A Framework for the MAGS-2 Scientific Programme

October 1999

Mackenzie Basin Climate-Hydrological System: MAGS Phase 2

Executive Summary

The Global Energy and Water Cycle Experiment (GEWEX) is an international effort developed by the World Climate Research Programme as a coordinated group of activities aimed at improving our understanding and prediction of the role that the water cycle plays in the climate system. As a major contribution to GEWEX, the Canadian Mackenzie GEWEX Study (MAGS) focuses on understanding and modelling the flows of energy and water into and through the atmospheric and hydrological systems of the Mackenzie River basin which yields the largest North American source of fresh water discharge into the Arctic Ocean. The Basin itself is subjected to wide climatic fluctuations, and is currently experiencing a warming trend. MAGS necessarily involves coordinated research into many atmospheric, land surface and hydrological issues associated with cold climate systems.

Substantial progress has already been made in Phase 1 of MAGS on quantifying and understanding of key atmospheric and hydrological processes affecting the water and energy cycles of the Basin. Phase 2 is our final stage to gain and to demonstrate predictive expertise to assess scientifically the effects of climatic variability and climate change on the water and energy cycles and to apply our knowledge to scientific, policy and economic issues in northwestern Canada specifically and all of Canada in general. MAGS will encompass the integration of the various physical processes into a unified climate-hydrological framework to characterize and enhance understanding of the cold climate system, particularly of the Mackenzie Basin and areas with similar environments. Modelling will be performed at different scales, from small catchment and individual events, through the regional scale atmospheric and entire drainage systems, to coupled modelling of the Mackenzie Basin as a unified atmospheric-hydrological entity. Armed with the suite of models, appropriately tested using data acquired from the field, from historical records and from remote sensing platforms, we will use the models to analyze the sensitivity of the system and its components to climatic forcings and to study their effects on the water and energy cycles, including spatial and temporal variability and extremes in climatic and hydrological events. In collaboration with users, the models will be applied for such purposes as improvement of weather prediction, especially at high latitudes, operation of hydroelectric power plants and providing scientific information to improve policy making decisions.

The completion of Phase 2 (2001-2005) of MAGS is expected to benefit not only the scientific

community, but it will greatly assist the government sector in making informed decisions, provide the private sector with direct and indirect economic gains and enrich the public with information and knowledge to better utilize their resources and to enhance their environmental well-being. We will leave major legacies. The records of scientific achievement will include publications and models.

1. Overview of the Canadian GEWEX Programme

In 1988, the World Climate Research Program initiated the Global Energy and Water Cycle Experiment (GEWEX) to improve our understanding and prediction of the role played by the hydrological cycle in the climate system. Several regional research activities cover a wide range of climatic conditions, including the GEWEX Continental-Scale International Project (GCIP), the Baltic Sea Experiment (BALTEX), the GEWEX Asian Monsoon Experiment (GAME), the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and our Mackenzie GEWEX Study (MAGS). Each must quantify the water vapour flux into and out of their particular region, characterize the precipitation and evapotranspiration fields, and handle runoff and discharge. Each must also work with local water resource agencies to provide immediate benefits of their activities, carrying out many diagnostic and model improvement studies, and engaging user communities.

Canada, through its high latitude position, has a natural interest and strong concern for cold climate processes. It is in this area that Canada is expected to make a major contribution to the understanding of the global energy and water cycles. The high latitude environment has special effects on the climate and hydrology. One major characteristic is the extreme seasonal radiation contrasts due to the long days in summer and long hours of darkness in winter. Low sun angle and high reflectance of snow surfaces lead to low radiation receipt which is largely responsible for the intense and persistent coldness. Atmospheric processes and air mass dynamics are strongly influenced by the energy conditions (Stewart et al. 1998a). Water is subject to annual freeze-thaw, be it moisture in the atmosphere, on the land and lake or underground. Snow, ice, seasonal frost and permafrost are inseparable parts of the landscape. All these phenomena affect the regime of water storage and flow.

In 1994, Canada began its participation by undertaking the Mackenzie GEWEX Study (MAGS), emphasizing the cold climate system and using the Mackenzie Basin as the initial focal point of research. The Mackenzie region is particularly suitable as a study site. It is physiographically composed of three major zones: the mountainous Cordilleran region in the west, the flat interior plains with myriads of lakes and wetlands, and the rolling to rugged Canadian Shield to the east where the glaciated Precambrian bedrock with thin soil mantles favour a patchwork of lakes, wetlands and uplands. Latitudinally, the Basin extends from the prairies of Alberta, through the boreal and subarctic forests discontinuously underlain by permafrost, to the continuous permafrost tundra zone along the Beaufort Sea coast. The environments found in the Mackenzie basin exist in many other parts of Canada and as such, they are representative of areas beyond the confines of the study basin.

The overall goal of the Canadian research programme is to describe, understand, model and predict the climate-hydrological system and to apply our methodology and results to the high latitude environment to address national and international issues. This programme was and is envisaged to be a multi-year project, overlapping with a large part of the international GEWEX time table.

The high latitude climate-hydrological system is complex but has been little studied. The scarcity of data poses serious problems. Extensive field studies are necessary to gain knowledge of the processes by which water and energy flow into and through the Mackenzie basin. These studies have constituted the primary research effort in Phase 1 of our programme (abbreviated as MAGS-1). Modelling offers an approach that would piece together results of these process investigation. Current climate prediction models, however, cannot adequately simulate water and energy flows in northern regions and this has major implications for the prediction of the ecological, economical and social impacts associated with water resources. Phase 2 of our programme (abbreviated as MAGS-2) addresses the modelling issue head-on. Our proposed studies will ensure that our models properly account for all major components of the physical system and that our unified knowledge and verified models have the predictive capability to tackle water resource problems in northern Canada.

Canada must have a strong, independent voice on water, one of our most precious resources. Models to be developed in Phase 2 will improve the numerical prediction of climatic and hydrological activities. The models will have significant applications at various scales, from the operation of small hydroelectric power dams to the prediction of Mackenzie river outflow to the Arctic Ocean; from the analysis of local forest fire events to weather forecasting on a regional scale. Interactions with concerned groups dealing with water and related issues, initiated in MAGS-1, will be pursued vigorously in Phase 2.

2. Goal of MAGS

The *overall goals* of the Canadian effort in the International GEWEX Programme are (1) to understand and model the high-latitude water and energy cycles that play roles in the climate system, and (2) to improve our ability to assess the changes to Canada=s water resources that arise from climate variability and anthropogenic climate change. Building upon the achievements of phase 1, and aiming at the attainment of the long term goals, the *tasks for Phase* 2 are to:

(1) close the Mackenzie Basin water and energy balance at annual, monthly or shorter time scales and at spatial scales ranging from sub-basin to the entire catchment;

(2) develop and validate models that yield results within acceptable error limits;

(3) use observations and models to describe and understand the flows of energy and water through the Mackenzie region under the present range of climate variability and climate change;

(4) apply these models to address scientific, environmental and water resource problems;
(5) transfer our models to similar environments in Canada and in other areas of the GEWEX Continental Scale Experiments.

Thus, this second phase concentrates on the *modelling, prediction and application* aspects of our long-term goal. By the end of MAGS-2, we will (a) have an improved understanding of, and ability to model, the response of energy and water cycles in the Mackenzie Basin to climate variability and change, (b) be able to characterize the impacts of its atmospheric and hydrological processes and feedbacks on the regional and global climatic systems, and (c) have the ability to apply our predictive capabilities to climatic, water resource and environmental issues in the Mackenzie Basin and other high latitude regions.

3. Achievements of Phase 1

Although there have been collaborative efforts prior to MAGS to understand cold region processes (e.g. BOREAS, ACSYS, CRYSYS), much remains insufficiently understood about many of the atmospheric and hydrological processes and the interactions of these processes as part of a unified system in a high latitude setting. Phase 1 of our Programme was designed to

∃ quantify the major processes affecting the water and energy cycles of Mackenzie Basin
∃ assess the relative importance of various high latitude processes
∃ develop datasets for model parameterization and verification, and
∃ develop a framework for coupling the models required to reproduce the observed transport of moisture and energy into and through the Basin on monthly and longer time scales.

We have made considerable progress towards completing these tasks. The many achievements of Phase 1, described below, provides us a solid foundation to launch MAGS-2.

3.1.1 Cold Climate Processes

Through MAGS-1, we gained considerable knowledge on the processes occurring in high latitudes. The following section outlines the major scientific questions, the achievements in addressing these problems and the research questions that will lead to future investigations.

What are the important moisture sources for the Mackenzie?
Typically, about 400 mm of precipitation falls over the Basin (Louie et al., 1999), approximately evenly divided between rain and snow (Mekis and Hogg, 1999), but there is a large inter-annual variability in these values. Through our studies (Lackmann and Gyakum, 1996; Hudak and Young, 1999), we found that the moisture mainly originates over the north Pacific Ocean, but the mountains of the Western Cordilleras (Fig. 1) greatly reduce this moisture flow into the area, leading to enhancements of precipitation over the high elevations (Mackay et al., 1998; Misra et al., 1999). These effects vary seasonally due to differences in large-scale forcing and stability. Although we begin to appreciate some of the important consequences of orography, much

remains to be done before these effects can be captured reliably by our models. We also found that there are large year-to-year variations in the strength of the Pacific moisture source; how this translates into changes in the Basin=s climate system is still uncertain. In most years, this advection from outside of the basin dominates the atmospheric water budget of the Basin, but summer periods can sometimes be linked with net divergence, implying that local evapotranspiration is stronger than advection (Smirnov and Moore, 1999; Cao et al., 1999; Liu and Cho, 1999). There is considerable uncertainty in these estimates, however; one contributing factor is that the large diurnal moisture cycles are not being well re-produced in our models (Strong, 1997). Further documentation of the moisture budget is needed and this must address both the surface and sub-surface reservoirs and fluxes.

How do clouds affect the Basin=s climate system?

The Mackenzie Basin generally occupies a very cloudy region, with estimated basin-fractional cloud coverage being approximately 50% (Isaac and Stuart, 1996; Stewart et al., 1998b). We found that clouds are commonly associated with cyclonic storms that pass over the region (Hanesiak et al., 1997; Szeto et al., 1997; Stewart et al., 1998b; Asuma et al., 1998). These systems are greatly disrupted by the orographic barrier, and the occurrence of lee cyclogenesis on the eastern flank of the barrier is associated with this process (Lackmann and Gyakum, 1996; Lackmann et al., 1998). During the summer, we noted a substantial amount of convection, often in the form of thunderstorms (Kochtubajda et al., 1999). These storms, under dry conditions, initiate many devastating forest fires within the basin (Kochtubajda et al., 1999). Clouds significantly affect the climate, not only through their cutback on surface radiation but also by their augmentation of precipitation, with impacts on evaporation and snowmelt. One example is delay of the initiation of snowmelt in northern areas due to cloudiness, affecting the timing and magnitude of melt. Dry sub-cloud conditions also affect climate by reducing the efficiency of converting water vapour to precipitation. For example, Burford and Stewart (1998) estimated that, in the autumn, half of the ice produced at cloud base does not reach the surface.

How well is surface radiation accounted for?

Direct surface observations are inadequate to evaluate the reliability of the radiation fields generated by the project=s atmospheric models, but satellite measurements and special surface measurements are being used to deduce the surface solar radiation budget (Masuda et al., 1995) and to evaluate the fields generated by the atmospheric models (Leighton et al., 1999). However, this task is far from complete and will be pursued further in MAGS-2.

How important are winter processes to the atmosphere and to surface hydrology?

Existing atmospheric and hydrological models assume that the snowfall, once accumulated on the ground, is subject to little change over the winter. However, field studies in Phase 1 showed that blowing snow causes the loss of up to 30% of the total winter snowfall due to sublimation both in tundra (Pomeroy et al., 1997) and in boreal forest environments (Pomeroy et al., 1998a). This limits the snow available for runoff, but provides an important vapour source to the atmosphere. Predictive equations for these processes compare favourably with field measurements (Pomeroy et al., 1998b; 1997), thus allowing the estimation of snow cover amount and distribution over a grid or drainage basin. The developed model components are now available for incorporation into land surface schemes, though Dery and Taylor (1996) have suggested theoretical limitations in our understanding of blowing snow. Ongoing work aims at bridging such discrepancies between observations and theory, as well as testing improved techniques in MAGS models.

How should heterogeneous land surfaces be accounted for in large scale models?
Large horizontal gradients in the boundary layer characteristics occur because of the variable terrain, land cover and vegetation in the Basin. During MAGS-1, special measurements of the boundary layer were made by ground-based instrumentation and by aircraft to improve the representation of boundary layer processes in large scale models. In the snow-covered period, heat advection from the bare ground to snow patches increases the local melt rates in both tundra (Marsh et al., 1997) and forested environments (Woo and Giesbrecht, 1999). We developed algorithms simulate this effect (Marsh et al., 1997, Pomeroy et al., 1998b) and they are available for incorporation into land surface models. During the snow-free period, our field observations demonstrated significant variations in evapotranspiration efficiency for different landscape types (Rouse, 1999), and the role of surface wetness in controlling energy partitioning. The presence of lakes further complicates the land surface schemes. Rouse (1999) showed that during a >normal= year, evaporation is minimal in the autumn period, yet for an above-average warm summer, such as that in the1998 El Niño episode, the fall evaporation season is extended by several weeks. Progress is being made to improve the representation of all these processes in our models (e.g. Xu and Taylor, 1997a,b; Neumann and Marsh, 1998). Given the complexities of the hydrological processes due to heterogeneity of the land surface, further research in MAGS-2 is needed to characterize the sub-grid scale variability in the models.

How do surface processes control water delivery to streams in permafrost and Shield regions?
Zhao and Gray (1998) have shown that the infiltration of meltwater is greatly retarded by frozen mineral soils. However, the presence of an organic layer, which is common in the Mackenzie Basin, greatly enhances infiltration (Carey and Woo, 1998) and facilitates slope runoff through preferential pathways (Quinton and Marsh, 1998). In discontinuous permafrost zones, Carey and Woo (1999) found that some slopes do not yield water to streamflow. In areas with extensive wetlands, conventional field work is extremely difficult and stable isotope techniques were used to estimate the relative importance of groundwater versus wetland storage (Gibson and Prowse, 1998). The Precambrian Canadian Shield is dominated by exposed bedrock which have traditionally been considered to be impervious. Our recent work has shown that the presence of many fissures and cracks significantly increases the bedrock capacity to store and transmit water as baseflow (Spence, 1999). Incorporation of these processes into hydrological models is crucial to the improvement of runoff prediction. The Shield region also has numerous lakes which also affect the regional water balance due to their storage capacity and enhancement of evaporation, both of which substantially delay and limit streamflow responses to snowmelt and rainfall events (Spence et al.,1999). Much work remains to advance our understanding of the hydrology of bedrocks and lakes.

3.1.2 Insights into the Mackenzie Energy and Water System

We have obtained an understanding of the internal circulation of moisture and heat within the Mackenzie Basin and we have started to improve our knowledge of its atmospheric and hydrological linkages with areas outside the Basin (Lackmann and Gyakum, 1996). In winter, the region experiences a great deal of heat loss, generating cold air that spreads southward while the upper level cyclones propagate towards eastern Canada. In summer, local evaporation is a major moisture source and convective clouds redistribute this atmospheric moisture (Szeto et al., 1999). In general, there is strong evidence that climatic anomalies are amplified in the Basin during winter, but are reduced in summer (Cao et al., 1999).

Our basin-scale studies have just begun and understanding the basin system as a whole remains a task for MAGS-2. The land surface has large diversity in hydrological environments due to large contrasts in topography, vegetation, soil, rock outcrop and frost distribution, and the presence of myriads of lakes and large areas of wetlands. Superimposed on these features is the seasonal presence of snow and ice which adds complexity to the energy and water fluxes at the near surface zone. Through our process studies reported in Section 3.1.1, MAGS-2 is in a position to comprehend the dynamics of the whole atmospheric-hydrological system.

3.1.3 Database Development and Access

The MAGS-1 data strategy comprised a three-phased approach to obtain information for process studies, model initialization and validation: (1) compile available data from operational networks, satellite, radar and research basins, (2) augment long-term observations, and (3) carry out the following enhanced measurement over the 15-month (1998-99) Canadian GEWEX Enhanced Study (CAGES): soundings, discharge, radar, aircraft and tower flux measurements, hillslope runoff, and additional surface stations. Examples of the resulting data sets include:

Surface observations: CAGES enhanced discharge estimates during the ice-cover/breakup periods for the Mackenzie River and major tributaries are available, as are surface meteorological measurements for typical vegetation covers, and surface sensible and latent heat fluxes for the research basins. In addition, basin-wide monthly precipitation and temperature gridded datasets (50 km grid squares) for the 1950-97 period are available.

Remote sensing (satellite): AVHRR images have been used to develop data sets of land and water surface temperatures at 1-km resolution over the Basin, and also combined with ScaRaB data to provide radiation maps during CAGES. SSM/I EASE-Grid microwave radiometer images have been used to develop snow water equivalent (SWE) for the basin and snow cover and lake ice characteristics for Great Slave and Great Bear Lakes for the years 1987-99.

Aircraft and radar: Sensible and latent heat flux data sets are available from aircraft measurements of the dynamic evolution of surface-atmosphere fluxes of sensible and latent heat during and following snow-melt, and for the snow-free period. A radar-based precipitation accumulation product is available for Environment Canada=s operational radars in the southern Mackenzie Basin, while the IPIX radar was used to provide data sets on the detailed kinematic description (e.g. vertical structure, wind fields) of the cloud systems in central Mackenzie Basin.

Data Management: A Data Management System was established in MAGS-1 to maintain, describe, and promote accessibility and distribution of the data sets necessary to meet the MAGS objectives. These goals are being met through: (1) the availability of data and information on the World-Wide Web, including archived and real time data from the enhanced surface stations, and access to over 300 pages of information describing the objectives, background, status, and clients for the project, and (2) the production of specialized data products. These data are being archived in a series of CD-ROMS. In addition, the CMC have been archiving enhanced global model data since October 1 1995. All these MAGS-1 data sets are a legacy from Phase1 and will be used in model development and validation in Phase 2.

3.1.4 Developing a Coupled Model Framework

∃ Besides the atmospheric and hydrological models for specific processes, we contribute to the development of the Canadian Regional and Global Climate Models and to the Canadian numerical weather prediction models: MC2 and GEM (Global Environment Multiscale).

- A major contribution is the coupling of land surface and hydrological process modules to the above, helping to capture the roles played by natural variability of land surfaces and thus to improve the closure of the large scale water budget in the atmospheric models. A combined WATFLOOD-CLASS model offers the appropriate framework for this task and, as they evolve based on process study results, allows the magnitudes of the various components of the water cycle to be represented correctly.
- The proof-of-concept for the coupled system was demonstrated in MAGS-1. Tests with the prototype code have increased confidence in the ability of these models to simulate the present reality and ultimately to simulate the future. Development of a formal operational framework is proposed for MAGS-2.

3.2 Relationship with MAGS-2

Phase 1 research has placed emphasis on gaining knowledge of the physical processes that govern the atmospheric and hydrological systems. This knowledge will be employed toward furthering model development, testing and application. Insights into the Mackenzie water and energy system provide an increased understanding of the internal cycling of moisture and heat and its relation to synoptic weather patterns, the linkages of the water and energy balance to extra-basin processes, the amplification of cold climatic anomalies in winter and the inefficiency of the basin in converting atmospheric vapour to precipitation. Ongoing research will enhance our understanding of the role played by the natural variability of land surfaces in the hydrological cycle; provide an initial coupling of atmospheric, land surface and hydrological models; and demonstrate that coupled models can yield the correct magnitudes for water cycling in the basin.

4. MAGS-2 Scientific Issues

To reach the goals stated in section 2 (understanding and modelling the high latitude energy and water cycles and their responses to climate variability and change), the primary issue to be considered by MAGS-2 is to determine how the Mackenzie River Basin operates both *in situ* and in the context of its role in the global climate system. This is to be achieved by a combination of modelling, prediction, and analyses, using the best-available data and models. One of the principal products of this research will be an improved analysis and modelling system so that responses of the atmospheric-hydrological system to climate variability and climate change in the Mackenzie Basin can be predicted and understood. Such knowledge and predictive capabilities will allow us to answer a variety of scientific and operational questions.

Process Integration Scaling

MODELLING

Prediction Application Enriched scientific insight

4.1 Phase 2 Research Activities

MAGS-2 will follow several overlapping themes of investigation (labelled I to V below) to address major scientific questions which can be expressed in terms of eleven research objectives. The following sections elaborate upon the scientific investigations to be conducted.

4.1.1 Theme I: Integration of Knowledge of the Physical Processes

Integrating the processes studied, both in Phases 1 and 2, into a group of MAGS models will be a crucial step that provides understanding of the cold climate processes *as one unified system*. This integration and understanding will strongly augment Canadian expertise in tackling atmospheric and hydrological issues in the Mackenzie Basin and in other areas with similar environments.

Objective 1*: To extend the process studies to encompass the important physical processes not comprehensively covered in Phase 1.*
Several major processes important for the achievement of MAGS goals were not comprehensively studied in Phase 1 due to limited funding. These will be investigated to complete the process studies required to improve the linked models. Topics include orographic precipitation, convective processes, diurnal water vapour variations, evaporation, blowing snow, overall contribution of lakes to water and energy balance, basin storage, groundwater, river ice formation and breakup effects on water level and river flow and channel storage.

Objective 2*: To consolidate knowledge of the atmospheric-hydrological system of the Mackenzie Basin in a unified framework.*
Facets of atmospheric research and components of hydrological studies will be consolidated into a form appropriate for inclusion in the MAGS models. This will be achieved through collaborative investigations, frequent discussions and increased use of mini-workshops among research groups and collaboration with the modelling groups to ensure that the algorithms developed are incorporated into the appropriate MAGS models.

4.1.2 Theme II: Scaling of Data and Processes to Harmonize Temporal and Spatial Resolutions

Scaling refers to the linkage or transfer of information across temporal and spatial scales. Energy and moisture fluxes occur at many natural scales but data are seldom collected at the scale required by the models, thus they have to be adjusted appropriately (e.g. field observations made at local sites need upscaling to match investigations at large basin scales; products of many climate models, generated at the scale of tens to hundreds of kilometres, need downscaling for use in the study of energy and water fluxes at local and small basin levels).

Objective 3*: To develop appropriate physically based techniques for parameterization.*
Scientific investigations of atmospheric and hydrological phenomena will be carried out at different scales, ranging from local to regional levels. Both downscaling and upscaling are needed to bring the data to common resolutions in time and spatial intervals that befit scientific studies at the scales required. Parameters will be derived for models at different scales based on physically sound approaches. To obtain distributed data and parameters at required scales, remote sensing (especially taking advantage of the upcoming generation of sensors) and ground-level measurements will provide information that can be extended to cover the large but data-sparse areas; spatial statistics and Geographic Information Systems will enable the synthesis and interpolation of data obtained from point observations.

Objective 4*: To bridge the temporal and spatial scales from local to regional levels of modelling.*
Physical processes which are important at the local scale (e.g. local advection of energy and moisture) may be unimportant when averaged over a large area while large scale processes may not be easily disaggregated to the sub-grid level to provide sufficient resolution for local scale

investigations (e.g. convective cells which influence local rainfall). Various approaches will be used to model the processes to bridge the information hiatus between scales (e.g. hydrological investigations, Group Response Units are used to characterize the processes of local zones within a large drainage basin). In addition, high resolution models provide synthetic datasets from which parameters will be derived for large-scale models; outputs of water and energy fluxes from models at different scales and for the same area will be compared to ensure that scaling is carried out appropriately.

4.1.3 Theme III: Model Development and Evaluation

Models provide a tool to test sensitivities and to predict the response of the system to external disturbances imposed by human-induced or natural forces. To account for the highly diversified Mackenzie Basin environment, synoptic-scale and meso-scale modelling must cover a large range of terrain types and must simulate the seasonality of the environmental variables (e.g. winter as distinct from summer activities). Coupled models will be developed for the Mackenzie Basin atmospheric-hydrological system.

Objective 5*: To enhance, and develop as appropriate, a hierarchy of models based on knowledge of the processes, to enable the evaluation of how individual processes or phenomena affect the atmospheric and hydrologic systems.*
Models will include those tested and developed in MAGS-1, as well as new models as required. Through linkages with Themes I and II, these models will be updated to include the latest process and scaling results. The models to be employed encompass a variety of phenomena and cover a range of scales. Details regarding the models are provided in Section 5.2. Major projects that contribute to this objective will utilize the Canadian Regional Climate Model (CRCM); the Mesoscale Community Model (MC2); the Global Environmental Multiscale (GEM); the Canadian Land Surface Scheme or CLASS, and WATFLOOD; and various process-based hydrological and river ice models.

Objective 6*: To improve coupled models developed in MAGS-1 to assess the overall behaviour of the Mackenzie system*.
Large-scale hydrologic modelling will make use of the WATFLOOD model which calculates the horizontal transfer at the land surface with physics that is easily adapted to atmospheric models. CLASS, a sophisticated soil-vegetation-atmosphere transfer scheme that explicitly resolves the energy and water budgets, will provide the interface. The coupled model developed in MAGS-1, called WATFLOOD/CLASS, will continue to be modified to reflect northern conditions, and then linked with the atmospheric models such as MC2 and CRCM. This coupled model will be an important final product of MAGS capable of representing the climate-scale water and energy system.

Objective 7*: To evaluate model performance using field, historical and remote sensing data.*
Data collected during the 1998-99 CAGES water year, 1994-95 water year, observations during other water years, and through remote sensing will provide the requisite information for the validation of the above noted models at a variety of scales and for a variety of processes. For

large scale and coupled models, criteria for the assessment of model performance will be established, one of which will be the analyzed fields from the GEM model and another the streamflow data from the Mackenzie and the experimental basins of MAGS-1.

4.1.4 Theme IV: Prediction and Analysis of the Climate-hydrological System

Incomplete knowledge of the physical system and data scarcity have prevented accurately assessment of the water balance of large basins such as the Mackenzie. The system also subjected to short term climatic variability due to teleconnections with El Niño events and long term changes, notably climatic warming. Prediction of the responses of the climate-hydrological system remains quantitatively inadequate, though these system responses have important implications for the cold environment such as permafrost melt or alterations of the streamflow regimes. MAGS-2 will produce the tools and the knowledge required to perform this important task.

Objective 8*: To close the water budget for the Mackenzie hydro-climatic system at a variety of scales.*
The water budget of the Mackenzie will be closed at a variety of scales, using the improved models described in section 4.1.3. The target years will be the 94/95 and 98/99 water years and the international Coordinated Enhanced Observing Period (CEOP) of 2001-02 when another data set will be acquired. At the small scale, realistic simulation of the hydro-climatic system will close the water balances of drainage basins with permafrost, lakes, wetlands, tundra, forests and other attributes typical of the Mackenzie landscape. At the regional scale, we will attempt water budget closure for the entire Basin. These studies will use a range of model products, remote sensing, and observations, to determine the relative importance of local vs external factors in controlling the water cycle of the Mackenzie region.
Objective 9*: To assess the local and regional responses to external forcing under climate variability and climate change, including the feedbacks and sensitivity of the various elements of the atmospheric-hydrological system.*
The models developed will be calibrated with historical data and then subjected to external forcing to simulate climate variations and changes in climate based on scenarios depicted by the General Climate Models and other climatic time series. Our predictive capability will range over temporal and spatial scales and will be applied to various atmospheric-hydrological processes, including: episodic and local events to precipitation on a regional scale, ice jam flooding, seasonal and inter-annual regional variability of droughts or lake storage changes, changes in snow cover, streamflow and lake evaporation. The responses of components of the atmospheric-hydrological system to perturbations will be studied through statistical analyses of correlation structures, time and spatial series and extreme event occurrences.

4.1.5 Theme V: Applications of Predictive Capability

Capability for applying our research findings and methodology to problems relevant to our partner institutions has strong scientific merit and practical value; collaboration with our partners will extend our outreach effort. It is also important to apply the predictive capability to regions outside of the Mackenzie to demonstrate the generality of our modelling tools and to satisfy the scientific obligation of MAGS to international GEWEX.

Objective 10*: To interact with users in the application of the knowledge, the observational capability and the modelling prowess to address water and climate related problems of importance to the industries and to the governments.*

A variety of modelling application activities is planned to provide benefits to the user communities:

– For contributions to weather and climate prediction, we will interact with CMC and CCCMA to provide inputs to operational models to enhance forecasting accuracy for northern Canada; this

Table 1. Major themes and objectives of MAGS-2

Themes	**Objectives**
Theme I: PROCESS STUDIES AND INTEGRATION	(*1*) Extend process studies (*2*) Integrate process studies to produce a unified atmostpheric-hydrological framework
Theme II: SCALING OF DATA AND PROCESSES	(*3*) Parameterization techniques (*4*) Bridge temporal and spatial scales
Theme III: MODEL DEVELOPMENT AND EVALUATION	(*5*) Develop a hierarchy of models (*6*) Improve coupled models (*7*) Evaluate model performance
Theme IV: PREDICTION AND ANALYSES	(*8*) Close the water budgets (*9*) Assess responses to climate forcings
Theme V: APPLICATIONS AND MODEL TRANSFER	(*10*) Application to problems (*11*) Transfer of information and models

- will include addressing the regional influences on the global weather and climate (e.g. cold air generation in winter).
- We will assess climatic control on northern river discharge which significantly influences the Arctic Ocean circulation, a topic of particular importance to oceanographers.
- We will co-operate with industrial users to tackle water resource management problems by providing hydrometeorological expertise on seasonal snow, ice regimes, lakes and water supplies for use in the management of water for consumption, flood control and forecasting, hydro-power production, northern river transport and ecological demands. The likelihood, severity and spatial extent of extreme events (e.g. severe weather, floods and droughts), lightning will be examined as essential elements of our application strategy because of their importance to the northern communities.
- We will contribute scientific advice to governments in their decision making process, such as water licensing and other regulation issues. We expect to participate in scientific discussions on inter-basin water transfer from northern basins, a subject that is attracting increasing interest.

Objective 11*: To transfer the information and models to other areas to extend the benefit to national and international bodies.*
Applications of our capabilities over regions other than the Mackenzie Basin will directly benefit Canada as well as contributing to the global initiative. Suitable candidates include (1) the Saskatchewan River Basin where, for at least one full year, our model capabilities will be assessed in this water-sensitive area. (2) other continental-scale experiments under GHP. One strategy of GHP is to develop diagnostic and modelling capability for various regions around the world, notably northern Europe through BALTEX and over the Lena River basin through GAME-Siberia. This will take advantage of CEOP, in association with other GEWEX organizations.

5. Modelling Strategy and Computation Capabilities

To realize the objectives of MAGS, a hierarchy of models, ranging from small scale catchment to a variety of large domain atmospheric, land surface and hydrologic models must be used. Canadian models will largely be used but, to ensure transferability over the world as a contribution to the GEWEX Hydrometeorology Panel, use in the future will also be made of models from other countries. The Canadian models can also be applied to other areas of the world, which will facilitate evaluating the transferability of the MAGS algorithms to other regions.

Models to be employed encompass a variety of phenomena and cover a range of scales. Small basin hydrological models with permafrost, snow, lake and wetland components will be developed in order to test methods for modelling sub-grid square variability. A concerted effort will be pursued to improve climate modelling through the Canadian Regional Climate Model

(CRCM) with its GCM physics package. Through the use of the CRCM, features of the water and energy cycles of the Mackenzie Basin can be assessed. Fine scale (down to 1 km) features of the atmosphere and surface will be simulated with non-hydrostatic models such as the Mesoscale Community Model (MC2) which can address, for example, water budgets, and interactions between many surface and atmospheric factors. Our researchers will interact with the Canadian Meteorological Centre (CMC) to assimilate fields of atmospheric and surface parameters using its operational Global Environmental Multiscale (GEM) model which uses a variable resolution strategy for limited area modeling to produce forecasts valid over North America for a 48-h period. For surface hydrological research, the coupled WATFLOOD/CLASS model will continue to be modified to reflect northern conditions, merged with the atmospheric models and the then version will be fully tested. One of the final products will be the Canadian Regional Climate Model (CRCM) coupled to CLASS and WATFLOOD to replicate the Basin=s climate-scale water and energy cycles. The Canadian models developed should also be transferrable to other areas of the world.

Data collected during the 1998-99 CAGES water year, data to be gathered in the 2001-02 period of CEOP, observations made in the field and through remote sensing will provide the requisite information for the validation of models of various scales. For large scale and coupled models, model performance will be assessed by comparing modelled results with the analyzed fields from the GEM model, and with the streamflow data obtained from the Mackenzie and the test basins.

The assessment of some of the model products will be facilitated through the use of a common analysis system, referred to as IDPro, which is based upon IDL software, and has been developed within the Climate Research Branch of the AES to allow efficient display and analysis of model and/or observational products on a PC=s or on workstations.

6. TimeTable

MAGS-2 will span five years to ensure a stage by stage completion of the sequence of overlapping tasks. The proposed activities and their accompanying milestones are realistic (Table 2):

∃ Years 1-3: Carry out integration of processes to enable a good understanding of the high latitude climate-hydrological system and to provide information for modelling.

∃ Years 1-4: Improve and complete a suite of process models and coupled models, properly scaled and verified for operation.

∃ Years 4-5: Apply our models and accumulated knowledge to prediction studies and evaluate our model outputs.

7. Summarizing Comments

The Canadian GEWEX programme is at an important crossroad. MAGS, within GHP, has progressed rapidly over the last few years, and we are now poised at a position to reap major benefits. In Phase 2, we will not only improve our scientific knowledge on the atmospheric-hydrological system of high latitudes, but will also apply our capabilities to address real-life problems associated with the climate and water resources. We have, in the past several years, built a strong team and a structure to conduct network research. We propose to capitalize on this momentum, enlarge our teamwork and strengthen our effort in MAGS-2, so that our scientific and practical visions can be realized.

8. References

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