

CLASS has been tested using datasets from a wide variety of landscapes. It has the capability to model organic soils, snow dynamics and different "tiles" of landscape types within a single grid cell. CLASS has also been modified to better represent grassland ecosystems and snow in the boreal forest. Additional enhancements in MESH include the ability to model lateral movement of soil water and provide the option for multiple layers in soil at depth and ice sheets. CLASS is being run for all of the eight IP3 research basins and forced with observational data.

Versions of CLASS have been as follows:

- CLASS 2.7 (1997)
- CLASS 3.0 (2002)
- CLASS 3.1 (May 2005)
- CLASS 3.2 (May 2006)
- CLASS 3.3 (Nov 2006)

CLASS 3.3 is compiled using FORTRAN90 and can be run using single precision. Changes to the physics within the code include modelling liquid water in the snow pack, snow unloading in forest canopies, and an independent calculation of snow and soil behaviour. Issues that continue to be addressed are version control (since so many different people are using CLASS, it is critical to keep the code standardized so that everybody has access to and uses the same version) and including procedures for tile connection and basin/landscape classification. Other planned improvements include modelling the movement of wetting fronts (infiltration into frozen/organic soils), the development and removal of soil frost (particularly in organic soils), thermal properties of snow, and representation of snow layers. Also, new tiles need to be developed to represent hydrologically important landscapes at the study sites such as channel fens, small (i.e. sub-grid) lakes, and shrub-covered terrains.

More information on the IP3 Network including some publications can be found on the website http://www.usask.ca/ip3/

List of Abbreviations

CFCAS	Canadian Foundation for Climate and Atmospheric Sciences
CLASS	Canadian Land Surface Scheme
CliC	Climate and Cryosphere Project, World Climate Research Programme
CRHM	Cold Regions Hydrological Model
CRCM	Canadian Regional Climate Model
GCM	Global Climate Model
GEM	Global Environmental Multiscale Model
HLSS	Hydrology - Land Surface Scheme
HRU	Hydrological Response Unit
IHD	International Hydrological Decade
IP3	Improved Processes and Parameterisation for Prediction in Cold Regions
IPY	International Polar Year
LAM	Limited Area Model
LSS	Land Surface Scheme
MEC	Modélisation Environmentale Communautaire
MESH	MEC - Surface and Hydrology
MSC	Meterological Service of Canada
NAESI	National Agri-Environmental Standards Initiative
NWP	Numerical Weather Prediction
PUB	International Decade for Prediction in Ungauged Basins (2002-2012)
SVAT	Soil-Vegetation Atmospheric Transfer scheme

Appendix A - IP3 Research Basins

Baker Creek, NWT, is a series of interconnected lakes draining a 150 km^2 watershed north of Great Slave Lake that is typical of Canadian Shield drainage basins. The landscape is taiga woodland and boreal forest. The basin has 3 meteorological stations and one streamflow gauging station. Photos below of Baker Creek are provided by Chris Spence.

Wolf Creek, YT, is part of the headwaters of the Yukon River near Whitehorse, YT. The watershed encompasses 195 km^2 and has a sub-arctic climate with vegetation zones ranging from boreal forest to windswept alpine tundra. The basin is partially underlain by permafrost. It has 6 permanent meteorological stations ranging in elevation from 750 to 1,600 m and 3 gauged sub-basins. Photos below of Wolf Creek provided by Rick Janowicz and Sean Carey.

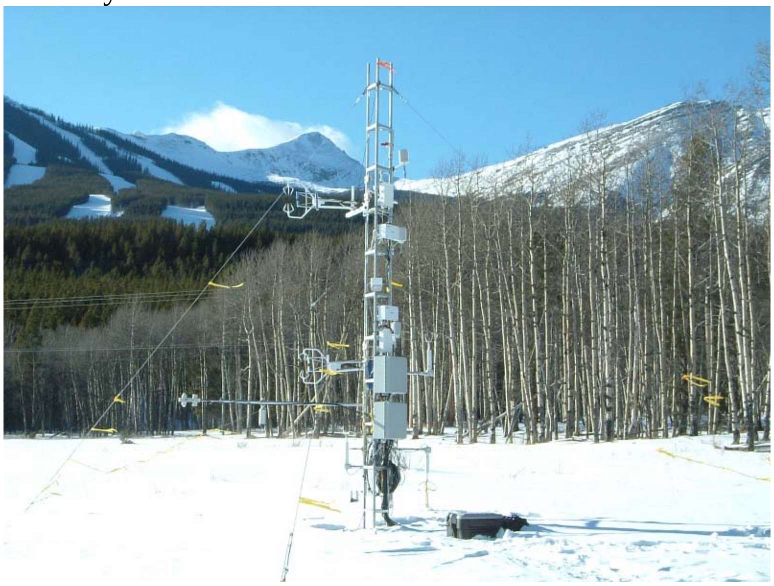
Trail Valley Creek, NWT, flows into the Arctic Ocean through the Eskimo Lakes system. The basin covers 70 km^2, is primarily covered with sparse/shrub tundra and tundra ponds, and is underlain by continuous permafrost. It has 3 permanent meteorological stations and two streamflow gauging stations.

Havikpak Creek, NWT, flows into the Mackenzie River near the Mackenzie Delta. The basin is primarily an open taiga woodland, with some open wetlands and upland shrub tundra. The basin is underlain by continuous permafrost, some of which is ice-rich. It has 2 meteorological stations and a streamflow gauging station and is near the Inuvik MSC weather station.

Scotty Creek, NWT, flows into the Liard River near its confluence with the Mackenzie River at Fort Simpson. It drains a broad permafrost wetland with islands of sparse woodland surrounded by open fen and muskeg. The research basin has 2 meteorological stations and is near the Fort Simpson MSC weather station.

Peyto Creek, AB, drains a 24 km^2 basin in Banff National Park that forms part of the headwaters of the North Saskatchewan River, to which it connects through the Mistaya River. The watershed is 60% covered by the Peyto Glacier which has been the subject of intensive mass balance, energy balance, and runoff observations since the basin's adoption as an International Hydrological Decade (IHD) research site in 1965. The basin has an automatic weather station adjacent to the glacier, a glacier mass balance field programme that is part of the National Glaciology Programme of Natural Resources Canada, and a streamflow gauge. Data assets include hourly measurements of solar radiation, air temperature, humidity, wind speed and precipitation, winter and summer mass balance measurements, streamflow records, and glacier surface meteorology records. Photo below of Peyto Glacier provided by Scott Munro.

Marmot Creek, AB, feeds the Kananaskis River and the Bow River system from the Rocky Mountains in Alberta. The Marmot Creek watershed is 14 km^2 and is primarily covered with montane and sub-alpine forest with alpine tundra ridgetops. The basin has seasonally frozen soils. The basin has been subject to intensive hydrometeorological studies since the IHD. It has 9 permanent meteorological stations at elevations from 1,450 m to 2,500 m collecting precipitation, snow depth, soil moisture, soil temperature, short and longwave radiation, air temperature, humidity, wind speed, and turbulent fluxes of heat and water vapour. Observations of groundwater levels and streamflow are made by the federal and provincial governments. Photo below of a Marmot Creek meteorological station provided by John Pomeroy.



Lake O'Hara, BC, is in a 14 km^2 watershed which ranges in elevation from 2,010 to 3,490 m. Three small glaciers occupy approximately 5% of the basin. The basin has 2 meteorological stations and 5 stream gauging stations, and current work includes intensive investigation of groundwater pathways. Photos below of snow surveying in Lake O'Hara watershed and the Opabin Glacier and moraine field provided by Masaki Hayashi.