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REPORT OF THE GEWEX/ACSYS WORKSHOP ON COLD REGIONS HYDROLOGICAL MODELLING

(Quebec City, Canada, 25-27 August 1998)

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1. INTRODUCTION

1.1 Background

On August 25 to 27, 1998, a joint GEWEX/ACSYS workshop was held to discuss hydrologic modelling in cold regions and, in particular, to determine the need for an intercomparison study between hydrological models using data from northern basins. The workshop was an outgrowth of discussions at the ACSYS Scientific Steering Group (SSG) and the GEWEX Hydrometeorology Panel (GHP) meetings. This report summarizes the results of the workshop. After some introductory remarks a description of GEWEX and other hydrologic modelling activities is given. The document then provides summaries of the science presentations, reports from the working groups established at the meeting and workshop recommendations.

Appendix A contains a list of the attendees, Appendix B provides a list of acronyms used in the report.

The goals of the workshop were: 1) to develop a recommendation on hydrologic models that could be used in estimating runoff for basins of all spatial scales that drain into the Arctic Ocean; 2) to provide a status report on these models; 3) to determine the data requirements for running these models; 4) to determine the physical processes that should be represented in these models and 5) to select several basins where these models could be run on an experimental basis. The scientific planning group for the meeting included representatives from the ACSYS hydrology community and from the GEWEX Continental-scale Experiments. Four out of the five principal Continental-Scale Experiments in the GEWEX programme include important cold region and/or cold season modelling activities. The four experiments with relevance to the Arctic Basin include the GAME (GEWEX Asian Monsoon Experiment)-Siberia, MAGS (Mackenzie GEWEX Study), BALTEX (Baltic Sea Experiment) and GCIP (GEWEX Continental-scale International Project). All of these experiments are giving emphasis to resolving water balances for their basin. In the case of MAGS and GAME-Siberia, closing the water balance implies the production of reliable estimates for the contributions of these basins to the freshwater influx into the Arctic Ocean.

Oceanographers need better estimates of runoff into the Arctic Ocean. While some ability to produce such estimates does exist, the large differences between estimates from different models of Arctic Basin runoff suggest that the models lack consistency and transferability. The availability of reliable runoff estimates is also an issue. In some cases the runoff into the Arctic Ocean is measured reasonably well, while in other basins it is not monitored. Issues that need to be considered include:

1. How large an increase in accuracy can be realized in modelling freshwater inputs to the Arctic Ocean by improving hydrologic models? It was unclear at this workshop how oceanographers would interpret a revised estimate of inflows of freshwater fluxes into the Arctic Ocean due to the use of improved hydrologic models. Furthermore it was not clear that hydrologists would be able to determine when they had achieved a significant increase (e.g. 10%) in model accuracy.

2. Given that a fractional increase in the accuracy of hydrologic models is important for ACSYS, what models are most appropriate for describing runoff estimates? Should an intercomparison rely on watershed scale models or distributed models run at much coarser resolution?

3. Do experimental basins exist where the data sets are of sufficient density that a model development and validation exercise could be carried out? While both MAGS and GAME-Siberia have enhanced data collection activities it is not clear that these data are the most useful for a hydrologic model intercomparison. Would it be necessary to mount an observational activity to support a hydrological model intercomparison?

4. How should new basin studies resulting from this workshop be planned, designed, funded and initiated?

(Rick Lawford)

1.2 ACSYS Hydrological Modelling

In accordance with its Initial Implementation Plan (IIP), one of the main aims of ACSYS Hydrological Programme is to develop mathematical models of the hydrological cycle under specific Arctic climate conditions, suitable for inclusion in coupled climate models. As indicated in the ACSYS IIP, macroscale models of the hydrological cycle have not yet been developed for Arctic conditions. Cooperation with GEWEX sub-programmes, particularly MAGS and GAME-Siberia, is needed to address this issue. The Initial ACSYS Implementation Plan calls for:

- Adaptation of macroscale hydrological models developed within the framework of GEWEX to Arctic (high-latitude) climate conditions; and
- Development of physical (conceptual) or parametric mesoscale hydrological models for selected river catchments within the Arctic region.

The ACSYS hydrological programme has adapted some hydrological cycle models to Arctic conditions. Different types of models (CLASS, WATFLOOD, VIC-nL, HYDROGRAF) have been run for different Arctic watersheds. However, different groups of ACSYS hydrological modellers have not focused their efforts on a specific basin.

(Valery Vuglinsky)

2. CONTRIBUTIONS OF GEWEX CONTINENTAL-SCALE EXPERIMENTS (CSEs) TO COLD REGION HYDROLOGICAL MODELLING

2.1 Contributions of MAGS to Cold Region Hydrological Modelling

One of the objectives of MAGS is to develop a coupled atmospheric/hydrologic modelling scheme that properly completes the vertical and horizontal water budget for the Mackenzie River basin. This will involve the Canadian Regional Climate Model (RCM) coupled to a land-surface scheme (CLASS) and a distributed hydrologic model (WATFLOOD). The modelling goal is to run the enhanced RCM satisfactorily for a 12 month period without reinitialization. The Canadian GEWEX Enhanced Study (CAGES) will provide independent assessments of the basin state variables during the study year. It will also provide enhanced data sets required for testing and validating models. It will focus on a water year of September 1998 to August 1999. An additional component of the MAGS hydrologic modelling strategy is to carry out detailed process studies for the validation of vertical water budget and routing methods, and for the development and improvement of algorithms.

The coupling process is occurring over three progressive stages. Level 1 coupling refers to atmospheric models linked to a land-surface scheme. In Level 2 coupling, there is full interaction between a land-surface scheme and a runoff model but no atmospheric component. These are essentially hydrologic models with a land-surface scheme providing the vertical water and energy budget. They can be forced by conventional meteorological station data or NWP or GCM output. Level 3 coupling refers to full coupling among atmospheric and hydrologic models, and a land-surface scheme.

The coupling strategy involves the Canadian Regional Climate Model (RCM), the Canadian Land Surface Scheme (CLASS) and the University of Waterloo distributed hydrologic model WATFLOOD. These models have similar physics and use land cover fractions for energy and water budget calculations. For Level 2 coupling, WATFLOOD/CLASS is being tested in southwestern Ontario, on BOREAS watersheds and on the Columbia River basin. WATFLOOD draws overland flow, interflow and base flow from CLASS's surface and subsurface reservoirs and routes the runoff hydraulically to stream gauges of interest. This improves the vertical budgets in CLASS and provides simulated streamflow. The tests are being conducted with a variety of observed meteorological data and NWP output. A code to modify CLASS for Level 3 modelling is being implemented. CLASS will incorporate the runoff calculations from WATFLOOD and will produce overland flow, interflow and base flow as output fields for each model grid element. WATFLOOD will route the results to points of interest in selected basins.

(W.L. Quinton and P. Marsh)

2.2 GAME-Siberia

The starting year for the Siberian regional study was 1997, when local observation sites were established in tundra and taiga areas, and measurements using newly introduced instruments were initiated. Another important milestone was the participation of the Frontier System for the Global Change Research (Japan) in this project. The Frontier System will take responsibility of the modelling and dataset assembling components for GAME-Siberia.

The main scientific accomplishments are the results related to water/energy exchanges coming from local scale observations. The results of flux measurements obtained on a tower and a mast at Yakutsk for the wet 1997 summer show high values of evaporation until July and decreasing values afterwards. This tendency was different from what was expected based on earlier studies. Many new data related to the thermohydrological characteristics of ground surface layers have been obtained from tundra sites. Non-uniform accumulation of snow and the spatial variation of thawing depth seem to affect the time variation of discharge in the tundra area. In relation to modelling studies, simulation and verification of large-scale drainage (Lena River scale), small tundra drainage ($5.5 km^2$) and heat/water exchange modelling in forested zone have been undertaken.

The main directions of work planned for the 1999-2001 period are: (1) Year 2000 Intensive Observation Period is planned at a taiga site mainly to evaluate diversity of surface fluxes using surface observation network and aircraft measurements; (2) Clarification of the annual water/heat exchange and circulation in tundra and southern mountain taiga regions; (3) Application and improvement of atmospheric, hydrological and land-surface model using experimental and operational data. The decrease in the operational hydrometeorological observations of Russia is a concern for GAME-Siberia.

The objective of modelling activities in GAME is to develop new models or modify already existing models which can simulate:

(1) One-dimensional heat/water exchanges.
(2) Drainage scale water budgets.
(3) Large scale river runoff.
(4) Thermohydrological conditions under changes in land cover.

The Frontier Research System for Global Change will be responsible for developing and running hydrometeorological models within the GAME framework.

(Tetsuo Ohata)

2.3 BALTEX

The main factor that differentiates BALTEX from the other CSEs is the Baltic Sea itself, which acts as a transition zone between the world ocean in the west and the Eurasian continent in the east. The importance of oceanographic processes on the energy and water cycle are thus emphasized, and coupling meteorological and hydrological models to oceanographic models is a primary goal. Like the other GEWEX projects, BALTEX also has the goal of transferring methodologies to other continental areas with similar characteristics in order to both improve global climate modelling and to enhance regional-scale modelling.

There are four primary components to hydrological model research under BALTEX. These are as follows:

- development of a full hydrological model for the BALTEX region;
- use of hydrological models and observations to validate the hydrological components of the meteorological models;
- development and intercomparison of hydrological models for selected river basins; and
- development of a coupled atmosphere/ocean/land surface model.

An intercomparison of models will be conducted in four test basins in significantly different parts of the Baltic Sea Drainage Basin. These are the Odra, Daugava, Neva and Torne River Basins. Two phases of the intercomparison are planned including: 1) intercomparison and validation of hydrological models, and 2) intercomparison and validation of the representation of individual processes of the surface energy, water balance and soil water dynamics of atmospheric and hydrological models. Phase 1 will utilize at least ten years of daily data. Phase 2 will cover the main BALTEX experiment observation period, April 1999 to March 2001, and focus on both large scale data and data that are available from field experiments. It will not be limited to the four test basins mentioned above.

Thus far, modelling work within BALTEX has concentrated on the first two research components. A large-scale hydrological model of runoff for the entire Baltic Sea Drainage Basin, HBV-Baltic, was developed at SMHI. This model was then used in offline coupling to evaluate hydrological components of both the ECHAM4 and UKMO-UM atmospheric climate models. This comparison helped identify systematic compensating errors in the land parameterization schemes. Further tests with other climate models are planned, as well as applications in which hydrologic input will be provided for oceanographic models.

A grid based distributed hydrological model for use on large river basins was developed at GKSS. Thus far, it has been used for applications on the Odra and Elbe Rivers. It is designed to be compatible with the REMO regional atmospheric climate model and there are plans to use it in coupling experiments with this model in the near future. Groups in Russia, Latvia and Poland are currently carrying out other hydrological modelling work focused on applications to large basins. These activities are all steps that lead us closer to fulfillment of the fourth component of BALTEX, namely coupled atmosphere/ocean/land models.

(Phil Graham)

2.4 Cold Season Studies in GCIP

The GEWEX Continental-scale International Project (GCIP) is currently undertaking cold season research in the northern part of the Mississippi River Basin during the winter and spring seasons. The focus of this research is to determine how the land-atmosphere coupling changes during the winter to spring transition. An understanding of cold season land-surface processes is needed to assist GCIP in achieving its mission of demonstrating the capability to predict changes in water resources on time scales up to seasonal and interannual as an integral part of a climate prediction system.

The overall objective for GCIP's cold season research is to quantify cold season regional water and energy budgets based on the improved understanding of land-atmosphere processes and the representation of these processes in models. The scientific hypothesis being addressed in this study is related to the perception that during the winter months when a snow cover persists the land surface has relatively little influence on the atmosphere. However, during the spring when the snow melts, the ground thaws and then warms and the vegetation "greens", the surface begins to have a major effect on the atmosphere through the surface latent and sensible heat fluxes. Research on cold season processes is intended to test this hypothesis and to quantify the rates at which these processes occur.

The thrust of the GCIP cold season research includes data collection, data analysis and modelling activities in the upper Mississippi River Basin during the winter and spring of 1997-98 and 1998-99 winters. Observational studies have been very important in providing unique data sets for model development and validation. In particular, the data on ground freezing and melt ponding are useful in validating hydrometeorological models. Other studies are considering the time variations in the snow cover heterogeneity during the melt season in differing vegetation types. These observations are being used to incorporate snow processes into the RAMS, SSiB, BATS, VIC-nL and Eta models. Other studies relate to the derivation of better snowfall fields through the correction of gauge data, the use of satellite data to provide better snow cover information and the merger of satellite and aircraft data to produce better snow water equivalent products. These products are available through the GCIP data management system and can be accessed through:
http://www.ogp.noaa.gov/mpe/gcip/index.htm

(Rick Lawford)

3. HYDROLOGIC MODELS

3.1 High-Latitude Land-Surface Processes in Climate Models: The VIC Perspective

Despite the importance of Arctic freshwater fluxes to the thermohaline circulation of the world ocean and the global heat balance, the hydrology of the Arctic basin land surface is not well understood. The Arctic basin, defined by ACSYS as the land area draining to the Arctic Ocean (17,400,000 km^2), spans 37 degrees latitude from 46°N to 83°N. Over 40 percent of this drainage lies south of 60°N in the zone of sub-Arctic boreal forest, so that forest effects account for a substantial component of the hydroclimatology of the basin. In tundra areas, sublimation and wind redistribution of snow are important determinants of the snow available for runoff. Space-time analysis of historical streamflow and climatological observations, along with remotely-sensed snow cover data, demonstrate the importance of surface storage, latitude and elevation on runoff generation in the Arctic basin. Such intercomparisons can serve to assess and improve process representation in hydrologic models.

The Variable Infiltration Capacity (VIC) model was applied to the Arctic basin at two-degree spatial resolution using daily precipitation and minimum and maximum temperature data prepared as part of a previous study by Schnur. The Mackenzie and Ob River basins were used as preliminary test basins, prior to extending the model implementation to the entire Arctic drainage basin. Model results were evaluated using remotely sensed snow cover extent and snow depth (from the EOSDIS NSIDC Distributed Active Archive Center), in addition to observed streamflow hydrographs. An initial application of the model (VIC-2L) utilized the Anderson temperature index snow model, which resulted in an overprediction of the length of the snow season. Subsequent application of a more current version of the VIC model, which incorporates a physically-based snow model, was able to represent the annual cycle of snow extent reasonably well. However, while the major features of seasonal streamflow variation are represented, the recession following the spring snowmelt is generally too rapid.

Ongoing work focuses on simulation of the hydrology of the entire Arctic drainage basin. To assess model transferability, calibration parameters from the Ob River have been used to simulate Yenesei and Lena River discharge. The simulated Yenesei discharge represents the observed annual cycle well. However, the simulated Lena River discharge highlights that differences in basin-wide soil moisture storage must be explicitly represented. A preliminary application of the VIC model to the entire Arctic Basin indicates that the average annual length of snow cover is well represented when compared to remotely sensed snow cover extent.

(Laura C. Bowling and Dennis P. Lettenmaier)

3.2 Physically Based Hydrological Models for Polar Regions

Current activity in hydrologic modelling is directed towards more physically based distributed models. This often requires subdividing the watershed into smaller aggregated units in order to more closely represent the observed hydrologic or hydraulic phenomena. One method of discretisation is the Grouped Response Unit (GRU) approach, which is a grouping of all areas with a similar land cover within a specified grid or sub-basin boundary. The grid square or sub-basin will contain a number of distinct GRUs, each generating runoff independently using the same meteorologic forcing. Runoff generated from the different groups of GRUs are then summed together and routed to the stream and river system. The major advantage of the GRU approach is that it can incorporate the necessary physics while retaining simplicity of operation. The WATFLOOD model divides a watershed into a number of GRU and discritises the basins into a series of square grids. The objective of using the GRU method of discretisation is to model hydrologically consistent sub-areas of the watershed, each with known properties. Flow rates of inter flow and base flow depend upon the hydraulic conductivity which is optimized on the basis of land cover. Routing between grids follows the storage routing method. Input from a digital elevation model (DEM) and land cover are the spatial data sources needed to generate the required physiographic files.

The GRU approach is appropriate for northern environments for a number of reasons. Firstly, the landscape based approach for model parameterization requires a minimum amount of ground based data for model calibration. Although not an optimal scenario for modelling, this situation is especially true for remote northern basins. The GRU approach also allows for detailed physics in the vertical water budget on a landscape basis, being entirely consistent with the mosaic approach currently being implemented in atmospheric models. The WATFLOOD model theoretically can incorporate any surface vertical water budget (SVAT) model and is currently being coupled to the Canadian Land Surface Scheme (CLASS). WATFLOOD-CLASS will improve the vertical water balance calculated by CLASS alone, since a surface gradient will move the water into the micro drainage system. Without topography, CLASS overestimates evapotranspiration and underestimates infiltration. By providing local slope effects through WATFLOOD, the WATFLOOD-CLASS approach increases total runoff while decreasing soil moisture. The WATFLOOD-CLASS scheme is easily incorporated into an atmospheric model provided soil parameterizations are established through calibration using the streamflow hydrographs. This then leads to a fully coupled atmospheric-hydrologic model with improved feedback to the atmosphere.

(W.L. Quinton, A. Pietroniro, E.D. Soulis)

3.3 Summary on Existing River Discharge Data for Pan-Arctic Hydrological Modelling

In order to assess the contemporary river discharge into the Arctic Ocean, it is necessary to create reliable runoff forming models in the pan-Arctic region. This requires the collection of the most complete discharge data covering the entire Arctic drainage system. A database of river discharge at monthly time steps for the pan-Arctic drainage system was created within the framework of the NSF project “Contemporary Water and Constituent Balances for the Pan-Arctic Drainage System”. The database currently holds 3539 hydrological sites found in the Pan-Arctic drainage system. These have been compiled principally from three sources (Table 1).

Table 1. Gauge Coverage and Sources of the Pan-Arctic River Discharge Data

REGION	**SOURCE**	**NUMBER OF GAUGES**
Eurasia	State Hydrological Institute (Russia)	1422
Canada	Environment Canada	2082
United States	USGS	35

Table 2. Drainage Areas, Number and Density of Gauges for Arctic Hydrological Regions

REGION	DRAINAGE AREA (km^2)	NUMBER OF GAUGES	OBSERVED AREA (% OF TOTAL AREA)	DRAINAGE AREA PER GAUGE (km^2 $gauge^{-1}$)
Bering Strait	1,192,212	103	87	11,600
Chukchi Sea	223,312	4	20	59,000
Beaufort Sea	2,094,649	520	87	4,030
Artic Archipelago	1,242,713	25	24	50,000
Artic Subocean	75,618	0	0	
Baffin Bay	156,865	2	2.5	76,900
Hudson Bay	3,242,213	1444	79	2,250
Hudson Strait	435,233	29	58	14,900
Foxe Basin	276,224	0	0	
South Greenland	215,597	2	1.6	111,000
Greenland Sea	85,937	5	10	17,200
Norwegian Sea	161,289	7	12.4	23,300
Barents Sea	1,277,428	270	80	4,740
Kara Sea	6,222,540	854	92	7,300
Laptev Sea	3,669,690	188	90	19,600
East Siberian Sea	1,351,234	86	88	15,600
Greenland ice cap	1,834,000	0	0	
TOTAL	23,766,754	3539		6700

The Eurasian gauges include data from Russia, Norway, Kazakhstan, Mongolia, Finland and Iceland. Much of the data for Russia was digitized from hydrological yearbooks for the purposes of the NSF project.

The pan-Arctic region has been defined to include all land area draining into the Arctic Ocean as well as those regions draining into Hudson Bay, James Bay, Hudson Strait and the Bering Strait. Large drainage area gauges are most important for comparing continental scale water balance model results to the observed record. Table 2 shows the drainage area of the Arctic Sea Basins along with the total number of gauges, the observed area as a percent of total area and the drainage area per gauge. The drainage area from each basin was defined using a digital river network, STN-30, at 0.5° x 0.5° grid spacing, developed at the University of New Hampshire, USA.

Based on analysis of the pan-Arctic river discharge database a number of statements can be made regarding the quantity and quality of the data.

Data Quantity: The duration of the Eurasian observations is typically longer than observations from North America. However, there are more gauges in North America. After 1986, the total number of available gauges decreases dramatically for Eurasia. The time period from 1970 to 1985 provides the largest number of gauges and therefore the greatest density of points for runoff analysis covering the entire pan-Arctic region.

Data Quality: There is a bias in the distribution of gauges toward lower latitudes. The amount of missing data for those years with some data is greater in North America. Most of the missing data gaps occur during the winter period from November to February. Based on the availability of river discharge data, any model intercomparison covering the entire pan-Arctic should restrict the time range to the years 1970 to 1985.

An updated version of this database, R-ArcticNET v2.0 (Lammers et al., 1999), is now available on the WWWeb at http://www.R-arcticnet.sr.unh.edu/.

(A.I. Shiklomanov and R.B. Lammers)

3.4 Retrieval of Altitudinal Distribution of Snowfall Using a Distributed Hydrological Model and Remote Sensing Data

The objective of this study is to retrieve snowfall distributions using a fully distributed hydrological model (Lu et al., 1996) which is capable of simulating the snow accumulation, snowmelt and runoff generation processes over the basin. In the model used in this study, the basin is divided into grid blocks connected by a channel network which is derived from altitude data at central points of grid blocks. It consists of two sub-models: one for runoff generation of each grid block and the other for channel routing between grid blocks. The runoff generation sub-model calculates the snowmelt and runoff from each grid block by using a snowmelt model (Koike et al., 1985) based on radiation budget, and the XinAnJiang rainfall runoff model (Zhao, 1992). The runoff is then routed to the study points using the kinematic wave model in the routing sub-model.

In this study, in the Uono River Basin, a small basin located in the most snowy region of Japan, is selected as a study area. The drainage area of this basin is 355 sq. km, and the elevation is from 160m to 2000m. There is significant altitudinal distribution of snowfall. The following linear function

$$P(h) = A\,(1 + B\,(h - hs))\,P(hs)$$

is used to represent this distribution, where hs is altitude at which rainfall becomes snowfall; P(h) and P(hs) are snowfall at altitude h and hs respectively; A is a reciprocal of gauge catch ratio; and B is a coefficient of altitudinal distribution. Two models are implemented for A. One fixes A as constant, and another one expresses A by the following function

$$A = \exp(0.157w^{1.28}),$$

where w is wind velocity. This function is proposed by WMO intercomparison project of solid precipitation measurement (Yang et al., 1995). The parameters are optimized by comparing the simulated hydrograph and snow covered area with the observed ones. In the first model, the optimal parameters are A=1.8 and B=0.0007; and in the second model, the optimal parameter is B=0.0007. By using optimal parameters, the simulated snow covered area and hourly hydrograph and observed ones show a good correspondence. This suggests the possibility of long-term management of melt water. The research also indicates that snowfall distribution is an in important factor in modelling small basins.

(M. Lu)

3.5 Coupled Thermal and Hydrologic Model for Arctic Conditions

A process based, spatially distributed model that couples thermal and hydrologic processes has been developed and applied to a nested watershed in the Alaskan Arctic. This model was developed to improve our understanding of energy and mass fluxes between atmospheric, terrestrial, and aquatic systems in an environment dominated by permafrost. The model first generates the drainage channel network for a watershed from a digital elevation data set that captures all of the watershed's drainage area and characteristics. The grid elements outside of the watershed boundary are identified and eliminated from calculations to improve model efficiency.

The next step is to determine the soil temperature profile and the distributed depth of thaw of the active layer. This is accomplished by solving the surface energy balance equation (net radiation, latent and sensible heat fluxes, and conduction) to obtain the surface temperature (Hinzman et al., 1998). This surface temperature is then used to drive the thermal algorithms that predict the temperature profile and depth of thaw. Data used in this component of the model are 10 m profiles of air temperature, relative humidity and wind speed, reflected and incoming shortwave radiation, emitted and atmospheric long wave radiation, soil temperature at 10 cm and soil thermal properties. These data are distributed across the watershed from numerous meteorological sites using a kriging technique. Soil properties were determined for various typical landforms and distributed according to a vegetation map.

The final component of the model is the estimation of various hydrologic processes that include snowmelt, overland flow, subsurface flow (soil moisture in active layer), channel flow routing, evaporation from snow and summer evapotranspiration. Using distributed water content of the snowpack as initial input into the model, the remaining snow water equivalent is determined at each time step over the watershed through the surface energy balance. This approach allows for the determination of evaporation and cooling and refreezing of the snowpack when there is insufficient energy to melt snow. Data required for this component of the model are all of the energy fluxes mentioned above (Kane et al., 1997). A simple degree-day algorithm, based upon air temperature, is included in the model for use where complete data is not available for determining the various energy fluxes.

In a similar approach, the distributed evapotranspiration is also calculated by surface energy balance (Mendez et al., 1998). The Priestley-Taylor technique can be used where data are limited. Darcy's equation is used to calculate subsurface flow. The slope of each element (from digital elevation data), snowmelt and rainfall input, initial water table, and hydraulic properties of the active layer are required. Outputs include outflow to the surface drainage network, active layer soil moisture contents, subsurface flow to neighboring elements and the water table. Overland flow is calculated when saturation of the active layer occurs (water table rises above ground surface). Overland flow is routed using a simplified kinematic wave technique and Manning's equation. Inputs include the surface roughness, surface slope (from digital elevation data) and precipitation inputs. Routing of flow in the channels is also by a modified kinematic wave and Manning's equation. Overland flow and subsurface flow are obtained from model components above using channel slope (from digital elevation output), geometry and roughness as inputs.

Paralleling this modelling effort was a field data collection programme for several nested watersheds on the North Slope of Alaska (Kane et al., 1998; Lilly et al., 1998; McNamara et al., 1998). The Kuparuk River (8140 km^2) and sub-watersheds of this basin have been studied by an interdisciplinary group for the past five years. Imnavait Creek (2.2 km^2) and the Upper Kuparuk River (146 km^2) are two sub-watersheds studied intensively. Distributed snow water equivalents, discharge and meteorological data were collected in each basin. Meteorological data included profiles of wind, relative humidity and air temperature, long and short wave radiation (April to September) and rainfall.

Application of the model to Imnavait Creek and Upper Kuparuk watersheds produced estimates that compared well with field measurements of snowmelt and channel runoff (Zhang et al., 1999). To verify the spatial performance of the model, estimates of near surface soil moisture contents using SAR (synthetic aperture radar) imagery were compared with spatially distributed soil moisture from the model (Meade et al., 1999). The patterns are quite similar, although the absolute values differ. This occurs because model output is an average of the upper 10 cm while the penetration of SAR imagery is estimated at 2 to 3 cm. Moisture contents generated by the model are generally higher than SAR estimates, as one would expect. Application of the model to the entire Kuparuk River has demonstrated that the model works well in the foothills, but not so well on the coastal plain where surface storage in lakes, ponds and wetlands is important. Field measurements indicate that these areas typically produce runoff only during snowmelt. This is because evapotranspiration exceeds precipitation, and this produces sufficient surface storage for intermittent summer precipitation. The model presently does not account for these large changes in surface storage.

The model was originally designed to be a physically based, spatially distributed hydrologic model. Although we tried to minimize empiricism in the model, current limits in our data and understanding of arctic processes necessitated some empirical relationships. Therefore the model is described as a process based, spatially distributed model. Element size varied for each watershed from triangular elements of 50 m by 50 m to the Kuparuk River elements of 1000 m by 1000 m. Obviously, some detail is lost as element size increases. The lack of spatially distributed data in arctic regions, such as soil maps, is an obstacle in this detailed modelling effort. This programme is written in Fortran 77 and has recently been adapted for parallel processing on the Cray T3E (Morton et al., 1998).

(Douglas L. Kane, Larry D. Hinzman, Ziya Zhang and Douglas J. Goering)

3.6 Toward a Distributed Simulation of the Accumulation and Melt of the Snowpack of Watersheds

With an expertise in hydrology (deterministic and statistical), hydrological modelling, environmental chemistry and geochemistry (contaminants and nutrients), ecotoxicology (aquatic) and waste water treatment, INRS-EAU has considered important to proceed to various ways of technical transfer, particularly as software packages. Most of them have to deal with cold climate processes. However, in the present communication, we will only talk about two of them, HYDROTEL and EQ-eau.

The HYDROTEL model can be applied to a range of watersheds with varying levels of data input. It also allows the simulation of the various processes. Algorithms derived as much as possible from physical processes, together with more conceptual or empirical algorithms have been selected. Also, natural units have been chosen for the simulations: small subwatersheds for the vertical water budget and flow towards the outlet of the unit and river reaches for channel flow. In this communication, the preparation of the watershed data base from remotely sensed and GIS data is discussed first. It is followed by a description of the various components of the model. Examples from an application of the model to the Chaudière watershed in Southern Québec completes the picture.

The HYDROTEL model has been developed with the objectives of being compatible with remotely sensed and GIS data, able to simulate hydrological effects resulting from modifications of the watershed and helpful for understanding hydrological processes. Concerning the compatibility with remotely sensed data, the latter have been used in the above examples only to prepare the land use data base on the watershed. The examples have also shown the importance of representative meteorological data both in time and space. Models are far from being perfect, but even if they were, nothing can compensate adequately for the lack of good meteorological and watershed data. The information available during a simulation run are also very useful not only to understand what is going on simultaneously in various parts of a watershed but also to provide additional ways of checking the accuracy of simulations on intermediate variables. The use of snow survey data to verify the snow water equivalents simulated by the model is a good example.

HYDROTEL offers more than one option to simulate each of the sub-processes in the watershed, from the areal distribution of precipitation to streamflow at its outlet. Consequently, the model can be applied to more watersheds but also to make a better use of the available data on each of them. Some models accurately simulate hydrologic processes on small very well equipped watersheds while others are applicable to a large number of watersheds with minimum amount of data, but producing less accurate simulations. In practice, most hydrological models are somewhere between those two extremes. The HYDROTEL model also falls between these extremes, but at the same time can be applied to a wide range of watersheds by adapting it to available data.

The first prototype of EQ-eau, a software package for the estimation and mapping of snowpack water equivalent on watersheds, should be nearly operational next winter. Preparation of hydrological forecasts based on estimation of snow-water equivalent on large watersheds dedicated to electricity production in northern Quebec is an essential operational task for Hydro-Québec. Indeed, a better assessment of the areal distribution of the water equivalent of the snowpack (SWE) leads to an improved streamflow forecasting accuracy. With the purpose of evaluating the implementation of SAR technology to obtain more accurate SWE, a joint project including INRS-EAU, Hydro-Quebec and VIASAT Géo-Technologies was started a few years ago. Encouraging results having been obtained usingh ERS-1 images as a step towards verifying the potential of RADARSAT imagery. A follow-on project was then started, with the help of the ADRO (Application Development and Research Opportunity) programme of the Canadian Space Agency, with the objective of adapting the ERS-1 algorithm to RADARSAT data and developing a prototype of an operational procedure allowing estimation of the water equivalent of the snow cover over the La Grande watershed, in northern Québec.

As various products are available with RADARSAT, one of the objectives of the project is to select the most appropriate mode and acquisition strategy, given the accuracy of the radar data, the monitoring requirements and the dimensions of the watershed. The other one is the development of a software package allowing estimation of values of snow water equivalents meeting Hydro-Québec spatial integration requirements in a format compatible with their GIS software. This software package will include the following modules: estimation of snowpack water equivalent (SWE) on a pixel by pixel basis, spatial integration of SWE for specific grid sizes or watershed boundaries, production of statistics and interface with Mapinfo. Calibrated RADARSAT images, in both Standard and Wide modes, have been acquired during the 1996-1997 and the 1997-1998 winters. The first results indicate that images taken at small incidence angles, corresponding to ERS-1 angles, might give more accurate estimations due to a larger dynamic range than those acquired at larger incidence angles. Also, in our first tests, the new RADARSAT algorithm has been able to furnish estimations of the water equivalent of the snowpack within 1% of the mean value of our tests sites.

(J.-P. Fortin, M. Bernier and R. Turcotte)

3.7 The Role of the Hydrological Cycle in Polar Climate Variability and Change

An overview was presented on the role of the Arctic hydrologic cycle in polar climate variability and change. Potential feedbacks involving the Arctic hydrologic budget were discussed, followed by reviews of the major components of the hydrologic cycle, available data sets and observed high-latitude environmental change over the past several decades.

Assessing variability in Arctic precipitation presents a significant problem due to insufficient station coverage. Information on evaporation is largely limited to long-term annual means and short-term records collected during field programmes. The veracity of modelled fields of precipitation, evaporation and other variables from "reanalysis" projects was addressed. Overall, the European Reanalysis Agency (ERA) effort appears to provide realistic depictions of spatio-temporal variability in Arctic precipitation. By comparison, the National Centers for Environmental Prediction (NCEP) model grossly overpredicts summer precipitation over land areas. Both models provide realistic fields of precipitation less evaporation (P-E) based on the vapor flux convergence. Despite recognized shortcomings in reanalysis products, they nevertheless may represent viable inputs into large-scale hydrologic models particularly useful for assessing runoff from ungauged basins. A new 40-year reanalysis project is underway at ERA which should provide improved Arctic fields.

The past several decades have seen pronounced changes in the Arctic atmospheric circulation characterized by decreasing sea level pressures over most of the Arctic Ocean and increases in cyclone activity. While largely consistent with the generally positive phase of the North Atlantic Oscillation (NAO) during the last several decades, other evidence suggest a link with a more fundamental mode of low-frequency variability termed the Arctic Oscillation (AO). The circulation changes have been attended by warming over both land and ocean regions, a reduction in total Arctic ice extent, increases in the flux of sea ice through the Fram Strait and increased areal extent of Atlantic water in the Arctic Basin. Regional increases in precipitation have been observed but there is no clear evidence for attendant changes in runoff from the major Arctic rivers.

(Mark Sereze)

4. SUMMARIES OF WORKING GROUP DISCUSSIONS

4.1 Determination of Test Basins for Modelling the Hydrological Cycle in the Arctic River Basins Including Major and Small River Test Basins

This session began with a quick overview of the intercomparison that will be carried out within BALTEX. Four basins in significantly different parts of the Baltic Sea Drainage Basin have been identified for the BALTEX intercomparison of hydrological models. Of these, one lies in the far north, mostly above the Arctic Circle, and would logically be of most interest for cold region intercomparisons. This is the Torne Basin that is situated along the Swedish-Finnish border and flows southeast into the Bothnian Bay of the Baltic Sea.

The characteristics of the Torne Basin (Torne Iven) were briefly presented to the workshop participants. The basin area is 40 200 km^2, of which 57% lies in Sweden, 42% in Finland and 1% in Norway. The western part of the basin consists of mountainous terrain with the river channel itself rising to an elevation of almost 700 m. The dominant vegetation is boreal forest with significant bog areas. The highest mountain terrain rises above the treeline. Less than 1% of the basin is used for agriculture. River flows are for all practical purposes unregulated (i.e. there are no significant dams). A natural bifurcation of the main river channel in the center of the basin results in diversion of some of the runoff to the Kalix Basin in the south.

The Torne Basin is well represented with measurement stations; 14 precipitation stations and 10 synoptic stations have complete data coverage for the period 1968 to the present. Snow comprises some 40-50% of the precipitation that falls on the basin. The annual mean temperature is less than 0°C for most of the basin. River gauging stations are strategically located at 18 sites. A factor that plagues flow measurements in this region is the occurrence of ice jams on rivers during spring thaw, which serve to create temporary dams that influence gauging records. This is a problem that likely affects gauging in many cold region areas. A number of hydrologic institutes have developed routines to adjust for this type of occurrence, but there is nevertheless added uncertainty to the records during these periods.

The presentation of the Torne Basin served both to summarize what BALTEX can offer to future intercomparison studies and to spark the discussion of which other basins could be of interest. It also set the foundation for discussions of data needs and the general sparcity of data in Arctic basins. A critical question to be answered is, what are the minimum data requirements for hydrological models that can be applied in the Arctic?

The plenary discussion opened with the question of what other basins would be appropriate for intercomparison studies. Two were mentioned; the Kuparuk River basin that has been studied intensively by the University of Alaska, and Trail Creek, a test basin used under the MAGS project. A substantial amount of data has been collected on these basins, but the periods are generally short. Additionally, they are small basins, and may not be representative of larger regions. It may be unrealistic to assess the performance of large-scale models on basins of this size. These basins may be more appropriate for detailed process studies and more detailed physical modelling.

The question of scale was raised, "what do we consider a small basin?” and “what is a large basin?" In the context of this workshop, it was practically adopted that the Torne River could be considered a small basin, as compared to large basins such as the Mackenzie River. It was reiterated that focus should be put on identifying basins at both of these scales that could be used for the intercomparison of models. Another key focus, to compare models developed in one climate zone to models developed in other climate zones, was pointed out. Can the models effectively converge in the results they produce? That is, can we reduce errors with improvements after model comparisons and thus accelerate the development of hydrological models?

Further discussion centered on, "what do we want to capture in an intercomparison?" Peaks, extremes, interseasonal variability are all important. The required temporal resolution (daily, monthly) was also discussed. The kind of model and the applications desired should be clearly defined. For example, one of the goals of ACSYS is to study the natural role of estuaries in the Arctic Ocean. How accurate should the results be? Can we define river flow within a certain level of uncertainty or level of complexity? How long a time period do we need for an intercomparison? Ten years may be sufficient for a daily model but something like 30 years would be desirable for a monthly model.

Intercomparisons are expensive and time consuming. It was proposed that the group look at the results of other studies first. For instance, several models are already running on the Mackenzie (at least four groups). What has been learned from the PILPS studies? Perhaps an intercomparison is not needed because of what has already been done and what is already underway.

Candidates for large basin comparisons were discussed. The Mackenzie Basin (MAGS) and the Lena Basin (GAME) received most attention. Discussion also focused on using one of these two basins for detailed intercomparisons and then applying the models to the other one to test transferability. Historic data coverage may be better on the Lena, but only eight years are available electronically (1986-1992, GAME). It may be most reasonable to use the Mackenzie first in an intercomparison and then apply the same models to the Lena for tests of transferability.

The general recommendations from this session are that IF an intercomparison is to be done, two likely test basins are the Mackenzie Basin for large-scale application and the Torne Basin for smaller scale application. It was recommended that work should begin with the smaller scale basin. Before any intercomparison work begins, inventories should be compiled of appropriate models, additional candidate test basins and data coverage, and results of relevant studies. Furthermore, the aims and expectations of the intercomparison should be clearly defined. Lastly, the question still remains as to how much this overlaps with the work on transferability that is already included under GEWEX.

(Rapporteur: Phil Graham)

4.2 Hydrologic Modelling: Data Issues

Data Requirements

The various hydrologic models considered as candidates for the model intercomparison study were assessed with respect to needed data inputs. Based on this assessment, the following minimum data requirements which will satisfy all models are as follows:

1) Daily temperature and maximum/minimum
2) Daily precipitation

3) Daily solar radiation
4) Daily wind speed
5) Topographic information (for compiling river networks)
6) Soil and vegetation information (type, coverage)
7) Daily discharge.

Ideally, these data should be provided as gridded fields. Additional ingest data not absolutely critical but desired for some models are:

1) Daily cloud cover (for calculation of solar radiation)
2) River channel geometry
3) Root depth of vegetation.

Data Sources

For meteorological inputs of precipitation, temperature, solar radiation, cloud cover and winds, it is recommended that full use be made of station data already available or being compiled as part of ongoing modelling efforts under GEWEX/MAGS, GEWEX/BALTEX, GEWEX/GAME and related programmes (e.g., NSF/ARCSS). GEWEX and related efforts should also be relied upon to provide daily discharge data.

With regard to cloud cover and solar radiation, is also recommended that the utility of the new 3-hourly (D2) data sets from the International Satellite Cloud Climatology Project (ISCCP) be assessed. In comparison with the earlier (C2) products these new data feature improvements in calibration, cloud detection algorithms and the radiative transfer model. The utility of gridded fields from "reanalysis" efforts by the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and European Reanalysis Agency (ERA) should also be explored.

Through ACSYS efforts, NCEP/NCAR and ERA outputs of precipitation and solar radiation have been validated against available surface-based observations. Both models are shown to capture the known major spatio-temporal patterns of Arctic precipitation, but with considerable errors in magnitudes, especially in summer. Overall, the ERA model performs better. Despite known shortcomings, the winter ERA precipitation fields may be sufficiently accurate to act as a base for blending with available station data to improve spatial coverage; efforts already underway through ACSYS to explore this avenue should be further promoted. Solar radiation fields from the ERA model also agree reasonably well with observations in the mean sense and because superior spatial coverage as compared to the surface station network they should also be considered as a candidate for model input. Gridded wind fields from both the NCEP and ERA models are also likely to be sufficiently accurate for model ingest. A new 40-year reanalysis effort by ERA, using an improved prediction model, is slated to start in mid 1999. If available in time, it is recommended that efforts be made to assess these outputs for use in the intercomparison effort.

For topographic, vegetation and soil information, it is recommended that reliance be placed on global data sets (e.g., through GEWEX) as this fosters transferability of hydrologic models to watersheds other than those to which they are presently being applied. Regarding river channel geometry, further input is needed from the modelling community to define required spatial resolution. Little information is available regarding the root depth of vegetation: this will likely have to be derived from land cover information as is presently being done with respect to the University of New Hampshire Water Balance Model (WBM).

Verification

The following verification data sets are identified as critical:

1) Discharge
2) Snow depth and snow cover
3) Thaw depth and soil temperature.

Discharge data should be provided through the Global Runoff Data Center (GRDC) and related efforts. For snow cover (extent), reliance should be place on the weekly NOAA analyses. Snow depth is also available from synoptic station observations. Information on thaw depth and soil temperature is likely to be available from only a few stations.

Additional Issues

It is recommended that when possible and appropriate, input and verification data sets be gridded to the equal-area EASE grid. While aiding model transferability, such a gridding scheme also provides for compatibility with remote sensing products (e.g., pathfinder) available at the National Snow and Ice Data Center (NSIDC) at Boulder, Colorado, USA. It is also recommended that the period over which the intercomparison project is performed be chosen to provide the best possible combinations of surface data, remote sensing data and output from the NCEP/NCAR and ERA reanalysis efforts. As both the Russian and the Canadian surface data network degradation started in the early 1990s, a time frame of 1980-1989 is suggested.

(Rapporteur: Mark Serreze)

5. RECOMMENDATIONS FOR A STRATEGY FOR A HYDROLOGICAL MODEL INTERCOMPARISON

Hydrological models are the most plausible means of representing runoff to the Arctic Ocean from ungauged basins (IAPO Informal Report No. 1, 1998). Hydrological models for cold regions are in an advanced state of development within each CSE concerned with the ACSYS study region. An intercomparison of hydrological models for cold regions was envisioned as an important part of future cooperation between ACSYS and GEWEX (WCRP, Report of the third GHP session, Sapporo, 1997), as well as part of the overall GEWEX programme (WCRP, Report to the fourth GHP session, Boulder, 1998, in preparation). The second session of the WCRP/GEWEX hydrometeorology panel (Toronto, 1996) recommended that a workshop be held to identify the current capabilities of the hydrological models, and identify a joint GEWEX/ACSYS course of action for addressing gaps, including a strategy for model intercomparison.

This workshop recommends that an intercomparison of hydrological models be undertaken to identify the capabilities of models to simulate high latitude water and energy cycles. An intercomparison would aid the goals of both ACSYS and GEWEX, since it would define the range of variability of model estimates, provide valuable feedback for model improvement, help assess the transferability of models, and ultimately improve estimates of discharge from ungauged basins.

The workshop also recommends the following strategy to initiate the intercomparison process that will culminate in a workshop to be held in 2000. A small working group should be formed jointly by ACSYS and GEWEX to develop a science plan for the intercomparison. The working group should be formed shortly after the ACSYS Scientific Steering Group meeting in November 1998, and should consist of one member each from BALTEX, GAME and MAGS as well as representatives from ACSYS. The working group should recommend a Principal Investigator (PI), and a lead institution (or institutions) to coordinate and take responsibility for the intercomparison. The PI will be expected to apply for funds to help finance the intercomparison.

Recommendations from the working group should be made at the eleventh session of the GEWEX Scientific Steering Group. The Science Plan will include: i) a procedure describing how models will be compared; ii) a time frame to be followed; iii) the test basin(s), iv) modelling parameters; v) data sets; vi) time and space scales to be used in the intercomparison; vi) the model output to be compared; and vii) the models to take part in the intercomparison.

The Lena, Mackenzie and Torne River Basins, as well as some of their sub-basins, were considered as possible test basins. It is recommended that the working group invite all cold region, regional-scale models within GEWEX to participate in the intercomparisons, and then use criteria to decide which of them will take part in the intercomparison, such as the requirement that a land-surface scheme (for the calculation of the vertical water balance) be included and coupled to an atmospheric model. Modelling runs will be conducted prior to a modelling workshop that will serve as a forum for the intercomparison. It is recommended that the working group draw upon the experience of other intercomparisons of hydrological models, as well as intercomparisons in related disciplines (e.g. atmospheric models, sea ice flow models, etc.).

(Rapporteur: W.L. Quinton)

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APPENDICES

APPENDIX A

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APPENDIX B

ACRONYMS

ACSYS	Arctic Climate System Study (WCRP)
AO	Arctic Oscillation
ARCSS	Arctic System Science
BALTEX	Baltic Sea Experiment
BATS	Biosphere-Atmosphere Transfer Scheme
CAGES	Canadian GEWEX Enhanced Study
CEOP	Coordinated Enhanced Observing Period
CSE	Continental Scale Experiment
CLASS	Canadian Land Surface Scheme
DEM	Digital Elevation Model
EOSDIS	Earth Observing System Data and Information System
ERA	European Reanalysis Agency
FRSGC	Frontier Research System for Global Change
GAME	GEWEX Asian Monsoon Experiment
GCIP	GEWEX Continental-scale International Project
GCM	General Circulation Model
GEWEX	Global Energy and Water Cycle Experiment
GHP	GEWEX Hydrometeorology Panel
GRDC	Global Runoff Data Center
GRU	Grouped Response Unit
HBV	Hydrologiska Bryans Vatterbalansavdelnings Model
ILTS	Institute of Low Temperature Science
ISCCP	International Cloud Climatology Project
MAGS	Mackenzie GEWEX Study
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NIES	National Institute for Environmental Studies (Japan)
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction
PI	Principal Investigator
PILPS	Project for Intercomparison of Land Surface Parameterization Schemes
RAMS	CSU Regional Area Modelling System
RAS	Russian Academy of Sciences
RCM	Regional Climate Model
REMO	Regional Model
SAR	Synthetic Aperture Radar
SHI	State Hydrologic Institute (St. Petersburg, Russian Federation)
SMHI	Swedish Meteorological and Hydrological Institute
SVAT	Soil Vegetation-Atmospheric Traveler
UKMO	United Kingdom Meteorological Office
UM	Unified Model
VIC	Variable Infiltration Capacity Model
WBM	Water Balance Model
WCRP	World Climate Research Programme
