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IP3
Improved Processes & Parameterisation for Prediction in Cold Regions

2009 Progress Report

IP3: Improved Processes and Parameterisation for Prediction in Cold Regions

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1.0 Progress to Date

IP3 has made substantial progress in completing process studies on snow, frozen ground, lakes, glaciers, forests, hillslopes, and wetlands. The network has also incorporated new process understanding into model parameterisations for blowing snow redistribution, intercepted snow unloading, forest and shrub snowmelt, hillslope flow and water storage, frozen soil infiltration, permafrost thermodynamics, fill-and-spill of lakes and ponds, evaporation from lakes, and turbulent transfer to glaciers. These model parameterisations have been used to improve the Cold Regions Hydrological Model (CRHM) and Modélisation Environmentale Communautaire – Surface and Hydrology (MESH) and to test model results against basin observations. The tests show substantial model improvement as well as model components which require further development. CRHM development is proceeding with network support. During the IP3 Prediction Workshop, network members developed a detailed plan to improve MESH, and work has begun on this plan in cooperation with Environment Canada (EC).

1.1 Describe progress towards meeting the project objectives. How are the original milestones being met? List the key objectives and results achieved to date as well as any relevant application(s) of the results.

<u>Theme 1 – Processes</u>

Theme 1 has largely come to a close with most field activities being completed in 2009. Basin observations support all themes. Process information has been used to develop new parameterisations (Theme 2) which are aiding Theme 3.

Year 3 Milestones and Deliverables

- **All data collection for Theme 1 complete**

Data collection for Theme 1 is complete, with required data sets for model validation and calibration available. All research basins saw activity in 2009, and in most cases, instrumentation is retained in the basins for future research projects.

- **Analysis of aircraft flux and historical MAGS data complete**

This milestone focuses on improving understanding of the spatial variability in turbulent fluxes at an Arctic site and improving our ability to model this spatial variability at a range of scales. In particular, we are considering how spatially variable land cover, due to the alternation of open tundra and shrub tundra as well as topographic variation, affects turbulent fluxes and other energy balance components. Flux maps were developed at no cost to IP3, and gridded data and assistance in interpreting aircraft flux data have been made available to IP3.

To model fluxes at a range of scales and compare these fluxes to those measured by aircraft, the distributed hydrological model GEOtop was used. This model was chosen for several reasons: It considers the effects of small-scale topographic and land cover variability on the surface energy balance, it has a full surface energy balance component, it can be linked to other models, and it can run in a small-scale gridded mode. The model was modified for improved performance and applied in point mode and distributed mode for all of Trail Valley Creek (TVC). GEOtop was tested in point mode at two instrumented sites in TVC characterized by different land covers to determine whether the model provides reasonable estimates of turbulent fluxes. Results show that the model can predict turbulent fluxes in different land cover types reasonably well and is able to correctly describe the influence of shrubs, especially at the end of the melt period, on the sensible heat fluxes supplied to the snow, accelerating snowmelt, even if they contribute to reduce the wind speed at the surface.

Given the success of GEOtop in modelling fluxes at point scale, the gridded fluxes derived from the aircraft observations were compared with small-scale (20 m resolution) GEOtop modelled fluxes. Using a Digital Elevation Model (DEM) and Light Detection And Ranging (LiDAR) derived vegetation height, model results averaged to a 3 km x 3 km grid (for direct comparison to the aircraft flux data) demonstrate considerable ability to model the spatial variability in sensible and latent heat flux at a range of scales, from 10s of meters up to a few kilometers, and provide new insight into the range of fluxes at various scales. The results from these GEOtop simulations will be used in MESH modelling (outlined below) to improve the definitions of the Grouped Response Units (GRUs) to better simulate surface fluxes and runoff.

- **Sources, residence times, and pathways of water for intra-basin HRUs resolved; New basin runoff description linking hillslope processes and stream routing complete**

This work has been brought to maturity over the previous three field seasons and, in most cases, is ongoing as our conceptual basin understanding evolves. The role of different landscape units and their ability to generate runoff has been reported for each basin, and field data from each basin has been used to evaluate storage and flow parameters from different Hydrological Response Units (HRUs). Much of this information is now being used in Theme 2 for the parameterization and prediction of runoff. New research in Lake O'Hara includes a micro-gravity survey conducted to delineate potential pathways of groundwater in the moraine and talus fields. Papers on runoff generation and flow processes have been presented for Lake O'Hara, Wolf, Scotty, and Baker Creeks. Techniques used in this work include water balance, tracer-based hydrograph separation, recession, and time-series analysis.

Improved representation of lateral water flow in a tile/HRU is an important component of the energy and water balance. Available representations of lateral flow are generally from two unsatisfactory extremes, either simple empirical functions that require local calibration or sophisticated numerical methods not suitable for regional use. The theoretical framework, which was completed this year, involves application of Richard's equation to a sloping near-surface layer. The characterization of soil physics is consistent with the current MESH programme: No new parameters are required and those parameters used have precise physical meaning. The results were verified by excellent comparison with numerical analyses. Coding of WATDRAIN 3, which deals with intra-tile water movement, is in progress for use in MESH.

A by-product of this work is an expression for retained soil moisture in a sloped layer that takes into account influences of slope and layer thickness. This extends the definition of field capacity and resolves some of the discrepancies in published data.

- **Seasonal energy and water balance of arctic lakes determined**

Ongoing studies are considering the processes controlling lake evaporation at the sub-grid scale, in a landscape dominated by an array of lakes of various size, shape, and volume. Studies are concentrating on two lakes, one round and shallow, and the other long and deep.

- **Role of lakes in regional climate established and numerical descriptions of lake advection for all stability conditions complete**

At Crean Lake, the open water evaporation study in 2009 continued the data record begun in 2005. A flux station on the island provided direct measurement of turbulent fluxes over ice-free water as well as profiles of wind speed, temperature, and humidity; an instrumented buoy near the centre of the lake provided water temperatures; and flux instrumentation over the forest adjacent to the lake provided "upwind" land-based observations. The 2009 data is being used as a validation data set. With a contribution from IPY, Landing Lake, NWT, has been instrumented with 3 similar sites since 2007, with these data allowing for the better assessment of the size (or fetch) effect on lake evaporation. A simple, reliable model for hourly lake evaporation has been developed which requires inputs of both lake data (surface temperature, wind speed and direction, fetch distance from shore) and land data (air temperature and humidity).

- **New algorithms for turbulent closure atop glaciers complete**

Spatially distributed radiation modelling is progressing, with further exploration required for boundary-layer heat transfer, specifically bulk transfer and katabatic flow parameterization. Two masts with 1, 2, 4, and 6 m measurement levels were set 650 m apart on the Peyto glacier tongue to form the ends of a glacier wind "box" to test whether air exiting the box is cooler and faster than air entering the box (***1st Hypothesis***), whether heat flux should diminish to zero in the vicinity of a local wind speed maximum (***2nd Hypothesis***), and whether there is significant diurnal delay in meltwater flow response at the glacier surface (***3rd Hypothesis***).

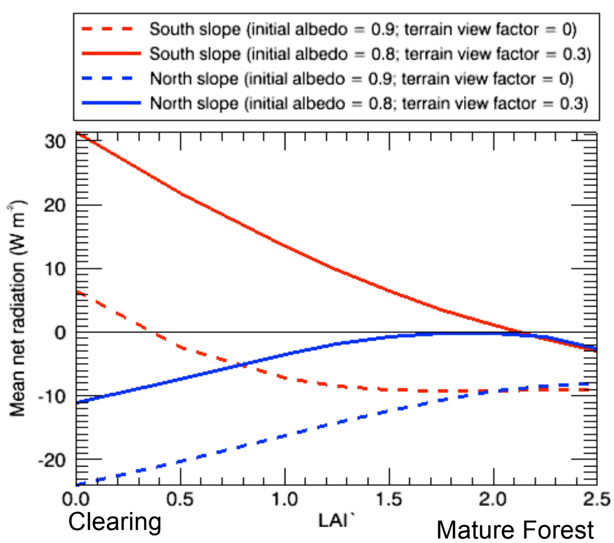
***1st Hypothesis*:** Both upwind and downwind profiles show the maximum wind speed to be 4 m above the surface, so if this level signifies a heat flow barrier, the hypothesis should hold. However, warming rather than cooling is observed at the downwind end of the box, and wind speed acceleration is modest. Because eddy correlation data suggest periodic collapse of the flow structure, it seems that such collapse would allow the invasion of warm air from above (effectively a "barrier collapse" model of glacier boundary-layer flow), thus explaining the unanticipated warming.

***2nd Hypothesis*:** Results suggest that sensible heat flux diminishes toward the 4 m level (although not to zero) and that flow structure collapse seems too infrequent to supply sufficient heat to overcome the glacier cooling effect. Persistent downward sensible heat flux across the 4 m level suggests that a "leaky barrier" model of glacier boundary-layer flow (rather than "barrier collapse") is the answer. The results also invoke caution in the use of a coordinate rotation scheme for flux estimates because inappropriate use would incorrectly rotate significant low frequency heat flux away.

***3rd Hypothesis*:** A 4-6 hour delay in the surface runoff response of the glacier ice surface is often associated with internal drainage of the glacier rather than the surface itself. It is important to accurately ascribe the cause of the delay because, although the Peyto Glacier basin is currently ungauged, realistic outflow simulations are possible via a fine-grid, spatially-distributed snow/ice reservoir model. Modelled outflow signatures will be tested against archived data from the period when the basin was gauged.

- **Numerical process descriptions of long-wave exitance from snow and shortwave radiation transfer through canopies complete**

Energy for snowmelt in forests is dominated by radiation, which is strongly affected by forest cover through the extinction of shortwave radiation along with longwave irradiance to snow via forest thermal emissions. Consequently, radiation to forest snow varies greatly with forest cover density and atmospheric condition and is further complicated in mountain environments by large variations in slope, aspect, and elevation. The sensitivity of snow to changes in these variables was evaluated using a physically-based model incorporated into CRHM of shortwave and longwave radiation fluxes, with particular attention paid to the effect of longwave emissions from forests heated by shortwave radiation absorption. This feature was simulated by calculating the vertical distribution of shortwave absorption in the canopy and the probability of longwave emissions from heated foliage being transferred to sub-canopy snow. The new model provides a useful representation of the widely varying shortwave and longwave radiation regimes observed on hillslopes of various grade, aspect,



and elevation. Seasonal model simulations show that the cumulative radiation contribution to snowmelt depends strongly on forest cover density, slope, and aspect, suggesting that the impact of changes in mountain forest cover (pine beetle, fire, logging) on the timing and rate of snowmelt are strongly controlled by topography. A strong sensitivity to albedo was also found (see Figure). Implications of this work are that opposite effects on snowmelt rate are observed from clearing forests on a south-facing versus a north-facing slope (clearing south-face increases radiation and snowmelt whereas clearing north-face decreases radiation and snowmelt) and that lowering of albedo due to dust or forest litter can significantly accelerate melt rate and also change the optimal forest structure for melt rate increase.

Theme 2 – Parameterisation

The major focus of the network in 2008-2009 has been implementation and testing of new parameterisations developed during the IP3 "year of parameterisation" (2007-2008). These parameterisations have been tested, and recommendations for model development have been made.

Year 3 Milestones and Deliverables

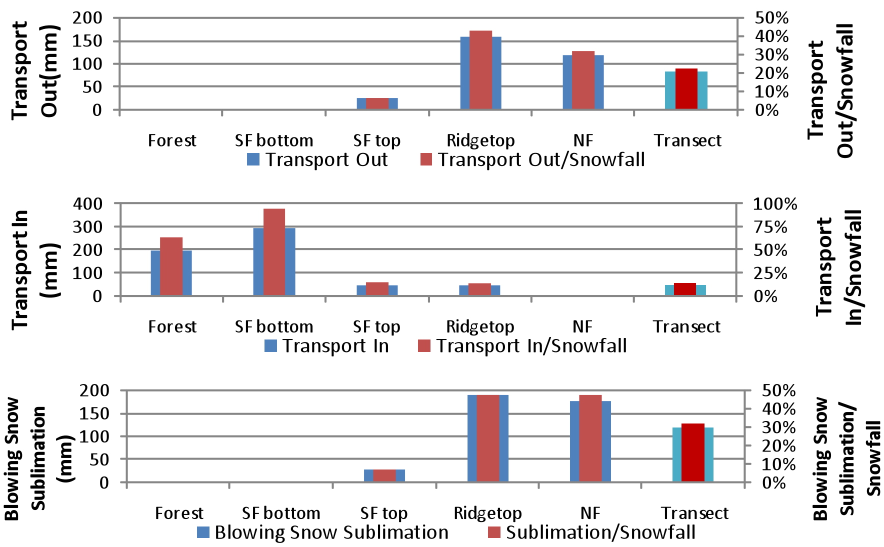
- **Incorporate numerical representations of snow redistribution, advection, lakes, landscape, and water course connectivity, into CRHM and MESH**

A new fill-and-spill scheme developed at Baker Creek has been incorporated into CRHM, providing the ability to simulate pond and lake level and runoff generation for prairie pothole (in association with the CFCAS Drought Research Initiative, DRI) and northern lake-dominated basins. Field studies suggest that HRUs and landscape tiles might be better parameterized by hydrological behaviour rather than land cover. These schemes are being tested in CRHM and MESH. At Baker Creek, primary interest is the HRU/tile connection strategy to improve mass and energy transfer between HRU/tiles. In MESH, all tiles are currently assumed to have a direct connection to the grid channel network. In fact, the destination of the runoff water could be a neighbouring tile, groundwater, or the channel network. This was addressed in WATCLASS, by a routine called WATDIVERT that was used to establish a cascade of tiles within a grid. Each tile description included three destination classes and reference percentages to be transferred from the source to destination. The actual percentage transfer depends on the relative areas of the source and destination tiles. In CRHM this is represented by a flow direction matrix where water from HRUs is routed to downstream HRUs with preference specified by weighting values determined from relative areas and slope. Similar schemes have been implemented for inter-tile/HRU transfer of blowing snow using aerodynamic principles.

Modelling studies of blowing snow over alpine terrain are showing great promise in prediction of spatial distributions of snow water equivalent (SWE) in complex environments including high-relief Rocky Mountain alpine basins and more moderate arctic tundra basins. Algorithms have been incorporated into both CRHM and MESH which include a complex terrain wind flow algorithm coupled to a two-phase flow snow transport and sublimation algorithm. This algorithm calculates snow accumulation as a residual of the snow transport, redistribution, and sublimation processes. An important feature is the spatial application of the model to aggregated HRUs or tiles having common physiographic and aerodynamic characteristics. These

HRU/tile landscape frameworks require much less physiographic information than do fully spatially-distributed blowing snow models and are suitable to application in remote alpine regions with sparse data.

Comparisons of model outputs to snow surveys suggest that calculating blowing snow redistribution at the HRU level of spatial resolution and physically-based simulation can produce reliable snow accumulation estimates in Canadian Rocky Mountain alpine catchments. Of interest are the following results: Substantial blowing snow sublimation (~30% of snowfall) occurs in alpine catchments, and tremendous redistribution of snow from alpine ridges to the near-treeline environment is occurring. This redistribution is the controlling factor in runoff generation from snowmelt in wind-swept landscapes as the variability of snow accumulation controls the snow covered area (SCA) depletion and the change in contributing area for runoff generation through spring to mid summer in this environment.



Improvements have been made to CRHM's operation in larger basins through Muskingum routing both within HRUs and between sub-basins as streamflow, and it is being interfaced with models such as the Global Environmental Multiscale Model (GEM) and is being run in batch mode over large areas. Longwave radiation routines for forest and alpine environments have been added as were methods to estimate atmospheric transmittance from daily air temperature variations, time of year, and latitude. These new features permit estimation of net radiation to level, sloped, and forested surfaces without any measurements of radiation. The model now has atmospheric information requirements restricted to air temperature, humidity, wind speed and precipitation, vastly increasing its applicability in regions with sparse measurements or for using inputs from atmospheric models. Other improvements to CRHM include a simpler user interface for assembling modules, improvements to the help file, and improvements to the forest energetics, snowmelt, blowing snow, and evapotranspiration modules.

- **Develop upscaled mass and energy balance equations for cryospheric processes in complex vegetated terrain**

Snow interception studies have been uncertain due to inadequate parameterisation of snow unloading from canopies resulting from incomplete understanding of the process. Snow unloading decreases snow available for sublimation from the canopy, which can be significant: Sublimation losses of 65% of seasonal snowfall have been observed in Marmot Creek during the course of IP3. A detailed study of snow unloading using suspended, weighed tree lysimeters and sub-canopy snow unloading lysimeters has shown that canopy snow unloading is not correctly modelled by CRHM or MESH. Unloading is not a simple function of residence time, wind speed, air temperature, or solar radiation. Instead it has been parameterised as a function of the sublimation process, in that sublimation of canopy snow both destroys the snow physical structure and is associated with energy inputs that reduce adhesion to the canopy and cohesion of snow crystals. A new parameterisation calculates unloading as a proportion of the sublimation rate. The ratio of unloading to sublimation is greater with higher air temperatures, partly explaining why sublimation is more important in cold regions than in temperate forests.

A fundamental difficulty in snowmelt calculations in complex terrain is the spatial frequency distribution of melt energy and of snow accumulation and the statistical association between the two. Snow ablation studies have focussed on application of the energy balance to estimate snowmelt over complex landscape units with consideration of sub-unit depletion of SCA as a solution to this problem. In this case, HRUs are segregated based on snow accumulation characteristics and applied melt energy fluxes. Within the HRU, variability of snow accumulation (probability density function) is allowed but not variability of melt energy. The calculated depletion of SCA and melt rate agree well with observations from oblique time-lapse digital photography, LiDAR, and snow surveys in Rocky Mountain alpine environments. Improved algorithms resulting from this application of field technology are being used to update CRHM for prediction of both snow dynamics and streamflow from high mountain areas.

Specifications for MESH have been made from these tests as the MESH snowmelt algorithms vastly overpredict alpine snowmelt in late winter and the SCA depletion algorithm uses parameters with no physical existence (D100) and thus can only be applied after calibration. It is unclear at this time as to the cause of the overprediction of melt rates by MESH in the alpine environment, but a more detailed and physically-based snow energetics routine may be necessary to obtain reliable snow simulations using MESH. Successful modelling of snowpacks in open environments was achieved with a new model being developed for IP3 and with the SNOBAL and SNTHERM models which incorporate layering, improved internal energetics allocation, alternative albedo decay functions, and sophisticated turbulent transfer schemes. The new model incorporates exchange of air through the porous media of the snowpack which can provide substantial energy inputs under certain conditions (see Theme 3 below).

At the micro (*i.e.* pore) scale, comparison of high-resolution 3-dimensional tomographic images with laboratory measurements of hydraulic conductivity on the same peat samples provided insight into variation with soil water pressure of moisture flow and redistribution processes. These tests also defined values for key thermal and hydraulic properties of peat, including some (e.g. shape factor) hitherto believed to be un-measurable by direct means. This work has improved the understanding of and ability to simulate the over-winter redistribution of moisture and energy within the active layer.

Saturated hydraulic conductivity (Ks) profiles of tundra, taiga, boreal forest, and wetland were found to exhibit uniformly high and low Ks in the upper and lower regions of the peat profile, respectively, separated by a transition zone in which Ks decreases by several orders of magnitude with depth. CRHM was modified so that Ks is parameterised as a continuous function of depth below the ground surface, so that it can be used for a wide range of organic cover thicknesses.

Numerical parameterizations for ground thaw and numerical simulation of infiltration into frozen ground have been completed and are being evaluated in the Canadian Land Surface Scheme (CLASS) to test its sensitivity to new algorithms at different sites (Wolf Creek and Scotty Creek). Modelling of Scotty Creek using MESH in its current form focused on simulation of soil temperature and soil moisture. Of particular concern is the extreme underestimation of winter ground temperature by as much as 20ºC. No reasonable combination of model parameters could maintain the modelled temperatures at the measured values.

Parameterisation in CRHM of runoff generation processes of individual permafrost plateaus have produced accurate runoff simulations from the permafrost plateau HRU for a range of hydrological input, soil moisture, and thaw conditions. A relatively simple quasi-three dimensional, coupled heat and water transfer model, Simple Fill and Spill Hydrology (SFASH), was developed to simulate the thawing of the active layer and runoff generation in an individual plateau. This is a novel application of the fill-and-spill hypothesis for organic-covered permafrost since unlike surface water impounded by bedrock, water stored in frost table topographic depressions can be released due to melt-out of the impounding ground ice without precipitation forcing as the frost table topography evolves with soil thaw.

From observations of the control of soil moisture and tree canopy density in controlling spatial variations of the soil thaw depth in the permafrost plateau HRU, a new conceptual approach was developed that will form the basis of a new parameterisation of permafrost plateau runoff coupled to active layer thaw. Thinning of the canopy by natural or anthropogenic processes can lead to increased radiation loading to the plateau surface below, leading to a local depression and enhanced thaw due to pooling. The elevated soil moisture increases the bulk thermal conductivity of the peat in the depression, allowing transfer of more heat from the surface and further deepening the frost table depression and pooling. As this process continues, the remaining trees in the area may be unable to survive due to water-logging, thinning the canopy further and increasing radiation loading of the ground surface above the depression. This positive feedback may lead to a local removal of permafrost and creation of a new isolated flat bog. This permafrost degradation appears to be occurring in Scotty Creek basin, where the permafrost cover within a 2 km^2 area decreased from 72% in 1947 to 40% in 2008. As part of the development of this new conceptual model, new LiDAR applications have been developed that precisely define the edges of permafrost plateaus for the purpose of evaluating the accuracy of aerial and satellite-based delineation of permafrost plateau locations. New techniques have also been developed to obtain consistent results among photographs and images of different resolution and spectral characteristics.

An energy-based framework for delineating runoff-contributing areas for cold regions basins continues to be developed and tested. The distribution of energy-based runoff-contributing areas in catchments persists from year to year, since spatial variations in aerodynamic and radiant energy are strongly controlled by surface topography, namely aspect and slope angle. The LiDAR-based DEM for TVC has been used in CRHM and GEOtop modelling to define the topography of the impermeable frost table at several stages of active layer thaw. The frost table topography defines the spatial distribution of Ks, local hydraulic gradients, and the location of preferential flowpaths. Modelling runs have produced frost table depths and frequency distributions that compare well with field measurements. Since arctic and alpine tundra, taiga, and the forests and peatlands of the boreal zone support a similar suite of peat-forming species, there are strong similarities in the hydraulic and thermal properties of organic soils of these terrains, which adds to the transferability of the new framework.

Various conceptual models of rainfall-runoff have been explored for Marmot Creek. The evaporative regime of the basin was explored using CLASS, the land cover was characterized using high-resolution remote sensing data, and topographic relations were compared between high-resolution LiDAR data and Shuttle Radar Topography Mission (SRTM) digital elevation data. TOPMODEL, which uses the topographic index (ln(a)/tanB) to divide the watershed moisture regime into areas of varying degrees of wetness, was selected for the hydrological modelling. While the TOPMODEL solution is subtle and elegant, the lack of a robust modeling framework, such as snowmelt and evaporation routines, make it difficult to evaluate the topographic index concepts in a natural watershed setting.

The second part of the Marmot rainfall-runoff study was undertaken via a model developed at the University of Washington, called DHSVM, the Distributed Hydrology Soil Vegetation Model. Meteorological and land surface data from Marmot were used to force DHSVM. Rather than making assumptions regarding relations between topography and moisture, this model calculates them explicitly. In DHSVM, gradients between adjacent cells are resolved and used to explicitly route surface runoff and groundwater from grid to grid. In addition, DHSVM has been coded as a robust hydrographical model able to simulate the annual hydrologic cycle of the Marmot Basin, including snowmelt and evaporation. As a result, a continuous 4-year simulation was performed over the Marmot Creek basin with very promising first results.

- **Representation of regionally averaged fluxes over lake and snow dominated terrain**

A new release of the Distributed Blowing Snow Model (DBSM) was prepared, including the implementation of two different methods for simulating wind flow over complex topography. These were tested against wind measurements from Wolf Creek and implications for the modelling of snow redistribution were investigated. A deterministic model for the bending of shrub branches under applied snow loads was developed. This process is important because the degree to which shrubs are buried by snow is an important control on the radiative characteristics of tundra landscapes. A parameterisation for radiative transfer through discontinuous forest canopies has been developed. A parameterisation for heat and moisture fluxes to the atmosphere over heterogeneous vegetation and snow cover has been evaluated. A parameterisation for the landscape fraction of exposed vegetation is being developed from the shrub bending process model.

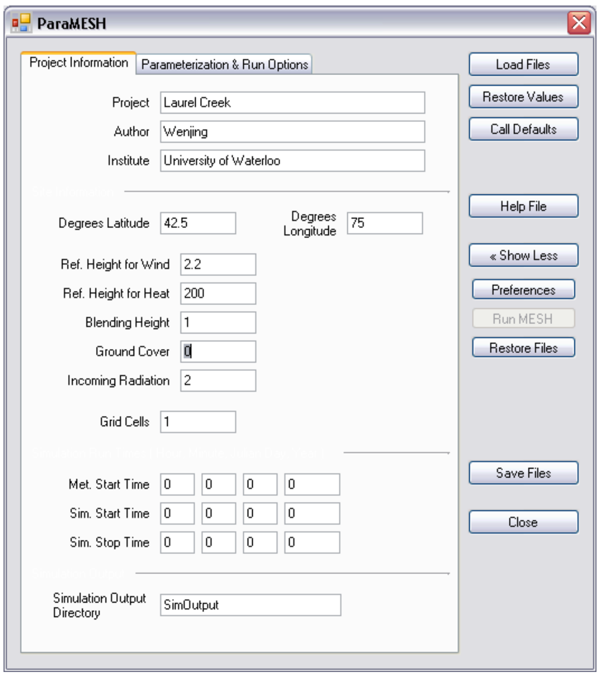
Theme 3 – Prediction

The focus for Theme 3 is on model improvement and testing using the parameterisations and other results of process-based experiments, scaled from the measurement point to the watershed using landscape units such as the HRU or tile. Improved basin segmentation and process parameterisation in hydrological and land surface models, including CRHM and CLASS, is being applied to MESH development via close partnership with IP3 personnel in Themes 1 and 2. All IP3 members have access to CRHM, CLASS, and MESH for testing. It is expected that advances made through IP3 will be operationalized into the EC modelling system for weather forecasting and climate modelling as well as hydrological cycle prediction.

Year 3 Milestones and Deliverables

- **On-going improvements of MESH with new algorithms on each research basin, and evaluate model performance with reference to measured mass and energy balances**

MESH has been run on each basin in its current form, and its successes and failures have been instructive in confirming appropriate components of the model and recommending specific improvements. Significant progress in MESH development has been achieved through the MESH software group which is composed of IP3 members and other EC personnel. The MESH 1.3 code has been examined and profiled, with significant performance bottlenecks identified in several subroutines including several redundant loops. Dramatic improvements in speed (3 times faster) and stability have been accomplished via use of a high end Intel Fortran compiler and double precision. Recommendations have been made to improve the numerical performance of MESH which will permit high resolution runs of the model. Further improvements to vertical water and energy budgets (in CLASS), tile sequencing (required by the Meteorological Service of Canada, MSC), and the MESH interface (to deal with distributed inputs and initial conditions) are planned for Year 4.



MESH development in the past year includes contributing to the release of MESH 1.2 (August 2009) and the beta version of MESH 1.3, consolidation of the DDS optimization interface, and development of ParaMESH, a GUI interface for MESH. ParaMESH was developed as a result of using MESH 1.2 in a graduate course where it became clear there was a need for a more robust interface for novice users. ParaMESH is a form-based interface that includes file editing with context help. It performs rudimentary consistency checks, retains history of previous parameter changes made by the user, and allows parameter space exploration by a variety of strategies. It is sensitive to version number and thus maintains downward compatibility. It has a developer interface that provides direct access and editing of the ASCII files. Specific code contributions relate to lateral flow.

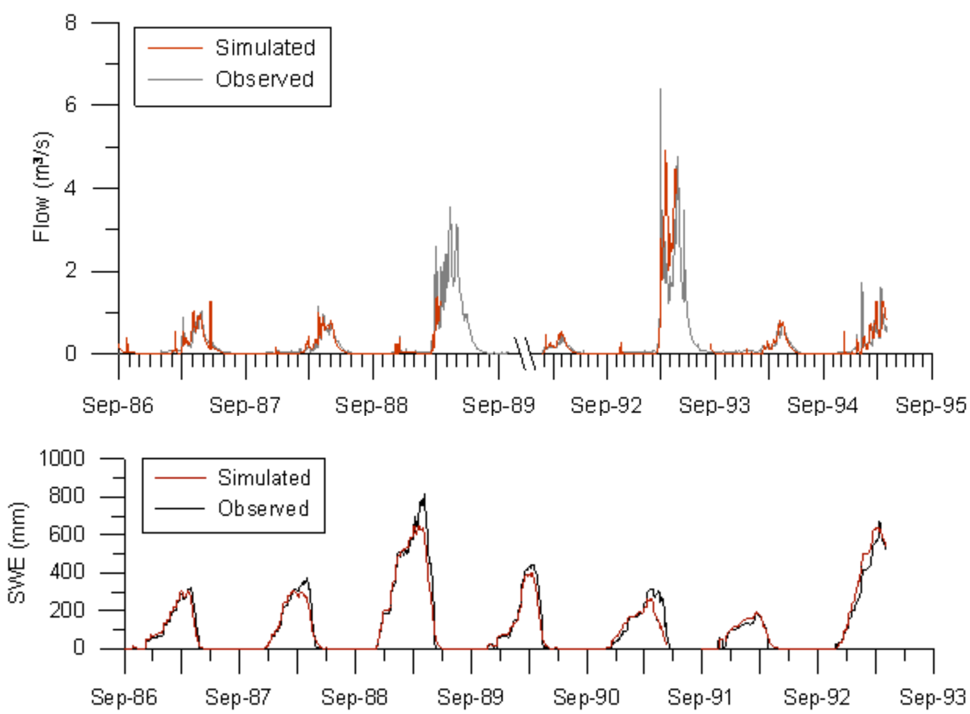
To complement the IP3 modelling suite, a new snowpack physics model has been developed based on the improved process understanding developed in IP3. The model assumes penetration of windflow into the porous structure of the snowpack and thus explicitly considers atmospheric exchange in the upper snowpack layer. Initial tests with this new model are very encouraging as it is able to describe atmospheric energy exchanges with snow in conditions where existing models fail. The model also explains features such as the windless exchange coefficient which has been necessary to prevent snow surface temperature collapse in models run for extremely stable, low wind speed, cold, clear-sky nights.

- **Re-evaluate regional hydrological response based on improved parameterization from research basins and IP3 field studies**

MESH version 1.3 has been tested for multiple years in TVC to determine its ability to model changes in snow cover, turbulent fluxes, and runoff. Initial runs for 2 years, 1996 and 1999, using standard tiles with additional parameters are ongoing, with the results from the high-resolution GEOtop runs guiding tile modification to better represent the spatial heterogeneity of the tundra. The MESH results indicate that the model reliably predicts snowmelt runoff and change in SCA but does a poor job of modelling summer rainfall runoff, possibly due to extreme drying of the basin soils after the snowmelt runoff. At Lake O'Hara, MESH has been run in a single column mode to identify algorithms requiring significant modification, with results indicating that MESH will require major work to function properly in alpine basins.

A modified version of standalone MESH (built on version 1.2) was utilized for various modelling and calibration experiments on IP3's Reynolds Creek Research Basin in Idaho. Reynolds Creek is a well-instrumented research basin operated by the US Department of Agriculture (USDA) and thus forms an excellent case study for thoroughly testing MESH performance. A limited number of experiments were also performed for Wolf Creek. Calibration experiments involved applying single or multi-objective automatic (i.e. optimization) calibration strategies to calibrate the model to streamflow and/or SWE data. Modification made to MESH included the ability to isolate and only simulate a sub-area or sub-basin instead of simulating the entire basin. All changes to MESH were made in conjunction with EC MESH developers.

Calibration experiments show that a case-study specific, data-based initial parameter set greatly improved calibration results over a simple random sampling approach to define the initial model parameter set. Similarly, the use of uninformed parameter ranges that are too large caused the automatic calibration algorithm to fail at practical computational constraints specified in the experiments (1000-10,000 model evaluations). A very large set of model parameters was calibrated, and although results at Reynolds Creek are quite good using only 1000 model evaluations for calibration, results at Wolf Creek indicated that a computational budget increase from 1000 to 10,000 model evaluations notably improved calibration results.



For Reynolds Creek, a 2 km grid was defined along with multiple land cover based GRU configurations (1 GRU vs. 6 GRU). The calibrated 6 GRU model and the calibrated 1 GRU model generated similar quality streamflow predictions but the 6 GRU model was also capable of high quality SWE calibration results across 3 of 5 sites. Increasing spatial detail in the Wolf Creek model (1 GRU → 4 GRU) substantially degraded model calibration results. A simple multi-objective approach for simultaneous SWE and streamflow calibration was demonstrated to generate reasonable quality results with a calibration budget of only 1000 model evaluations.

Overall, without model calibration, the MESH model predictions under the initial model parameter set were quite low (daily streamflow Nash-Sutcliffe coefficient of 0.20, aggregated daily SWE Nash-Sutcliffe coefficient across 5 sites of -0.72). The simulated results under the best parameter sets for Reynolds Creek SWE (at the snow pillow site, Nash-Sutcliffe of 0.96) and streamflow (at the Tollgate station, daily Nash-Sutcliffe of 0.85) were compared to the measured data (see Figures) for the validation period. These model results turned out to be very difficult to generate due to MESH instability issues (i.e. the model terminated with an error near the beginning of the validation period and thus simulation results from 1987-1993 are based on multiple model runs rather than a single extended model run).

- **The prediction team will work closely with the research teams in Themes 1 and 2 to evaluate the relative importance, sensitivity and cumulative effect of introducing algorithms, parameterizations and new landscape segmentations derived through field and basin experiments**

The IP3 Prediction Workshop was attended by most investigators and many collaborators who drafted a detailed plan for development of and improvements to MESH/CLASS by the action of subject area teams. Work is proceeding on this plan, detailed below with specific investigators, students, and collaborators identified for element delivery:

1. Single-column tests of CLASS, using either RUNCLASS (which does not include interflow) or stand-alone MESH (for testing CLASS on a slope). *Vincent Fortin and Ric Soulis.*
2. Modelling vegetation (shrub) interactions with snow and including new parameterisations in CLASS. *Paul Bartlett, students of John Pomeroy, students of Richard Essery.*
3. Radiation on complex topography (elevation, slope, aspect, vegetation), incorporation into MESH and CLASS. *Diana Verseghy, Al Pietroniro.*
4. Conversion of explicit time stepping scheme (up to 1 hour) for snow and soil layer (as thin as 1 cm) temperatures to a higher-order explicit scheme, and incorporation into CLASS. *Bruce Davison, Diana Verseghy.*
5. Empirical lake evaporation parameterisation. *Anthony Liu, Vincent Fortin, Raoul Granger.* (Long-term: Inclusion of full physically-based lake model in CLASS – *Murray Mackay*).
6. Basin discretization – not clear, as basins are all so different. Recommendation is for sensitivity testing, to determine relative effect of different discretization strategies. *Individual basin groups.*
7. Inclusion of spatial variability of energy fluxes and snow into MESH. *Chris Marsh.*
8. Need different tile connectors for different processes – need to be able to transfer surface flow, interflow, groundwater flow, snow. Should connectors be two-way? *Matt MacDonald.*
9. Debug the model – new version, rename shed file. *Chris Marsh working on CLASS/MESH. Diana will provide comments on review.*
10. Make parameters transferable – set up GRU library. Elevation differences between GRUs determine flow between GRUs. Set up a separate drainage GRU layer. *Brenda Toth, Bruce Davison, HAL lab (custodian).*
11. Grid connector: Split basin into smaller grids, set threshold flow for water to leave grid. Be able to transfer water without using the stream channel (use drainage area and set a flag for each square to determine if grid has a channel), using probability (grid <10 km) or surrogate river systems (grid >10 km). *Frank Seglenieks.*

12. Use other variables (like soil moisture, snow measurements) in addition to streamflow and timing to measure success. *Everybody.*
13. Shortwave and longwave radiation distribution for each tile according to slope and aspect – consider direct/diffuse, sky view factor, elevation/temperature. Incorporate into CLASS, MESH. Each basin lead to calculate distribution of slope and aspect for their basin, to be imported into Green Kenue, which could be improved to do this calculation itself if this information results in improved modelling. *Al Pietroniro (Green Kenue), John Pomeroy, Matt MacDonald/Chris Marsh.*
14. Basin discretization by distribution of input data by elevation: This would allow elevation-dependent GRU temperatures/water vapour and accommodate snow/rain line, but may be difficult in complex topography if grid size nears 1 km. *Al Pietroniro, John Pomeroy, Matt MacDonald/Chris Marsh.*
15. Distribution of wind speed across grid – need generic distribution function, hard coded into MESH (eventually into Green Kenue), to avoid computational complexity and large input data. Some code may already be available in CRHM? *Matt MacDonald, student of Bryan Tolson.*
16. Blowing snow incorporated into MESH, considering slopes, GRU segmentation, for Prairies/Arctic and mountains. *Matt MacDonald.*
17. Snow unloading – improved approach for CLASS. *Jimmy MacDonald, John Pomeroy, Paul Bartlett.*
18. Radiation transfer through forest in CLASS, considering slope/aspect in addition to LAI. *Chad Ellis, John Pomeroy, Diana Verseghy.*

For MESH and CRHM, optimization of model parameterisation at the basin scale is being accomplished using field estimates of SWE and streamflow hydrographs. Both inductive and deductive approaches to hydrological simulation were used, with multi-objective optimization required for the inductive approach. Standard methods of basin segmentation based solely on land cover are being refined through new knowledge that indicates variability in snow accumulation and ablation is controlled by position with respect to windflow, slope, aspect ,and elevation; thus basin segmentation, is a function of local topography. MESH is designed to allow for the establishment of various combinations of grouped HRUs or tiles so that optimal basin segmentation schemes can be proposed and evaluated at the GEM-Limited Area Model scale.

For CLASS and MESH, work is well underway to incorporate algorithms describing incident shortwave and longwave radiation on sloping surfaces in complex topography; the development of new parameterizations for the interaction of vegetation, particularly shrub tundra, with snow cover; and the implementation of blowing snow into the CLASS/MESH framework. Further progress has been made on setting up CLASS for the various research basins, and a project has been initiated to investigate the conversion of the prognostic variable calculations from an explicit forward-stepping scheme to an implicit one, to enhance the speed of the model.

An application of MESH to glacier contribution to streamflow was made for the Peyto Glacier and nearly headwaters of the North and South Saskatchewan Rivers in the Rocky Mountains. A new volume–area scaling relationship was applied to estimate glacier wastage and seasonal melt contribution to the North and South Saskatchewan Rivers from 1975 to 1998. Wastage was defined as the ice-melt volume that exceeds the volume of snow accumulation into the glacier system in a hydrological year, causing an annual net loss of glacier volume and an enhancement of annual streamflow. Melt was defined as the snow and ice melt volume that is equal to, or less than, the volume of snow that accumulates into the glacier system in a hydrological year. Simple parameterisations were used in this study to calculate snow and ice melt, but the approach can be used for the full CRHM or MESH models. Using the MESH routing scheme for the headwaters, wastage was estimated to vary between basins with similar glacierized areas reflecting the individual response of glaciers to climate. Glacier wastage contributed over 10% to July to September streamflow in some headwater basins, but less than 3% annually to the river flow at Edmonton and Calgary. Melt was positively correlated with basin glacierized area and contributed over 27% to the July-September flow from basins with greater than 1% glacierized area, and over double the wastage contribution to annual streamflow at Edmonton and Calgary. Future glacier decline is expected to result mainly in an advancement of peak flow towards a non-glacierized snowmelt regime hydrograph, resulting in significantly reduced late summer flows further reduced by decreasing wastage contributions.