Proceedings of the 7th Annual Scientific Meeting of the Mackenzie GEWEX Study (MAGS)

7 - 9 November 2001
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The following posters were on display for the duration of the meeting:

2. Evaporation and Lake Size in the Mackenzie River Basin. (C. Oswald and W.R. Rouse)
3. Foothills Orographic Precipitation Experiment. (C. Smith)
4. Internal Boundary Layers and Evaporation from Lakes. (S. Savelyev)
7. Retrieval and Monitoring of Surface Albedo and Radiation Budget over MAGS Region. (A. Trischenko)
9. Simulation of Turbulent Heat Fluxes at Trail Valley Creek Using the Canadian Land Surface Scheme (CLASS). (D. Rodgers)
A. INTRODUCTION
Welcome and Introductory Remarks

Lawrence W. Martz
Chair, MAGS Scientific Committee

Welcome to the seventh annual meeting of the Mackenzie GEWEX Study (MAGS). This is something of a watershed in that it is the first annual meeting of second phase of MAGS. The overall goals of this second phase remain the same as those of the first; namely:

- to understand and model the linked hydrologic-atmospheric system of the Mackenzie River Basin,
- to provide tools to predict system response to climate variability and climate change for a variety of needs,
- to enhance the Canadian scientific skill base in hydrology and climatology,
- to contribute to resolution of global issues related to water and climate.

As well as being directed toward national scientific priorities, MAGS is the major Canadian contribution to the Global Water and Energy Cycle Experiment (GEWEX) coordinated by the World Climate Research Program. The objectives of GEWEX are:

- to measure global hydrological cycle and energy fluxes,
- to model global hydrological cycle and its impact on atmosphere, oceans and land surfaces,
- to predict global and regional response of water resources to environmental change,
- to advance observing techniques and data management and assimilation systems.

Although the transition from the first to the second phase of MAGS does not involve any change in the study goals, it does involve a major shift in the research focus (Table 1).

Table 1: The MAGS-1 to MAGS-2 transition.

<table>
<thead>
<tr>
<th>MAGS-1</th>
<th>MAGS-2</th>
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<tbody>
<tr>
<td>1996</td>
<td>1 January 2001</td>
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<tr>
<td>- Data collection, management and assimilation</td>
<td>- Process integration</td>
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<tr>
<td>- Atmospheric and hydrologic process studies</td>
<td>- Develop linked hydrologic-atmospheric models</td>
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<tr>
<td>- Modelling framework and capability</td>
<td>- Apply models and understanding to environmental and social issues</td>
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MAGS-1 was a foundation study that was largely concerned with:

- the collection, management and assimilation of data on the Mackenzie River Basin,
- conducting basic atmospheric and hydrologic process studies,
- developing a modelling framework and capability.
MAGS-2 builds on this foundation to:
- integrate the results of process studies into a conceptual understanding of water and energy cycling in the Mackenzie River basin,
- develop a physically-based, predictive model of water and energy flow in the hydrologic-atmospheric system of the Mackenzie Basin,
- apply data, understanding and models to environmental and social issues.

The transition to MAGS-2 brings a change in the organization of scientific activities. MAGS-2 has 11 specific objectives that are grouped under 5 theme areas. Each theme has a designated leader who sits as a member of the SC and is responsible for coordinating research activities in each theme area. The themes and objectives are summarized in Table 2.

Table 2: MAGS-2 themes and objectives.

<table>
<thead>
<tr>
<th>THEMES</th>
<th>OBJECTIVES</th>
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</table>
| I. Process studies and integration | 1. Extend process studies  
|                                 | 2. Integrate process studies to produce a unified atmospheric-hydrological framework |
| II. Scaling of data and processes | 3. Parameterization techniques  
|                                 | 4. Bridge temporal and spatial scales |
| III. Model development and evaluation | 5. Develop a hierarchy of models  
|                                   | 6. Improve coupled models  
|                                   | 7. Evaluate model performance |
| IV. Prediction and analyses      | 8. Close the water budgets  
|                                   | 9. Assess responses to climate forcings |
| V. Applications and model transfer | 10. Application to problems  
|                                   | 11. Transfer of information and models |

These themes are associated with a timeline of activities. This is shown in Table 3. Activities have proceeded according to schedule through the first year of MAGS-2. Several new activities are scheduled to be initiated in the year ahead. These are:
- the analysis of process data collected in Phase-2
- the development of data upscaling procedures
- the development and validation of new process models.
Other activities are scheduled to be completed by the end of 2002. These include:
- the integration of process studies into a conceptual foundation for modelling
- the identification of user needs for model application

Table 3: The MAGS-2 thematic timeline.

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<thead>
<tr>
<th>Theme</th>
<th>Objective</th>
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<th>2001</th>
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The MAGS Annual Meeting serves a number of purposes. It provides a venue at which most of the scientists participating in the research network come together to report on their scientific progress over the past year. This provides us with a valuable opportunity to assess our individual and collective progress. An important element of this self-assessment is the discussion sessions that follow each of the presentation sessions. These discussion sessions promote interchange between the participating scientists and provide input to the planning and resource allocation exercises of the Scientific Committee. While the discussion of the scientific significance of individual study results that takes place in these sessions is important, it is also important that we use these sessions to examine the implication of those results for other studies and for the overall MAGS goals. I further encourage you to use these sessions to look ahead and to consider how study results will contribute to future transferability, prediction and application objectives.

– ⭐⭐⭐ –
B. ATMOSPHERIC STUDIES
Evaluation of Radiation Budgets from Atmospheric Models for Northern Canada

H. Leighton

Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec

1. Objectives

- Evaluate the solar forcing supplied by atmospheric models to the surface models;
- Evaluate the satellite retrievals of net solar radiation at the surface from surface-based observations in the Mackenzie River Basin (MRB).

2. Progress

- We have derived a dataset of solar radiation fluxes at the top of atmosphere and at the surface in the MRB from AVHRR observations for the CAGES period. The derived solar radiation fluxes at the surface have been evaluated against surface measurements taken in the basin and they showed good agreement;
- The datasets referred to above were compared with the output from the special Global Environmental Multiscale (GEM) model results for the spring phase for GEWEX-CAGES in May-July 1999;
- The preliminary output from the new version of the Canadian Regional Climate Model (CRCM III) was evaluated against the solar fluxes at the top of the atmosphere (TOA) and at the surface derived from ScaRaB observations in 1994; and
- In addition, we have started to look at the sensitivity of some of the water budget terms from WATCLASS simulations for the MRB to uncertainties in the solar radiation forcing from GEM. We have noticed that there are large discrepancies (of the order of 80 W m\(^{-2}\)) between the net solar radiation at the surface deduced from the satellite observations and from the GEM output under overcast conditions. If we can interpret this difference as an indication of errors in the model fluxes, it is important to understand how sensitive the results of simulations with WATCLASS might be to these errors in solar forcing. We have recently started to carry out simulations with WATCLASS being forced by the satellite data and by the GEM solar fluxes. This work is currently underway.

3. Results

Solar Fluxes at the TOA and at the Surface in the MRB from Satellite Measurements

The processed dataset for CAGES includes the solar fluxes at the TOA and at the surface for each overpass, the interpolated values at each hour, the monthly means and the basin average of the monthly means at each hour. The data cover the period from June, 1998 to September, 1999, a total of 15 months.
As an example, basin averages of the monthly mean at each hour are shown in Figure 1. In March and April, more solar radiation was reflected to space than absorbed at the surface since the surface of the basin was almost completely covered by snow. During May, part of the basin was covered by snow and part was snow free. The net surface solar radiation (NSSR) flux near noon was larger than the TOA reflected flux, but in the early morning and late afternoon, this was reversed. From June to September the basin was almost snow free. More solar radiation was absorbed at the surface than reflected to space.

Comparison of Solar Fluxes between Satellite Retrievals and the Output from the GEM Model

Derived solar fluxes for CAGES were compared with the outputs from a research version of the GEM model, which was run during the spring phase of CAGES in May-July, 1999. The comparisons were made at 25 sites in the basin.

As an example, we show the results for June, 1999. Table 1(a) shows that on average the TOA reflected flux was underestimated by the GEM model by 61 W m\(^{-2}\) or 28% in June, 1999. The model atmosphere absorbed less solar radiation than was deduced from satellite retrievals with the mean difference being 14 W m\(^{-2}\). Correspondingly the model overestimated the (NSSR) flux by 75 W m\(^{-2}\). Table 1(b) shows that of all incoming solar radiation, the model reflected 23% to space, absorbed 19% in the atmosphere and 58% at the surface; while the satellite retrievals gave the partition reflected to space to be 32%, absorbed in the atmosphere 21% and at the surface 47%.

To investigate the differences in TOA albedo and net solar flux at the surface between the GEM and the satellite retrievals, comparisons were done separately for clear-sky and overcast conditions. In this way, the effects on solar fluxes due to differences in cloud amounts in the model and actual conditions are excluded. For each pair of satellite and GEM data, the scene was classified as clear sky when the cloud amount from both the GEM and the satellite data were less than 5%, and overcast when they were both greater than 95%. Figures 2(a) and 2(b) show comparisons of the solar fluxes at the TOA and at the surface when both the GEM model and the satellite retrievals considered skies to be clear. It can be seen that the GEM model simulated the TOA reflected flux and the NSSR flux very well under clear skies. For TOA reflected flux, the mean difference is 6.9 W m\(^{-2}\) and the standard deviation is 36 W m\(^{-2}\). The GEM model overestimated the NSSR flux by 3.2 W m\(^{-2}\) with a standard deviation of 38 W m\(^{-2}\). The overestimation of the TOA flux and the NSSR flux means the atmospheric absorption in the model is 9.7 W m\(^{-2}\) less than satellite retrievals. Table 1(c) shows that the GEM model and the satellite retrievals agree very well in the values of TOA albedo and the partition of solar radiation between the atmospheric absorption and the absorption at the surface under clear skies with the mean differences of 0.9%, -1.3% and 0.4% respectively. Figures 2(c) and 2(d) show that for overcast skies, a significant constant bias exists in the model's TOA reflected flux with an underestimation of 150 W m\(^{-2}\) on average. Such an underestimation was distributed to the overestimation of the NSSR flux by 145.1 W m\(^{-2}\) and the overestimation of atmospheric absorption by 5.2 W m\(^{-2}\). Table 1(d) shows that of all incoming solar radiation under overcast conditions, in the model 36% was reflected to space, 42% was absorbed at the surface and 23% was absorbed in the atmosphere; while in the satellite retrievals, these 3 numbers were 57%, 21%
and 22%. Under overcast skies, the absorption in the atmosphere by the GEM and satellite retrievals agreed well and both were larger than those for clear sky by 3%-4%.

The results for May and July, 1999 are similar to those for June, 1999.

Fig. 1. Basin averages of the monthly mean at each hour from March to August 1999. The triangle with/without an open circle denotes the mean value derived from the satellite observations covering the whole/partial basin.
Comparison of Solar Fluxes from Satellite Retrievals and Preliminary Output from CRCM III

ScaRaB data were used to evaluate the preliminary results from the new version of the CRCM. In the previous version of the CRCM, the atmospheric absorption in the model was found to be too low compared with satellite-retrieved values (Feng et al., 2000). In the new version, the calculation of solar radiation absorption by water vapour has been improved, and a climatological aerosol background has been added. The evaluation of the outputs from the CRCM showed that absorption by the CRCM was reduced from 68 W m\(^{-2}\) to 7.6 W m\(^{-2}\) for June, 1994. The TOA reflected flux was overestimated by about 9%, mainly due to two reasons. One is that the cloud amount simulated by the CRCM is a little higher than that deduced from the satellite data. The other reason is that in about 15% of the basin the surface albedo in the model appears to be too high (see Figure 3). Excluding the influence of the difference in cloud amount by only considering clear-sky and overcast-sky scenes, it was found that the radiation fluxes
simulated in this version of CRCM agreed with the satellite retrievals very well at the TOA, the surface and in the atmosphere under both clear and cloudy skies. The distribution of the cloud amount over the basin was not captured very well by the CRCM for the month of June, 1994, which affected the distribution of the radiation flux over the basin. Further improvement of the simulation of radiation fluxes will mainly depend on improvement of the simulation of clouds.

### 4. Relevance

This work directly addresses the second and third goals of MAGS-2, viz. to develop and validate models that yield results within acceptable error limits; and to 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.
5. Networking and Collaboration

The work with WATCLASS is being done in close collaboration with E.D. Soulis and his research group. Natalie Voisin, a M.Sc. student at McGill University, spent a week at the University of Waterloo to become familiar with running WATCLASS and she is planning to spend more time with the Waterloo group in the near future.

The comparisons of satellite data with CRCM-III are being carried out in close cooperation with M.D. MacKay. Similar comparisons with the GEM rerun data for CAGES have resulted in meetings and discussions with scientists at RPN led by Jocelyn Mailhot.

W. Schertzer, P. Marsh and W. Rouse kindly supplied surface radiation measurements that were used to test our retrievals of net solar radiation at the surface. We expect to have a close collaboration with Schertzer in his study of the energy budgets of lakes.

We have an ongoing collaboration with Dr. Rainer Hollmann at GKSS in Germany on the retrieval of radiation budgets from satellite data. Dr. Hollmann is a participant in BALTEX.

Conference/Workshop Presentations


(W. Schertzer incorporated some of our results in his talk at the MAGS-GAME Workshop in Sapporo, Japan in October, 2001.)

6. Summary

We have found that, on average, the GEM model underestimated the TOA reflected flux by 27% to 35% and atmospheric solar absorption by 3.4% to 10% for May to July in 1999. The solar radiation absorbed at the surface was overestimated by 25% to 31%. Comparisons for clear sky condition show that the model's outputs agree with satellite retrievals very well, although there are biases of several W m$^{-2}$ in the TOA reflected flux, and solar flux absorbed in the atmosphere and at the surface. Comparisons under overcast conditions reveal that the model reflected too little solar radiation back to space and such an underestimation caused a significant overestimation of solar radiation absorbed at the surface; atmosphere absorption of solar radiation was comparable with satellite retrievals except for May when the surface was partly covered by snow. The results suggest that the simulated cloud optical depth by the GEM model
was too thin and too much solar radiation was transmitted to the surface. In order to understand the source of these differences we believe that the cloud optical depths in the model need to be investigated. For the atmospheric absorption of solar radiation, the GEM model agrees well with satellite retrievals, with the mean differences being around 9 W m\(^{-2}\) for the 3 months in 1999.

7. **Publications**


Precipitation and Weather Disturbance Evolution in the Mackenzie River Basin: 
Its Interaction with the Global Circulation

J.R. Gyakum¹, M.K. Yau¹, I. Zawadzki¹ and H. Ritchie²
¹Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec
²Meteorological Service of Canada, Dartmouth, Nova Scotia

1. Objectives

- to understand the processes responsible for successful medium-range and short-range predictions of precipitation in the Mackenzie River Basin (MRB);
- to understand the thermodynamic and dynamic processes responsible for the generation of synoptic-scale disturbances in the MRB that trigger subsequent downstream cyclogenesis; and
- to understand the role of these synoptic-scale disturbances in the modulation of the global atmospheric circulation.

2. Progress and Results

A. The Ph.D. work of Marco Carrera on interhemispheric mass exchanges will be completed by December 2001, with the thesis defense expected then. The study of this process, surface anticyclogenesis, provides insight into the amplification of Available Potential Energy (see SubSection B, following), and the associated cold surges that often are associated with precipitation in the MRB. We expect at least two refereed publications from this thesis work. A key recent result is that many of these Northern Hemispheric collapse cases are associated with continental cold surges over both Asia and North America in which the surges trigger equatorial and Southern Hemispheric moisture convection. These instances of convection apparently trigger a series of downstream anticyclonic developments in the Southern Hemisphere that represent the manifestation of the mass increase in the Southern Hemisphere.

Figure 1 (taken from the Ph.D. thesis of Marco Carrera) shows the importance of the Mackenzie River Basin and the east Asian continent as key contributors to the Southern Hemisphere's building sub-tropical anticyclones during the life-cycle of a significant inter-hemispheric mass transport event. Figure 1 also illustrates those regions in the Southern Hemisphere that have gained mass at the expense of the indicated regions in the Northern Hemisphere that have lost mass.
Figure 1: Composite of 25 cases of Northern Hemisphere mass collapse, with difference (hPa) between sea-level pressure at the end time of the collapse and sea-level pressure at the beginning time, nine days earlier. Shaded regions represent the 95 and 99% thresholds of confidence that the null hypothesis of zero change may be rejected.
B. The Ph.D. work of Werner Wintels on available potential energy (APE) will be completed by December 2001, with the thesis defense expected to occur sometime in January 2002. The abstract of the refereed paper that appeared in the journal *Tellus* (Wintels and Gyakum, 2000) follows:

Three recurring regional patterns of extratropical baroclinic development associated with synoptic-scale collapses of Northern Hemisphere available potential energy (APE) are identified using a 1979-95 time series derived from the National Centers for Environmental Prediction (NCEP) reanalysis. A time series of the intraseasonal signal (from 1.6 to 180 days) of APE is used to discern an average cycle of approximately 3 days in the APE generation rate $dA/dt$ (referred to as the APE depletion rate if negative). An APE depletion event is defined as a fall and subsequent rise in the time series of $dA/dt$ associated with this cycle. We define synoptic-scale APE collapses as APE depletion events with maximum depletion rates ($dA/dt_{\text{min}}$) and maximum APE falls ($\Delta A_{\text{min}}$) of less than $-0.145 \times 10^6 \text{ J m}^{-2} \text{ day}^{-1}$ and $-0.280 \times 10^6 \text{ J m}^{-2}$, respectively. All are cold season (15 October - 15 April) events. APE collapses were classified based on the evolution of regional synoptic patterns during the 2 days centered at the time of $dA/dt_{\text{min}}$. All are accompanied by deep tropospheric warming. The west Pacific warm surge (Type A) is driven by cyclogenesis over Japan and anticyclogenesis over the west-central North Pacific. The Bering warm surge (Type B) is associated with an intense southerly flow across the Bering Strait brought on by cyclogenesis near the Kamchatka Peninsula and an intense anticyclone over Alaska. The Atlantic Canada warm surge (Type C) is characterized by an onshore flow of warm air ahead of a continental storm track over eastern North America.

The final phase of the thesis research involves local budgets of APE, in which the regions are defined as having no net fluxes. Thus, we have isolated specific areas in which couplets of rising and sinking motions relating to cyclones and anticyclones are acting to contribute to the Northern Hemispheric APE collapse. One of the most important regions in which this is occurring is that of the MRB and the upstream regions of the north Pacific Ocean.

C. As a continuation of Richard Danielson's Ph.D. research, kinetic energy and moisture budget analyses have been conducted on cyclonic systems affecting the MRB for the cold and the warm seasons. Part of the motivation is to follow up on the work of Wintels to determine the details of the energy conversion from APE to kinetic energy. Many of the cyclonic systems that affect the MRB originate in the western Pacific basin (Gyakum and Danielson, 2000).

A further purpose of this research is to identify the source regions for the water vapour that precipitates and ultimately runs off in the MRB. Particular attention will be paid to the lower latitudes as source regions for cold-season precipitation. These regions have been identified by Lackmann and Gyakum (1996), and Lackmann et al. (1998) for specific cases of MRB precipitation. We will focus on the mechanisms by which the water vapour is transported in the MRB, and whether lower-tropospheric cyclones or anticyclones are responsible for this
transport. For the warm-season cases, we will focus on both local and remote locations of evaporation as a source of water vapour.

Cyclonic storm structures and dynamics have been studied with the aid of potential vorticity inversion techniques. Such inversion techniques have been applied to the problem of identifying mechanisms of water vapour transport into the MRB.

D. In collaboration with M.K. (Peter) Yau at McGill University, we have followed up our modelling study of ex-Hurricane Earl using the MC2 (McTaggart-Cowan et al., 2001) with two additional research papers associated with water vapour's impact on cyclogenesis (McTaggart-Cowan et al., 2002a, b).

E. In collaboration with H. Ritchie of the Meteorological Service of Canada (MSC), we have submitted a manuscript discussing the ensemble forecast issues relating to ex-Hurricane Earl of 1998 (Ma et al., 2002).

F. In collaboration with I. Zawadzki at McGill University, Florence Bouquet has begun her M.Sc. work documenting the large-scale atmospheric environments of severe convective weather that has been detected by the Canadian radar network.

G. In collaboration with R. Kochtubajda of the MSC, we have begun to study lightning activity in the Mackenzie basin, and have begun a detailed examination of the associated meteorology, including the large-scale environments and thermodynamic and wind soundings.

H. Work has begun in collaboration with G. Ingram of UBC, a PI with CASES, on the relationship of weather systems in the MRB to the runoff into the Beaufort Sea. C. Lin of McGill University expects to be involved with this collaborative effort, as it relates to large-scale atmospheric indices, such as ENSO, PNA, NAO, etc.

3. Relevance

The objectives of MAGS include:

- To understand, quantify and model the critical components of the water and energy cycles that affect the Mackenzie basin climate system; and
- To improve the capability to predict changes to the water resources of the Mackenzie basin that are influenced by natural climate variability and that which may be altered by anthropogenic climate change.

The following letters correspond to those projects discussed in section 2 above.

A. The Ph.D. work of Marco Carrera relates regional atmospheric mass buildups in the MRB to interhemispheric mass exchanges. The study of this process, being surface anticyclogenesis
provides insight into the amplification of Available Potential Energy, and the associated cold surges that often are associated with precipitation in the MRB.

B. The Ph.D. work of Werner Wintels is providing an improved understanding of Available Potential Energy, and its conversion to kinetic energy on a Hemispheric scale. The recent finding that thermodynamic processes in the MRB are an important regional contributor to the Hemispheric Available Potential Energy supply, shows the importance of further study of the energy cycle in the basin.

C. The Ph.D. research of Richard Danielson relates to the transports of both moisture and energy into the MRB.

D. The research performed by Ron McTaggert-Cowan on extratropical transformations (ETs) of tropical cyclones provides valuable insight into dynamical systems that may be especially efficient in transporting water vapour into high-latitude regions. Such systems occurring in the Pacific basin are also responsible for transporting water vapour into the Mackenzie basin.

E. The collaborative work with H. Ritchie and S. Ma provides additional insight into the role of ETs in transporting water vapour into high latitude regions.

F. The work with I. Zawadzki focuses on severe weather in the high latitudes and its role in transporting water vapour horizontally and vertically.

G. The collaborative work with R. Kochtubajda enhances our knowledge of high latitude weather systems' impact on the MRB environment within the context of a warming environment.

H. The collaborative work with G. Ingram and C. Lin promises a rigorous assessment of changing weather regimes during a period of global (and more particularly, the MRB) warming.

4. Networking and Collaboration

Seminars and Presentations

East Asian cold surges and cross-equatorial atmospheric mass transports. Second MAGS-GAME Workshop, Sapporo, Japan, October 8-9, 2001.


A two-week Winter Weather Course was held during February, 2001 at COMET in Boulder, Colorado, USA, for the Meteorological Service of Canada. The enrollment was 18 students, including two from the US National Weather Service.

The Mackenzie GEWEX Study (Invited Presentation). First Planning Workshop of the Canadian Arctic Shelf Exchange Study (CASES), Montreal, Quebec, January 20-21, 2001.

Participation in MAGS and/or non-MAGS Workshops


First Planning Workshop of the Canadian Arctic Shelf Exchange Study (CASES), Montreal, Quebec, January 20-21, 2001.

Collaborative Research

- C. Lin (McGill University) – initiation of collaborative research on relationship of weather in the MRB to large-scale circulation indices;
- G. Ingram (UBC) – initiation of collaborative research on relationship of weather in the MRB to freshwater outflow into the Beaufort Sea;
- R. Kochtubajda (MSC) – collaborative research on forest fire relationship to weather and climate in the MRB;
- W. Perrie (Bedford Institute of Oceanography) – collaborative research on ocean-air surface fluxes and their relation to tropical cyclogenesis;
- R. Greatbatch (Dalhousie University) – collaborative research on ocean-air surface fluxes and their relation to tropical cyclogenesis; and
- A. Bellon (McGill University) – severe weather climatology study.

5. Summary

Our research has linked global circulation parameters that include available potential energy, and inter-hemispheric mass transports, to synoptic-scale circulation systems in high latitude regions that include the Mackenzie River Basin. We are studying severe weather in high latitude climates, and its relationship with planetary-scale circulations. We are also studying the dynamics of both tropical and extra-tropical cyclones, and their role in transporting heat and moisture to high latitudes.
6. Publications


– ◆◆◆ –
Convection, Lightning and their Impacts over Forested Areas of the Mackenzie Basin

B. Kochtubajda\textsuperscript{1}, R.E. Stewart\textsuperscript{2}, J.R. Gyakum\textsuperscript{3} and M.D. Flannigan\textsuperscript{4}

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\textsuperscript{2}\textit{Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario}
\textsuperscript{3}\textit{Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec}
\textsuperscript{4}\textit{Canadian Forest Service Northern, Forest Research Centre, Edmonton, Alberta}

1. Objectives

The specific objectives of this study are:

- to understand the role of convective processes over the Mackenzie basin through an examination of its spatial, temporal, and topographic distribution and its relation to atmospheric and surface forcing;
- to validate numerical model output which resolves convection; and
- to examine the impacts of convection and lightning on forest fires.

2. Progress

Progress continues in our efforts to understand the climate-fire-ecosystem interactions in the Mackenzie basin. This year we initiated studies to examine and compare the relationship of atmospheric severity indices and large-scale circulations with lightning activity and fire behaviour in the Northwest Territories (NWT). Two fire seasons were selected. The summer of 1995 was an extreme fire year, during which fires burned 2.8 Mha. In 1998, another above average fire year, fires burned about 1.4 Mha.

Several data sources were used. These include the archived lightning strike data from the Northwest Territories government; fire data from the Canadian Forest Service’s national Large Fire Database (Stocks et al., 2001); sounding data from the Environment Canada upper air digital archive; and the historical gridded data from the National Center for Environmental Prediction (NCEP).

Several thermodynamic and severity indices including George’s K Index (George, 1960), the Lifted Index (Galway, 1956), the Showalter Index (Showalter, 1953) the Total-Totals (Miller, 1972), and the Lower Atmosphere Stability Index, or LASI (Haines, 1998) were calculated from the 00 UTC radiosonde releases at the upper air stations near Fort Smith and Norman Wells. The 00 UTC soundings were selected instead of the 12 UTC soundings because few “nocturnal” and early-morning lightning strikes are detected, and because the atmospheric conditions at this time are more representative of the conditions when forest fires are most active.

To investigate whether the various thermodynamic and severity indices were related to fire behavior, we calculated the head fire intensity (HFI kW m\textsuperscript{-1}) for each large fire in the NWT during the 1995 and 1998 fire seasons using the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada, 1992). We assumed a standard fuel type, black spruce, in this case. Meteorological variables required to calculate the HFI include temperature, relative humidity,
wind speed and 24-h precipitation. These values were interpolated from surrounding meteorological stations in a procedure outlined in detail in Amiro et al. (2001).

To assess the large-scale atmospheric circulation in association with fire incidents, we utilized the NCEP reanalysis global gridded data (Kalnay et al., 1996), to produce composite, or averaged, geopotential fields at 500 hPa. Anomalies, with respect to a 35-year monthly climatology, were also produced. The composites were produced for LASI values of 3 and 5 for those cases with areal coverage greater than 1000 ha.

Partner Involvement

This year we also initiated discussions with officials from Alberta, the Northwest Territories, the Yukon Territories and Alaska. Although we are in the preliminary phase, partner response has been positive. All contacted have indicated that this work is needed and will contribute to studies of future fire regime patterns and recovery planning for various species including the boreal caribou. Several partners are prepared to contribute additional data towards this project. Discussions are continuing and we anticipate broadening our collaborative partnership base in the future.

References


3. Results

Special Issue for MAGS 1994/95 Water Year

A paper concerning the nature of lightning, convection and forest fire activity over the basin was accepted for publication in the special issue for MAGS 1994/95 Water Year of *Atmosphere-Ocean*.

The convective storm season and resultant lightning activity in the Mackenzie basin is characterized as short but intense with a strong peak in cloud-to-ground lightning during June and July. The maximum area of lightning activity is generally located south and southwest of Great Slave Lake, but varies in space and in time and is influenced by local moisture sources (such as wetland areas and small lakes) and by topography. The diurnal distribution of strikes indicates that most of the lightning is linked with daytime-heating initiated thunderstorms.

Evidence was shown for the existence of a complex interaction between the circulation patterns, the thunderstorms, the polarity of the ensuing lightning, the forest fires, and the associated smoke that acts to enhance forest fire activity.

Weather - Fire Interactions

Stability, moisture and LASI index distributions for the large fires in both seasons are shown in Figure 1. The indices were also calculated for the entire 1995 and 1998 fire seasons (May 1 – September 30) to provide a climatology on the relative frequencies of the indices. The analysis of the mid-level stability, Factor A, shows an ability to discriminate large fires. We found that less than 1% of the fires started when the mid-level temperature difference between 850 - 700 hPa is less than 6°C, and that about 60% of the fires began when the mid-level temperature difference is greater than 11°C. The mid-level moisture, Factor B, on the other hand was not useful in discriminating large fires. About 20% of the fires were initiated when the dew point depression at 850 hPa was greater than 13°C, and about 40% of the fires began when the dew point depression was less than 6°C. Our observations did not change significantly when fires larger than 1,000 ha, and 10,000 ha were considered. These observations differ from the Haines (1988) analysis and suggests that either air mass characteristics in the Northwest Territories are different from those in the United States, or that the vertical structure of the atmosphere in the 1995 and 1998 fire seasons was anomalous. Long-term averages at each upper air station may be required for proper comparisons. Another possible explanation is that the wind profiles from the upper air stations may not be entirely representative of the environment near some of the more distant fires.
There were no statistically significant relationships (at the 95% level) found between the HFI and any of the indices. A partial explanation for the poor performance is that we used only the day one HFI. Forest fires can burn for days, weeks, or until winter arrives. We can calculate the HFI for multiple days but we decided to examine the day the fire started first, to determine if there was any relationship.
Correlation analyses suggest a potential predictive capability between several thermodynamic indices and lightning activity. These results are promising and additional analyses are needed. An analysis of the averaged geopotential fields at 500 hPa for LASI values of 5, shows a coherent trough that travels eastward from the Pacific into coastal areas of Alaska (Figure 2). The downstream ridge line passes to the east of the NWT fire region by the onset of the fires at T0. This typically signifies the beginning of large-ascent that triggers a potentially unstable environment into the production of thunderstorms. There was no such coherent signal observed for the LASI-valued composite of 3. The fact that the former composite has substantially more lightning suggests that the preferentially-strong lightning count is a consequence of a synoptic-scale trigger in the form of an upper-level trough that travels eastward from the Pacific basin.

Further analyses are underway to examine the influences of low-level wind speed and direction, antecedent precipitation conditions, and the 12-hr change in 500 mb height on the behaviour of these large fires. Results are not yet available.

Figure 2: A 13-case composite of 500-hPa height (interval of 60 m; light solid), and anomaly (interval of 20 m; heavy solid for positive, heavy dashed for negative) for (A) 24 h prior to the fire onset and (B) the onset of the fires.

4. Relevance

Weather is critical to forest fires. Not only does it affect the ignition of fires through lightning, but it also influences fire behaviour. Strong winds, high temperatures and low humidity enhance the rate of fire growth. Atmospheric instability, another important factor in fire growth, can influence the spread and intensity of wildfires.
Predictions of future fire regimes in Northern Canada suggest that fire weather will become more severe with significant increases in area burned likely (Flannigan et al., 1998; Stocks et al., 1998). This work is enhancing our knowledge of the interactions between the atmosphere, devastating fires and their ecological impacts in the basin. The historical relationships found in our study and used in combination with GCM output to estimate future fire activity will then assist forest and wildlife managers to develop appropriate mitigation and adaptation strategies.

5. Networking and Collaboration

Seminars and Presentations

Kochtubajda, B., November, 2001: Climate-fire interactions: Hot times in northern Canada. McGill University, Montreal, Quebec.


Kochtubajda, B., May, 2001: Climate and fire in northern ecosystems. MSC-AHSD Science Forum, Saskatoon, Saskatchewan.


Participation in MAGS and/or non-MAGS Workshops


Networking Activities and Collaboration with other Researchers

- Dr. Gerhard Reuter, University of Alberta – provision of CLDN lightning data and precipitation data;
- Dr. Charles Lin, McGill University – provision of summer precipitation data within Carvel radar range;
- Drs. Aldo Bellon and Isztar Zawadzki, McGill University – provision of winter precipitation data within Carvel radar range for selected case studies;
- Dr. William Burrows, MSC, Downsview, Ontario – collaboration on national lightning climatology study;
- Dr. Anne Gunn, Caribou Biologist, Yellowknife, Northwest Territories;
- Dr. Suzanne Carriere, Ecosystem Management Biologist, Yellowknife, Northwest Territories;
- Mr. Nick Nimchuk, Fire Weather Supervisor, Edmonton, Alberta;
- Mr. Al Beaver, Fire Management Planning Supervisor, Whitehorse, Yukon Territory; and
- Mr. Joe Stam, Chief, Fire and Aviation, Anchorage, Alaska.

6. Summary

Forest fires pose the greatest danger within the boreal ecosystem for fire managers in the Mackenzie basin. Weather, ignition sources and the condition of the forest vegetation are factors that influence fire occurrence. Strong winds, high temperatures and low humidity enhance the rate of fire growth. Atmospheric instability, another important factor in fire growth, can influence the spread and intensity of wildfires.

Preliminary statistical analyses of two fire seasons suggest a potential predictive capability for several thermodynamic indices and daily lightning activity. Higher values of the Head Fire Intensity (HFI) and more lightning activity were associated with indices representing a greater likelihood of extreme fire behaviour, but the relationships were not statistically significant. For fires greater than 1000 ha, a very coherent large-scale circulation anomaly structure was associated with extreme fire behaviour days that was absent on low potential fire days.

7. Publications

Journal Articles


**Conference Papers**

Optimum Estimates of Surface Precipitation from Volumetric Doppler Radar Data for Hydrological Use and for Model Validation

I. Zawadzki and C. A. Lin
Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec

1. Objectives

During MAGS-1, we concluded that the relationship between cloud measurements (VIS, IR) and precipitation was relatively weak at the latitudes of the Mackenzie River Basin, permitting monthly RAINSAT estimates that were skillful only during the three summer months of the 5-year study. Our objective for MAGS-2 has thus been redirected towards the development of techniques for improving the direct measurements of precipitation by radar, in particular the Carvel and Spirit River radars located in the southern part of the basin. These improved estimates can then be safely interpreted as ground truth for a) NWP model verification, b) as direct input into a hydrological model operating in local sub-basins and c) for assessment of local climatological and orographic effects. We anticipate that the procedure developed will also be applicable to the other radars of the Canadian network since they have a common scanning strategy.

Theoretically, the ultimate limit to the precision of radar rainfall measurements is the variability of the drop-size distribution, which is of the order of 15%. However, since the availability of digital radar data over 25 years ago, the routine operational and research use of these data sets by the meteorological and hydrological community has been hampered by the need of a proper interpretation. There are in fact other factors that prevent raw radar data sets from being a hydrological product. The most important are:

- Range effects caused by beam broadening;
- Regular and variable clutter, the latter caused by anomalous propagation (AP);
- Vertical Profile of Reflectivity (VPR) causing a range-height dependence on reflectivity measurements; and
- Radome and rain path attenuation (for C-band radars).

Precipitation information from radar data is usually obtained from low altitude CAPPI maps but the combination of the above factors can seriously affect the measurements, thus reducing the quantitative usefulness of a radar over a large percentage of its coverage. In this first year, we concentrate on the derivation of the VPR from volumetric data devoid of AP and on demonstrating its importance in correcting CAPPI-based accumulation maps. Simulations on how fine resolution data is perceived by the radar at various ranges have also been performed in order to derive the error structure of rainfall measurements. In subsequent years, we will use radial velocity information from the Doppler cycle to eliminate AP and to derive the so-called Optimum Surface Precipitation (OSP) maps. Techniques for the measurement and compensation of radome and rain path attenuation will also be devised.
2. Progress

At McGill, as part of our RAPID (Radar data Acquisition, Processing and Interactive Display) system, we provide with each CAPPI map the corresponding VPR so that forecasters may assess the suitability of the height of the CAPPI map in representing surface precipitation. Thus, the first step in achieving a similar analysis with the other URP (Unified Radar Plan) radars of the Canadian network was to decode the URP volumetric data and to convert it into a format compatible with the McGill system so that the existing RAPID software would be more easily adaptable. This task has been achieved and the actual VPR generation has then been finalized as follows:

For each 3-D reflectivity scan cycle of 24 elevation angles performed every 10 minutes, instantaneous vertical profiles of reflectivity from 0 to 7 km in height are computed for 5 range intervals 20 km wide from 10 to 110 km in range. Each profile is composed of 35 layers, each 0.2 km in thickness. Of course, an increasing number of lower layers on the VPRs at farther ranges are devoid of any information below the minimum height of the first elevation angle on a curved earth. Data from more than one elevation angle can be integrated inside the same height layer of a given range interval. Since these VPRs are only a function of range, data from all azimuts within a given range interval and height layer are combined, even though such points may be as much as 200 km apart for the last VPR. The integration may be performed in dBZ, mm hr$^{-1}$ or Z depending on the relative weight we want to assign to the stronger reflectivities. An average reflectivity is computed for a given range interval and height layer if it is based on a sufficient number (~200) of non-zero data points.

It is essential to only include precipitation echoes in this integration procedure. At McGill, we have simultaneous Doppler information to help us in this respect. With other radars, we have to rely on an average 3-D ground echo mask derived by integrating volume scans collected during an extended period of no precipitation. Data from the current volume scan in pixels with a non-zero average on this mask are not used in the derivation of the VPR. Such a procedure, however, fails during conditions of AP, when strong ground echoes appear at locations normally devoid of them, thus seriously contaminating the VPR. This problem will have to be resolved in the future by using the available radial velocity information from the previous Doppler scan.

The instantaneous VPR appearing with every CAPPI map is usually sufficient to properly diagnose the height and range dependence of reflectivity measurements. If a bright band is present under normal propagation conditions, its intensity, height, depth of influence and range variability are clearly revealed. An example is provided in Figure 1 where we illustrate the case of a CAPPI map from the Carvel radar at a height that coincides with the peak of the bright band. The VPR display shows that the reflectivities at the 2 km height are on the average about 5 dBZ higher (or a factor 2 in rainfall rate) than those unaffected by the bright band closer to the surface. This observation would be sufficient to warn us of serious overestimation on rainfall maps based on CAPPIs at this height. (In this and other similar figures, the usual color images would have better highlighted the relevant features). The bright band becomes diffuse with range partly because of smoothing by the beam and partly because the precipitation at those ranges is indeed weaker. The VPR information terminates at the height of the snow top and at the height corresponding to the lowest elevation angle (about 0.3 degrees) at the bottom.
In other situations, the characteristics of any other precipitation type would also become evident, like low level growth from warm rain processes and snowfall situations as well as evaporation above a dry layer, or the high reflectivity at upper altitudes of a convective regime, would also become evident. The animation of the CAPPI maps then concurrently provides the variability with time of the VPR.

3. Results

VPR-corrected Rainfall Accumulations

When using the VPR for correcting rainfall measurements, it is desirable to integrate the instantaneous VPRs over a user-selectable time interval in order to avoid unrepresentative correction factors based on transient conditions or on too few data points. Since the RAPID software generates 'multiple hour' accumulations from previously computed 1-h accumulations, it is reasonable to correct each of the 1-h accumulations according to a time-averaged VPR (of the order of at least 30 minutes). A correction factor is independently obtained for each of the 5 VPRs by comparing the reflectivity at the CAPPI height with the one at the lowest available
layer. The latter is clearly a function of range. In order to avoid any possible ground echo contamination at this lowest layer, the user has the option of choosing a slightly higher offset, corresponding to one or two layers. The reflectivity difference between the reference layer and that corresponding to the CAPPI height is converted into a rainfall rate factor according to the user-selected Z-R relationship. This is done only for those VPRs with a sufficient number of layers with data and of course if a value is available at each of the two required heights. When more than one factor can be obtained, an interpolation is performed to derive smoothly varying factors at every kilometer in range up to 110 km, the outermost limit of the VPR information. The uncorrected 1-h rainfall estimates are then simply multiplied by these correction factors. For data beyond 110 km, there is the option to apply the correction factor derived from the farthest profile. However, when dealing with 2 km resolution accumulation maps that extend up to 240 km, a more realistic approach has been devised.

It is known that beyond a certain range, the actual height of the data is above the nominal height of the CAPPI map because the lowest elevation angle is being used at these farther ranges. It typically reaches a height of at least 4 km beyond ranges of 200 km, a height that is usually above the bright band in the snow region. The reflectivity at the lower reference level of the farthest available profile is thus compared with the VPR layer corresponding to actual height of the CAPPI data. Moreover, at these farther ranges the last observed VPR would be additionally smoothed by the increasing beam width of the radar. Therefore, a Gaussian smoothing procedure is applied to all layers within its influence in order to derive a modified reflectivity that is more representative of what would have been detected at these ranges. When this influence extends beyond the upper limits of the time integrated VPR at 5 km, a decrease with height of 6 dBZ/km is assumed. Since the last profile is itself already smoothed, the Gaussian smoothing is actually performed over an equivalent beam width that is less than the actual radar beam width.

Figure 2 exemplifies the case of a 3-h accumulation from the Carvel radar ending at 1059 GMT on 9-July-2000 first obtained in (a) without any VPR correction and the in (b) as the result of three 1-h VPR-corrected accumulations as just described. The correction factors obtained at each hour from each of the 5 VPRs as well as those derived beyond 100 km by Gaussian smoothing are presented in Table 1. As is also evident by examining the time-averaged VPR display over the 3-h period, the coincidence of the bright band with the CAPPI height necessitates correction factors that reduce the uncorrected estimates by at least a factor of two within ranges of 60 km. It is conceded that the bright band contamination at nearer ranges may not have been completely removed since these correction factors are based on time-averaged VPR while the accumulations are the result of 'non-linear' contributions from the 10-minute measurements. Nevertheless, the procedure just outlined is a relatively simple approach that achieves an adequate result to the first order, even more so when the CAPPI height does not coincide with that of the bright band peak. As the influence of the bright band weakens, the correction factors are closer to 1 at a range of 100 km. The subsequent factors derived by Gaussian smoothing the VPR profile centred at 100 km are more realistic than what would have been achieved by extending those observed at 100 km up to the edge of the display. Thus, the original estimates in Figure 2a are more than doubled at ranges beyond 200 km, yielding a final rainfall field that exhibits less functional dependence on range than in Figure 2a. This enhancement, however, may not be sufficient to represent the true surface rainfall at these remote
ranges. An examination of the overall VPR reveals that the lowest layers of the last available profile are already partially affected by the bright band due to beam broadening. Thus, it may have been more appropriate instead to smooth the profile centered at 80 km, or some combination of the inner profiles, that would have resulted into higher correction factors. This alternate course of action is presently being programmed into the algorithm. After finalizing this VPR-corrected radar rainfall accumulation algorithm, the next obvious step will be to compare the resultant estimates with actual rain gage measurements.

![Figure 2](image)

**Figure 2:** Uncorrected 3-h rainfall accumulation derived from 2-km CAPPI maps in (a) and VPR-corrected in (b). The VPR display shown represents the average profile over the 3-h period.

**Table 1:** Correction factors derived as a function of range (km) for each of the three 1-h accumulations that contributed to the total rainfall shown in Figure 2.

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**Simulations**

An assessment of the errors caused by ignoring the vertical profile of reflectivity can be obtained by simulating how an artificial reflectivity profile (or actual reflectivity measurements at close ranges), will be sampled by the radar at various ranges and heights. This approach has the advantage of isolating errors due solely to the VPR while ignoring all other sources of errors that would be present when comparing real radar measurements with gauges.
In Figure 3 we first simulate a horizontally uniform field of 32 dBZ at the surface associated with a Gaussian-shaped bright band peak of 38 dBZ centred at the indicated heights. The bright band thickness has been fixed at 0.7 km, but, on the basis of climatological profiles obtained from vertically pointing radars, the reflectivity drop to the top of the bright band in the snow is forced to be 2 dBZ more than the 6 dBZ drop from peak to rain. The reflectivity gradient in the first 1 km of snow has been chosen to be 6.5 dBZ km\(^{-1}\) and then half this value the rest of the way. This ‘true’ field is initially assumed to be a sector 20 km in range between 15 and 35 km. (Closer ranges are not considered because the higher heights would not be viewed by the highest elevation angle of the radar which is of the order of 30 degrees.) The field is then placed at farther ranges in discrete increments of 20 km, the last interval being from 195 to 215 km, and sampled at every degree in azimuth by a radar with a vertical and horizontal beam width $\theta = 0.86$ degrees. The exponentially decreasing Gaussian weight $w_v$ applied to data of reflectivity $Z_i$ at far ranges that corresponds to a vertical offset of $\theta_v$ degrees from the beam center is given by

$$w_v = \left[\exp\{-0.5(\theta_v/\sigma)^2\}\right]^2$$

where $\sigma$ is the standard deviation of the Gaussian beam given by $\sigma = \theta/2.354$, resulting into a weight of 0.25 at half a beam width from center. The second exponent is to take into account both the transmitting and receiving part of the process.

A similar formulation is applied to derive the horizontal weight $w_h$ and the combined weight $w_i$ is simply their product $w_v w_h$. The simulated reflectivity

$$Z = \frac{\sum w_i Z_i}{\sum w_i}$$

is derived by applying this smoothing to all pixel data within $\pm 1.25 \theta$ from the beam center in both directions where the weight drops to nearly zero. However, on account of the horizontal uniformity of the presumed field, our simulation is really only a function of the vertical gradient of reflectivity. The portion of the inner range data that would be below horizon height at various ranges is assumed to be invisible, that is, it contributes only to the sum of the weights in the previous equation.

The results show that the true surface reflectivity of 32 dBZ is properly measured only by the 1.5 km CAPPI in Figure 3c when the bright band peak is at 2.5 km (and then only within a 90-km range). Beyond this range, a combination of beam broadening and of the fact that the lowest elevation angle ($\sim 0.5$ degrees) rises above the nominal 1.5 km height of the CAPPI, causes the top portion of the beam to be captured by the bottom portion of the bright band. A 2dB overestimation ($\sim 33\%$ in rainfall rate) occurs while traversing the center of the bright band, quickly followed by a rapid decrease as the snow region is sampled beyond a range of 150 km.
Figure 3: Average reflectivity measured at various ranges and CAPPI heights for the case of a uniform surface reflectivity of 32 dZB (~3.6 mm hr\(^{-1}\)) associated with a bright band of 38 dBZ centred at 1.5, 2.0 and 2.5 km height in (a), (b) and (c) respectively and, in (d), with the actual 3-D near-range reflectivity distribution for the case portrayed in Figure 1. Consult the text for other characteristics of the bright band.

The first 3 examples portrayed the obvious overestimation when the bright band peak coincides with the CAPPI height. This bias decreases with range due to beam broadening until the rapid decrease when the CAPPI height rises completely into the snow region. Note that the bright band peak of 38 dBZ is not reproduced even in the original field at near range. This is a consequence of the finite number of elevation angles yielding measurements that are exactly at the bright band peak only at a few specific range points, being instead slightly above it or below it throughout the rest of any range segment. Figure 3d is the simulation of the actual 3-D reflectivity distribution of the data in Figure 1 between 20 and 40 km. It is seen that the simulated outcome is quite similar to that of Figure 3b with a bright band centred at 2.0 km. This should not be surprising since the bright band characteristics were defined to reflect the near-range VPRs as displayed in Figure 1. Given that the average reflectivity of the pattern is
plotted, and not a point-by-point comparison between original and simulated fields, the smoothing of the existing horizontal gradients again does not affect the presented results.

With a significant proportion of the yearly precipitation falling as snow in the Mackenzie River basin, it is also relevant to simulate how radar samples winter precipitation. When the surface temperature is relatively warm (> -6°C), snow crystals are relatively moist and tend to aggregate or stick into larger snowflakes, exhibiting a vertical reflectivity profile as that assumed earlier for the top of a bright band, that is, of ~6.5 dBZ km⁻¹. At colder surface temperatures, single dry crystals predominate yielding a reflectivity profile that is assumed to decrease at half that rate. In Figure 4a, the standard 1.5-km CAPPI of most radar systems would report at most a reflectivity of ~21.5 dBZ, 60% of the assumed surface snowfall rate of 1 cm h⁻¹, (26 dBZ with a Z-R of Z=400R²). The underestimation would be even greater (~8 db or only 40% of the true surface snowfall rate of 1.6 cm h⁻¹) if, as in Figure 4b, we assume warmer surface temperatures that are normally associated with higher reflectivities. These negative biases will be worse beyond ~90 km when the lowest elevation angle samples the snow at progressively higher altitudes (or at higher CAPPI heights). The noticeable increase of the reflectivity with range for all assumed CAPPI heights is due to the combined effect of beam broadening and of the assumed linear decrease in dBZ. The latter implies a proportionately higher contribution in terms of ‘Z’ weighting from a pixel at a given offset below the beam center compared with the one at the same offset above.)

![Figure 4: Average reflectivity measured at various ranges and CAPPI heights for two snowfall situations: (a): dry surface snowfall of 26 dBZ (~1 cm h⁻¹) (b):'wet’ surface snowfall of 30 dBZ (~1.6 cm h⁻¹). A snow top of 5 km is assumed in both cases.](image-url)
It is thus not surprising that most snowfall estimates by all radar systems fall short from the truth if the VPR is not taken into account. We intend to perform a systematic evaluation of the errors due to the extrapolation to ground of measurements aloft and then verify our simulations with actual data from snowfall conditions around the Carvel radar as soon as the appropriate radar and snow gauge data sets are available.

Discussion

In order to obtain the best estimate of surface rainfall rate, it may be necessary to depart from the concept of constant altitude (CAPPI) maps. Instead, the reflectivity over each pixel should be at an optimal lowest height selected on the basis of ground echo, shadow and VPR considerations. The latter will also provide the necessary adjustment required to relate the intensity of the precipitation aloft to that of the surface. We are currently formulating the algorithm to generate this radar product that we refer to as the **Optimum Surface Precipitation (OSP)** map. In our effort to select data as close as possible to the surface, it is crucial to avoid the ground echoes themselves. This task is simplified when dealing with radar volume scans consisting of 24 simultaneous Doppler and reflectivity PPIs as is the case with the McGill Doppler radar system. However, the other Canadian radars have Doppler information on only 4 elevation angles every other cycle (10 minutes) when the full 24 reflectivity angles are then not available. The strategy for deriving OSR maps is thus being substantially modified, as is the algorithm for identifying AP echoes.

As listed below, there are a number of radar rainfall accumulation procedures that need to be formulated and tested with URP radar data and extensively verified with surface measurements in order to determine their relative accuracy.

1. From CAPPIs synthesized from the 24 reflectivity PPIs scan every 10 minutes with horizontal interpolation over the normal ground echoes as in Figure 2a.
2. As above but with VPR correction as exemplified in Figure 2b.
3. From pseudo-CAPPIs generated from the 4 reflectivity PPIs of the Doppler scan where ground echoes and AP have already been removed by signal processing techniques. (10-min resolution, with and without VPR correction obtained from #1).
4. As in #2 above, that is, from CAPPIs derived from 24 reflectivity PPIs, but introducing the Doppler information available at the adjoining cycles in order to attempt AP elimination in addition to regular ground echoes removal.
5. If steps #3 and #4 are both skillful, combine them in order to generate accumulations with a 5-minute time step.
6. How do the OSP estimates compare with the best of the above?

The answer to this question is of primary importance not only for the goal of optimum precipitation measurements over the Mackenzie River basin but throughout Canada.
4. Relevance

Mesoscale model precipitation outputs must be validated. Radar data are probably the only source of information with scales comparable to those of models. It is of paramount importance to ensure that radar precipitation fields are themselves reliable. Proposed research for the next year includes radar-model comparisons (in collaboration with C. Lin), and in particular within the context of downscaling model information.

5. Networking and Collaboration

In order to develop, and especially test, algorithms that remain robust under a variety of meteorological conditions it is necessary to acquire large quantities of radar data. So far in this development phase, we have relied on David Hudak of the King City radar facility for providing us with some samples of a specific precipitation type, like bright band events, over the Carvel region. Bob Kochtubajda of Environment Canada in Edmonton has recently guided us in selecting cases of moderate snowfall precipitation that we have just received and will shortly analyzed. Eventually, we may need to acquire Carvel (as well as Spirit River) volume scans on a routine basis in order to permit the continuous monitoring of precipitation over sub-basins of the southern Mackenzie Basin. This requirement is also appropriate for modelling requirements and is a fundamental departure from an analysis of isolated case studies. These studies will also need corresponding gauge data from the Alberta group. Discussions have been initiated among the interested parties in order to achieve this goal.

6. Summary

Meteorological radars have been around for nearly 50 years but it was not until digital radar data became available about 20 years ago that the information they collected could have been used by both scientists and the general public alike. However, the routine operational and research use of these data sets by the forecasting and hydrological community has been hampered by the need of a proper interpretation. There are in fact a number of factors that prevent raw radar data sets from being directly related to surface precipitation. The most important are: a) range effects caused by the widening of the radar beam, b) the presence of regular and of anomalous ground echoes, c) the general decrease, and at times increase, of precipitation intensity with height, and d) reduction of intensity with range due to the attenuation caused by the intervening precipitation. Thus, the primary goal of this research is to develop algorithms that automatically remove, or correct for, these sources of errors. We have already been successful in extracting from the three-dimension radar data sets a vertical profile of precipitation, providing the relative intensity of precipitation at various altitudes. This has allowed us to correct precipitation measurements that are forcibly made aloft in order to avoid most ground echoes. Another goal of our project consists in improving the short range forecasting of meteorological models by providing them with corrected precipitation information derived from radar. These techniques are currently applied to data collected in the southern part of the Mackenzie River basin, but are expected to be applicable to any radar system in Canada.
1. Objectives

The objective is to evaluate the ability of the land surface scheme CLASS (Verseghy, 1991: *Int. J. Climatol.* 13: 347-370) to simulate surface sensible and latent heat fluxes, and precipitation over a summer period. Data from CAGES are used for this evaluation. We have coupled the CLASS and force-restore land surface schemes with the high resolution meteorological model MC2 (Mesoscale Compressible Community Model), (Benoit et al., 1997: *Mon. Wea. Rev.* 124(3): 362-383), and applied the coupled model to simulate the 1996 Saguenay flood in Quebec (Wen et al., 2000: *Mon. Wea. Rev.* 128: 3605-3617). The results showed that the partition of the sensible and latent heat fluxes is quite different between MC2-CLASS and MC2-force restore, but the sums of the fluxes are similar. It is thus important to determine the ability of CLASS to simulate these surface fluxes.

2. Progress

The land surface scheme CLASS (Canadian Land Surface Scheme) has been set up as a stand-alone model over the Trail Valley Creek site in the Northwest Territories. Measurements of meteorological variables needed to drive CLASS (surface pressure, low level wind and temperature, specific humidity, incoming solar and longwave radiation, precipitation) as well as the surface sensible and latent heat fluxes are available for the 3-month CAGES period from June to August 1999, at intervals of 30 minutes. We use the observed fields to drive CLASS to simulate the surface sensible and latent heat fluxes, which are in turn compared against the observed values.

We have also generated land surface characteristics for the Mackenzie basin using a 1-km soil property and vegetation cover data set from the USGS and Agriculture Canada. This is a necessary step in setting up the coupled MC2-CLASS model for the simulation of summer precipitation of selected cases during the CAGES period.

3. Results

CLASS has 3 soil layers for the thermal and moisture regimes, and resolves 4 types of vegetation. The Trail Valley Creek site consists largely of hummock-hollow topography. The stand-alone CLASS model has been run for 3 months with a time step of 30 minutes. Table 1 compares the sensible and latent heat fluxes simulated by CLASS with the observed values. For comparison, we also show the statistics for the heat fluxes simulated by the GEM operational model, which uses the force-restore land surface scheme (Table 2).
Table 1: Comparison of fluxes simulated by CLASS and observed values. [MBE: mean bias error, RMSE: root mean square error, D: dimensionless index of agreement between 0 (poor agreement) and 1 (perfect agreement)].

<table>
<thead>
<tr>
<th>Heat flux</th>
<th>MBE (W m⁻²)</th>
<th>RMSE (W m⁻²)</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible</td>
<td>11</td>
<td>34</td>
<td>0.86</td>
</tr>
<tr>
<td>Latent</td>
<td>-6</td>
<td>41</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 2: Comparison of fluxes simulated by operational model GEM and observed values.

<table>
<thead>
<tr>
<th>Heat flux</th>
<th>MBE (W m⁻²)</th>
<th>RMSE (W m⁻²)</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible</td>
<td>17</td>
<td>55</td>
<td>0.70</td>
</tr>
<tr>
<td>Latent</td>
<td>-23</td>
<td>73</td>
<td>0.59</td>
</tr>
</tbody>
</table>

We see that the stand-alone CLASS model produces estimates of heat fluxes which have smaller errors than GEM. The RMS errors of the former are of order 30-40 W m⁻²; for comparison, the observed daytime sensible and latent heat fluxes are of order 100 and 200 W m⁻² respectively. Thus the RMS errors of CLASS are of order 20-30% of the daytime fluxes. The RMS errors of GEM are larger than the CLASS values by about 50%. However, we need to be cautious in comparing the CLASS and GEM results. The land surface scheme of GEM is force-restore, not CLASS. The forcing fields in the two models are also likely quite different. Finally, the stand-alone CLASS model is at a point location, while the GEM results are averaged over 24 km × 24 km grid squares. Preliminary results with the GEM-CAGES model (at a resolution of 10 km) show that the index of agreement over a 30-day period is 0.62 and 0.69 respectively for the sensible and latent heat flux, comparable to the results of the operational GEM model. We note that the land surface scheme for GEM-CAGES is ISBA. We plan further work to determine the ability of the three land surface schemes (CLASS, ISBA and force-restore) to simulate surface fluxes.

4. Relevance

The results are relevant to MAGS objectives, as MAGS-2 focuses on the modelling of the major components of the Mackenzie basin physical system to improve our predictive capability for water resource problems. Surface sensible and latent heat fluxes are important components of the surface energy balance; it is thus important to assess the ability of different land surface schemes (CLASS, ISBA, force-restore) to simulate these fields.
5. Networking and Collaboration

We have interacted with Phil Marsh’s group during this project. They have provided valuable guidance on the characteristics of the Trail Valley Creek site, and on the observational data. The project has also used data from the GEM-CAGES runs.

6. Summary

We have used the land surface scheme CLASS in a stand-alone mode to simulate the surface sensible and latent heat fluxes during the 3-month period from June to August of 1999. As part of CAGES, observed meteorological data needed to drive CLASS are available, and observed values of the surface heat fluxes are also available for verification. The results show that CLASS performs well, with root mean square errors that are about 20-30% of the daytime flux values. We also examined the performance of the GEM model runs, which use a different land surface scheme (force-restore). The RMS errors are about 50% larger than those of CLASS. There is ongoing work to determine the sources of errors.
1. Introduction

In our MAGS-1 Final Report last year, we indicated that the Canadian Regional Climate Model (CRCM) had been coupled with the Canadian Centre for Climate Modelling and Analysis (CCCma) third generation GCM physics package (GCMIII), which includes amongst other improvements the Canadian Land Surface Scheme (CLASS), and that initial testing had begun. In this report we highlight progress we have made with the new model, which we call the CRCM 4.0 (MAGS).

2. Geophysical Data Sets

Vegetation cover, soil texture, and other geophysical data have been assembled and gridded at 1 km resolution over North America for the use of CRCM 4.0 (MAGS). A brief description is given here.

Land Cover Data

An assessment of various land cover data sets for the Mackenzie basin was conducted by Pietroniro et al. (1999). According to this assessment, the Canada Centre for Remote Sensing (CCRS) 1995 31-category 1 km resolution land cover for Canada (CCRS-2) was found to be superior in representing the Mackenzie basin land features to other data sets such as the USGS North American land cover and the OLSON global ecosystem land cover. The CCRS land cover was thus chosen to represent the Mackenzie basin and other Canadian regions for use in the CRCM. The USGS North American and the Olson Global land cover classifications were still needed to provide data for non-Canadian locations.

All of these land cover data sets were available in their own geographical projection, and required reprojection onto the polar stereographic grid used by the model. Also, since each land cover classification differed in the number and types of classes, a series of further transformations was required. First, the USGS’ 27 categories and the OLSON’s 94 categories were (subjectively) converted to the CCRS’ 31 categories. Examination of continuity at political borders indicated a number of problems related to the differences between the various schemes. A number of \textit{a posteriori} adjustments were made to improve matching of the USGS and OLSON categories at the borders. Once all the land cover data had been converted to the CCRS-31, these were transformed into the 22 categories used by CLASS as described in Verseghy et al. (1993). A further transformation into 5 broad categories was also required to suit the current software implementation of CLASS. These final classes are: tall conifers, broadleaf trees, crops, grass/swamp/tundra, and urban. Finally, these data were aggregated onto the lower spatial resolution grids used by the model by counting the number of cases in each category within each
destination cell. The final result is a map of occurrence, in percent, of each of the 5 categories. An example of this aggregation for 3 simulations described later in this report is shown in Figure 1. In this figure, the “tall conifer” classification (%) is shown for a common sub-region of the 3 simulations described below in Section 4. The horizontal resolution of these simulations is 150 km, 50 km, and 15 km for experiments “O”, “J”, and “N” respectively. Note that while the mean value over this sub-region is nearly the same (0.54, 0.50, 0.50), the standard deviation increases with increasing resolution (0.18, 0.20, 0.27). The impact of this increasing heterogeneity in land surface features on the surface energy balance is one of our research focal points.

Note that Figure 1 seems to indicate vegetation cover over the two major lakes in the region: Great Slave Lake and Lake Athabasca. In these simulations we have not incorporated a dynamic lake model, and instead have simply “filled in” the lakes by nearest neighbour interpolation. The impact of lakes on surface climate is currently a major research activity for us, recently funded outside of MAGS through the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS).

**Soil Data**

Soil texture profiles and depth-to-bedrock information are required by CLASS. Since there are no readily available gridded soil data suitable for this purpose, a 1 km gridded resolution soil dataset was prepared for the simulations. The gridded soil data were derived from SLC (Soil Landscapes of Canada, Centre for Land and Biological Resources Research, 1996), Geographical Information Systems (GIS) coverage of digitized soil maps over Canadian regions, and from the USGS soil data processed by CONUS-SOIL (Miller and White, 1998) for the US regions. Data processing includes the mapping of soil information on irregular map polygons to a 1 km
resolution gridnet covering the model domain; the extraction of soil texture (sand and clay %) profile data from descriptive soil classifications; the mapping of soil texture profile at each grid to standard vertical CLASS soil layers; the consistency check for land-sea mask, water and ice points by using the CCRS-2 vegetation data as the standard; and the smoothing of data across political boundaries. For consistencies in the soil data across the US and Canadian border, procedures used in the preparation of the CONUS-SOIL dataset (Miller and White, 1998) were employed to extract soil texture and depth-to-bedrock data from descriptive soil classifications, and to map the profiles to CLASS soil layers. Figure 2 shows the variation in sand cover in the first soil layer for simulations “O”, “J”, and “N” over the same sub-region shown in Figure 1.

![Figure 2](as in Figure 1, but for first layer sand.)

Other Surface Data

In addition to vegetation cover and soils data, the CRCM requires a variety of other geophysical and initialization data. Topography is taken from the 30 arc-second resolution GTOPO30 digital elevation model, averaged over the grid cells for the model grid of any given experiment. Figure 3 shows elevation over the same sub-region as in Figures 1 and 2 for the 3 simulations described below in Section 4.

SST and ice cover are specified from the monthly, 1 degree resolution Hadley Centre data set GISST 2.3b, linearly interpolated in time to the model time step. Ice mass, which is also required by the model, is as used in Environment Canada’s general circulation model (CCCma GCMII), reconciled with the observed ice cover fraction.
Apart from fixed soil properties (texture, etc.), CLASS also requires initial values of soil moisture and temperature. Sufficiently unrealistic values might contaminate the simulation of surface climate for many years while the land surface model “spins up” to reach its own equilibrium. However, there is very little observed information - particularly of soil moisture - in our region of interest. Our strategy was to initialize soil moisture to its saturation value based on the porosity of the soil, and then allow the model to spin up for 2 complete annual cycles starting in April, 1993. Here the assumption is that in April, all the snow has melted, and soil moisture is at its peak value. In fact, CLASS appears to equilibrate relatively quickly using this approach, though a detailed spin-up analysis is still underway. Temperature in the first soil layer is initialized to the mean atmospheric temperature near the surface from operational analysis for the first day of the simulation. Initial temperature for the third (deepest) soil layer is taken from the annual average surface temperature of the Climatic Research Unit’s half-degree monthly climate timeseries (New et al., 2000). The second soil layer is initialized as the average of the first and third layers.

3. Mackenzie Basin Water Year Simulations

Our first simulations of CRCM 4.0 (MAGS) were of the Mackenzie basin 1994-95 Water Year. Details of our baseline run (simulation “A”), along with a similar run made with the previous version of the CRCM, can be found in MacKay et al. (2001). Simulation “A” includes the GCMIII physics package (internal version GCM13) without modification - i.e. no adjustments were made to account for the large increase in horizontal resolution compared to the GCM for which it was designed. Simulations of both versions of the CRCM were found to be somewhat problematic, as discussed in the above mentioned report; nevertheless, this study represents our first serious effort at CRCM evaluation over the MAGS region. Based on these early simulations
of the new model, a number of inconsistencies in the geophysical data and other aspects of the model were found and corrected. Some results of this study are briefly summarized here.

**Surface Energy Balance Highlights**

Basin-averaged monthly screen level temperature from simulation “A” is compared with the gridded, monthly observed data set described in Louie et al. (2002) in Figure 4. Simulation “A” (solid line) is evidently too warm during the winter, and too cold during the summer. It appears that this bias is associated with excessive cloudiness (Figure 5). A second simulation with a modified cloud onset function (more in line with the previous version of the CRCM), labeled simulation “B”, indicates a more realistic basin-averaged cloud cover fraction (dashed line in Figure 5) and improved screen temperature (dashed line in Figure 4). Note that surface vapour flux (i.e. evapotranspiration) also improved, as discussed below.

![Figure 4: Mackenzie basin-averaged screen temperature for Water Year 1994-95: CRCM simulation "A" (solid); CRCM simulation "B" (dashed); CRCM simulation “J” (dotted - spring only); Observed (asterisks).](image-url)
Surface Water Balance Highlights

Basin-averaged monthly precipitation and evapotranspiration from Simulations “A” and “B” are compared with the observed estimates from Louie et al. (2002) in Figures 6 and 7.
Figure 6 indicates that at the basin scale at least, monthly accumulated precipitation is simulated quite well in run “A”, and with somewhat excessive summertime amounts in “B”. The increase in summer precipitation in “B” is likely associated with the increased evapotranspiration in “B” through the process of precipitation recycling. Note that, as discussed in Louie et al. (2002), the observed evaporation estimate is very likely too large, and should be regarded as an upper limit only. Nevertheless, as discussed below, we feel that run “A” is probably underestimating this parameter.

The mean annual water balance for “A” and “B” is summarized in Table 1, along with observed estimates from Louie et al. (2002).

Table 1: Annual Mackenzie basin water balance: MSC observed mean estimate for 1972-95; MSC observed estimate for 1994-95; Run “A”; Run “B”.

<table>
<thead>
<tr>
<th></th>
<th>1972-1995</th>
<th>1994-95</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>(mm)</td>
<td>422</td>
<td>365</td>
<td>402</td>
</tr>
<tr>
<td>Evaporation</td>
<td>(mm)</td>
<td>274</td>
<td>271</td>
<td>205</td>
</tr>
<tr>
<td>Discharge</td>
<td>(mm)</td>
<td>176</td>
<td>135</td>
<td>175</td>
</tr>
<tr>
<td>Storage change</td>
<td>(mm)</td>
<td>~0</td>
<td>?</td>
<td>-10</td>
</tr>
<tr>
<td>Residual</td>
<td>(mm)</td>
<td>-28</td>
<td>-41</td>
<td>32</td>
</tr>
</tbody>
</table>

A number of comments regarding this table are in order. First of all, note that the observed climatology has a moisture budget residual of -28 mm. Louie et al. suggest that this is largely due to an overestimation of evaporation resulting from the use of Morton’s method. Nearly every year in the period of record showed a negative residual, with 1994-95 being no exception.
An independent estimate of summertime evaporation based on a modified Priestly-Taylor calculation suggests a value of around 225 mm. This lower value is also consistent with summertime estimates based on AVHRR data. This supports the idea that the bulk of the water budget residual is a result of errors stemming from the use of Morton’s method. Note that there is no observed estimate for the change in storage for the 1994-95 Water Year, and this might account for some of the observed residual. It is very unlikely, though, that the climatological average change in storage is significantly different from zero, and the observed residual of -28 mm truly reflects the error in the analysis. Assuming no error in the discharge and precipitation measurements, one can view the budget residual as providing a range for the observed evaporation estimates. Thus the 1994-95 observed estimate of E is likely in the range of 230-271 mm. Viewed this way, simulation “A” is likely underestimating this parameter, while “B” is overestimating it. Note that both simulations are probably overestimating precipitation.

Table 1 indicates that both simulations “A” and “B” also have a moisture budget residual. This error has been traced to the presence of surface rock over several grid points in the basin, which corrupts the surface water balance in CLASS. With surface rock removed (as is done when using CLASS in the CCCma GCM, for example), the simulated moisture budget residual vanishes. Of course this has an impact on the simulated surface climate. A 3 month springtime simulation (labeled “J”) with surface rock removed (as well as a few other inconsistencies corrected) is compared with “A” and “B” in Table 2.

Table 2: Spring (Apr-Jun, 1995) Mackenzie basin water balance: MSC observed estimate for spring 1995; CRCM simulation “A”; CRCM simulation “B”; CRCM simulation “J”.

<table>
<thead>
<tr>
<th></th>
<th>OBS</th>
<th>A</th>
<th>B</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm)</td>
<td>71</td>
<td>99</td>
<td>117</td>
<td>118</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>176</td>
<td>81</td>
<td>109</td>
<td>117</td>
</tr>
<tr>
<td>Discharge (mm)</td>
<td>?</td>
<td>147</td>
<td>147</td>
<td>137</td>
</tr>
<tr>
<td>Storage change (mm)</td>
<td>?</td>
<td>-149</td>
<td>-159</td>
<td>-136</td>
</tr>
<tr>
<td>Residual (mm)</td>
<td>?</td>
<td>20</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

Screen temperature, cloud fraction, precipitation, and evaporation from simulation “J” are also shown in Figures 4-7 (dotted lines). Table 2 indicates that while “B” and “J” have somewhat larger P and E than was found in “A”, the hydrologically relevant flux P-E is still unrealistically positive (or close to zero) compared with observations during this season. In fact, Figure 8 shows that P-E is only marginally improved in “B” and “J”, though it is important to keep in mind that the observed E is likely too large as discussed above. This suggests that the model may have a somewhat over-active hydrological cycle, i.e. excessive precipitation recycling. Interestingly, the simulations discussed in the next section show that springtime P-E becomes more negative (and thus more realistic for this extremely dry water year) as horizontal resolution is increased.
Hydrographs

Six-hourly accumulated run-off from simulation “A”, as well as from a simulation of the previous version of the CRCM, “X2”, were routed through the University of Waterloo’s WATROUTE channel routing scheme in an effort to simulate a hydrograph at Arctic Red, near the mouth of the Mackenzie River. Complete details can be found in MacKay et al. (2001). Simulated and observed hydrographs for Water Year 1994-95 are shown in Figure 9.
Total discharge for the Water Year corresponds to 125 mm, 148 mm, and 169 mm respectively for observed, simulation “X2”, and simulation “A”. While “A” shows an obvious improvement in timing, the spring freshet is grossly exaggerated compared with the observed estimate. However, in light of the analysis presented above, we believe we can explain - and remove - much of the discrepancy. Our analysis, as it pertains to Figure 9, is now summarized.

- As noted above, screen temperatures in “A” were on average much colder in autumn than was observed. Thus much of the precipitation that fell in September and October (1994) fell as snow, yielding a basin-average snow water equivalent (SWE) of 20 mm on Oct. 1 and 60 mm on Nov. 1. Observed estimates of basin-average SWE based on SSM/I passive microwave data suggest a Nov. 1 value of only 16 mm. If “A” generated more rain instead of snow in the autumn of 1994, then the simulated discharge would have been larger in October and November (1994) and correspondingly smaller during the freshet - more in line with observations.
- By driving WATROUTE “offline” with the water excess of the CRCM we have precluded the possibility of interflow, which occurs at a slower rate than overland runoff. Thus, the spring freshet would tend to be less intense initially, and more spread out over time - again more in line with observations. A fully coupled CRCM/CLASS/WATROUTE is of course our ultimate objective. As noted in Soulis et al. (2000), inclusion of interflow is also expected to influence surface vapour flux, and thus the entire hydrological cycle.
- While generating quite different moisture fluxes, simulations “A”, “B”, and “J” all produced remarkably similar net P-E, which is the relevant flux in terms of simulating hydrographs. In each case P-E was much too large in summer, and in the case of “A” contributed to the excessive summer discharge shown in Figure 9. This may be indicating excessive precipitation recycling in the model, an issue worth exploring. Interestingly, while P and E were both much larger than observed estimates in the previous version of the CRCM (simulation “X2”), P-E was actually much better simulated than in “A” and “B”.

4. Mesoscale Circulations During Snow Melt in High Resolution Simulations

It has long been recognized that differential surface forcing resulting from surface heterogeneity can result in mesoscale circulations in the lower troposphere. Surface heterogeneity can exist in vegetation cover, soil moisture, snow cover, or any combination of these. Patchy snow cover is of particular interest since this evolves dynamically and the possibility exists for feedback between the snow patch boundary and any low level atmospheric circulation.

The snow melt period is a particularly critical time in the surface hydrological cycle of the Mackenzie basin and it is thus of interest to see whether a high resolution 3-D climate model forced with observed atmospheric data can generate mesoscale circulations of relevance to the surface climate, and in particular the surface energy balance of the snow pack.
As mentioned in Section 2, the CRCM has been configured for 3 simulations of the spring snowmelt period of 1995 (April-June) over Western Canada. The 3 runs were identical except for the actual domain and the horizontal resolution used, which was 150 km, 50 km, and 15 km respectively for simulations “O”, “J”, and “N”. 29 levels in the vertical were used in each case, with 8 levels below 900 hPa, and lateral boundary conditions were specified using analyses from the global data assimilation system of the Canadian Meteorological Centre. Initial conditions for soil temperature, soil moisture, and snow cover for April 1, 1995 were taken from a long, previous simulation of the model (simulation “A”, in fact) and interpolated onto the appropriate grid. The simulations are compared below over a sub-region common to all 3 experiments – essentially the domain of “N” minus a 10 point lateral sponge zone required for nesting the lateral boundary conditions. Surface features of this sub-region are indicated in Figures 1-3.

**Results**

Details of the study are presented in MacKay et al. (2002). Indeed we have found that simulation “N” generated diurnally forced shallow mesoscale circulations associated with surface flux heterogeneity regularly throughout the snow melt period. One example is illustrated in Figure 10 which shows a snapshot for 00 UTC May 7 of surface sensible heat flux (shaded) and 900 hPa vertical velocity (contoured). While “O” and “J” can produce only very weak circulations, “N” generates much stronger vertical velocities with maxima reaching 16 cm/s on this 15 km horizontal resolution grid. Peak vertical velocities are obviously associated with peak sensible heat flux. Note that even though the ground is largely snow covered in these simulations on May 7, it is the bare canopy poking through the snow cover that provides this heat flux. It is of interest to know whether these heat flux driven circulations generic to simulation “N” (in late afternoon) can play a role in the energy budget of the snow-covered surface.
The diurnally averaged surface energy budget for the 3 simulations, averaged over the common sub-region (Figures 1-3) is shown in Figure 11. It is clear that horizontal resolution has an impact on net radiation (Figure 11a). Simulation “N” has more net solar radiation at the surface because it is less cloudy than the others, and increased net radiation over the bare canopy generates increases in both latent and sensible heat fluxes (Figure 11b), especially in May. The net available energy for snow melt (for those parts of the grid cell that are snow covered), however, is remarkably similar for all 3 simulations (Figure 11c) as is the actual snow melt (Figure 11d). Separate energy budgets have been computed for the snowpack itself, as well as that part of the snowpack that is not under the canopy. Note that snow under the canopy is somewhat sheltered from the overlying atmosphere, while any snow out in the open could potentially feel more strongly the influence of mesoscale circulations in the lower atmosphere through an interaction with turbulent heat exchange. Our conclusion from these experiments is that, at least in the current formulation of the model, there appears to be little impact of heat flux driven circulations on the surface energy balance.

5. References


1. Objectives

The objectives of this study are:

- Document the nature of clouds and cloud systems over the Mackenzie basin and to better understand their role in the climate system; and
- Better appreciate the complete nature of the Mackenzie basin climate system as well as other regions.

2. Progress

This research has relied upon several datasets and approaches. Cloud studies have been utilizing the surface-based operational observations from all the sites located within the Mackenzie basin. The precipitation event studies have been focusing on the 1999 CAGES period and using data from the Carvel radar, geostationary satellite, and surface weather stations. The Mackenzie study has relied upon many observational and model datasets; the Saskatchewan basin study has so far only utilized the 1948-2000 NCEP re-analysis dataset.

Considerable attention had to be paid to accessing, reading and interpreting these various datasets. These stages have largely been completed and the analysis effort is proceeding briskly.

3. Results

3.1 Cloud Fields

Many of the characteristics of clouds are quite consistent with those expected for a cold climate system with its short warm season. Clouds occur over this region about 80% of the time, they cover on average about 60% of the sky, and, when present, multiple layers occur for about half the time. Clouds can be very persistent, with duration sometimes exceeding 1000 h. The cloud characteristics are strongly linked with diurnal, seasonal and inter-annual variations. The occurrence of convective clouds is in particular strongly peaked in the mid-afternoon during the summer. The maximum cloud fraction occurs in the autumn in association with the north Pacific storm track; the minimum occurs in midwinter. Although these diurnal and seasonal cycles are pronounced, the actual magnitudes of cloud fraction and other characteristics vary substantially between years. There is some evidence of change in cloud features over the last few decades. In particular, cloud fraction has increased significantly, although there is considerable inter-annual variation. Such a trend is associated with the general increase in surface temperature that has
been experienced over this region. During the cold season, this is also linked with higher night
time cloud fractions. In tandem, there has been a tendency towards more convective clouds
during the summer.

3.2 Rainfall Events

The six largest rain-producing systems that occurred during the spring and summer of 1999
within the southern Mackenzie basin and in the vicinity of Edmonton are being examined. First
of all, and as typical, these 6 events made up about 50% of the region’s annual rainfall. For this
particular period, the storms were almost all banded-like, produced rainfall mainly through
stratiform processes, and typically had very weak anvil regions. The storms occurred under
conditions of weak wind shear and were generally linked with moisture entering the region from
the south.

Mackenzie Basin

Finally, the special 1994/95 Water Year issue of Atmosphere-Ocean is coming to fruition. For
the synthesis paper, it was shown that the basin operates in an inefficient manner, and that it was
even more the case in 1994/95. A number of atmospheric, surface and hydrological processes
were at work to lead to this effect. Although preliminary, this tendency towards basin
inefficiency characterizes other low discharge years as well, whereas the basin tends to
efficiency for high discharge years.

Saskatchewan Basin

The National Center for Environmental Prediction/National Center for Atmospheric Research
(NCEP/NCAR) reanalysis data were used to calculate the atmospheric moisture fluxes into and
out of the Saskatchewan River Basin (Figure 1). The direction of the meridional moisture fluxes
across the Saskatchewan River Basin changes with the seasons, but that of the zonal moisture
fluxes does not. For example, moisture flows into the basin from the south in summer and this is
usually related to the long-distance meridional transport of water vapour from the Gulf of
Mexico. In contrast, moisture always flows into the basin from the west and it always flows out
of the basin to the east. Vertical profiles of the moisture flux divergence over the basin show a
steady moisture loss below 700 hPa and weak moisture gain above this level. These features are
very different from those found in the Mackenzie River Basin where moisture is gained at all
levels. While significant differences are found between the Saskatchewan River Basin and
Mackenzie River Basin in terms of the temporal and vertical variations of water vapour fluxes,
there are connections between these two regions. The Saskatchewan River Basin receives
moisture from the Mackenzie River Basin over most periods of the year. In contrast, the
Mackenzie River Basin receives moisture from the Saskatchewan River Basin only during the
early summer when the meridional moisture transport from the Gulf of Mexico is strong.
Figure 1: Average annual cycle of the moisture fluxes ($\times 10^{14}$ kg/month) from the four main boundaries of the basin: west (thick solid line), east (dot-dashed line), south (dashed line), and north (thin solid line). Negative values indicate flux into the basin and positive values indicate flux out of the basin.

4. Relevance

These issues are directly relevant to MAGS overall objectives. For MAGS to be successful, research must address the complete climate system and its variations, through approaches such as being done within this research. As well, commonly occurring clouds represent a major impediment to our ability to adequately account for all water and energy variables in our models; we need to address this issue head-on. As well, precipitation occurs within episodic events; unless these are properly handled, longer time scales cannot be properly addressed. Finally, a major aspect of MAGS must be to consider another region and to test our capabilities there. In this regard, work over the Saskatchewan basin is addressing this.

5. Networking and Collaboration

Much of the cloud- and precipitation-related work is being carried out in consultation with, in particular, D. Hudak, B. Kochtubajda, K. Szeto, M.D. MacKay and B. Currie.
Mr. Stephen Whillans (M.Sc. student, York University) is focusing on the episodic rainfall events that occur over the region, and J. Liu (PDF) is examining water vapour features over the Saskatchewan River Basin.

6. Summary

Progress being made on clouds, precipitation and the climate system is important for the success of efforts such as MAGS. Cloud fields over the Mackenzie basin vary in a consistent manner to that expected on the basis of warming, warm winter episodes are linked with more and lower cloud, and cold episodes show the opposite character. Episodic precipitation events are one of the features of the long-term climate that must be well handled; typically about 6 or so of these account for 50% of the region’s annual rainfall. The Mackenzie basin itself is quite inefficient in terms of processing water and converting vapour into discharge. And, there are fundamental differences in the water fluxes affecting the Mackenzie and Saskatchewan River Basins; convergence occurs at all levels over the Mackenzie but only above 70 kPa for the Saskatchewan.

7. Publications

Journal Articles


Attempts to close the water budget of the Mackenzie basin for Water Years 1994-95 through 1996-97 resulted in a 14% positive annual bias in the atmospheric $P-E$ compared with the surface water budget. This is close to the accepted uncertainty in annual discharge of $\pm 10\%$, and was achieved primarily through the use of the University of Waterloo WATFLOOD hydrological model to estimate monthly changes in surface water storage. Eight potential error sources (four hydrologic and four atmospheric) have been identified thus far, including the inter-monthly water storage, and the elusive diurnal signature in the atmospheric moisture resulting from local evapotranspiration, which is not fully quantified using only the two available operational radiosonde soundings per day.

This ‘near-closure’ of the MAGS’ water budget has prompted further investigation. In this follow-up study we attempt to improve both the monthly and annual water budget closure in several ways: first, by enhancing the monthly storage estimates using a corrected precipitation database rather than GEM model output; second, by improving our estimates of the diurnal signature by employing high resolution GPS moisture estimates of precipitable water at Fort Smith compared with the two-soundings-per-day approach; third, we make estimates of the uncertainties in our computations resulting from six other potential sources of error identified in our previous reports; and fourth, we apply two additional years of data including the CAGES 1998-99 Water Year.

1. Introduction

One of the main goals of the Global Energy and Water Cycle Experiment (GEWEX) is to quantify the hydrological cycle and energy fluxes of major basins using atmospheric and hydrologic measurements. Quantifying the hydrologic cycle also implies closing the water budget of the basin. For a hypothetical closed atmospheric and water basin system, one can equate the difference between precipitation ($P$) and evapotranspiration ($E$) to the discharge at the mouth of the basin ($R$); i.e., $P - E = R$. This equation is true for the earth-atmosphere system as a whole, but when applied to a river basin, even one as large as the Mackenzie River system, the relation is no longer explicitly true because of various lags in surface water discharge, as well as systematic and random errors.
We have previously reported results showing closure for the annual MAGS water budget within acceptable error limits (Strong et al., 2000, 2002), and MAGS is the only international GEWEX Study which has been able to achieve this. However, these results were somewhat short on the monthly closure issue. We have identified eight potential error sources in the water budget work as follows:

Atmospheric error sources:
- errors in radiosonde data resulting from sonde sensors;
- errors of computation resulting primarily from the coarse spatial resolution of radiosonde data;
- errors due to poor temporal resolution of operational soundings (diurnal signal); and
- missing radiosonde (and/or model) atmospheric data.

Hydrologic error sources:
- errors in measuring discharge;
- errors in observed precipitation data, both in terms of actual measurements of rain and snow, and in terms of other condensed hydrometeors not normally included in measurements such as fog, dew, and hoar frost, deposition of moisture from fog, rime icing, and ice crystals;
- errors in estimating evapotranspiration, including transpiration, open-water evaporation, and sublimation; and
- changes in surface water storage over monthly, annual, and decadal periods due to discharge lag from precipitation over headwaters (typically ~2 months for the Mackenzie River, for example), snowmelt runoff, sub-surface runoff, soil moisture storage, seasonal ponding and wetlands created during flood events, human damming of large water bodies, glacier changes, and permafrost melt over northern latitudes.

To date, we have quantified what we believe to be the three largest sources of error, those due to poor temporal resolution in sounding data, errors in discharge, and errors resulting from monthly changes in surface water storage. We continue to resolve these in the current study, and will later be estimating the uncertainties resulting from remaining error sources using scaling arguments (not reported in this paper).

The poor temporal resolution in sounding data results from the fact that all operational radiosonde sites conduct only two atmospheric profiles per day (at approximately 1200 and 2400 UTC). During summer periods in particular, this results in a failure to capture the full diurnal signal in atmospheric moisture resulting from evapotranspiration over the basin. For the Canadian prairies, Strong (1997) estimated that this could result in underestimates of vapour mass increase due to evapotranspiration as high as 40% for a given day. During MAGS-1, three summers of two-week sequential radiosonde soundings were conducted during 1997-99 at Fort Smith, Northwest Territories in an attempt to quantify this diurnal uncertainty for MAGS-1 moisture budgets (Strong, 2000). The 1997 data suggested that the error may be as large as 2 mm day$^{-1}$, but this was not confirmed by the 1998 and 1999 data, perhaps due in part to these being El Niño and La Niña years respectively. High-resolution GPS vertically integrated moisture data for July, 2000 are now available to help address this problem, and preliminary results have been reported by Smith et al. (2001).
To estimate errors in operational discharge data, we have borrowed published results which indicate that errors in monthly discharge can range from 2-21% (O’Brien and Folsom, 1948; Rosenberg and Pentland, 1966; WCRP, 1994), while errors in the annual discharge of the Mackenzie are probably less than ±10%.

Changes in surface water storage due to lags in discharge are probably the largest single source of error for closing the water budget, and are also the most difficult to estimate accurately. Lags in discharge include: (1) lags resulting from the time it takes for rainfall to reach the river mouth (~ 2-3 months from headwaters to the mouth of the Mackenzie); (2) seasonal lags due to snowfall in the mountains; (3) inter-annual lags resulting from cyclical ponding of water; and (4) decadal lags resulting from glacial processes. All of these lags can contribute to uncertainties of >50% in a single monthly estimate of discharge using \( P - E = R \). However, Soulis and Kouen (2001) have developed a technique to estimate the monthly change in surface water storage using the WATFLOOD hydrologic model. In essence, the model uses precipitation and computed evapotranspiration to compute a local runoff at each grid point in the model. Monthly differences between the ensemble results for the modelled basin discharge and the observed discharge then provide a reasonable estimate of the monthly change in surface water storage.

It was recognized that this technique for estimating surface water storage change might be applied to the problem of closing the MAGS water budget, by comparing both the atmospheric moisture budget and the surface water balance of the Mackenzie system (Strong et al., 2002). The technique was applied to the three water years 1994-95 through 1996-97 by introducing a new term called the hydrologic \( P - E \), \( (P - E)_h \), which was obtained by adding the monthly change in surface water storage to the monthly discharge from the Mackenzie basin. This was compared with the atmospheric \( (P - E)_a \), which is typically computed from computations of horizontal and vertical fluxes of atmospheric moisture as measured by radiosonde profiles. The comparisons resulted in a surprising linear correlation of 0.90 between monthly values of \( (P - E)_a \) and \( (P - E)_h \), and an average annual bias of only +13% for the atmospheric over the hydrologic \( P - E \). Individual monthly differences, however, ranged as high as +10.9 mm, or +36% of the average monthly difference. The current study then, attempts to improve on our estimates of the above error sources, and on the water closure results.

2. Current Methodology

In the current study, we attempt to improve on the above results using two additional Water Years of data, 1997-98 and 1998-99, and an adjusted/gridded precipitation database for the Mackenzie basin (Louie et al., 2001), which replaced the GEM-modelled precipitation used in Strong et al. (2000, 2002).

The MAGS moisture budget results to date have employed the RFE Run-0 model output prior to February, 1997, and Run-0 GEM model output after February, 1997 for atmospheric variables rather than using the raw radiosonde data. This allows us to take advantage of the sophisticated data assimilation system of the RFE/GEM models. Run-0 RFE/GEM model data are a blend weighted approximately 75% with new observations, including globally-assimilated radiosonde and surface synoptic data, and 25% from the Run-12 output of the forecast model of 12 hours
earlier (S. Larouche, CMC, personal communication). The RFE model output is available on an approximate 35-km grid, while the GEM model output grid is closer to 25 km. All data were therefore interpolated to a 0.5° X 0.5° (approximately 50-km) grid. The GEM model output suffers from the same shortfall of loss of diurnal signature in atmospheric moisture resulting from only two soundings per day. This study will try to obtain quantitative estimates of this error source from estimates of the diurnal change in precipitable water. This is accomplished in two ways, one by using sequential radiosonde data at three-hour intervals from Fort Smith (Strong, 2000), and secondly, by using new GPS moisture integration techniques to obtain high-resolution estimates of the precipitable water (Smith et al., 2001).

The basic equations used in the atmospheric moisture budget and surface water balance computations are given in Strong et al. (2002) as:

\[
\langle P - E \rangle_a = - \langle \nabla \cdot Q \rangle - \langle \partial q/\partial t \rangle + err_a = R \tag{1}
\]

\[
\langle P - E \rangle_h = R + \langle \partial S/\partial t \rangle + err_h \tag{2}
\]

\[
= \frac{\partial S_{\text{land}}}{\partial t} + \frac{\partial S_{\text{channel}}}{\partial t} + \langle R_{bs} (S_{\text{channel}}) \rangle + err_h = \langle P - E \rangle_h \tag{3}
\]

The variables are as follows:
- \( P \) = precipitation (mm), and \( E \) = evapotranspiration (mm), both averaged over the whole basin (as indicated by the brackets, \( \langle > \); subscripts \( a \) and \( h \) refer to atmospheric and hydrologic respectively);
- \( R \) = total discharge for the basin measured as the average water depth loss for the total basin (mm);
- \( \nabla \cdot Q \) = vapour mass divergence, where \( \nabla \) is the divergence operator, \( Q = qV \), where \( q \) is vertically-integrated vapour mass, and \( V \) = vector wind velocity;
- \( \partial q/\partial t \) = local rate of change of vapour mass resulting from evapotranspiration;
- \( \partial S/\partial t \) = monthly change in surface water storage;
- \( err_a \) and \( err_h \) refer to cumulative uncertainties from atmospheric and hydrologic error sources respectively;
- \( R_{bs} \) is the simulated basin outlet stream flow determined as a function of the \( S_{\text{channel}} \);
- \( S_{\text{land}} \) and \( S_{\text{channel}} \) represent the storage components of the land surface and the river routing network respectively.

3. Results

Figure 1 shows monthly \( P - E \) computations based on Equation 1 for each of the five Water Years, 1994-95 through 1998-99, along with the five-year average values. The data archive for the 1994-95 Water Year contains significant gaps, with one or two months missing as many as 15 days of data. Consequently, there is less confidence in the \( P - E \) computations for this year, including the tri-modal peaks in Figure 1. Apart from Water Year 1994-95, the \( P - E \) lines exhibit similar trends, with a peak in early fall, decreasing slowly until spring, then more rapidly to a minimum value during summer. The convergence term is by far the dominant term,
following a similar trend to P - E, which suggests that the basin is a sink of moisture through much of the year, except during summer, when the flux convergence occasionally becomes negative, inferring that the basin becomes a source of moisture during these short periods. Because the two daily operational soundings (at 1200 and 2400 UTC) do not capture the complete diurnal cycle in atmospheric moisture resulting from local evapotranspiration, the summer values are conceivably under-estimated, possibly resulting in a larger value for the local change term during summer.

Figure 1: Monthly atmospheric P - E computations for the Mackenzie basin for the Water Years 1994-95 through 1998-99, and the five-year average monthly values; computations employ Run-0 RFE/GEM model output rather than raw radiosonde data.

Next, Mackenzie basin discharge is adjusted for monthly storage change, yielding the hydrologic P - E, following Equation 2. Figure 2 compares the atmospheric and hydrologic P - E monthly trends, averaged for the five Water Years 1994-95 through 1998-99. The storage change term is computed using the adjusted gridded precipitation data as described by Louie et al. (2001), rather than the GEM model precipitation as used in our earlier results (e.g., Proctor et al., 2001).
Figure 2: Comparison of monthly atmospheric and hydrologic P - E and differences for the Mackenzie basin for Water Years 1994-95 through 1998-99.

The average annual bias between the atmospheric and hydrologic P - E values has steadily decreased as the monthly storage change improves with more data: from +123 mm (+47% of (P - E)ₐ) for the 1994-95 Water Year to +2 mm (+1%) for the 1998-99 Water Year. The 5-year average annual bias is only +10% when the four largest outliers are removed, justified on the basis of missing RFE/GEM data in the data archive. The largest monthly differences between atmospheric and hydrologic P - E values are four outlier values with biases ranging from 21 to 28 mm. When these four outliers are removed from the dataset (on the basis of significant missing RFE/GEM data during these months), the largest remaining differences are then four values between 15 and 19 mm.

In discussing closure of the MAGS water budget, one must also consider the uncertainties in discharge data. Several sources, including Rosenberg and Pentland (1966), suggest that for large Canadian rivers, the uncertainty in any given monthly value can be as high as ±21%, while the largest annual uncertainty is ±13%. In this context, our 5-year MAGS results may indicate closure of the water budget at the monthly as well as annual timescales.
4. Discussion

The 5-year comparison of atmospheric and hydrologic P - E (Figure 2) shows remarkable similarity for the two trends. However, the comparison actually exhibits more scatter than in our earlier results (Proctor et al., 2000; Strong et al., 2002), as shown by the linear correlation dropping from 0.90 to the present 0.82 (with the four largest outliers removed). Regardless, an important new result is the gradual convergence of the difference between the two P - E trends towards a zero value (thin-dotted line of Figure 2). The projected trend would appear to reach zero by the 7th Water Year, 2000-2001, for which we do not yet have discharge data.

While we feel that these results demonstrate near-closure of the MAGS water budget at the annual and monthly timescales, there are still a number of tasks remaining that may improve on these results. We are uncertain why the results, in terms of scatter in \((P - E)_{\text{a}} - (P - E)_{\text{h}}\) values, have deteriorated after we switched precipitation data input from the GEM model data to Louie’s adjusted precipitation data. Since the results have improved in other respects, we plan to investigate this problem further. Regardless of this issue, the results for both the monthly and annual closure of the water budget are within the limits of uncertainty of discharge data alone.

We shall also be attempting to evaluate the uncertainties resulting from the other potential error sources described in Section 1, particularly the issue of evaluating the complete diurnal signature of atmospheric moisture that is presently based on just two operational radiosonde soundings per day. We plan to address this issue, partly through the use of GPS moisture integrator data.

5. Acknowledgements

This MAGS study is funded jointly by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Climate Research Branch of the Meteorological Service of Canada.

6. References


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C. LAND SURFACE STUDIES
Modelling the Energy and Water Balance of Lakes in the Cold Regions of Canada

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1. Objectives

General Objectives

- To fully understand and model the role of lakes in the energy and water balance in the cold regions of Canada; and
- To forecast the role that lakes will play in the water balance, energy balance and hydrology of the Canadian cold regions during climatic change.

Specific Objectives

- To document the areal coverage of lakes in the select regions of subarctic and low arctic Canada;
- To develop models relating lake size to lake depth for specific geographical and geological regions;
- To develop models of the energy and water balance as they relate to:
  (a) lake area, volume and latitude,
  (b) lake abundance in a geographical area, and
  (c) the longevity of the ice-free period for lakes in (a) and (b); and
- To scale energy and water balance modelling from individual lakes to local, regional and macro-scales.

2. Progress

Schedule of Activities from Original Proposal

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Activity</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>i.</td>
<td>Assemble field equipment, maps, air photos, existing satellite images, and ice cover databases.</td>
<td>Winter, summer and fall, 2001</td>
</tr>
<tr>
<td>ii.</td>
<td>Begin measurements at Yellowknife and Churchill lake sites.</td>
<td>Spring, 2001</td>
</tr>
<tr>
<td>iii.</td>
<td>Initiate documentation of lakes in various regions. Work up field data. Begin work on lake models. Begin monitoring of ice-cover with ENVISAT* data.</td>
<td>Fall and winter, 2001-02</td>
</tr>
</tbody>
</table>

* Note that the launch of ENVISAT was delayed to late November, 2001
Actual Activities to Fall, 2001

i) The following field equipment was assembled and/or refitted and recalibrated:
   • Eddy correlation and surface radiation systems for measurement on Great Slave Lake;
   • Complete energy budget and lake temperature sensing systems for three different-sized lakes;
   • Lake depth-radiation measuring systems and turbidity measuring systems for lake depth profiling in different-sized lakes;
   • Albedometer and radiation Diffusograph system for studying changes in albedo with cloud cover and solar zenith angles; and
   • Sonic system for lake depth profiling.

ii) The following measurements were initiated in the Yellowknife River Basin and Great Slave Lake in June, 2001 and continued through September, 2001:
   • Eddy correlation and surface radiation measurements on Great Slave Lake (ongoing measurements throughout the year);
   • Complete energy budget and lake temperature sensing systems for three different-sized lakes;
   • Lake depth-radiation profile measurements and turbidity measurements in four different-sized lakes during different periods of the spring-summer-fall; and
   • Continuous albedo and direct/diffuse beam radiation Diffusograph system for studying changes in albedo with cloud cover and solar zenith angles.

iii) The following lake inventorying and lake ice modelling were carried out:
   • An inventory of lake sizes derived from 1:50,000 topographic maps has allowed the construction of a size-frequency histogram in a region from mid-Great Slave Lake to near Great Bear Lake (includes the Yellowknife River Basin). This is shown in the results;
   • A digital mosaic of 1:50,000 topographic maps of shallow lakes in the Old Crow Flats was produced and depth measurements were made on 40 lakes;
   • An historical database on in situ lake ice observations was compiled for the Mackenzie basin;
   • The depth contouring of a variety of lakes lagged because of equipment problems with the depth-sounder-GPS equipment. In the vicinity of Yellowknife, the bathymetry of Long Lake and Sleepy Dragon Lakes, both of which are important measurement sites, was accurately determined;
   • A lake ice model (Canadian Lake Ice Model, or CLIMO), based on the 1-D thermodynamic sea-ice model of Flato and Brown (1996), was developed and used successfully to simulate ice phenology on shallow lakes in Arctic (Barrow, Alaska), sub-Arctic (Churchill, Manitoba), and high Boreal Forest (Poker Flat, near Fairbanks, Alaska) regions; and
   • CLIMO was also used to simulate ice phenology in Back Bay on GSL (see results).
3. Preliminary Results

Lake Frequency Histograms

The large number of lakes in the Canadian Shield Portion of the central Mackenzie basin is evident (Figure 1). Equally evident is the great size range and the high frequency of small to medium-size lakes.

![Lake Frequency Histogram](image)

Figure 1: Frequency-size distribution in the central Mackenzie River Basin (North Slave District).

Cumulative Evaporation from Different Sized Lakes

Lake depth and lake size are important to the magnitude and timing of moisture and latent heat release to the atmosphere (Figure 2). Shallow lakes (usually small) start their evaporation cycles early in the spring and terminate them with freeze up in early winter. The total amounts are small relative to deep lakes (usually large). The latter do not start significant evaporation until mid-summer but continue into the mid-winter period. The total amounts are much larger than for any other high latitude terrain types. The timing and magnitude of the evaporation cycle is, of course, a response to the total thermal regime of a lake, and lake size must be handled adequately in energy budget-thermal models in order to achieve acceptable results.
Figure 2: Cumulative evaporation from lakes of different sizes. The designation is: “Lake Name (Area (km$^2$): Average Depth (m))”. GR - Gar (0.3: 0.6); SK - Skeeter (0.05: 3.2); SD - Sleepy Dragon (5.5: 12); GS - Great Slave (18500: 60).

**Solar Heating of Lakes**

Except right at the surface where the incoming long-wave terrestrial radiation is absorbed, the heating of lakes is primarily a result of penetration and absorption of solar radiation by lake waters. Such penetration and absorption occurs primarily in the ice-free period and is a function of solar zenith angle which influences the surface albedo and the path length of the solar beam that does penetrate surface waters, cloud cover which also influences albedo through the direct/diffuse ratio, and the turbidity and dissolved organic carbon (DOC) of the water which determines a lake’s absorptivity. Preliminary analysis indicates that there is strong seasonality to the magnitude of solar radiation that penetrates surface waters and the depth to which it penetrates. Turbidity varies strongly in Great Slave Lake as a result primarily of sediment plumes from the inflowing rivers, and lesser sized lakes also show a great range in turbidity due primarily to seasonal changes in biological activity and DOC. The maximum depths to which measurable solar radiation penetrated into lakes in the Yellowknife vicinity varied from 1.5 to 6.5 m in Great Slave Lake and 1.0 to 10.0 m in lesser sized lakes during the field season of 2001 (Devon Worth, personal communication).

**Ice Modelling on Great Slave Lake**

Preliminary results show that the Canadian Lake Ice Model (CLIMo) can reproduce the ice phenology in Back Bay on Great Slave Lake very well (Figure 3). It is evident that thaw is independent of the mixing depth used in the model but that freeze-up is quite sensitive to this parameter.
Figure 3: Break up and freeze up dates simulated with the Canadian Lake Ice Model (CLIMo). BU_x refers to break-up and the mixing depth used in the model; FU_x refers to freeze-up date and the mixing depth used in the model. FU_Back Bay and BU_Back Bay correspond to in situ observations of freeze-up and break-up dates.

4. Relevance

The lakes research is relevant to the overall MAGS research objectives which are to understand and model the response of energy and water cycles in northern Canada to climatic variability and change; to define the impacts of its atmospheric and hydrological processes and feedbacks on the regional and global climatic systems; and to apply our predictive capabilities to climatic, water resource and environmental issues in the cold regions of Canada.

The research is relevant to the specific MAGS goal which is to integrate our knowledge into models for prediction and application to northern regions and the following specific objectives:

- Scaling of data and processes (in this case lakes);
- Model development and evaluation; and
- Prediction of impacts on the climate-hydrological system.
5. Networking and Collaboration

Collaboration with other Researchers during 2001

- W. Schertzer and D. Tam, National Water Research Institute (NWRI), on measurements in Great Slave Lake and on lake energy balance and thermal modelling;
- M. MacKay, Meteorological Service of Canada (MSC) - interfacing lake models with Canadian Regional Climate Model;
- P. Blanken, University of Colorado, on flux measurements from Great Slave Lake;
- J. Jasper and C. Spence, Environment Canada, Northern Division, and R. Reid, Department of Indian and Northern Affairs, Yellowknife, on water balance of lakes in the Canadian Shield;
- M. Jeffries, Geophysical Institute, University of Alaska, Fairbanks, on radar remote sensing and modelling of ice from small lakes;
- N. Filatev et al., Northern Water Research Institute, Karelia, Russia. (Rouse as member of Special Task Force, Northern Research Basins, charged with reporting on hydrologic research in Northern Lakes);
- G. Flato, Canadian Centre for Climate Modelling and Analysis, Meteorological Service of Canada, on lake ice modelling;
- T. Pultz, Canada Centre for Remote Sensing, Natural Resources Canada, on radar remote sensing of lake ice; and
- B. Ramsay, Canadian Ice Service - ice cover database from large lakes.

Participation in MAGS and/or non-MAGS Workshops, Conferences, etc.


Rouse, W.R.: As member of Canadian Delegation to *Northern Research Basins, Finland-Russia*, presented The carbon budget for fen and forest in a wetland at arctic treeline. August, 2001.


6. Summary

The large number of lakes in the Canadian Shield portion of the central Mackenzie basin display a Gaussian distribution in their size-frequency distribution. The heating of lakes is primarily a result of penetration and absorption of solar radiation by lake waters. Preliminary analysis indicates that there is strong seasonality to the magnitude of solar radiation that penetrates surface waters and the depth to which it penetrates. Lake depth and lake size are very important to the magnitude and timing of moisture and latent heat release to the atmosphere. Preliminary results show that the Canadian Lake Ice Model (CLIMo) can reproduce the ice phenology in Back Bay on Great Slave Lake very well.

7. Publications


− ⬤ ⬤ ⬤ −
Preliminary Assessment of Inter-Annual Variability in Heat and Mass Exchange Components of Great Slave Lake

W.M. Schertzer¹, W.R. Rouse² and P.D. Blanken³
¹National Water Research Institute, Burlington, Ontario
²School of Geography and Geology, McMaster University, Hamilton, Ontario
³University of Colorado, Boulder, Colorado, USA

1. Objectives

The primary objectives of this study for FY2001-02 are:

- to conduct field investigations in FY2000-01 winter, FY2001 summer and FY2001-02 winter on Great Slave Lake to augment the FY1998-2000 successful programs to construct a database suitable for inter-annual variability assessments for this northern lake;
- to formulate FY1998-2001 meteorological, limnological and thermal data into hourly and daily-averaged, 1-dimensional (lake-wide) observational databases suitable for modelling and for model verification;
- to collaborate and network with other MAGS researchers (i.e. N. Bussières, Meteorological Service of Canada - MSC; A. Walker, MSC; H. Leighton, McGill University) and others on verifications of remotely sensed satellite lake computations for Great Slave Lake; and
- to provide GEWEX data archives with processed lake data collected from FY2000-01.

2. Progress

FY2000-01 Winter Measurement Program

Thermal observations were conducted during the FY2000-01 winter (September - June) at the ODAS and NW-2 sites (Figure 1) conforming to the site patterns established in previous winter observations. Stowaway Tidbit thermistors were placed at ODAS (12, 14, 16, 20, 25, 30, 40 and 54.5 m depths) and at NW-2 (12, 14, 16, 20, 25, 30, 40 and 54.5 m) to avoid possible ice rafting. We make the assumption that during winter, the temperature is uniform from the 12 m depth to the surface. The FY2000-01 winter field program had a > 95% data return.

FY2001 Summer Field Experiment

Meteorological, radiation, sea-state (waves) and thermistor observations were conducted in a 6-station cross-lake configuration shown in Figure 1. The station in the north arm (NA) provides additional temperature data not available in previous experiments. Redesigned meteorological buoy moorings include a rigid lower tripod to increase stability and minimize the risk of overturning during high wind and wave conditions. No over-turn of the meteorological buoys occurred in years 1999 to present. The FY99 summer field program had > 95% data return.
Figure 1: Great Slave Lake bathymetry and station locations along the cross-lake transect adopted for the FY2000-01 field program. Summer moorings included all 6 stations along the transect; winter moorings were located at ODAS and NWRI-2.

**FY2001-02 Winter Measurement Program**

A winter measurement program was deployed in September FY2001 which includes measurements at Hay River and at NWRI-2. These observations include meteorology and radiation at Hay River and temperature at NWRI-2. The data allow study of the annual thermal cycle (temperature and heat content) and provide data which will be useful for energy budget/ice modelling and for verification analyses. The winter program extended to June 2002 and will be reported on in next year’s annual report.

3. Results

*Meteorological, Radiation and Limnological Databases*

A listing of the primary measurement fields conducted at the main cross-section and north arm of Great Slave Lake during FY2001 is shown in Table 1. Meteorological and radiation fields were recorded at 10-minute intervals and thermistor data were recorded at 20-minute intervals. Data have been processed to hourly and daily averages.
Table 1: Meteorological, radiation and thermal fields observed at Hay River (HR), ODAS, NWRI-1, NWRI-2, NA and the MAC site.

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<tr>
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<th>NWRI-1</th>
<th>NWRI-2</th>
<th>MAC</th>
<th>NA</th>
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*Inter-annual Variability of Great Slave Lake Evaporation*

Evaporation for the ice-free period on Great Slave Lake has been computed from eddy correlation on Inner Whaleback Island (IWI) and by mass transfer formulation from the over-lake buoy sites. Figure 2 shows cumulative evaporation for the lake based on the IWI data and shows significant inter-annual variability in the lake evaporation estimates (386 mm, 505 mm and 402 mm for years 1997, 1998 and 1999 respectively). Years 1998 and 1999 are CAGES experimental periods. The high evaporation in 1998 approached the range of evaporation experienced on some of the Laurentian Great Lakes (Schertzer, 1997) and resulted from a significantly longer ice-free period (i.e. 213 days) compared to a 12-year mean of 172 days (Walker et al., 2001). Progress is being made on estimating evaporation over years 2000 and 2001 and will be reported later. The uncertainty in evaporation estimates will be tested subsequently by comparing alternate evaporation techniques with the estimates derived here from eddy correlation.

*Inter-annual Variability of Great Slave Lake Heat Content*

The heat content for Great Slave Lake has been derived (Schertzer et al., 2000) by applying thermistor observations from the lake moorings (Figure 1) to the derived 2 x 2 km bathymetry (Schertzer, 2000). Figure 3 shows inter-annual variability between heat content computed for 1998, 1999 and 2000. Total heat content in 1998 (2.543 x 10^{19} J) was significantly larger than that determined in 1999 (2.100 x 10^{19} J). Significantly longer ice-free condition was partly responsible for the higher heat content observed in 1998. It is interesting to note that while the rates of heat loss at the lake cooling phase (i.e. August - December) are similar for both years, there is a significant difference in the higher rates of heating during spring in 1998 compared to 1999. Figure 3 shows winter heat content in year 2000 higher than in 1999. Progress is being
made on completing computations of the heat content over the period June 2000 to June 2001 and will be reported subsequently.

Figure 2: Inter-annual variability of cumulative evaporation from Great Slave Lake over the period 1997 - 1999 based on eddy correlation measurements (Rouse et al.).

Figure 3: Comparison of the inter-annual variability of heat content in Great Slave Lake over the period 1998 - 2000.
4. Relevance

This investigation builds upon ongoing research conducted to understand the processes controlling heat and mass exchange from large deep northern lakes (e.g. Blanken et al., 1997; Rouse et al., 2000; Schertzer et al., 2000). The FY2001-02 program focused on Great Slave Lake and involved field observations in an ongoing effort to collate databases for assessment of inter-annual variability in evaporation, surface energy exchange, sea-state (waves), lake thermal development and lake heat storage based on a cross-lake transect in main Great Slave Lake. Annual (summer and winter) data are critical for development/testing of models for parameterizing the lake responses, and also for future evaluations of climate/climate change (warming) effects on the energy exchange and thermal responses of large northern lakes. The investigation adds significantly to understanding the role of very large lakes in the energy and water cycles of cold environments and adds to the archive of climatological and air-water interaction databases for model verification. Temperature moorings have provided information on the thermal development and dynamic responses to surface forcing. The combined meteorological and radiative fluxes and temperature profiles will form the basis of testing/developing simulation models of the lake heat and mass transfer.

This investigation has provided detailed over-lake meteorology, radiation fluxes, and limnological components which are critical for understanding the response of the large lakes in the northern region, and has provided important data for verification of models from other MAGS researchers. We intend to continue such collaboration in MAGS-2. A recent successful proposal for funding from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) will include a significant research program which considers Great Slave Lake and contributes to MAGS goals.

5. Collaboration and Networking

Verifications of Remote Sensing of Ice Break-up and Surface Temperature

Surface temperature is measured from the mid-lake through temperature sensors mounted on the 3-m discus buoy. These temperature data are recorded at 10-minute intervals. The data have been formed into hourly averages. These data have been used to verify the dates of ice break-up though SSM/I (Walker et al., 2000) and also to help in the development and verification of lake-wide surface temperature (Bussières et al., 2000). Further verifications are anticipated to be conducted with FY 2001-02 data.

Verifications of Remote Sensing of Net Surface Solar Radiation

Very few solar radiation observations are conducted in the Mackenzie basin. On Great Slave Lake, observations are conducted on Inner Whaleback Island (IWI) and also at sites Hay River, NW-1 and NW-2. Net surface solar radiation derived from AVHRR was compared to observations at IWI and also compared with over-lake values at NW-1 and NW-2 (Leighton and Feng, 2000). Even though albedos were used from IWI to derive net surface solar radiation at the over-lake sites, over-lake verifications showed relatively small errors with mean differences
between satellite and buoy NSSR ranging from 5.5 - 3.9 W m$^{-2}$ and standard deviation ranging 52.4 - 59.4 W m$^{-2}$ for NOAA-12 and NOAA-14 satellite data respectively. Further verifications are anticipated to be conducted with FY2001-02 data.

Ice Model Development and Verification

Development and verification of ice models on Great Slave Lake are planned by Dr. Greg Flato. For FY2001-02 Flato has requested the 2 x 2 km bathymetry file which was derived during the initial stages of this investigation in 1998/99 (Schertzer, 1999).

Verifications for Coupled CRCM Model Testing

Development and testing of a coupled lake thermal model as part of the CRCM is being conducted. As part of this testing, information on the Great Slave Lake 2 x 2 km bathymetry (Schertzer, 1999) has been transferred to Anne Frigon/Rene Laprise of the University of Quebec à Montréal (UQAM).

Networking of Research on MAGS-Great Slave Lake through Funding from the Canada Foundation for Climate and Atmospheric Sciences (CFCAS)

During FY2001-02, a collaborative research proposal was developed entitled, "Cross-evaluation of the Canadian Regional Climate Model (CRCM) and Lake Thermal Models using Observations and Objective Analysis". This proposal includes research scientists D. Swain (Professor, University of Guelph), W. Rouse (Professor Emeritus, McMaster University), W. Schertzer (Adjunct Professor, University of Guelph; NWRI) and D. Lam (Adjunct Professor, University of Guelph; NWRI). Funding was received for the 3-year period 2001-2003. The research will focus on climate and thermal modelling on Lake Erie and Lake Ontario, and on understanding heat and mass exchange processes and modelling of lakes in the Mackenzie basin. This research will contribute to MAGS objectives and will also allow continuing collaborative research with MAGS scientists on assessment of potential climate impacts on northern water sources.

Data Processing and Archiving

It is recognized that an important aspect of the Mackenzie basin GEWEX investigations is archival of measured data. In this investigation, very detailed observations have been collected on meteorological and radiation components at 10-minute intervals and water temperature data at 20-minute intervals for summer and winter programs. These data have been processed at NWRI in standard formats used at NWRI and have been forwarded to the GEWEX archives in Phase I activities. Observations from the FY2000-01 field seasons are currently available for final transfer to the GEWEX archives with appropriate documentation.
6. Summary

Detailed observations of over-lake meteorology, radiation fluxes and limnological components have been conducted over FY2000-01 winter, FY2001 summer and FY2001-02 winter. These observations have been formed into consistent databases to form time-series from 1998 which will have direct application to research on physical lake processes and inter-annual variability of major heat and mass transfer components on Great Slave Lake. The databases have proven to be useful in the verification of model results from other MAGS researchers such as remote sensing determinations of ice break-up, water surface temperature and net surface solar radiation. Lake bathymetry determined under FY1999-2000 is also proving to be important not only in this investigation but also for extended research on lake ice modelling and for future applications in coupled lake CRCM applications. Measurements conducted over 1998 and 1999 CAGES years have been used to determine cumulative evaporation and heat content of the lake and have shown very significant inter-annual variability largely in response to the intense El Nino in 1998. The high evaporation and heat content observed during the intensive El Nino year 1998 compared to other years is a strong indication of the sensitivity of large deep northern lakes to climatic influences.

7. Publications, Conference and Workshop Presentations

Publications and Reports


Conference/Workshop Presentations


Two Possible Land Surface Schemes for the Northern Environment of the Mackenzie Basin

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Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta

1. Introduction

The overall strategy of MAGS includes the development of basin-scale representations of water and energy cycles of the Mackenzie River Basin (MRB) through atmosphere-surface hydrology modelling, and large-scale observations and data assimilation techniques. Currently, one of the primary focuses of MAGS is the coupling of CRCM with CLASS and WATFLOOD, and the development of WATCLASS. The intent is to understand and to model the high-latitude water and energy cycles, to replicate the critical water and energy cycles of the MRB, to make longer predictions of MRB’s water resources, and to assess the changes to Canada’s water resources due to climate change (Stewart et al., 1998).

In this report, important factors related to the development or application of Land Surface Schemes (LSSs) from past work, especially that of Project for the Intercomparison of Land-surface Parameterization Schemes (PILPS) are identified (Section 2). Scale and sub-grid variability is discussed in Section 3. The Interactions Soil-Biosphere-Atmosphere (ISBA) scheme and the Biosphere-Atmosphere Transfer Scheme (BATS), as part of our effort in finding a simplified alternative of CLASS to improve the flexibility of MAGS’s modelling structure to take advantage of the strengths of each LSS, are reviewed in Section 4. ISBA, which is currently coupled to the GEM atmospheric model of CMC, was developed by Noilhan and Planton (1989), and BATS was developed by Dickinson et al. (1986). Some possible changes to the two LSSs from the perspective of Mackenzie’s northern environment are outlined in Section 5, some preliminary results of BATS are presented in Section 6, and finally recommendations for future work are put forth in Section 7.

2. Literature Review

From Phase 1 of PILPS based on one year of forcing data from the CCM1-Oz GCM and 23 LSSs, it was found that multi-year runs might be required to adequately determine the effects of changes in land surface characteristics (Henderson-Sellers et al., 1995). From further experiments performed, in which the treatment of albedo, vegetative cover, heat flux calculations, and moisture conditions were fixed, it was concluded that even under identical forcings and vegetation types there are significant differences between model results due to interactions between evaporation and runoff formulations (Koster and Milley, 1997).

As the model complexity of LSSs grows, so do the number of parameters. To overcome the challenge of parameter estimation, a priori relationship linking parameters with land surface and soil characteristics are available with many LSSs. However, many a priori parameters are based on point measurements, and assume that inter-class variations are small, or average out at larger
scales. Moreover, such *a priori* relationships may not be properly validated. Phase 2 of PILPS was based on comparisons with observed measurements. Phase 2c used 10 years of data (1979-1988) at a basin scale in the Arkansas-Red River Basin (Wood et al., 1998). The larger data set of Phase 2c allowed for calibration and validation of the LSSs and proper calibration was found to significantly improve simulations of large-scale quantities. This suggests that such *a priori* relationships should be refined through model calibration and validation. Phase 2c also found that LSSs tended to underestimate storage changes and summer evapotranspiration, and overestimate summer runoff and winter evapotranspiration.

From Phase 2b of PILPS based on the 1985 data set of HAPEX-MOBILHY in SW France, the wide variation of the treatment of soil moisture among LSSs was found to be the key factor causing differences between the results of LSSs. In addition, the 1997 hydrology experiment conducted in the Southern Great Plains of the USA showed that wet soils were more sensitive to variability than drying soils, and that including soil moisture variability significantly improved the predicted spatial distribution of surface fluxes (Mohr et al., 2001). Further, Ghan et al. (1997) found that increasing the precipitation and vegetation resolutions brought improvements in the simulation of runoff.

Phase 2d of PILPS used 23 years of data (1966-1988) from the boreal grassland of Valdai, Russia (Slater et al., 2001). This was the first PILPS study to include a well-defined seasonal snowcover. Variations in the treatment of snow in the model structure as well as variations in the assumed thermal and physical properties of snow were the primary reasons cited for inter-model variability, which was found to be more sensitive to ablation than accumulation due to differences in fractional snowcover and albedo, especially for low snow depths. Single year recursive runs demonstrated that the treatment of frozen soil can influence conditions into the following season, again emphasizing the importance of multi-year runs.

### 3. Scale and Sub-Grid Variability

LSSs are usually based on one-dimensional (1-D) physics meant for point or field scale applications, but are applied to scales on the order of 100 km² to 10,000 km². Since small-scale variations cannot be expected to average out at larger scales, heterogeneity plagues LSS applications just as it does with all numerical modelling involving non-linear relationships. Conversely, when a LSS is applied to coarse grid cells, sub-grid heterogeneity should be accounted for. Many studies have been conducted regarding the effects of sub-grid parameter variability on the output of LSSs (e.g., Wetzel and Chang, 1988; Entekhabi and Eagleson, 1989). However, most studies were conducted in mid-latitude croplands or grasslands, usually under summer conditions, and over varying scales ranging from an 11.7 km² watershed (Famiglietti and Wood, 1995) to a typical GCM grid scale of up to 100,000 km² (Noilhan and Lacarrère, 1995; Ghan et al., 1997).

Parameters that tend to have significant heterogeneity are hydraulic conductivity, soil moisture, precipitation, vegetative cover, snowcover, and topography. The simplest approach to this problem is to assign a single number to each parameter to represent the bulk or average value in the grid area. Noilhan and Lacarrère (1995) found that averaging the surface parameters...
produced superior results in comparison with prescribing surface properties associated with a dominant land use. Beyond the aforementioned approach, there are two basic ways to account for sub-grid variability. If adequate data is available, a more realistic approach is to divide grids into sub-grids, each with its own set of parameters, or partition a grid cell into tiles, with each tile having distinct land use and physics, just like Koster and Suarez (1992) who represented sub-grid variability by a ‘mosaic’ of homogenous vegetation ‘tiles’. Effectively, this means that several parallel simulations are conducted and the resulting fluxes are combined using an area-weighted average. Shuttleworth (1988) suggests that for horizontal length scales less than 10 km, turbulent processes prevent the formation of any circulations in the atmospheric boundary layer. As a result of this, at these scales surface fluxes can be calculated by representing the grid as a ‘mosaic’ of tiles.

Alternatively, sub-grid parameter variation can be described statistically which is likely more feasible for remote regions with limited data that dominate the MRB (e.g., Wetzel and Chang, 1988; Entekhabi and Eagleson, 1989; Sivapalan and Woods, 1995; Mohr et al., 2001). Besides, Famiglietti and Wood (1995) found that a statistical representation of sub-grid variability was sufficient if the grid scale was greater than a threshold of 1-2 km. At smaller scales the actual patterns were required. It may even be advisable to consider a suite of models to deal with different scales and environments (Szeto et al., 2001).

4. ISBA and BATS and the Treatment of Snowcover

ISBA parameters are divided into two categories: four primary parameters that are specified at each grid point (% sand, % clay, vegetation type, and land-water ratio), and 22 secondary parameters, which are determined from the primary parameters. Snow albedo decreases linearly (for melting snow) or exponentially (for non-melting snow) with time between 0.85 and 0.5. Fractional snowcover decreases asymptotically with snow depth, such that:

For bare soil,

\[
\text{snowcover} = \frac{\text{SWE}}{\text{SWE} + 10\text{mm}}
\]  

(1)

For vegetative cover,

\[
\text{snowcover} = \frac{\text{depth}}{\text{depth} + D}
\]  

(2)

\(D\), the snow depth at which fractional cover is 50%, is proportional to the roughness height, and therefore also to the height of the vegetative cover. Since the height of vegetation decreases significantly as we approach the tree line, this method is not reasonable when applied to the entire MRB. In ISBA, snow density increases exponentially with time from 100 to 300 kg m\(^{-3}\), snow temperature is assumed to be equal to the surface temperature, and the heat capacity is that of ice. The thermal conductivity (W m\(^{-1}\)oK\(^{-1}\)) is:

\[
K_{\text{snow}} = 2.22 \left( \frac{\rho}{1000} \right)^{1.88}
\]  

(3)
Douville et al. (1995) introduced a new snow parameterization scheme into ISBA which included changes in how ISBA calculated surface albedo, snow melt, and the heat transfer coefficient.

In BATS, the land surface characteristics are defined by 18 classes of vegetative type, 12 classes of soil texture, and 8 classes of soil colour. Snow albedo is calculated for both short-wave (< 700 nm) and longwave (> 700 nm) radiation, and modified by the solar zenith angle, and snow age (Dickinson et al., 1993). The estimation of fractional snowcover is similar to ISBA, such that:

For bare soil,

\[
\text{snowcover} = \frac{\text{depth}}{\text{depth} + 10 \text{cm}} \quad (4)
\]

For vegetative cover,

\[
\text{snowcover} = \frac{\text{depth}}{\text{depth} + D} \quad (5)
\]

where \( D \) is once again proportional to the vegetative roughness height. Snow density increases in time from 100 to 400 kg m\(^{-3}\). The thermal conductivity (W m\(^{-1}\) K\(^{-1}\)) is:

\[
K_{\text{snow}} = 2.93 \left( \frac{\rho}{1000} \right)^2 \quad (6)
\]

Snow temperature is assumed to equal surface soil temperature, and the heat capacity is a combination of soil, soil moisture, and snowcover. This has ramifications during snow melt, where heat energy from rain and the atmosphere has to warm up both the surface soil and the snow before melting begins, however the lower albedo of soil will tend to make more energy available to snow.

From PILPS phase 2d where both ISBA and BATS were included, Slater et al. (2001) found that all the 21 LSSs behaved similarly in terms of maximum snow water equivalent (SWE) accumulated and the season length, but there were significant differences in the timing of the final snowmelt and the response to mid-season ablation events. The models varied significantly in their predictions of snow sublimation. ISBA was noted for its large mid-winter sublimation rate (averaged ~20 mm yr\(^{-1}\)) while BATS (averaged ~1 mm yr\(^{-1}\)) had one of the lowest sublimation rates. This variation was attributed to differences in how snow interacted with the atmosphere and soil, specifically the difference between snow and air temperatures, and the ways snow albedo and fractional snowcover were simulated. There were no observed sublimation measurements to compare with the model predictions.

Other important issues brought forward were model treatments of heat capacity, snow density, emissivity, thermal conductivity, and the model structure of soil and snow. The tendency of most models to ignore snow’s thermal and physical sensitivity to current and previous conditions was also addressed. In general, most models performed well under some conditions and poorly
under others, suggesting that the assumptions underlying snow schemes are not robust enough to properly simulate the behaviour of snow over widely varying conditions.

5. Possible Improvements to LSSs for the Northern Environment of Mackenzie

Alternative LSSs should be designed for northern environments; unfortunately, most LSSs have been designed and verified in mid-latitude environments. As a result, the treatment of snow is simplistic, and snow is usually treated as a generic substance with little consideration of its sensitivity to current and previous environmental conditions. Possible improvements of snow parameterization suggested herein for further research work are:

A. Annual spring snowmelt runoff is the most important hydrologic event in MRB. During snowmelt, the land surface becomes patchy with significant sub-grid variance in albedo, surface temperature, and heat fluxes. Snowmelt has been found to be enhanced by local scale advection between snow-covered and snow-free areas; this, however, is difficult to model in LSSs of 1-D physics. Also, sub-grid variations in soil moisture, precipitation, and vegetative cover have been shown to have a significant effect on water energy balances. Partly due to lack of data in MRB, some sub-grid variability has to be modelled statistically; for example, using the Xinanjiang distribution for soil moisture variation (Zhao, 1992):

\[
F(x) = 1 - \left(1 - \frac{x}{x_{\text{max}}} \right)^\beta \\
0 \leq x \leq x_{\text{max}}
\]

where \( \beta \) is an empirical parameter (see Figure 1). This distribution can be completely defined by the maximum and mean values of \( x \).

![Figure 1: Xinanjiang distribution.](image)
B. Following Entekhabi and Eagleson (1989), and Sivapalan and Woods (1995), the spatial variation of precipitation, \( P \), can be modelled using the exponential distribution:

\[
F(P) = 1 - \mu + \mu \left[ 1 - \exp \left( -\frac{\mu P}{P} \right) \right] \quad P \geq 0
\]  

(8)

where \( \mu \) is the fraction of the area wetted by precipitation, which can be represented as a function of \( P \).

C. For the sub-grid variability of vegetative cover and soil properties, given that both BATS and ISBA are too complicated to allow a statistical relationship to be used, the ‘mosaic’ approach (Koster and Suarez, 1992) can be considered and the sub-grid resolution would depend on the types of data available.

D. Both ISBA and BATS use a force-restore method based on Deardorff (1978) for calculating soil and snow surface temperatures. The force restore method has been found to be better for calculating snow surface temperatures (Yang et al., 1999) than other schemes such as the heat diffusion method, but may be inappropriate for permafrost conditions where it can become too cold and unresponsive (Tilley and Lynch, 1998). The use of a heat diffusion method in permafrost regions will be explored.

E. BATS calculates snow density as a function of snow age, but resets snow age to zero when more than 1 cm SWE of fresh snow falls. This might result in overestimating snow depth in regions where a significant snow pack may persist for the entire winter, as in a large part of MRB. The relative merits of the snow age model of BATS compared with ISBA’s model, which calculates a weighted average of new and old snow, will be studied. Most LSSs assume that the snow thermal conductivity is a simple function of snow density, but Strum et al. (1997) showed that snow density is not the dominant factor determining the thermal conductivity.

F. Both BATS and ISBA use a simple formula for calculating fractional snowcover (Equations 1,2, 4 and 5), while CLASS assumes that the snowpack will maintain a minimum depth (i.e. the snowpack melts sideways). Since the snow depletion curves or fractional snowcover will exert a strong influence on the surface albedo, especially for snow depths close to 100% snowcover, several fractional snowcover equations will be tested, such as that of Hamlin et al. (1998), where \( D_{100} \) is the depth above which the snow cover is 100%, e.g.:

\[
\text{snowcover} = \frac{\text{depth}}{D_{100}} \quad \text{if} \quad \text{depth} \leq D_{100}
\]  

(9)

where \( D_{100} \) is a function of vegetation type and ranges from 20 to 40 cm in the Fort Simpson region.
G. The significant and systematic variation of vegetative heights (i.e. the reduction in tree height as one approaches the tree line) in the MRB forces us to allow for variation in roughness length among vegetative cover types. Alternatively, we may choose to introduce some climate-dependant land cover types (e.g. three types of coniferous forest instead of just one).

H. Recent studies showed that blowing snow has a significant effect on the energy and mass balances, especially during ablation events (Pomeroy et al., 1993). The effect of blowing snow has been often cited as an area for future development in LSSs, but if we are not mistaken, currently no LSS includes this effect. Blowing snow tends to increase sublimation, representing over 10% of seasonal basin output according to one study (Marsh et al., 1994). Given that standard blowing snow models such as PIEKTUK-T, PIEKTUK-B, and SNOWSTORM (Xiao et al., 2000) demand excessive computational effort, one possibility would be to use a parameterized blowing snow algorithm, such as that Dery and Yau (2001) developed for the Trail Valley Creek.

I. Perform multi-layer snow modelling similar to that of SNTHERM (Jordan, 1991).

6. Preliminary BATS Simulations for Fort Simpson

Hourly meteorological data for the 1999-2000 snow year at Fort Simpson, NWT were used to force BATS for several simulations. Unless otherwise noted, all simulations used the standard BATS snow parameterization scheme and the *a priori* vegetative and soil parameter values. The most significant feature of this snow season was a significant warm spell in late December 1999 when daily maximum temperatures increased from -18 °C on December 21st to +14 °C on December 23rd and then fell back to -16 °C by December 25th. For almost 36 hours the temperature remained at or above 10 °C. Figure 2 shows the results for a mixed forest with a loamy soil. The observed snow depths are in cm while the SWE predictions are in mm. No SWE measurements are currently available to us.

![Figure 2: BATS simulation for Fort Simpson 1 June 1999 – 13 May 2000 for a Mixed Forest with loamy soil.](image-url)
To evaluate the effect of the \textit{a priori} settings for roughness length on the snow pack a simulation was conducted for both a short mixed forest (0.4m instead of 0.8m) and a tall mixed forest (2.0m) with a loamy soil (Figure 3). The only significant difference is the response to ablation events, which is much more severe for the tall forest than the short forest.

Figure 3: Effect of roughness height on simulated SWE.

To evaluate the effect of the BATS parameterization of snowcover and snow age two more simulations where carried out for a loamy soiled mixed forest (see Figure 4). BATS’ resetting of snow age to zero when fresh snow fall in one time step exceeded 1 cm SWE was removed and replaced with a weighted average (although the snow age scheme was still quite different from ISBA). The original BATS snow age formula was:

\[
\text{SnowAge}_{\text{new}} = \text{SnowAge}_{\text{old}} \left( \frac{1\, \text{cm} - \text{SWE}_{\text{newsnow}}}{1\, \text{cm}} \right)
\]

where the snow age was set to zero if the above formula produced a negative result.

The new formula is:

\[
\text{SnowAge}_{\text{new}} = \text{SnowAge}_{\text{old}} \frac{\text{SWE}_{\text{newsnow}}}{\text{SWE}_{\text{oldsnow}}}
\]

In the other simulation, the Hamlin \textit{et al}. (1998) relation was used with \(D_{100} = 40\) cm, their value for a transitional forest. There is virtually no difference between the original BATS and the new snow age method until the ablation event in late December. The difference is not due to the resetting of the snow age to zero after heavy snow events because no such event occurred during
the 1999-2000 snow year. Instead, the difference is due to the calculation of snow age for small events. For small snowfall events, Equation 11 will consistently produce an older snow age than Equation 10. Shortly before the ablation event, the only significant difference between the model predictions was that the snow age using the new formula (Equation 11) was more than twice as old as for the old formula (Equation 10). Older snow has a lower albedo and therefore absorbs more radiation than fresh snow resulting in a faster response to the ablation event. The change in the snow cover algorithm yields a negligible difference except during the ablation event, which is much weaker with the new algorithm. This is because this method predicts a greater fraction of snow cover then the original BATS method, resulting in a much higher albedo and therefore less available energy for snowmelt.

Figure 4: Effect of snow parameterization on simulated SWE.

7. Recommendations for Further Work

A. Set up ISBA for stand-alone tests with data of CAGES similar to that with BATS. ISBA should also be driven with re-analysis data that are a subset of the GEM archive dating back to 1995. Variables to be considered in driving ISBA (and also BATS, as a comparison to ISBA) include precipitation, temperature, humidity, wind, pressure, net short wave and downward longwave radiations. As much as possible, the \textit{a priori} parameters of ISBA and BATS should be calibrated using CAGES data. The calibrated LSSs can then be validated again using CAGES data, but for periods not used in the calibration experience, and based on variables such as snow depth, SWE, and possibly other variables.

B. Conduct sensitivity tests on some \textit{a priori} parameters of ISBA, grid cell resolution, land use classes, and soil parameters. Extend the test database to include several other stations of CAGES with hourly data, such as Macmillan Pass, Lindberg Landing, Lower Carp Lake, Fort Good Hope, Dease Lake, and Watson Lake.
C. Test the statistical algorithms for accounting sub-grid variability in ISBA proposed in 2001 work, and possibly modify certain algorithms of ISBA with regard to northern processes such as permafrost, snow interception by canopy, sublimation, and blowing snow, using the work of other MAGS researchers.

D. Test ISBA under coupled modes. Since ISBA is already coupled to GEM, the sensible approach is to begin testing ISBA in a coupled mode with respect to GEM, and compare the results with stand-alone modes. Output of ISBA such as snow depth, SWE will be checked against observed data of CAGES.

8. Summary

The preliminary results based on BATS show that the response of BATS (and probably most other LSSs) to mid-season ablation events is sensitive to the snow parameterization schemes and the \textit{a priori} set vegetative and soil parameter values. Since mid-season ablation events affect the snowpack for the rest of the winter, they have a significant influence on the volume of snowmelt available for spring runoff. Accurate simulation of these events is vital to the goals of GEWEX-MAGS.

9. References


Modelling and Parameterization of Blowing Snow and Limited Fetch Evaporation

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1. Objectives

The objectives of our research programme fall into three areas:

- Basic physics of blowing snow:
  Studies with our PIEKTUK model, including comparisons with similar models developed in the UK and The Netherlands and against field data, suggest that there are still basic uncertainties with our quantitative understanding of effective settling velocity, effective eddy diffusivity and appropriate lower boundary conditions. In order to investigate this in detail we are using an Inertial Particle, Lagrangian Simulation model of the dispersion of particles in atmospheric boundary-layer flow.

- Basic studies of limited fetch evaporation over lakes:
  An extension of the “Guidelines” (Walmsley et al., 1989) provides the simplest way to approach this problem for neutral thermal stratification, but more detailed boundary layer modelling of internal boundary layers (IBL), using higher-order closure models is being undertaken to provide a stronger theoretical basis for estimates of limited fetch evaporation in all stability conditions.

- Blowing snow and lake evaporation in weather and climate models:
  The Canadian Land Surface Scheme, CLASS (Verseghy, 1991; Verseghy et al., 1993), provides an excellent framework for the determination of fluxes at land surfaces and their “upscaling” within the context of meso-, synoptic- and global-scale atmospheric models. It has already been implemented in the Canadian Climate Centre GCM, the UQAM RCM and MC2. It also serves as a critical link with the hydrological model, WATFLOOD, being used within MAGS-2. Recent versions have open inland water as one type of surface and we will refine the flux estimates to take account of limited fetch effects. CLASS has always included snow as an additional soil layer, but we will add a representation of blowing snow.

2. Progress

One method for estimating settling velocity from field measurements of blowing snow is to fit density profiles to the classic power law solutions for snow density as a function of height, but problems have been noted for small particles where unrealistically large settling velocities are obtained. We have investigated this with a simplified version of PIEKTUK. We have also made significant progress with development and application of a 1-D Inertial Particle - Lagrangian Simulation model (IP-LS). Key results from both models are given in Section 3 below.
The Panofsky-Dutton internal boundary layer depth formula is, somewhat oddly, based on downstream surface friction velocity, rather than upstream, outer flow, values, to determine the rate of deepening of the IBL. A modified version of the formula has been derived and tested. In addition, progress is being made on a more detailed model of flow development within internal boundary layers, based on second-order closure of the Reynolds averaged flow equations.

We have so far held off on this component of the project, but we are familiarising ourselves with details of CLASS code and plan to embark on this soon.

3. Results

The realisation that the standard power law solution for suspended particles in a turbulent boundary-layer flow \[ \ln(N/N_1) = (-w_s/\kappa u^*) \ln(z/z_1) \] implies that an infinite amount of material is in suspension when \( w_s/\kappa u^* < 1 \), and studies with the simplified (no sublimation effects) version of the PIEKTUK model, led us to investigate the time variation of vertical fluxes of snow particles at different levels in the boundary layer under different conditions, but mostly with \( w_s/\kappa u^* < 1 \). We see in Figure 1 that in most cases there is a significant vertical flux in order to maintain an ever deepening layer of particles in suspension. This will be in addition to replacement of particles lost to sublimation.

![Figure 1: Temporal evolution of the vertical number fluxes for ice particles of radius 6, 21 and 43 µm (\( w_s = 0.0033, 0.04 \) and 0.16 m s\(^{-1} \)) in a boundary layer with \( u^* = 1 \) m s\(^{-1} \). Flux is the net effect of upward diffusion and downward settling.](image)

Investigations with the IP-LS model are providing new insight into effective settling velocity and eddy diffusivity as functions of height and particle size. Figure 2 shows that the effective settling velocity is significantly reduced near the lower boundary of the model, or near the ground, in part as a consequence of the assumptions made about particle behaviour when the boundary is encountered, and in part as a result of inertial effects delaying the adjustment of the particle velocity to that of the surrounding fluid. These effects cause slight modifications to the power
law particle concentration profiles expected in flow over a mobile snow, sand or sediment surface, as shown in Figure 3.

Figure 2: Effective settling velocity predicted by the IP model for particles with different terminal velocities ($w_g$) in still air above a uniform, mobile bed in turbulent surface boundary-layer flow.

Figure 3: Particle concentration profiles predicted by the IP model for particles with different terminal velocities ($w_g$) in still air above a uniform, mobile bed in turbulent surface boundary-layer flow.
In our opinion the ideas employed in the derivation of Panofsky’s IBL height formulae should dictate the use of upstream flow characteristics. However, statistical analysis of available measurements of the IBL height shows that the IBL grows faster in the smooth to rough transition than in the rough to smooth and we had to include an effect of the magnitude and sign of the roughness change in our model formulation. This took the form of a coefficient, $A = 1.0 + 0.1M$, which is linearly dependent on $M = \ln (z_{od}/z_{ao})$. Results have been written up and are in press.

4. Relevance

Basic studies of blowing snow transport and sublimation, and of evaporation from lakes are still necessary if we are to have confidence in our estimates of these quantities in the Mackenzie basin, in other high latitude areas and in regions with significant open water areas. Applications to improving our estimates of the role of blowing snow in the overall water budget of the Mackenzie are needed to assess the importance, or otherwise, of this process. For small (sub-grid scale) lakes, it is important to realise the effects of scale and the surrounding land on evaporation rates, and the work in hand should allow us to do this.

5. Networking and Collaboration

I have been in frequent e-mail contact with J. Wilson on our joint Lagrangian Modelling study, and I hope we can get together on a more intensive basis next year. We are also planning closer cooperation with D. Verseghy on the CLASS applications and with W.R. Rouse and W.M. Schertzer on lake evaporation studies once we have our models finalised and need data for validation.

6. Summary

Work is progressing well on two of the tasks but has been delayed slightly on applying our findings on blowing snow and lake evaporation within the CLASS land surface scheme. With the blowing snow studies we have found additional fundamental problems with the modelling of suspended material. I now hope to obtain NSERC Research Grant funding to pursue this. We have however successfully implemented an Inertial Particle, Lagrangian Simulation model to investigate impacts of turbulence and boundary conditions on effective settling velocity and eddy diffusivity, and have a deeper understanding of these issues.
7. MAGS Publications and Presentations

Journal Articles


Thesis


Conference Presentations

Talks on blowing snow (with J. Xiao) and internal boundary layers (with S. Savelyev). EGS, March, 2001.

8. References


– ☾☽ –
Modelling the Effects of Ice Phase Processes on the Water Budget in High Latitudes
Using a Coupled Blowing Snow-MC2 Model

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1. Objectives

The main objective of the proposed research is to study the effect of ice processes, in the atmosphere and near the surface, on the water budget in high latitudes. Our approach is through the development of a coupled blowing snow-MC2 model and better representation of microphysical processes.

2. Progress

In accordance with the time line set out in our MAGS-2 proposal, we will complete the improvement of the Dery-Yau blowing snow model and its coupling to MC2 by the end of 2001. This step has been completed together with progress in other areas. Specifically:

a) the development of the double-moment blowing snow model has been completed;
b) the first version of a coupled blowing snow-MC2 model has been developed and applied to study a winter blizzard event;
c) large-scale mass balance effects of blowing snow and surface sublimation has been studied;
d) the effects of small water bodies over the Mackenzie River Basin (MRB) has been investigated;
e) it was demonstrated, through the simulation of a summer time flood event, that the microphysics parameterization we developed can be applied to simulate summer precipitation events over the MRB;
f) a CAGES hailstorm using a grid size of 10 km has been simulated; and
g) a study of severe summer rainfall events over the MRB was conducted.

3. Results

\textit{Development of Double-Moment Blowing Snow Model}

Dery and Yau (2001b) described the development of a double-moment model of blowing snow and its application to the Canadian Arctic. The model involves prognostic equations for both the blowing snow mixing ratio and the total particle number concentration. Sensitivity tests showed that under idealized simulations, the model yields realistic evolutions of the blowing snow particle distributions, transport and sublimation rates as well as the thermodynamic fields at low computational costs. A parameterization of the blowing snow sublimation rate was also proposed and applied to a Canadian Arctic tundra site prone to frequent blowing snow events. Over a period of 210 days during the winter of 1996/1997, the near-surface relative humidity
consistently approaches saturation with respect to ice. These conditions limit snowpack erosion by blowing snow sublimation to ~3 mm snow water equivalent (SWE) with surface sublimation removing an additional 7 mm SWE. We find that our results are highly sensitive to the proper assimilation of the humidity measurements and the evolving thermodynamic fields in the atmospheric boundary layer during blowing snow. These factors may explain the lower values of blowing snow sublimation reported in this paper than previously published for the region.

**Development of Coupled Blowing Snow-MC2 Model**

Dery and Yau (2001a) described the development of a coupled blowing snow-MC2 model. Specifically, the double-moment blowing snow model is coupled to MC2 in a fully interactive manner. The coupled model is then applied to simulate a ground blizzard which occurred from 16 to 18 November 1996 in the northern sectors of the MRB and adjacent Beaufort Sea. This hazardous event, accompanied by a low-level jet with wind speeds approaching 20 m s\(^{-1}\) and extensive blowing snow near the surface (but clear sky aloft), is forced by a strong sea-level pressure gradient that forms between a rapidly intensifying anticyclone over the Nunavut and Northwest Territories (NWT) and an intense depression over the frozen Arctic Ocean.

The event is first simulated at a horizontal grid size of 18 km using the MC2 model without blowing snow. This experiment is shown to capture the rapid anticyclogenesis event within 2 hPa of its central sea-level pressure and the blizzard conditions near the Canadian Arctic coastline and the Beaufort Sea. Meteorological conditions observed at Trail Valley Creek (TVC), a small Arctic tundra watershed where ground blizzard conditions were experienced during the event, are also accurately reproduced by the uncoupled simulation with the notable exception of the blowing snow process. The mesoscale model is then coupled to the double-moment blowing snow model and a second simulation is conducted. This additional experiment reveals the presence of extensive blowing snow associated with a strong low-level jet over TVC and the adjacent frozen Beaufort Sea. Over the 2-day event, blowing snow sublimation and transport combined to erode 1.6 mm SWE from the surface mass balance of TVC. The concurrent moistening and cooling of near-surface air due to blowing snow sublimation arises during the blizzard, but to a lesser extent than when the blowing snow model was running in a stand-alone mode. It is concluded that entrainment and advective processes are important in blowing snow processes and enhance the blowing snow sublimation rates in the coupled model to 1.8 times larger than in the stand-alone application of the double-moment blowing snow model.

**Large-scale Mass Balance Effects of Blowing Snow and Surface Sublimation**

Dery and Yau (2001c) examines the effects of surface sublimation and blowing snow on the surface mass balance on a global and basin scale using the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA15) data for the years 1979-1993 at a resolution of 2.5°. The combined processes of surface and blowing snow sublimation are estimated to remove 30 mm a\(^{-1}\) SWE, disposing about 17 to 20% of the annual precipitation over Antarctica. In the Northern Hemisphere, these processes are generally less important in continental areas than over the frozen Arctic Ocean and polar seas where surface and blowing snow sublimation deplete upwards of 100 mm a\(^{-1}\) SWE. Areas with frequent blowing snow episodes such as the
coastal regions of Antarctica and the Arctic Ocean are also prone to a mass transport > 100 Mg m\(^{-1}\) a\(^{-1}\). Although important locally, values of the divergence of mass through wind redistribution are generally two orders of magnitude less than surface and blowing snow sublimation when averaged over large areas. For the entire MRB of Canada, surface sublimation remains the dominant sink of mass as it removes 29 mm a\(^{-1}\) SWE or about 7% of the watershed's annual precipitation.

**Effects of Small Water Bodies on Sensible and Latent Heat Fluxes**

Nagarajan, Yau, and Schuepp (2001) investigated the effects of small water bodies or lakes on the surface sensible and latent heat fluxes and the transport of heat and water vapour in the atmospheric boundary layer over the MRB. Two observed cases, occurring on 2 and 8 June 1999 during a typical warm season, were chosen for the study. The synoptic condition for the cases is representative of about 33% of the synoptic situation over the MRB.

The two events are simulated using the MC2 model. A one-way nesting grid approach is employed with the highest resolution of 100 m over a domain of 10 km\(^2\). Experiments were conducted with (LAKE) and without (NOLAKE) the presence of small water bodies, whose size distribution is obtained through an inversion algorithm using information of their linear dimension determined from aircraft measurement of surface temperature during the MAGS experiment in 1999. The water bodies are assumed to be distributed randomly in space with fractional area coverage of 10% over the MRB.

The results show that in the presence of lakes, the domain-averaged surface sensible heat flux increases by 35% on 2 June 1999, and by 43% on 8 June 1999. The surface latent heat flux is enhanced by 23% on June 2, and by 103% on June 8. The increase in sensible heat flux is caused by the advection of cold air from the lake areas to the land area, resulting in an increase in air-land temperature contrast. The air is cooled over the lakes due to reduced or downward transport of sensible heat flux relative to the adjoining land areas. The latent heat flux enhancement arises due to the availability of moisture from the lakes. The enhancement is smaller on 2 June 1999 as a result of colder lake temperatures and higher specific humidity of the air, which reduce the air-lake specific humidity gradient.

The domain-averaged apparent heat source and moisture sink due to turbulent transports were also computed. The results show that when lakes are present, heating and drying occur in the lowest 50-150 m from the surface. Above 150 m and within the ABL, there was apparent cooling on 2 June and heating on 8 June. However the apparent moistening profiles reveal that lakes tend to moisten the ABL through transfer of moisture from the lowest 50-150 m layer.

**Testing of Microphysics Parameterization and an Ensemble Forecasting Strategy to Improve Precipitation Forecast in a Summer Case**

Milbrandt and Yau (2001) tested the Kong and Yau microphysics scheme in a simulation of the 19-21 July 1996 Saguenay flood storm using MC2. It was shown that the new scheme is superior to other simpler schemes in the forecast of precipitation in terms of the threat scores and bias scores over a broad range of precipitation thresholds. To further improve quantitative
precipitation forecasting, Misra and Yau (2001) explored an ensemble strategy for very high-resolution forecasts using MC2. The perturbations used in the ensemble forecasts are generated by assuming that at very high resolutions, the largest errors arise from miss-specified diabatic heat sources and sinks and their inappropriate feedback to the grid scale variables in the initial state. We tested this methodology in a Proxy Observed System Simulation Experiment for the Saguenay flood case and showed that the Quantitative Precipitation Forecasts of the ensemble mean outperforms the control model run. The results obtained for this case give confidence to apply the MC2 model with explicit microphysics to simulate summer events observed during CAGES.

**Simulation of a CAGES Hailstorm**

Nicole Plette completed her M.Sc. thesis on the numerical simulation of a high-latitude hailstorm observed during the CAGES (Canadian GEWEX Enhanced Study) field experiment using MC2 with a grid size of 10 km. On 11 May 1999, a short-wave trough moved northward from British Columbia and continued its passage over the Northwest Territories. A weakly forced hailstorm developed in an environment of small convective available potential energy (CAPE). Although there was dynamic forcing associated with a short-wave trough, it was found that the hailstorm cannot be simulated realistically without improving the surface properties through the introduction of another soil type. Specifically, the original version of MC2 takes into account a single soil type, that of clay. The introduction of another soil type, a moist organic soil, improves significantly the modelling results in terms of the amount of CAPE and the amount, location, and evolution of the convective precipitation. The result demonstrated the importance of surface processes in the production of summer precipitation over the MRB.

**Analysis of Severe Summer Rainfall Events over the MRB**

The hydrological cycle of the Mackenzie River Basin is largely affected by rainfall during summer months. Rainfall events that span several consecutive days and have accumulation values exceeding 150 mm are responsible for a huge discharge of water into the Mackenzie River Basin. Gerhard Reuter and collaborators (K. Szilder, J. Brimelow, and C. Schinkel) at the University of Alberta analyzed rainfall data for 80 years (between 1921 and 2001), and identified 18 severe rainfall events over the MRB with accumulated rainfall exceeding 150 mm. The synoptic conditions for these events are remarkably similar. In all cases, the rain was associated with the passage of an upper cold low and lee cyclogenesis. The upper-air flow over North America and the eastern North Pacific displayed three distinct features during these severe rainfall events. First, a strong surface and upper-air ridge extended northwards from the North Pacific towards the Aleutians. Second, a split flow occurred over western Canada with a deep upper cold low located over British Columbia or Alberta. Third a well-defined upper ridge arcs northwestwards from southern Manitoba to Alaska. A case study for 27-29 July 2001 was completed.
4. Relevance

The study of the water budget at high latitudes and the development and use of coupled models are central to the goals of MAGS.

5. Networking and Collaboration

In addition to the collaboration between Reuter and Yau, we have continued our collaboration with Zuohao Cao and Ron Stewart. Both Reuter and Yau attended the March 23, 2001 MAGS Integration Workshop in Montreal. A number of presentations were made at the 35th Congress of CMOS. Yau continued to be a member of the GCSS Working Group IV and attended the workshop in Dublin, Ireland on June 26-28, 2001.

6. Summary

We made progress in studying the effects of blowing snow and small water bodies on the water budget of the Mackenzie River Basin. By developing a coupled blowing snow-atmospheric model, we showed that blowing snow and surface sublimation can impact significantly the water budget of high latitudes. Small water bodies can enhance the surface sensible and latent heat fluxes by at least 23% over the MRB. The property of the surface was found to be important in the initiation and development of summertime precipitation over the basin.

7. Publications

Refereed Journals


Dery, S.J. and M.K. Yau, 2001a: Simulation of an Arctic ground blizzard using a coupled blowing snow-atmosphere model. J. Hydrometeorology (in press). (This paper won the Best Student Presentation Award of the American Meteorological Society at the 6th Conference on Polar Meteorology and Oceanography, May 2001.)


**Conference Presentations**


– ♦♦♦ –
D. HYDROLOGIC STUDIES
Climate Impacts on Ice-Jam Floods in Northern Rivers with Specific Focus on the Hydroelectric Industry in Western Canada

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1. Objectives

Global warming and changes to snow and glacier resources of the western Cordillera are expected to modify the flow hydrograph, and thence, the ice regime of major rivers affected by hydro-electric regulation in western Canada. Of particular interest are extreme events, known to be caused almost exclusively by ice-jams that form during the spring breakup of the ice cover. The overall objective of the study is to identify and assess changes to the ice-jam regime of northern rivers that may result from anticipated modifications to local climatic conditions. This objective can be attained via combined utilization of climatic, hydrologic, hydraulic, and river ice models, after sufficient testing and calibration, and using appropriate field data sets. Socio-economic and ecological impacts can then be assessed, and adaptation strategies formulated for hydroelectric power production.

The initial focus of the study is the lower reach of Peace River. Here, the relative rarity of ice-jam floods in the period following construction of the Bennett Dam has resulted in serious habitat degradation and risk to aquatic ecology within large areas of Wood Buffalo National Park and Peace-Athabasca Delta (PAD). The specific objectives of this component of the study are to (a) identify and quantify the hydro-climatic parameters that are conducive to ice-jam flooding; (b) predict changes to the frequency of ice-jam floods in response to anticipated climate change scenarios; and (c) investigate possible regulation strategies to facilitate adaptation to, and mitigation of, attendant adverse ecological and socio-economic impacts.

2. Progress

Development of Database

A comprehensive database is being developed for use in the analysis of hydro-climatic conditions that cause ice-jam flooding, in numerical model calibration, and in prediction of climate change impacts on related flood frequency. This database includes the following components:

- GCM output data from six different models for assessment of utility in driving WATFLOOD, a hydrologic model that generates flow hydrographs, given basin properties and climatic inputs;
- Applicable daily temperature and precipitation data from recent CGCM1 simulations for “current” (1961-1990) and “future” (2070-2099) climates, based on IPCC Third Assessment Report Scenario (observed CO\textsubscript{2} concentrations for 1900-1996; increasing CO\textsubscript{2} concentrations at a rate of 1% per year for the period 1997-2100);
detailed Peace River bathymetry and hydraulics in the PAD reach (approx. lower 60 km of the Peace) for use in hydrodynamic and river ice models;

• review of 1996 and 1997 flood reports and extraction of important water-level data and ice condition descriptions for use in RIVJAM, a numerical model that computes ice-jam and flow properties along a jammed reach;

• historical freeze-up and breakup flows and water levels, extracted from WSC archives for the hydrometric gauging station at Peace Point, along with associated climatic indices (degree days of frost/thaw, snowpack accumulation) – this material is used as surrogate for corresponding conditions within the PAD reach, for which there is only anecdotal information for some of the flood years; and

• field observations and measurements designed to document river ice processes in the lower Peace River, including freeze-up and breakup events, and ice thickness growth and decay during the ice season.

Data Analysis and Interpretation

Data analysis and interpretation is advancing on several sub-projects, including:

• assessment of WATFLOOD model requirements for implementation on Peace River Basin, and suitability of using GCM/RCM output to drive the model;

• calibration of RIVJAM model using relevant data from the 1996 and 1997 ice-jam flood events;

• application of calibrated RIVJAM model to determine threshold flood flows, and to assess efficacy of water releases at the Bennett Dam as a means of enhancing flooding potential;

• delineation of hydro-climatic conditions that must be fulfilled for ice jams to occur in the PAD reach of the Peace; and,

• preliminary assessment of climate change impacts on the frequency of ice-jam flooding of the PAD.

3. Results

The RIVJAM model has been successfully calibrated on the basis of the 1996 and 1997 ice-jam events (Figure 1), using model coefficient values that are consistent with those of previous applications on other rivers. The calibration process also enabled delineation of the resulting reverse flows in the lower three tributaries of the Peace. Further runs with the calibrated model indicated that a Peace-Point flow in excess of 4000 m³ s⁻¹ is required for flooding when an ice jam forms at one of three prone sites within the Delta reach.
At the same time, analysis of historical Peace-Point hydrometric data and related climatic indices has shown that a second necessary condition for ice-jam flooding of the PAD is the occurrence of a “mechanical” spring breakup event. [In a mechanical breakup, the winter ice cover is set in motion by the increasing hydrodynamic forces, before its strength and thickness are subjected to advanced decay. Otherwise, a “thermal” event takes place, characterized by slow runoff and extensive in situ disintegration of the ice cover]. Though the identified two conditions are necessary, i.e. no flooding can be expected if either one, or both, are not fulfilled, they are not sufficient: the conditional probability of flooding, given a mechanical event and a flow over 4000 m$^3$ s$^{-1}$, is 0.60. This suggests that other factors are at work. Most likely, these factors pertain to local conditions and are presently being investigated via the field component of the study.

Physics-based criteria for mechanical event occurrence require knowledge of daily flow, air temperature, and precipitation. Ideally, the “future” ice-jamming regime will be assessed on the basis of climatic model output, coupled with hydrographs generated by an appropriate hydrologic model. The WATFLOOD model has been selected for this study and is presently being calibrated for the Peace River Basin, but implementation has been slower than originally anticipated. Assessment of GCM output revealed significant precipitation discrepancies between observed and GCM-generated “current” climatologies. The discrepancies are large enough to discourage use of GCM data for driving the WATFLOOD model, and reinforce the need for using RCM data.
In the interim, the occurrence of mechanical events has been quantified empirically, in terms of more readily available hydrologic variables (e.g., magnitude of snowpack and rate/magnitude of melt) as illustrated in Figure 2. Such variables can be estimated directly from GCM output for “future” conditions, and the resulting ice-jam regime investigated by tracking their values on a year-by-year basis.

![Figure 2: Delineating between thermal and mechanical break-up events in terms of snowpack index and rate of accumulation of degree-days of thaw.](image)

This preliminary analysis indicates that conditions will be less favourable for spring floods, largely because of significantly reduced snowpacks, and despite a slight increase in the pre-breakup rates of melt. Warmer temperatures will also cause shorter ice seasons and frequent mid-winter thaws and mid-winter breakup events. However, it is unlikely that mid-winter flows will reach the level required for a major ice-jam flood. At the same time, mid-winter runoff will contribute to reductions in the spring snowpack.

Furthermore, a longer open-water season and higher air temperatures will cause more rapid drying of perched delta basins, rendering the survival of such systems even more dependent on overbank flooding. With a potential decline in spring overbank floods, the development of adaptation strategies to minimize such climate change effects becomes a very important component of future studies. Work on this question has already started by evaluating the effectiveness of a Bennett Dam flow release in enhancing the 1996 ice-jam flooding of the PAD. Ongoing analysis of this event will contribute to a future publication and related presentation at an international workshop sponsored by the UNESCO International Hydrologic Programme and entitled “Non-structural methods for water management problems”.
The study has been the first to predict how potential climate change will alter winter ice regimes, and particularly the frequency of occurrence of extreme ice-jam floods. Although the focus so far has been on the lower Peace River and the Peace-Athabasca Delta in western Canada, the results of the study and the methodology that is being developed can find extensive application to other cold regions river systems.

4. Relevance

The research presently in progress contributes in many ways to both of the overall goals of MAGS, i.e.:

“(1) understand and model the high-latitude water and energy cycles that play roles in the climate system, and (2) 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 MAGS-1, the tasks for MAGS-2 have been broadly divided into five themes, with each theme encompassing two or three specific objectives. The following list identifies those themes and objectives to which the work described herein is most relevant.

Theme I: Integration of Knowledge on the Physical Processes

Several processes, important for the achievement of MAGS goals, were not comprehensively studied in MAGS-1 due to limited funding. These include river ice processes, and especially breakup and jamming. Field observations and historical data analysis that are carried out under the present study are advancing our understanding of such processes in the MAGS context (Objective 1). The present study also addresses ice-related aspects of hydrological components that are to be integrated with atmospheric studies towards a unified framework (Objective 2).

Theme III: Model Development and Evaluation

The RIVJAM model, which is driven by hydrological model output (river flow), is an important addition to a hierarchy of models that is being developed to enable evaluation of how individual phenomena affect the hydro-climatic systems (Objective 5). A methodology has been developed to test the performance of, and calibrate, RIVJAM using field and historical data. Already successfully applied in the PAD reach of Peace River, the same approach can be implemented on other important rivers of the Mackenzie basin to study ice-jam related issues (Objective 7).

Theme IV: Prediction and Analysis of the Climate-Hydrological System

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. The present study addresses the question of how climate forcing and climate change can alter the regime of extreme events, such as ice-jam flooding, an important component of Objective 9.
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. Present research findings are strongly focused on important ecological concerns in the PAD, and are of interest to local residents, various levels of government and to the hydro-industry (Objective 10). At the same time, the methodology, models, and analytical approaches that are being developed can be transferred to other river systems and basins to address similar (e.g. Mackenzie Delta lakes) or different (e.g. flood damage risks) concerns (Objective 11).

5. Networking and Collaboration

Collaboration has been ongoing within the study group, and findings by different researchers are synthesized to arrive at key conclusions, as described above. At the same time, networking with scientists/engineers/managers/technical staff from public and private agencies and from local groups, has proved valuable with respect to:

- obtaining important historical data for the various database components that are presently being developed (Environment Canada - operational groups);
- securing crucial logistical and personnel assistance for field operations under difficult access conditions (Parks Canada; First Nations); and
- obtaining supplementary field data and hydrograph-related information (BC Hydro; Alberta Environment).

6. Summary

Using a combination of archived data, process studies, field data collection, and numerical modelling, it has been possible for the first time to predict how potential climate change will alter the winter ice regime of a river. Of particular concern is the frequency of occurrence of extreme ice-jam floods on the lower Peace, which are essential agents of replenishment of the aquatic ecosystems of the PAD in western Canada. This frequency is likely to decrease under global warming. Coupled with longer open-water seasons and higher air temperatures, this trend will accelerate the drying of perched delta basins. Therefore, development of adaptation strategies to minimize such climate-change effects should be vigorously pursued in future studies. Although the focus of this research has so far been on the lower Peace River and the Peace-Athabasca Delta, the results of the study and the methodology that is being developed can find extensive application to other cold-region river systems.
7. Publications


Modelling the Interaction of Climate, Hydrology and River Ice Hydraulics

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1. Objectives

- Develop and validate a deterministic numerical model which integrates the interactive effects of climate, hydrology, and river ice processes; and
- Use this model to quantitatively assess the potential impact of global warming on basin hydrologic response in the Mackenzie basin and other high latitude regions.

Timeline for the 5-year Project (from the MAGS-2 NSERC Research Network Proposal)

**Year 1**

- Address the critical need for quantitative data describing dynamic ice processes by establishing an intensive river ice-jam monitoring program on the Athabasca River in the vicinity of Fort McMurray, Alberta, where ice jams occur frequently; and
- Commence work on the deterministic model of the simultaneous interaction of climate, hydrology and river ice, with preliminary development of the model framework based upon historical records which document meteorological and hydrological influences on break-up in the study basin.

**Year 2**

- Integrate the cdg1-D finite element hydraulic flood routing model with the existing basin hydrologic model (developed by Soulis et al. in MAGS-1); and
- Continue field program of ice-jam monitoring and the development of the deterministic model of dynamic ice-jam processes.

**Year 3**

- Commence work on integrating the deterministic model of dynamic ice-jam processes into the existing cdg1-D hydraulic flood routing model; and
- Continue field program of ice-jam monitoring and the development of the deterministic model of dynamic ice-jam processes.

**Years 4 and 5**

- Model completion, verification and application; possible additional field data collection.
2. Progress

Field Data Program

A. A meteorological station was installed at Fort McMurray, as well as 8 remote water level monitoring stations along the Athabasca River upstream of Fort McMurray (Figure 1).

Figure 1: Map of the field study reach showing the location of the remote water level monitoring stations.

The meteorological station measures precipitation, solar insolation, air temperature, and barometric pressure. Although this data is only needed in the fall, winter and spring periods, the station will be operated continuously throughout the year, primarily because measurements of solar insolation by Environment Canada (EC) were discontinued in 1996 and these data would be useful to other MAGS researchers. In addition, a sunshine ball is also operated at the site in order to develop a local relation between hours of bright sunshine and solar insolation.

The remote water level monitoring stations measure a continuous water surface profile which facilitates winter discharge determination and documents the unsteady aspects of flow hydraulics during ice cover formation and break-up. They also capture the propagation of ice-jam surge releases through the study reach. Five of the 8 remote stations are interactive: data can be downloaded on a real time basis. They are also equipped with alarms, which sound when significant ice events occur, to facilitate mobilization of the field team. This is essential, since visual observations of ice processes are needed during major ice movements.
in order to interpret the quantitative data. Three of the 8 stations were installed prior to break-up, 2001, and they were successful in measuring a small ice-jam release surge event.

B. We have completed the first year of field observations of river ice break-up on the Athabasca River at Fort McMurray. This included: documentation of ice thickness, discharge and water levels prior to break-up; continuous automated and manual water level measurements during break-up; and daily observational flights which monitored ice cover deterioration and major ice movements, and surge propagation. A severe ice jam did not occur.

C. We completed hydrometric (cross-section) surveys of the Athabasca River in the 35 km study reach upstream of Fort McMurray in August 2001, and established vertical control by locating and surveying to benchmarks established by Alberta Environment.

Development of the Deterministic Model of Ice Processes

A. Preliminary development of the model framework was to be based upon historical records documenting meteorological and hydrological influences on break-up in the study basin.

- We have completed the development of an extensive data archive of hydrometeorological data pertinent to river ice processes at this site, dating back to 1972. This includes: basin snow course data (from Alberta Environment); meteorological data (air temperature, hours of bright sunshine, and precipitation from Environment Canada); water level records at the WSC gauges in Fort McMurray (Athabasca and Clearwater Rivers); ice thickness; winter discharge; late fall soil moisture index (from Alberta Environment); and historical ice-jam levels and locations (University of Alberta, Alberta Environment, Alberta Research Council).

- Environment Canada discontinued measurements of bright sunshine in Fort McMurray in 1996; our meteorological station became operational in the fall of 2000. We have obtained an extensive data record (1988 to present) from a meteorological station at Syncrude, which was sufficiently close to develop a relationship for filling in the missing years of record.

- This data archive is being used first to develop a conceptual-empirical model to identify the risk of break-up ice jams, to identify the significant parameters in this context. (C. Robichaud, M.Sc. thesis; completion date: Nov. 2001).

B. We have commenced work on the deterministic model, specifically with respect to the hydraulic processes.

- The cdg1-D unsteady flow model was extended to accommodate natural channel geometry, to facilitate analysis of ice-jam release surges measured at the study site. The model was validated with ice-jam surge release data from an independent site. (J. Blackburn, M.Sc. thesis).

- A discrete-element/discrete-parcel model of ice floe propagation and accumulation is currently under development (Steve Yang, Ph.D. thesis project).

- This model is currently being built on the cdg1-D unsteady flow model, but will ultimately be ported to a two-dimensional hydraulic model based on the same CDG finite element numerical scheme (originally developed by Hicks and Steffler, University of Alberta).
Integration of the cdg1-D Finite Element, Hydraulic Flood Routing Model, with the Existing Basin Hydrologic Model (developed by Soulis et al. in MAGS-1)

A. Although scheduled for commencement in Year 2, we have already begun this aspect of the project. A hydraulic flood routing model of the Athabasca River from Fort McMurray to Embarrass has been developed, calibrated, and verified (W. Herrera, M.Eng. project). The model is currently being extended 800 km upstream from Fort McMurray to Whitecourt. The geometric database is complete for this reach, and calibration runs will commence in November 2001. (K. Unterschultz, Dean’s Research Project).

B. A user’s manual for the cdg1-D model has also been completed, which was assessed and revised by W. Herrera (M.Eng. student) in conducting his research project.

3. Results

Field Data Program

We obtained a unique data set, tracking the propagation of an ice-jam release surge through the study reach (see map in Figure 1) during the 2001 break-up. As Figure 2 illustrates, the water level rose 1.2 m in only 15 minutes as the surge passed station 135, and this surge propagated between stations 135 and 120 (~13 km) in only 55 minutes, moving at an average speed of 4 m s\(^{-1}\). This illustrates the highly dynamic nature of ice-jam release surges (note that typical mean channel velocities in this reach are less than 1 m s\(^{-1}\)). This data set provides unprecedented information on the effects of ice on ice-jam surge propagation.

![Figure 2: Water levels measured during ice-jam release surge event, 2001.](image-url)
Integration of the cdg1-D Finite Element, Hydraulic Flood Routing Model

The hydraulic flood routing model of the Athabasca River from Fort McMurray to Embarras has been successfully used to accurately route historical floods, based on a single value of the only calibration parameter, Mannings $n$, which was found to be applicable to a range of events (some results are presented in Figures 3 and 4).

Figure 3: Comparison of measured and routed flows, 1978.

Figure 4: Comparison of measured and routed flows, 1980.
4. Relevance

- River ice processes are a significant component of northern hydrology, and climate change has the potential to significantly affect the winter regime of Canadian rivers. This will have significant implications in terms of flood risk and transportation, particularly in northern Canada. As this area of research was not a component in MAGS-1, we are working hard to collect the necessary field data in order to facilitate the predictive modelling efforts appropriate to MAGS-2.
- At this point, the deterministic nature of our flood routing approach already facilitates upscale synthesis of processes and provides enhanced accuracy in predictive applications for open water situations.
- Together, our field data and deterministic model of the interaction of climate, hydrology and river ice will ultimately facilitate upscale synthesis of processes and provide enhanced accuracy in predictive applications for situations involving ice dynamics.

5. Networking and Collaboration

- I participated in the MAGS meeting in Montreal, (spring, 2001) and will also be participating in the meetings in Hamilton in November, 2001.
- Our flood routing model development efforts on the Athabasca River are in direct response to specific discussions with/requests by E.D. Soulis and were conducted in collaboration with engineers at Environment Canada.
- The meteorological station at Fort McMurray which provides real time data, dating back to 1972, is available to all MAGS researchers. This will be provided to the Data Manager on CD;
- Field data taken in relation to our study of river ice break-up at Fort McMurray from 2001 (as well as non-MAGS data from 2000) will be provided to the Data Manager on CD (including discharge determinations during the break-up period).
- Papers on MAGS-related research were presented at the CGU-HS Conference (River Ice Committee session) in Ottawa, May, 2001, and at the Canadian Society for Civil Engineering Conference (Victoria, June, 2001).

6. Summary

Virtually all of the rivers in Canada experience some ice effects each year, and in the spring when rivers break up, ice jams can occur. Ice jams have the potential to produce extremely dangerous flood events that threaten both life and property. This is particularly true at Fort McMurray, Alberta, where damages associated with ice-jam-related flooding totalled several million dollars during a single event in 1997. At present, very little is known about what causes ice jams; they are so unpredictable that few have actually been scientifically measured. In this study, using sophisticated instrumentation and communications technology, we have established an automated ice-jam monitoring network along the Athabasca River upstream of Fort McMurray, Alberta. In addition to providing unprecedented data on the dynamic aspects of river ice break-up, which is critical to developing a scientific understanding of ice-jam events,
the network also provides a flood warning system for the people of Fort McMurray, and could facilitate evacuation in the event of a major ice-jam event.

Our investigations of historical data at this site have also resulted in the development of a flood risk model, which enables flood forecasters to assess the risk of ice-jam occurrence in any given year, based on the severity of the preceding winter and the weather occurring during spring break-up. This model represents a new technology that can be transferred to other sites, and that can assess the influence of climate change on ice-jam occurrence.

7. Publications


Blackburn, J. and F.E. Hicks: Combined flood routing and flood level forecasting. Canadian Journal of Civil Engineering (accepted).


Hicks, F.E. and D. Healy: Determining discharge during river ice break-up. Canadian Journal of Civil Engineering, special issue on River Ice topics (in preparation).


– ☞ ☞ ☞ –
1. Objectives

The objective of this research is to model subarctic Canadian Shield hydrology in a fashion that accounts for the physical processes identified during MAGS-1.

2. Progress

A partnership was made with the Northwest Territories Power Corporation (NWTPC) to develop and improve hydrological modelling applications to subarctic Canadian Shield rivers. Activities during 2001 concentrated on improving collection of hydrometric and meteorologic data from the Snare River Basin, where NWTPC operates four hydroelectric generating facilities. There continues to be much discussion between partners on the options available to incorporate the findings of MAGS-1, notably sub-basin storage processes, into hydrological models. Parameterization and application of SLURP to the Snare basin is expected to be completed in 2002.

3. Results

Typical applications of conceptual hydrological models such as WATFLOOD and SLURP presently will likely not accurately predict streamflow because they do not account for landscape storage effects on intermittent hydrological connections at the sub-basin scale. There are two solutions which show potential for incorporating sub-basin storage processes into hydrological models. The first is development of a model scheme that routes sub-basin runoff based on land cover and elevation topology. The second requires that basins be modelled at the same scale as individual landscape elements so that routing of hillslope runoff to streams can be performed using present model reservoir routing.

4. Relevance

The results from MAGS-1 significantly improved our understanding of subarctic Canadian Shield water and energy cycles. These results are being incorporated into hydrological model applications to improve our ability to assess the changes to Canadian Shield water resources that arise from climate variability and anthropogenic climate change.
5. Networking and Collaboration

There is a partnership between Environment Canada and NWTPC on improving hydrometric and meteorological monitoring and streamflow forecasting in the Snare River Basin. Environment Canada, McMaster University and the University of Saskatchewan are involved in the incorporation of MAGS-1 results into the hydrological models which are to be applied to the Snare basin. The NWT Center for Remote Sensing completed classification of a Landsat TM image of the Snare River Basin for land cover in March, 2001. A digital elevation model of the basin was constructed at the National Water Research Institute during MAGS-1. All four partners participated in the MAGS Scaling Workshop in Yellowknife in June, 2001.

6. Summary

MAGS-1 identified that sub-basin storage processes are crucial in controlling basin runoff processes. These findings are presently being incorporated in hydrological model applications to the Snare River Basin in the Northwest Territories. Partnerships have been forged between Environment Canada, the Northwest Territories Power Corporation and several universities to facilitate hydrological model development and improve streamflow forecasting in the subarctic Canadian Shield.

7. Publications


1. Objectives

The long term objectives of this project are to integrate and synthesize process studies from MAGS-1, and use appropriate physically based hydrologic models, weather/climate model output, and remote sensing to analyse water and energy fluxes in the lower Mackenzie area at sub-grid scales. An important component of this work will address scaling issues within the research basins in the Inuvik area, and the broader area of the northern Mackenzie basin. Model application to other regions will allow a determination of the affects of climate variability; as well, future climate changes will be considered.

2. Progress

During the past year we have focused primarily on: (1) development of a consistent 9 year data base of daily water balance values (snowmelt, rainfall, runoff, evaporation, and storage) for the runoff period at both Trail Valley (TVC) and Havikpak Creeks (HPC) in the lower Mackenzie basin near Inuvik, (2) analysis and comparison of both tower and aircraft measurements of sensible and latent heat fluxes for TVC and HPC, and (3) modelling the spatial variability in the radiation, latent heat and sensible heat fluxes over the TVC basin, with an emphasis on the spring melt period. The following section will briefly highlight results from this work. Future research will expand and integrate this work with comparisons to GEM high resolution model runs during CAGES, RCM runs conducted in MAGS, and comparisons to WATCLASS output for the Inuvik area. New research on snowpack development in Alpine areas of the Mackenzie basin have been recently initiated as part of a PERD funded program.

3. Results

Water Balance Data Set

Over the last decade detailed hydrologic research has been carried out at two research basins in northwestern Canada by the National Water Research Institute (NWRI). In addition to detailed process studies, there has been an ongoing program to collect a comprehensive data set to allow the determination of the principal water balance components for each research basin for both the annual water year and daily periods over the spring/summer/fall period. Preliminary results from these studies have been presented by Marsh et al. (1994) and Marsh et al. (2001). This data set is
sufficiently long to provide a more comprehensive consideration of the water balance of this region, to begin considering if there are longer term trends, and to consider variations across the arctic treeline for example. Of considerable interest to MAGS is the use of this data set for validation of various hydrologic and land surface models.

The annual water balance of the TVC and HPC research basins can be described as:

\[ P_S \pm (T - S_B ) - S_S + P_R - E - Q = \Delta S \pm e \]  

where \( P \) is precipitation and subscripts \( S \) and \( R \) refer to snow and rainfall respectively, \( T \) is blowing snow transport into or out of the basin, \( S \) is sublimation during blowing snow (subscript \( B \)) or from the snow surface (subscript \( S \)), \( E \) is evaporation from snow free areas, \( Q \) is stream discharge, \( \Delta S \) is change in storage, and \( e \) is an error term. Marsh et al. (1994) outlined methods for determining the magnitude of each of these components. For this study however, the water balance is calculated only for the spring/summer/fall period when air temperature was consistently above 0°C. As a result, \( P_S \) is ignored and any mixed rain/snow events are included in the \( P_R \) term; blowing snow events did not occur and therefore \( T \) and \( S_B \) were not important; and as Marsh and Pomeroy (1996) suggested that sublimation during melt was small, \( S_S \) is assumed to be negligible. The snowfall input into the basin is then replaced by \( M \), snowmelt distributed over the snowcovered areas. Equation one then reduces to:

\[ M + P_R - E - Q = \Delta S \pm e \]

For this study, \( P_R \) and \( Q \) are measured, and \( \Delta S \pm e \) is estimated as a residual of equation 1. \( E \) is calculated from the Priestly-Taylor method (Marsh et al., 1994) using measured air temperature and net radiation, and ground heat flux estimated as a constant proportion of net radiation (18%) as determined from comparisons of measured net radiation and ground heat flux. The evaporation parameter in the Priestly-Taylor equation was determined as 0.60 and 0.55 for TVC and HPC respectively (Marsh et al., 2001), from evaporation lysimeters and eddy correlation measurements of latent heat flux. These values are lower than reported by Mendez et al. (1998) for an upland tundra site near Prudhoe Bay, Alaska (evaporation parameter of 0.91 to 0.95), but similar to the values of 0.54 to 0.86 provided by McFadden and Chapin (1998) for upland tundra sites on the Alaskan north slope. Reasons for these differences are not clear, but are likely related to a combination of both vegetation and soil moisture conditions. For daily estimates, \( M \) is determined from the surface energy balance weighted by snowcovered area as described by Marsh and Pomeroy (1996). In addition, a seasonal water balance total is determined by assuming that the end of winter snowpack entirely melts. In this case, \( M \) is assumed to be equal to the end of winter snowcover as estimated from distributed snow surveys following the procedures of Marsh and Pomeroy (1996).

Figure 1 provides the annual values of the main water balance terms (\( M \) or \( P_S \), \( P_R \), \( Q \), \( E \), \( \Delta S \pm e \)). On average these data show that for both TVC and HPC, \( (M + P_R) \) averages 231 and 283 mm respectively over the study period, with snow accounting for 56 and 52% respectively. Daily water balance was calculated for the entire period of record, and an example for TVC is shown in Figure 2 for the summer of 1998. A preliminary analysis of these data is available in Marsh et al. (2001).
Figure 1: Seasonal water balance values for both Havipak Creek (HPC) and Trail Valley Creek (TVC) for the period of record.

Figure 2: Example of daily cumulative water balance values for Trail Valley Creek (TVC) for the spring, summer, and fall of 1998.
Comparison of Tower and Aircraft Measurements of Sensible and Latent Heat Fluxes

During the CAGES period, measurements of the flux of sensible and latent heat were carried out from towers over typical terrain at both HPC and TVC. In addition, the NRC Twin Otter Flux Aircraft also carried out measurements during a spring and summer period. Ongoing collaboration is comparing these measurements, and using them to consider the sub-grid scale variability of fluxes at the arctic treeline. The following provides a brief synopsis of some of the results to date (MacPherson et al., 2001).

Absolute energy exchange (particularly sensible heat flux) differs very significantly between forested and non-forested areas at the time of full and partial snow cover, due to the low albedo of coniferous trees for shallow sun angles. The delineation between tundra and ‘forest’ in land cover classification schemes based on remote sensing, which is not easy in this transition landscape, is important for the extrapolation of findings to the larger scale.

The overwhelming importance of the non-turbulent energy fluxes (the ‘residual’ above) for the tundra during the snowmelt period is obvious and its correct representation in models will be a challenge to modellers. Comparison of fluxes measured by short towers on the tundra and in the sparse forest with fluxes measured by the aircraft at various scales showed reasonable agreement (Figure 3). This represents a promising start to scaling up the tower data to regional scales.

Figure 3: Example comparison between Grid and Aircraft segment for Trail Valley Creek.
Spatial Variability in Radiation, Latent Heat and Sensible Heat Fluxes over TVC

The aircraft program, in conjunction with tower measurements over a heterogeneous area, as well as over an early emergent snow-free area and a late lying snowpatch clearly demonstrate the large spatial variability in fluxes of radiation, sensible heat, latent heat and snow melt. This spatial variability is being considered through modelling the effect of slope angle and aspect on surface radiation. Figure 4 shows an example for both a single hour and for the entire day. Note the very large variation in radiation for both cases. In addition, variations in wind speed over the TVC basin are being estimated through the application of two rough terrain wind flow models. Figure 5 shows an example where the sensible heat flux to a snowcovered surface is estimated assuming a constant temperature, but spatially variable wind speed.

Ongoing work will integrate the effects of a variable snow pack, wind speed, air temperature, and incoming solar radiation, in order to consider the spatial variability of energy fluxes. This will then be compared to estimates of spatially averaged fluxes from aircraft measurements, from high resolution runs of GEM, and from WATCLASS model runs.

Figure 4: Distribution of solar radiation received at the ground surface on May 27, 1999 at 12 Noon. At this point in time radiation varied from 99.4 - 937.0 W m\(^{-2}\). Also shown is the sum from 02:00 to 22:00 hours for the same day when radiation varied from 3526.7 - 9111.7 W m\(^{-2}\).

Figure 5: Estimated sensible heat flux over a continuous snowcover at TVC. Wind speed was estimated from a simple rough terrain wind flow model from Liston. Windspeed was set at 5 m s\(^{-1}\) from the north for this simulation. Note that sensible heat flux varied from approximately 110 to 210 W m\(^{-2}\).
4. **Relevance**

This work is directly relevant to the MAGS-2 themes of Integration, Scaling, and Modelling.

5. **Networking and Collaboration**

- Ongoing collaboration with Dr. W. Rouse on surface energy balance of basins in the Inuvik area;
- Provide information and data to Dr. C. Lin for testing of CLASS over Inuvik research basins;
- Ongoing collaboration with Dr. I. MacPherson on analysis of aircraft flux data;
- Organization of MAGS workshop in Montreal in the spring of 2001;
- Organization of CAGES Special Issue of the *Journal of Hydrometeorology* and a related workshop in Edmonton in March, 2001; and
- Provided 2 data CD’s to MAGS Data Manager, covering hydrology of two research basins during CAGES.

6. **Summary**

This ongoing study has developed a comprehensive, 9-year hydrologic data set for two research basins in the northern Mackenzie basin. This data set will be used for the testing and validation of both hydrologic and land surface models. In addition, ongoing analysis of the fluxes of net radiation, sensible heat and latent heat flux from both towers and aircraft is demonstrating the large spatial variability in these fluxes at the sub-grid scale. Further consideration of this sub-grid scale variability is utilizing models of wind speed over rough terrain and models of the effect of slope and aspect on received solar radiation. These will then be used to estimate spatial variability of energy fluxes. Comparison with grid averages from both high resolution model runs, and as estimated from aircraft measurements will allow a better understanding of the importance of sub-grid square processes to both the hydrology and the atmosphere, and will result in improved model algorithms.

7. **Publications**


1. Objectives

Research in 2001 was carried out with the objectives of:

- developing a vertical frost and moisture flux model; and
- obtaining realistic parameter values from field studies to enable improvement of parameterization and testing the effects of grid size on flow parametrization.

2. Progress and Results

2.1 One Dimensional Frost and Moisture Model

Frost is a major seasonal or permanent feature that strongly influences the hydrology of basins in the cold region. One of our primary objectives in 2001 is to develop a one-dimensional frost algorithm that can subsequently be incorporated into existing models. The algorithm takes account of several considerations:

- it includes the coupling of the frost and moisture flux routines because of their mutual feedback;
- it provides sufficient vertical resolution to indicate the positions of the water table and the frost table;
- a limited number of parameters is needed; and
- the algorithm and/or the modelled output can be incorporated easily into macrohydrological models and land surface schemes.

The proposed algorithm consists of three components: a frost subroutine, a moisture subroutine and a frost-water linkage subroutine. In the model, a vertical soil column is sub-divided into \( n \) slabs of \( z \) thickness; each layer is given a porosity and a minimum moisture content it can retain, a saturated hydraulic conductivity and fractions of mineral and organic content. The initial moisture content of the soil slabs and the position of the initial frost table are specified. Daily inputs are the ground surface temperature and net water flux (positive or negative) into the column. The freezing or thawing of the soil slabs is then calculated, as is the daily soil moisture content for the slabs. The frost and moisture computations are linked through the changing thermal and hydraulic conductivity coefficients. Outputs include daily water and frost table depths, overland flow and interflow generalized over a pre-specified number of slabs comprising the layers in the macrohydrological model for which the outputs are applied.
**Frost Algorithm**

Finite element and finite difference models have been used extensively in the calculation of ground temperature and hence, frost. Besides requiring some knowledge of the initial and boundary temperature condition, such computations provide temperature details that are not required by most macro-hydrological schemes. A computationally simpler approach using the Stefan’s equation is adequate to obtain the depths of freeze or thaw.

Following Fox (1992), only the freezing or thawing degree-days at the ground surface provided by some land surface schemes or regional climate models are needed to drive the algorithm. On a daily basis, the heat flux needed to freeze or thaw a slab depends on the moisture or ice content in the soil, and its thermal conductivity. The emphasis on these two variables as the primary consideration in freeze-thaw is in complete agreement with field study results (Woo and Xia, 1996). The incremental depth of freeze or thaw is obtained through a ratio of the degree-days entering the column and the potential degree-days needed for the slab to freeze or thaw.

**Moisture Algorithm**

Water balance for all slabs in the soil column is evaluated to update the moisture status. The algorithm considers the net flux (positive or negative) into the column, which may be the infiltrated water or the water loss to evapotranspiration. Water enters and leaves a slab through vertical drainage, extraction by plant roots and matric suction (Feddes et al., 1974; Fetter, 1999). Moisture change is obtained as the residual of the slab water balance but the updated moisture content cannot fall below the specified minimum or exceed the maximum (considered to be the porosity) allowed. Water in excess of the maximum (i.e., saturated condition) moves to the higher slabs and if the surface is reached, any excess will join the overland flow. When a horizontal gradient is specified, lateral drainage from a saturated slab will be generated as sub-surface flow.

**Linkages of Frost and Moisture Algorithms**

Frost, through the sealing of the soil pores by ground ice, can greatly diminish the hydraulic conductivity of the soil (Burt and William, 1976). Hence, a soil slab is rendered relatively impermeable when it is considered to be frozen through the frost algorithm. Although porous frozen soils with low ice content have been found to permit infiltration and percolation (Gray, 1986), we take the general situation that drainage is inhibited when the soil is frozen.

The content of water and ice in the soil influences the thermal conductivity and Farouki’s (1981) equation is used to update the thermal parameter as the moisture status changes. The moisture content and the thermal conductivity are used in the Stefan’s equation in the frost model, and this completes the frost-moisture feedback.
Progress to Date

During 2001, the frost-moisture model was conceptualized and the algorithm developed. The programme is coded and being debugged. Limited tests will be performed later this year and then the model will be tested against field data previously acquired at several northern sites.

2.2 Spatial Representation of Parameters

Given the sensitivity of parameterization to scale and resolution effects (Martz and Garbrecht, 1996; Theiken et al., 1999), ongoing research on the spatial representation of hydrologically-relevant parameters is being conducted to support the development and validation of hydrological models appropriate for permafrost environments at point, through slope and small catchment scales to grid cells of land surface schemes. The primary goal of the first year of the study was to complete the collation of the necessary input data for the Wolf Creek Basin. This has been completed. Additional research on parameterization of horizontal flow properties was also initiated.

Parameterization of Input Data

A field campaign was conducted to complete the collection of data on surficial material properties that had been previously postponed. This field work was focused on obtaining parameter values to characterize the thermo-hydrologic properties of sub-zones within the Wolf Creek basin, including the surface cover and the vertical structure of the soil profile. Data collected in this past year included:

- thickness of the organic layer;
- organic layer bulk density;
- thickness of the mineral soil;
- particle size and bulk density for mineral soil; and
- calculated hydraulic properties for mineral soil (porosity, hydraulic conductivity).

These data have been incorporated into the Geographical Information Systems (GIS) database of Wolf Creek that was developed earlier. An example of some of the site-specific data is given in Table 1. Analysis of the inter-relationships between environmental variables is underway to test spatial interpolation techniques.

Horizontal Flow Parameterization

Research has proceeded on two closely related fronts: (1) the impact of grid cell resolution on basin delineation and parameterization and (2) the aggregation of fine resolution flow data to a coarser resolution modelling scale. Both of these studies are undertaken in collaboration with other research teams and serve to strengthen the MAGS network structure.
In the first case, an analysis of the impact of changing grid cell size on basin delineation and parameterization was undertaken on the Mackenzie and Mississippi River Basins and their major sub-basins. The analysis shows some significant shifts in basin properties such as slope steepness with changing cell resolution. However, the most pronounced impact is on the delineation of basin boundaries and the determination of basin area (Table 2). The implications of this for model parameterization are being assessed, and data analysis techniques to minimize this effect are under development.

Table 1: Hydraulic conductivity values for Wolf Creek Basin from bail tests of observation wells.

<table>
<thead>
<tr>
<th>Well</th>
<th>Date</th>
<th>Easting</th>
<th>Northing</th>
<th>Elev. (m)</th>
<th>Well depth (cm)</th>
<th>Water table (cm)</th>
<th>Well radius (cm)</th>
<th>Hydraulic conductivity (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>July 12</td>
<td>0489810</td>
<td>6712356</td>
<td>1369</td>
<td>47.3</td>
<td>21.5</td>
<td>2.54</td>
<td>4.72 x 10^{-5}</td>
</tr>
<tr>
<td>B</td>
<td>July 12</td>
<td>0489789</td>
<td>6712420</td>
<td>1385</td>
<td>59.3</td>
<td>7.0</td>
<td>3.81</td>
<td>1.96 x 10^{-4}</td>
</tr>
<tr>
<td>C</td>
<td>July 12</td>
<td>0489778</td>
<td>6712248</td>
<td>1389</td>
<td>58.5</td>
<td>46.8</td>
<td>2.54</td>
<td>1.08 x 10^{-5}</td>
</tr>
<tr>
<td>D</td>
<td>July 12</td>
<td>0489808</td>
<td>6712295</td>
<td>1371</td>
<td>39.0</td>
<td>18.4</td>
<td>2.54</td>
<td>5.33 x 10^{-6}</td>
</tr>
<tr>
<td>E</td>
<td>July 12</td>
<td>0489838</td>
<td>6712397</td>
<td>1374</td>
<td>58.5</td>
<td>14.5</td>
<td>2.54</td>
<td>3.05 x 10^{-5}</td>
</tr>
<tr>
<td>F</td>
<td>July 13</td>
<td>0483705</td>
<td>6706480</td>
<td>1325</td>
<td>82.8</td>
<td>37.0</td>
<td>2.54</td>
<td>2.26 x 10^{-6}</td>
</tr>
<tr>
<td>G</td>
<td>July 13</td>
<td>0483637</td>
<td>6706413</td>
<td>1326</td>
<td>62.0</td>
<td>24.5</td>
<td>2.54</td>
<td>1.18 x 10^{-4}</td>
</tr>
<tr>
<td>H</td>
<td>July 14</td>
<td>0504144</td>
<td>6715780</td>
<td>768</td>
<td>112.0</td>
<td>82.7</td>
<td>2.54</td>
<td>2.10 x 10^{-4}</td>
</tr>
<tr>
<td>I</td>
<td>July 14</td>
<td>0504431</td>
<td>6711082</td>
<td>784</td>
<td>81.5</td>
<td>48.4</td>
<td>2.54</td>
<td>4.32 x 10^{-5}</td>
</tr>
</tbody>
</table>

Table 2: Comparison of measured and calculated drainage areas for Mackenzie basin.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Cell resolution (km)</th>
<th>Measured drainage area (km²)</th>
<th>Calculated drainage area (km²)</th>
<th>Ratio of calculated to observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mackenzie</td>
<td>1</td>
<td>1,667,185</td>
<td>1,653,952</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,598,036</td>
<td>1,567,488</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1,653,952</td>
<td>1,567,488</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1,680,000</td>
<td>1,567,488</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1,597,440</td>
<td>1,560,576</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>1,597,440</td>
<td>1,560,576</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>1,597,440</td>
<td>1,560,576</td>
<td>0.93</td>
</tr>
</tbody>
</table>
The second aspect of horizontal flow studies concerned methods of aggregating flow pattern data to coarser grid cells for the purpose of hydrological model parameterization. This work is directly linked to the type of grid representation used in the WATFLOOD hydrologic model.

A new parameterization method was developed and implemented using the Arc/Info macro language (AML) to create an interface between the TOPAZ (Topographic Parameterization) digital terrain analysis model (Garbrecht and Martz, 2000) software and the WATFLOOD hydrologic model. The interface uses output raster data from TOPAZ (i.e. drainage identification) as the source of parameters for WATFLOOD. This new method facilitates the coupling of hydrologic models with RCM/GCM atmospheric models. An examination of flow directions from the new method (which maintains the hydraulics of the grid-square) with those from current GCM methods (which rely solely on elevation differences between aggregated grid-squares) shows substantial differences between the two approaches. One of the most notable is the high frequency of pits or flow dead-ends that result when the conventional GCM approach is used (Figure 1).

![Figure 1: Drainage patterns for Mackenzie basin using (a) coarse resolution elevations aggregated from fine and (b) WATFLOOD-like aggregation of flow pattern data for fine resolution elevations.](image)

References


### 3. Relevance

This project is concerned with the integration and modelling of the processes studied in MAGS-1. The development of models and the upscaling of inputs, parameters and process representation are directly relevant to the scaling and modelling themes. The models and the procedures followed will serve as an enabling technology for the prediction of regional climate-hydrological system response to changing external forcing. When completed and tested, the models will be applied to problems in parts of northern Canada in collaboration with users.

### 4. Networking and Collaboration

This research team has been an active participant in all of the MAGS workshops over the past year. They have also been active in presenting MAGS research results at other national and international conferences. Some of the research activities – particularly, the analysis of flow pattern aggregation for macrohydrological modelling – have been undertaken in collaboration with other research team members.
5. Summary

A one-dimensional frost and water flux model is being developed to simulate ground freeze-thaw in a permafrost environment. The algorithm makes use of the Stefan’s equation coupled with the soil water/ice contents which affect the thermal conductivity and the latent heat requirements for freeze-thaw. The model subdivides a soil column into multiple layers and requires temperature and net water input at the ground surface. It will be tested using field data from a continuous and a discontinuous permafrost site.

Field measurements of several hydrological properties of soils were made in Wolf Creek Basin, to improve the model parameterization for a subarctic environment. Such parameters have seldom been measured directly and our measurements will provide realistic representation of the soil attributes. In addition, an increase in grid size was found to distort the basin area and produce incorrect flow directions between cells.

These studies are a contribution to the overall MAGS objectives of modelling cold region processes and improving model parameters, and is also relevant to the upscaling theme.

6. Publications


Integrated Modelling of the Mackenzie: Bringing the MAGS-1 System to the Application Stage

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\(^3\)Dept. of Civil and Environ. Engineering, University of Alberta, Edmonton, Alberta

1. Objectives

The work proposed for this project is to bring the integrated MAGS-1 hydrologic modelling system to the application stage. This will involve model improvements, primarily to WATFLOOD and WATCLASS to reflect the experience gained in MAGS-1, and will include a validation program. The end result will be a robust system to serve both ends of the scale spectrum, producing improved fluxes to the atmosphere as well as output in support of water resources application work.

2. Progress

2.1 Model Revisions

These tasks are aimed at building an operational version of the MAGS-1 modelling system. One of the primary results will be an open interface for land surface schemes that will enable the code developed for both MAGS-1 and MAGS-2 to be placed in the public domain. The code for WATCLASS is now complete and ready for distribution.

Integration of Process Studies

MAGS-1 water balance studies identified several shortcomings in our process algorithms, most likely in the representations of snow sublimation, infiltration into frozen ground, and wetland routing in the model. Research basin data and simulations using WATFLOOD and WATFLOOD/CLASS are being used to refine the parameterizations for these and other processes. For example, Marsh has tested WATFLOOD and WATCLASS on Trail Valley Creek.

Code Update

To facilitate testing and application work, the model code needs revision. The current version reflects its experimental nature. For example, the mosaic approach is simulated using multiple subroutine calls, much of the FORTRAN code does not conform to current programming standards, and the file handling is inadequate for large databases. Further work will be required to incorporate CLASS 3.0.
Land surface scheme testing

This task is in the early stages. Work is continuing on the soil moisture parameterization using the BOREAS data set.

2.2 Validation Simulation Tests

The model system has been using the study validation data sets collected in MAGS-1. However, the ultimate test will be its performance on an independent data set. Within the next few years, we will be involved in exchanges with other Continental Scale Experiments (CSE’s), most likely BALTEX and GAMES. In the meantime, we will establish test data sets for the Saskatchewan and Great Lakes basins in Canada. This work will begin in 2002.

2.3 Validation of Data Sets - Basin Storage Estimation

One of the lessons learned from MAGS-1 is the importance of basin storage. This can often be safely ignored in southern watersheds but, in the case of the Mackenzie, year-over-year change in storage can be as much as 40 or 50 millimeters or about 25% of the mean annual run-off. This is the range of the closure error in both the hydrologic and atmospheric models. Thus it is important that we develop independent measures of basin storage to verify model values.

Basin storage is probably impossible to measure. However, it may be some function of measurable basin state variables. Time series of model storage will be generated for the simulation period (beginning November, 1993) over a test portion of the basin that includes the research watersheds. These will be compared to observable watershed surface characteristics, such as total open water area, flooded/wetland area, lake/wetland elevation and the extent of soil saturated areas (also known as run-off contributing areas). Data from the following sensors will be examined as potential sources for these data: RadarSat, ERS-2, Landsat, Terra MODIS SSM/I (DMSP), and AMSR (ADEOS-II). This will be in collaboration with Pultz.

We also propose to develop a monthly time series of basin storage. This will be our best estimate of the distributed water balance based solely on precipitation, temperature, and streamflow observations linked by a simple monthly water balance model. We will use gridded precipitation and temperature data generated by Louie. This work is in the early stages.

2.4 Water Resource Application Studies - High and Low Event Assessment

We will augment the MAGS-1 focus on monthly or daily water balances with studies of other dimensions of the hydrologic regime important for water resource applications, such as the probability of extreme hydrologic events and the spatial variability of run-off. By the end of MAGS-2, over 10 years of simulation results will be available. The statistics of streamflow generated from both CMC operational data and GCM-III output will be compared with the measured values at about 20 key stations in the basin. Differences will be used both to identify model shortcomings and to develop procedures to adjust GCM-III scenario results. This work has begun.
3. Results

The key contributions are the delivery of WATCLASS to several investigators, and the delivery of gridded atmospheric data sets for watershed modelling. Scientific contributions include an update of the Mackenzie monthly water balance (Figures 1 and 2) and the continued development of soil moisture water budget parameterizations (Figure 3).

Figure 1: WATFLOOD results, calibrated using 3 sub-watersheds (Peace, Athabasca, Liard) and 3 land classes (Forest, Water, Other) for 2 years (1995-1996). The heavy line is measured and the light line is simulated.
Figure 2: Comparison of atmospheric water budget and hydrologic water budget. Net annual difference in water budget is approaching zero.

Figure 3: Soil moisture budget parameterization sensitivity. Lower pair of hydrographs for NW1 reflect improved match between measured and simulated hydrographs.
4. Relevance

This work is an essential part of the integrated modelling work.

5. Networking and Collaboration

In addition to the items mentioned above, members of the team have participated in all MAGS workshops. We also worked with an M.Sc. student, supervised by H. Leighton, from McGill University.

6. Summary

There are two major benefits to MAGS. The first is the improved understanding of the role of the Mackenzie in the global climate system, which will advance both the Canadian numerical weather prediction and climate simulation capabilities. The second is better definition of the current and future climate scenarios in the basin in order to anticipate social and environmental consequences.

The tools necessary to reap these benefits are the same, despite the fact that the relevant scales are far apart. This is because predicting the large-scale response of the atmosphere, which is an integration of small-scale phenomena, and the local environmental response to atmospheric stimuli, which can vary widely in short distances, requires the same level of detail.

One of the roles of hydrologic models in MAGS is to provide the connection between the two scales. To this end, the goal of MAGS-1 was to start with a framework for connecting the local land surface schemes to the atmospheric models. Most of the activity was concerned with closing the atmospheric water balance. A system based on the linking of the three primary models (RCM, CLASS, and WATFLOOD) was developed, has been successfully tested, and has been able to simulate the outflow of the Mackenzie River system. Most of the interface and database issues have been resolved and many of the results of the process studies have been implemented.

The work proposed for MAGS-2 is to bring the prototype system to the application stage. This will involve model improvements to reflect the experience gained in MAGS-1, a validation program, and the development of interpretative tools for water resource applications. The end result will be a robust system that will serve both ends of the scale spectrum, producing improved fluxes to the atmosphere, as well as output in support of application work.
7. Publications

Refereed Publications


Soulis, E.D., K.R. Snelgrove, N. Kouwen, F.R. Seglenieks and D.L. Verseghy, 2000a: Toward closing the vertical water balance in Canadian atmospheric models: Coupling of the land surface scheme CLASS with the distributed hydrological model WATFLOOD. Atmosphere-Ocean 38: 251-269


Other Refereed Contributions


Non-refereed Contributions


–◊◊◊–
E. REMOTE SENSING STUDIES
Evaluation of Eco-Sensitive Operational Strategies for the WAC Bennett Dam Relative to Hydro-Climatic Relationships affecting Northern Deltas

A. Pietroniro¹, M. Conly², M. Mackay³, E.D. Soulis⁴, N. Kouwen⁴, R. Leconte⁵, J. Bullas²
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⁷University of Saskatchewan, Saskatoon, Saskatchewan
⁸Trent University, Peterborough, Ontario

1. Objectives

Global warming is expected to modify the flow regimes in the upper reaches of the Mackenzie basin. The overall objective of the study is to identify and assess changes to the hydrological regime of the Peace-Athabasca Delta (PAD) as influenced by changing climatic conditions and the WAC Bennett Dam. This objective can be achieved through appropriate calibration and validation of hydrological and hydraulic models. These models are forced with observed and modelled meteorological variables. In our case, GCM and RCM model outputs were assessed as potential forcing variables.

This project is closely linked with another MAGS-2 project: “Climate impacts on ice-jam floods in northern rivers with specific focus on the hydroelectric industry in western Canada”.

2. Progress

Development of Database

A comprehensive database was developed for use in the numerical model calibration, and in prediction of climate-change impacts of flow hydrographs and water levels in the PAD. This includes data required for WATFLOOD simulations and involves:

- using GCM output data from six different models for assessment of utility in driving WATFLOOD;
- operationalizing the WATFLOOD model for both the Peace and Athabasca Rivers. This requires projecting the database to match the RCM grid structure and generating the physiographic files required for WATFLOOD; and
- testing the application of the 1-D hydrodynamic model.
Data Analysis and Interpretation

Data analysis and interpretation is advancing on several sub-projects, including:
- assessment of WATFLOOD model requirements for implementation on Peace River basin, and suitability of using GCM/RCM output to drive the model;
- testing of the WATFLOOD model with RCM runs for 1994/95; and
- testing of the 1-D hydrodynamic model.

3. Results

The modelling framework for this study was established and is depicted below in Figure 1. The results presented are a summary of the last two years of work on this project.

Once this framework was established, a number of model considerations were taken into account. The Environment Canada 1-D hydrodynamic model was modified to accommodate changing lake levels in the PAD. (R. Leconte began this during his sabbatical at National Water Research Institute in 1999 and D.L. Peters has continued the model testing.) The modified boundaries are depicted in Figure 2 below, along with calibration and validation model runs.
The 1-D model has been calibrated and validated to simulate the 1996 flood. Results from this work were published in 2000 (Leconte et al., 2000). Remote sensing imagery is also being used to validate the flooding extents (levels) simulated with the 1-D model. Algorithms for deriving flood-extent from Radarsat and SPOT imagery are being used to assess the hydrodynamic model performance and improve the representation of the model cross-sections.

Simultaneous to this work, the WATFLOOD model was operationalized to match the current RCM grid used in MAGS. Physiographic information (land cover and elevation/slope) was derived from the CCRS-2 land cover map that was chosen by Pietroniro and Soulis (2001) as the best representation of the land cover in the Mackenzie. A Digital Elevation Model (DEM) derived from 1:250 000 contour maps was used to derive a 100 m DEM for the basin. A total of 73 map sheets (Figure 3) were collated and edited in order to derive the proper drainage network.
The final DEM was edited to compensate for problems with the original digital map sheets. TOPAZ was used to establish drainage boundaries and flow directions. The results yielded the necessary information to build the physiographic database for WATFLOOD as shown in Figure 4.

Figure 4: WATFLOOD physiographic files.
WATFLOOD was used to simulate the 1994/95 Water Year and provide the model boundary conditions required to run the 1-D model. This proof-of-concept is now complete and we are currently assessing and running the model with historic RCM simulations (see Figure 5). We expect that the results from these simulations will be complete by the end of this fiscal year.

Figure 5: Boundary conditions for the Peace Athabasca Delta derived from WATFLOOD.

4. Relevance

This research contributes directly to MAGS by providing calibration and validation of WATFLOOD and testing forcing of this model with the RCM and other potential numerical weather data sources. The modelling framework developed for MAGS is being followed here and provides what was referred to as “level 0” testing of hydrological/atmospheric models.

5. Summary

The successful implementation of this project required operationalizing of the WATFLOOD model, which is complete. The generation of DEM for physiographic inputs was successfully achieved, and an automated data extraction method was tested for use with WATFLOOD (and WATCLASS). The database conforms to the current MAGS RCM projection. GCM data was assessed for suitability as a forcing variable; precipitation was shown to be poorly simulated. The RCM 1994/95 Water Year run was used to force the WATFLOOD model, showing reasonable simulations and providing the important boundary conditions for the 1-D hydrodynamic model.
6. **Recent Publications**


1. Introduction

Evapotranspiration (ET) is an important component in the hydrological cycle and in the surface energy budget affecting local and global climate. ET is also closely related to plant growth and carbon uptake. ET over large areas at landscape and continent scales was traditionally estimated by relating ET with meteorological variables (Willmott et al., 1985; Potter et al., 1993). Recently, process models have been developed to quantify the spatial distribution of ET. Examples of these models include the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson, 1984) and the Simple Biosphere Model (SiB) (Sellers et al., 1986) at the global scale; the Regional Hydroecological Simulation System (REHESYS) (Band et al., 1991) and the FOREST biogeochemical cycles (FOREST-BGC) (Running et al., 1989) at the landscape scale.

In this study, the spatial distribution of ET over Canada’s landmass is estimated with a process model, the Boreal Ecosystem Productivity Simulator (BEPS) (Liu et al., 1997, 2001). The model was originally developed to simulate carbon uptake by vegetation. Because carbon uptake by plants is closely linked with the water regime, ET simulation is evidently the necessary component of the model. Land cover (Cihlar et al., 1999) and leaf-area index (LAI) (Chen et al., 2001) maps derived from AVHRR satellite images at 1 km resolution are the two key inputs for the model to enable spatially explicit ET calculations.

This study is a continuation of our earlier work (Liu et al., 1997, 1999a). It is also an integral part of our effort of estimating the carbon cycle of Canada’s landmass (Liu et al., 2001; Chen et al., 2000). The work was also stimulated by requests from Federal government agencies for quantitative information on Canada-wide spatial distribution of ET. This information is useful for assessing Canada’s water resources for agriculture, water transportation, etc., and for estimating the impact of climate change.

In this extended abstract, we will briefly describe our methodology and provide a summary of our results. More detailed description of the results and uncertainty analysis will be done in subsequent papers.

2. Methodology

Evapotranspiration Calculation in BEPS

BEPS calculates ET in daily time steps and produces an annual total ET for each pixel in an image. In consideration of Canada’s large forested and permafrost areas and long winter seasons,
transpiration from understory vegetation in forests and sublimation of snow and ice are taken into account, in addition to other common ET components. The complete ET estimation in BEPS is the sum of the following components:

\[
ET = T_{\text{plant}} + T_{\text{under}} + E_{\text{plant}} + E_{\text{soil}} + S_{\text{plant}} + S_{\text{ground}}
\]  

(1)

where \( T_{\text{plant}} \) is transpiration from plants, or overstory plants (trees) for forested areas. \( T_{\text{under}} \) is transpiration of understory in forests. It is zero for non-forest cover types. \( E_{\text{plant}} \) and \( S_{\text{plant}} \) are evaporation and sublimation from plants (or overstory for forested areas), respectively. \( E_{\text{soil}} \) is evaporation from soil. \( S_{\text{ground}} \) is sublimation from the snow and ice on the ground.

Among all the components, \( T_{\text{plant}} \) is the dominant component in vegetated areas. The Penman-Monteith equation (Monteith, 1965) has been widely accepted to describe this process at an instant of time for per unit leaf surface area, i.e.:

\[
T_{\text{plant}} = \left( \frac{\Delta R_n + \rho c_p VPD / r_a}{\Delta + \gamma (1 + r_s / r_a)} \right) / \lambda_v
\]  

(2)

where \( R_n \) is the net absorbed radiation in W m\(^{-2}\); \( \Delta \) is the rate of change of saturated water vapour pressure with temperature in mbar \(^{\circ}\)C\(^{-1}\); \( \rho \) is the density of air (=1.225 kg m\(^{-3}\) at 15 \(^{\circ}\)C); \( c_p \) is the specific heat of air at constant temperature (=1010 J kg\(^{-1}\) \(^{\circ}\)C\(^{-1}\)); \( VPD \) is the vapour pressure deficit in mbar; \( r_a \) is the aerodynamic resistance (fixed at 5.0 s m\(^{-1}\)); \( r_s \) is the surface resistance, or stomatal resistance, to water vapour; \( \gamma \) is the psychometric constant (=0.646+0.0006*\( T_a \) where \( T_a \) is the air temperature); \( \lambda_v \) is the latent heat of vaporization of water dependent on air temperature (=2.501-0.0024*\( T_a \))\(^{-1}\)\(^{10^6}\) in J kg\(^{-1}\)).

A convenient way of scaling up \( T_{\text{plant}} \) from leaf to canopy using the Penman-Monteith equation is to replace \( r_s \) with a canopy resistance. After the replacement, equation (2) becomes a 'big-leaf model'. Big-leaf models were found not suitable for estimating canopy photosynthesis, but were found adequate for ET estimation (Chen et al., 1999). However, big-leaf ET models need to be adjusted for variable canopy architecture between various vegetation types. Boreal forests are typically very clumped. To be consistent with the carbon component of BEPS, we developed a canopy ET model consisting of sunlit and shaded leaves. It can be simply described as follows:

\[
T_{\text{plant}} = T_{\text{sun}} L_{\text{sun}} + T_{\text{shade}} L_{\text{shade}}
\]  

(3)

where \( T \) represents transpiration from leaves, and \( L \) is the leaf-area index (LAI). The subscripts “sun” and “shade” denote the sunlit and shaded leaves. The equations for calculating \( L_{\text{sun}} \) and \( L_{\text{shade}} \) as well as radiation balance on sunlit and shaded leaves can be found in Chen et al. (1999).

The Penman-Monteith equation is also used for estimating transpiration from the understory. Understory LAI is derived from the overstory LAI using an empirical equation based on field measurements in Saskatchewan and Manitoba.
Evaporation and sublimation from plants are dependent on the intercepted precipitation (rain or snow) by plants and available energy to convert the solid or liquid water to vapour. The former is simply assumed to be proportional to leaf-area index \((L)\), constrained by precipitation, i.e.:

\[
P_{\text{int}} = \min (L b_{\text{int}}, \text{Precipitation})
\]

(4)

where \(b_{\text{int}}\) is a precipitation interception coefficient; the function \(\min\) takes the minimum of the two outputs. When air temperature is above zero, evaporation occurs. Otherwise, sublimation takes place. Therefore, the following equations are used to estimate evaporation and sublimation, respectively:

\[
E_{\text{plant}} = \min \left( \frac{R_{\text{int}} b_{\text{abs\_water}}}{\lambda_v}, P_{\text{int}} \right)
\]

(5)

\[
S_{\text{plant}} = \min \left( \frac{R_{\text{int}} b_{\text{abs\_snow}}}{\lambda_s}, P_{\text{int}} \right)
\]

(6)

where \(R_{\text{int}}\) is the intercepted daily solar radiation in J m\(^{-2}\) day\(^{-1}\); \(b_{\text{abs\_water}}\) is the water absorptivity to solar radiation. \(b_{\text{abs\_snow}}\) is the snow absorptivity to solar radiation. \(\lambda_v\) is the latent heat of vaporization (= \(2.5 \times 10^6\) J kg\(^{-1}\) at 0 °C); \(\lambda_s\) is the latent heat of sublimation (= \(2.8 \times 10^6\) J kg\(^{-1}\) at 0 °C).

Evaporation from soil is estimated with the Penman-Monteith equation for the areas not covered by snow, whereas evaporation in snow-covered areas is set to zero. The radiation input in the equation is the residual of incoming radiation from the atmosphere minus absorbed radiation by vegetation. The soil resistance to vapour serves as the surface resistance.

If snow pack exists on the ground, sublimation from snow is equal to the available energy to sublimate the existing snow, i.e.:

\[
S_{\text{ground}} = \min (\text{snow}, \frac{(R - R_{\text{int}}) b_{\text{abs\_snow}}}{\lambda_s})
\]

(7)

where \(\text{snow}\) is in water equivalent (mm); \(R\) is the daily total incoming radiation from the atmosphere in J m\(^{-2}\) day\(^{-1}\); \(b_{\text{abs\_snow}}\) is snow absorptivity to solar radiation.

**Model Tests with Tower Flux Measurements**

The measurements of water vapour flux using the eddy co-variance technique during the Boreal Ecosystem-Atmosphere Study (BOREAS) experiment (Sellers et al., 1995) provide a database for validation of the model. The half-hourly flux data were extracted and summed to daily totals at three tower flux sites for a whole year. The sites include a mature aspen site (53.629 °N, 106.20 °W) in the Prince Albert National Park, Saskatchewan; a mature black spruce site (55.879 °N, 98.48 °W) near Thompson, Manitoba; and a mature black spruce site (53.895 °N, 105.12 °W) near Candle Lake, Saskatchewan. If available at the sites, meteorological data, including radiation, air temperature, humidity and precipitation, were also extracted and processed for daily values. Missing data were supplemented with the meteorological data generated by NCAR (National Center for Atmospheric Research, USA).
ET Mapping Over Canadian Landmass

To execute the model over the Canadian landmass, spatially explicit input data are prepared in a domain covering Canada with a 5700 pixel by 4800 line at 1 km resolution. The domain is in a Lambert Conformal Conic (LCC) projection (49 and 77 °N standard parallels, 95 °W meridian). All input data are processed into this resolution and projection before or during model execution. These data include landcover, LAI, soil water available holding capacity (AWC), and daily meteorological data. Table 1 provides a list of the sources and original formats of input data. Detailed description is available in Liu et al. (1999b, 2001).

Table 1: Input data sources and original formats.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>Agency</th>
<th>Data Type</th>
<th>Grid System</th>
<th>Temporal Interval</th>
<th>Grid Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAI</td>
<td>AVHRR¹</td>
<td>CCRS³</td>
<td>Raster</td>
<td>Pixel/Line</td>
<td>10 days</td>
<td>1 km</td>
</tr>
<tr>
<td>Land cover</td>
<td>AVHRR¹</td>
<td>CCRS³</td>
<td>Raster</td>
<td>Pixel/Line</td>
<td>Annual</td>
<td>1 km</td>
</tr>
<tr>
<td>AWC</td>
<td>SLC²</td>
<td>CLBRR⁴</td>
<td>Vector</td>
<td>Long term</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>The NMC</td>
<td>NCAR⁵</td>
<td>Raster</td>
<td>Gaussian</td>
<td>Daily</td>
<td>~0.9 degree (varied with lat./long)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Medium Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity</td>
<td>Forecast Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Advanced Very High Resolution Radiometer  
²Soil Landscapes of Canada  
³Canada Centre for Remote Sensing, Natural Resources Canada  
⁴Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada  
⁵National Center for Atmospheric Research, USA

Daily radiation, temperature, and precipitation in the NCAR dataset were compared with measurements made at up to 60 stations over Canada, with over 5000 daily samples for each parameter. As found in a previous study (Liu et al., 1997), daily total radiation in the NCAR data was generally 30-40% higher than in the station data, mainly because of the neglect of radiation absorption by aerosols in the models that produced the NCAR dataset. This systematic difference is corrected in BEPS using a coefficient of 0.62 for 1994. The observed daily mean temperatures agreed well with the NCAR data with a correlation coefficient of 0.93. The daily difference between the observed and NCAR precipitation was large, with a root mean square error of 5.3 mm/day. However, the difference in annual precipitation between the stations and NCAR data was much smaller. At most stations where precipitation was less than 1500 mm yr⁻¹, the two datasets were close to each other (nearly a 1:1 line) with a R² value of 0.71 and root mean square error of 327 mm/yr. In the extreme cases of precipitation over 1500 mm yr⁻¹, there were 8 stations where NCAR values were 50-100% over or below the observed values.
With the input data, BEPS was run at daily steps in a spatially explicit mode for every 1 x 1 km pixel over the entire country for the year of 1994.

3. Results and Discussion

The modelled daily values of ET for the three sites were compared with tower H2O flux measurements (Figure 1). The model was able to follow closely the seasonal variation patterns and many pronounced drying events (not shown) at these sites, and it can capture about 60% of the variance in the measurements \((R^2=0.61)\). In daily step calculations, extreme sub-daily processes cannot be modelled well. Further improvements can be made by reducing the time step to hourly; but computationally it is not yet feasible for Canada-wide image calculations, and gridded hourly data are also not available. However, the uncertainty in the annual total ET values at these sites is much less than the daily ET values.

![Comparison of measured and modelled daily evapotranspiration (ET) in two black spruce and one aspen forest stand.](image)

The spatial distribution of ET over Canada in 1994 is shown in Figure 2. High ET values are associated with mixed or deciduous forests. Low ET values, as expected, appeared at high latitudes and high altitudes. Annual statistics show that the mean ET over the land pixels was about 42% of the precipitation. The precipitation was 517 mm for 1994 from the NCAR data (Figure 3). As a national mean, the understory in forests contributed about 10% to the total transpiration. Sublimation in winter accounted for 10-20% of evaporation. In annual totals for all Canada (excluding open water bodies), it is estimated that about 2000 \(\text{km}^3\) of water was vaporized, compared with about 4500 \(\text{km}^3\) of precipitation.
Figure 2: Canada-wide spatial distribution of evapotranspiration in 1994 at 1 km resolution, simulated with BEPS. Input data include AVHRR images, gridded daily meteorological data and soil data.
Figure 3: Annual statistics of modelled evapotranspiration and its components over Canadian landmass. Open water bodies are not included.

Compared with previous studies of regional and global ET, we have made the following progress: (1) the computation of ET at 1 km resolution was made possible through the use of remote sensing data; (2) the influence of forest type, density and canopy architecture on canopy radiation absorption and ET has been considered; (3) contribution of understory to ET is explicitly modelled; and (4) evaporation and sublimation of intercepted rainfall and snowfall have been included through the use of simple equations. However, many components and input data sets need to be improved. They include: (1) estimation of snow interception and sublimation of snow on trees; (2) sublimation of snow and ice at high altitudes and high latitudes; (3) downscaling of coarse resolution meteorological data to 1 km resolution, especially the influence of topography on downscaling of precipitation; and (4) heterogeneity with 1 km pixels. It is also highly desirable to have more tower measurements for map validation.

4. Acknowledgements

The authors wish to thank T.A. Black of the University of British Columbia, P.J. Jarvis of University of Edinburgh, and M. Goulden of the University of California at Irvine for permission to use the tower flux data.

5. References


1. Objectives

- To estimate ecosystem evapotranspiration (ET) at 1-km resolution in recent years over the Mackenzie River Basin (MRB);
- To model the soil moisture and thermal dynamics in recent years over the MRB;
- To investigate the changes of ET and soil moisture and thermal dynamics since 1900 over the MRB; and
- To develop satellite-derived data of biophysical parameters (e.g., land cover, leaf-area index) to support the above activities and other MAGS-2 studies.

2. Progress

- We finished a Canada-wide 1-km water-body coverage map from National Topographic Data Base (NTDB); and
- We have developed a model for simulating long-term soil temperature changes and soil thaw depth. Using this model, we produced the first Canada-wide map of annual maximum permafrost thaw depth, and its temporal changes during the 20th century.

3. Results

Figure 1 shows the water-body coverage. This product is a raster coverage representing the fraction of area within each 1-km grid cell over Canada's land mass covered by water bodies as mapped within the NTDB v3.1. The product involves negligible aggregation and data format conversion errors with respect to NTDB digital base maps used in its generation. As such, any errors between mapped and actual water fractions are due to differences between the NTDB source maps and the actual water body coverage in a grid cell. Since water area fluctuates seasonally and inter-annually, one should use caution in applying this product for local mapping and modelling purposes. At a minimum, one should verify that the survey dates of the source NTDB maps are recent. Furthermore, some consideration of seasonal shifts in water-body extents should be applied. At regional and national scales we expect that seasonal fluctuations in water-body extent are the major uncertainty. The majority of NTDB source maps were surveyed within the post-snowmelt growing season and should therefore be relatively unbiased during the growing season in the absence of drought or severe precipitation events.
Figure 1: Canada-wide 1-km water-body coverage from National Topographic Data Base Maps.

Figure 2 shows the spatial distribution of the changes of annual mean soil temperature at depth 20 cm from the decade 1901-1910 to the decade 1986-1995. Over the 20th century, annual soil temperature increased by 3°C in areas centered in the Prairie Provinces and Yukon Territory. In contrast, a cooling of up to 1°C has occurred in areas around Hudson Bay and Labrador. Averaged over all grid cells, annual mean soil temperature at 20 cm depth increased by about 0.6°C during 1901-1995. That is about half of the air temperature increase (1°C) during the same period. The inter-annual variation of soil temperature was also about half that of air temperature. Soil temperature was higher during the 1940s and in recent years.
Corresponding to the changes in soil temperature, the maximum thaw depth change over the 20th century had its largest increases, of up to 20 cm, in the Prairie Provinces and Yukon Territory (Figure 3). In some areas around Hudson Bay and Labrador, we found a reduction in the annual maximum thaw depth by up to 20 cm. To verify the results, we compared the simulated monthly mean soil temperature against measured values at the Ottawa climate station (45.4°N, 75.7°W), Mould Bay climate station (76.2°N, 119.3°W), BOREAS northern old jack pine (NOJ, 55.92°N, 98.62°W) site, and BOREAS southern old jack pine (SOJ, 53.79°N, 104.62°W) site. Overall, the simulated soil temperature agrees closely with the measurements, with $r^2 > 0.9$ at all depths at the 4 sites. We also compared point-measured soil thaw depth with our estimates. Our results are well within the range of these measurements, although strict comparison is not possible due to the difference in spatial scale.
Figure 3: Spatial distribution of the changes of annual maximum thaw depth from the decade 1901-1910 to the decade 1986-1995.

4. Relevance

- Distribution of water bodies is a key input to regional water cycle modelling and integration as identified by the MAGS Scaling Workshop (Szeto et al., 2001, Workshop Report).
- While MAGS-2 projects are mainly focused on current conditions, our simulation results of long-term soil temperature and thaw depth over the 20th century add a temporal dimension and will help put the MAGS results in a historical perspective.
5. Networking and Collaboration

- Attended the MAGS Integration Workshop (Montreal); and
- Visited Canadian Meteorological Centre (CMC). Collaboratively, CMC and CCRS will produce better-gridded meteorological data sets, which are crucial for water and ecological researches.

6. Summary

The CCRS team of W. Chen et al. has finished a Canada-wide 1-km water-body coverage from NTDB maps. Distribution of water bodies is a key input to regional water cycle modelling and integration, as identified by the MAGS Scaling Workshop (Szeto et al., 2001, Workshop Report). The team also developed a model for simulating long-term soil temperature changes and soil thaw depth. Using this model, the first Canada-wide map of annual maximum permafrost thaw depth, and its temporal changes during the 20th century was produced. While MAGS-2 projects are mainly focused on current conditions, the long-term soil temperature and thaw depth simulation results over the 20th century add a temporal dimension and help put the MAGS results in a historical perspective.

7. Publications


The Use of Thermal AVHRR Data for MAGS Energy and Water Studies

N. Bussières

Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario

1. Introduction

During MAGS-1, AVHRR-based quantitative data and products were used as tools to help understand components of the water and energy cycle in studies of the Mackenzie River Basin (MRB) 1994-95 Water Year. Initial work focused on the development of an AVHRR database and its application to evapotranspiration, and in particular in evaluating the spatial variability of evapotranspiration over the MRB. A map of 1994 maximum land surface temperature (LST) (Bussières, 2001a) served to make initial inferences on the spatial distribution of the energy and water cycle from the spatial variation in elevation, latitude, land surface type, soil moisture and lake water distribution. This also revealed the importance of the lake water and wetlands in some of the remote regions where conventional observational network data is not collected. Solar radiation budget estimates made by Leighton were compared with RCM model outputs. As MAGS-1 was completing, it was realized that the scope of applications of AVHRR data should include initialization and validation data for coupled models used in MAGS to study the water and energy cycles. The ever-increasing resolution of the earth-atmosphere models makes the 1-km resolution AVHRR data even more attractive. During CAGES (1998-99), a 16-month AVHRR database was developed to expand the above-cited research.

2. Objectives

The following goals can be set with MAGS-2:

• develop time series of water temperatures for the 8900 water bodies of size larger than 1km², following a method proposed by Bussières et al. (2001a). The time series is to be used jointly with MAGS investigators engaged in quantifying the role of lakes and surface moisture in the MRB water and energy cycle;

• continue previous work on the estimation of land surface temperature in relation to elevation, latitude, land surface type, soil moisture and lake water distribution. Knowledge of these fields and their variability impacts on the resulting aggregated data sets used in model initialization. Work can be expanded to evaluate the land surface temperature maps produced by TERRA/MODIS. This methodology can be applied to comparative studies with other basins (e.g. GAME-Siberia);

• update documentation on the WEB and increase the accessibility and usability of the CAGES data set;

• increase synergetic use of MAGS data with other researchers and participate in joint publications; and

• prepare and give training to researchers on the spatial variability and interrelation of elevation, land cover, lakes and temperatures over the basin.
3. Methodology

The AVHRR data which have been collected for MAGS are combined with other types of data, using various satellite and data analysis software tools at the Climate Research Branch of the Meteorological Service of Canada (MSC) in Downsview, Ontario. Main methods are described in publications (see list below). Production is continuous and oriented towards preparing and sharing data and analysis, as well as reporting to MAGS meetings and in scientific journals. The World Wide Web is the main information exchange tool with MAGS investigators.

4. Networking

Related types of work with 1-km resolution data, including AVHRR-based land cover data are expected to continue under the leadership of Diana Verseghy’s group proposal on the RCM/CLASS/WATFLOOD modelling effort. Collaboration and sharing of data exists and will continue with other MAGS investigators (Granger, Leighton, Oswald, Schertzer, Schuepp, Stewart). It is planned to extend this collaboration to Duguay (lake ice) and Yau (high resolution modelling). An outside network is developing gradually in relation with GAME-Siberia (Hirota).

5. Recent Publications/Conference Papers


Snow Cover and Lake Ice Determination in the MAGS Region
Using Satellite Remote Sensing and Conventional Data

Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario

1. Objectives

This investigation is a continuation of our MAGS-1 research work. The main goal is to improve our capability to characterize the spatial and temporal variability of snow cover, especially snow water equivalent (SWE), over the MAGS region, with particular emphasis on the use of new satellite sensors (e.g. EOS platforms) that are planned for launch within the MAGS-2 time frame. The new microwave radiometer AMSR will be launched on both the Japanese ADEOS-II satellite and the NASA EOS-PM satellite (currently planned for early 2002), and will offer enhanced spatial resolution (10 km vs. 25 km) when compared with the current DMSP SSM/I sensor. This enhancement may provide the opportunity to investigate the retrieval of snow cover information in areas of the basin with complex topography, as well as improve retrieval capabilities in areas with heterogeneity in land cover types. The investigation of long term snow cover variability using conventional data is also continuing as part of this work, and the potential of integrating conventional and remote sensing data sets to provide an improved characterization of snow cover of the basin will be examined. Conventional data sets collected during MAGS-1 (e.g. research basins, CAGES) will also contribute to algorithm validation activities. The lake ice freeze-up and break-up time series will be extended with additional years of SSM/I data and the opportunity to extend the technique to smaller lakes will be examined with new sensors, such as AMSR and MODIS. The investigation of lake ice thickness retrieval capabilities using lower frequency data from AMSR will be a new research area.

2. Progress and Results

The MAGS-2 milestone identified for 2001 was the generation of a 20-year time series of passive microwave derived SWE using combined SSM/I (1988-1999) and SMMR (1979-1987) EASE-Grid data sets using the current CRB algorithms. A time series of SSM/I derived SWE for March 1 of each year from 1988 to 1998 was completed as a deliverable for MAGS-1. This time series and the methodology used to generate it were documented in a refereed journal paper that was accepted for publication in the Annals of Glaciology and is currently “in press” (See Section 6, below). This SWE time series represents our current capability to characterize the spatial and temporal characteristics of snow water equivalent distributions over the basin; validation is an ongoing activity. Although it is possible to derive an “average” SWE value for the basin for each date in the time series and investigate interannual variations, the underestimation of SWE in the mountainous areas of the basin has to be taken into consideration. The extension of the time series back to 1979 is currently in progress using SMMR EASE-Grid data sets that were recently distributed by the National Snow and Ice Data Center (NSIDC). This year’s research activities have focused on the background work necessary before generating such a time series. It is important to understand the effects on the performance of the CRB
algorithms in combining data records from 2 different satellite sensors and potential biases in derived SWE. This investigation has been initiated with a focus on the Prairie provinces and is being conducted in collaboration with CRYSYS research partners at the University of Waterloo.

The current SSM/I-derived lake ice freeze-up and break-up time series for Great Slave and Great Bear Lakes covers the years 1998-1999, related to the availability of SSM/I EASE-Grid data sets from NSIDC. The time series is being updated and extended as more recent EASE-Grid data sets become available. The current time series is composed of a series of images depicting 85 GHz brightness temperature distributions over the two lakes and thus the delineation of ice and open water areas. The investigation of an alternate method to identify the timing of ice formation and decay for these lakes using time series graphs of average SSM/I 37 and 85 GHz brightness temperatures was initiated a few years ago as a CRYSYS collaborative research investigation with the University of Waterloo (documented in an undergraduate thesis). A key result of this investigation was the capability to identify freeze-up and break-up events in the 37 GHz data, despite its coarser spatial resolution than the 85 GHz data. Based on this result, the timing of ice formation and decay over Bear and Slave is being investigated using 37 GHz data from the SMMR data record with the objective of producing a complementary data set to the current SSM/I time series and extending the information back to 1979.

3. Relevance

This investigation focuses on the use of remote sensing and conventional data to derive information on the spatial and temporal characteristics and variability of snow cover and lake ice over the Mackenzie basin. This work is of direct relevance to the MAGS-2 objectives, by providing information to improve the understanding of the energy and water cycles and especially the interaction of snow cover with the other components of the system. The satellite derived information/data sets can be used to address the issue of scaling of data and processes, and provides information for model development, input and validation. With the availability of more than 20 years of passive microwave satellite data, there is the opportunity to examine snow cover variability and its relationship with the behaviour of the whole system (esp. short term climate variations, e.g. El Niño) thus contributing to the MAGS-2 objective of developing a predictive capability for impacts on the climate-hydrological system.

4. Networking and Collaboration

Collaboration with other MAGS Investigators

- provision of satellite-derived snow cover and lake ice information to M.D. MacKay for use in RCM validation activities over the MAGS region, and co-authorship on a poster paper presented at the May, 2001 CGU Congress;
- provision of SSM/I lake ice research results to W. Schertzer as contribution to a joint oral presentation given by Schertzer on MAGS lake ice research at the MAGS/GAME-Siberia Workshop (October, 2001, Japan);
• discussion on lake ice remote sensing issues, strategies and collaborative opportunities with C. Duguay (as an extension of an already established CRYSYS collaboration); and
• participation in teleconference meetings led by R. Stewart on the development of a Canadian CEOP strategy (SAGE).

Other Collaborations Related to MAGS

• presentation of MAGS SSM/I SWE methodology and time series as an oral paper to the international cryosphere remote sensing community at the 4th International Symposium on Remote Sensing in Glaciology (sponsored by the International Glaciological Society); companion peer-reviewed paper accepted for publication in the Annals of Glaciology;
• provision of SSM/I derived SWE maps for the Snare River Basin (northeast of Great Slave Lake) to D. Grabke, NWT Power Corporation. Maps were provided on a weekly basis in near real-time during the 2001 spring snow melt season for use by NWT Power in monitoring the progression of melt over the basin and prediction of run-off;
• contributed information derived from the SSM/I Great Slave and Great Bear Lake ice freeze-up and break-up time series to the CCAF-funded investigation on “The State of the Arctic Cryosphere during the Extreme Warm Summer of 1998” (government and university collaborative project, coordinated by B. Alt, Balanced Environments Associates).

5. Summary

This investigation is focused on the use of remote sensing and conventional data to derive information on the spatial and temporal characteristics and variability of snow cover and lake ice over the Mackenzie basin. A key achievement during MAGS-1 was the development of satellite-derived SWE and lake ice freeze-up and break-up time series for the MAGS region, using a 10 year data record (1988-1998) of SSM/I passive microwave satellite data. During MAGS-2, research efforts are focused on improving the capabilities developed in MAGS-1, and extending the passive microwave time series backwards in time to 1979 with gridded SMMR data sets, as well as forwards with the launch of new sensors and satellites. These satellite-derived data sets provide a perspective on snow cover and lake ice variations over the basin on spatial and temporal time scales that is not possible with conventional measurements and provide important information for MAGS model development and validation, scaling and processes research.

6. Publications

F. REPORTS AND COMMENTS
GEWEX and MAGS

Ron Stewart
Chair, GEWEX Hydrometeorology Panel

GEWEX

GEWEX has recently updated its goals. It will now focus more on the global water cycle and its potential change, including the associated feedback processes. The need to relate such issues to water resources continues to be a critical issue.

GEWEX Hydrometeorology Panel

The GEWEX Hydrometeorology Panel (GHP) is one of the three GEWEX panels. GHP is concerned with demonstrating improved capability to predict water-related parameters on time scales up to annual or so. It is expected that the Murray-Darling basin of Australia will soon be accepted as a new GHP focal point to join the existing continental-scale experiments including MAGS. Less detailed efforts over Africa and the La Plata basin of Argentina are being developed as well.

GHP's strategy for achieving its objectives has recently been updated and a summary of it will soon be added to its web site. The strategy includes the quantification of key water and energy variables, the closing of water and energy budgets, the identification of water-related parameters important to the user community, the demonstration of improved predictive capability for these parameters, and the development of a legacy for others who follow.

MAGS and the International Effort

MAGS is contributing to the global effort by:
- focusing its research on a particular climatic regime
- producing unique datasets

MAGS needs to make greater use of:
- global datasets
- global model products

MAGS also needs to increase its interactions with global efforts such as:
- water and energy budgets
- data management
- transferability from and to other regions
- water-related parameter prediction
- interactions with users
- CEOP (Coordinated Enhanced Observing Period) of 2002-04
Such greater use of international products as well as such interactions will assist MAGS in realizing its objectives and they will also demonstrate that MAGS is contributing to the global effort. For example, MAGS may wish to consider the development of comprehensive datasets that will serve as benchmarks for others who wish to test their capability to simulate a northern regional climate system.

–☆☆☆–
Progress and Activities of the Mackenzie GEWEX Study

Lawrence W. Martz
Chair, MAGS Scientific Committee

In reflecting on the past year, it is clear that our activities were dominated by the transition from Phase 1 to Phase 2. This has required a number of specific activities to be completed in 2001. These included:

- Staffing the MAGS-2 Secretariat with the hiring of a network manager (Peter di Cenzo), an information manager (Robert Crawford), and a financial manager (Joan Parker)
- Formulation of a new Scientific Committee (SC), Management Board (MB) and International Advisory Panel (IAP)
- The integration of new scientific partners such as the Canada Centre for Remote Sensing (CCRS)
- Enhancing our capability for networking among participating scientists and with the larger community
- The development of new planning and coordination mechanisms

An important new development in the past year was the initiation of thematic workshops to focus on specific scientific activity areas. Two thematic workshops were held in the past year to discuss issues around process integration and scaling. These are summarized below.

Theme I (Process Integration) Workshop

- Time and Place: Montreal – March 23, 2001
- Organizing Committee: Wayne Rouse, Charles Lin, Philip Marsh
- Purpose:
  - Discuss state of modelling capability and process studies at MAGS-1 to 2 transition
  - Explore mechanisms for integrating processes, data and models
- Attendance: 38 participants (11 presenters)
- Visiting contingent from UQAM-CRCM research group
  - Discussion of UQAM and MSC roles in model development and use
  - Briefing on model physics and run archives available through UQAM
- Major discussion points
  - Coupled vs. linked models
  - To be incorporated into MAGS models
    - Infiltration into frozen ground
    - Permafrost
    - River ice jams
    - Wetlands and lakes
    - Sublimation of blowing snow
  - Importance of scale
    - Observations and remote sensing data
    - Parametric representation of processes
  - The nature of modelling
    - “Acceptable” levels of error
    - Springboard to future models
• Scientific questions that need to be addressed
  ➢ What physics must be incorporated into models?
  ➢ Are data sets adequate for verification?
  ➢ Utility of case studies (CAGES etc.)?

**Theme II (Scaling) Workshop**

• Time and Place: Yellowknife – June 14-15, 2001
• Organizing committee: Kit Szeto, Al Pietroniro, Lawrence Martz
• Scientific workshop, field trip, and outreach activities
• Scientific objectives:
  ➢ Move forward the MAGS scaling theme
  ➢ Discuss strengths/weaknesses of scaling research
  ➢ Identify specific actions to meet scaling theme objectives
• Actions required
  ➢ Atmospheric studies
    - Large-scale influences on weather and fast climate in MRB
    - Numerical scaling experiments with RCM and MC2 for CAGES cases
    - Severe weather climatology incorporating lightning data
  ➢ Surface studies
    - Automate WATFLOOD parameterization
    - Large (i.e. resolvable) lakes interactions
    - Test a CLASS parameterization of small (i.e. not resolvable) lakes
    - Characterize and assess impact of sub-grid lake size frequency distribution
  ➢ Hydrologic studies
    - Apply atmospheric scaling experiment output to hydrologic models
    - Downscaling coarsely observed surface data including the potential use of statistical-dynamical approaches
    - Topological arrangements in modelling linkages of land-surface mosaic
  ➢ Other activities and outcomes
    - Seminar on models needed
    - Field trip: “Modellers in the Muskeg”
    - Outreach: community, industry, government
    - Application issues
      i  small-scale hydropower
      ii  river transport (ice season, water levels)
      iii  traditional lifestyle sustainability

Other significant highlights of the past year included:

• MAGS-1 synthesis article
  ➢ In progress
• MAGS 6th Scientific Workshop
  ➢ Saskatoon on 10-16 November 2000
  ➢ Focus on MAGS-1 completion and MAGS-2 initiation
• MAGS 1994-95 Water Year
  ➢ Special issue of *Atmosphere-Ocean* completed
- 2nd MAGS-GAME Workshop
  - Sapporo, Japan on 8-9 Oct 2001
  - Proceedings in production
- Saskatchewan GEWEX Experiment (SAGE)
  - Identified as internationally significant transferability study
  - Continuation of planning
- Canadian GEWEX Enhanced Study (CAGES)
  - Initiate special issue of the *Journal of Hydrometeorology*
  - on MAGS studies arising out of this special observation period
- Proof-of-concept of a coupled model application (SSPFF)
- Initial water budget closure at CSE scale

The year ahead holds a great deal of promise. Some planned activities include:

- Workshops and training seminars
  - CAGES and data management
  - Models training workshop
  - WEBS workshop
- MAGS scientific planning meeting (Mar 2002)
- Completion of the CAGES special issue of *Journal of Hydrometeorology*
- Development of a MAGS contribution to WEBS and CEOP international GEWEX projects
- Transferability studies
  - Continuing collaboration with BALTEX and GAPP
  - New MAGS model transferability study (SAGES)
- Outreach initiatives
  - A continuation of the northern school lecture tour and the integration of MAGS scientific results into northern school curricula is planned

The GEWEX Hydrometeorology Panel (GHP) has proposed a set of criteria for assessing the progress the various Continental Scale Experiments (CSE), of which MAGS is one, under its coordination. The scientific criteria for the assessment of CSE progress are presented in Table 1. Each criterion is rated as completed (C), progressing (Pr) or beginning (B). Italicized entries have been upgraded in the past year.

<table>
<thead>
<tr>
<th>Scientific criteria for CSE assessment.</th>
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<tbody>
<tr>
<td>Simulate the diurnal, seasonal, annual and interannual cycles.</td>
<td>Pr</td>
</tr>
<tr>
<td><em>Close water and energy budgets.</em></td>
<td>Pr</td>
</tr>
<tr>
<td><em>Determine and understand climate system variability and critical feedbacks.</em></td>
<td>Pr</td>
</tr>
<tr>
<td><em>Demonstrate improvements in predictions of water-related climate parameters.</em></td>
<td>Pr</td>
</tr>
<tr>
<td><em>Demonstrate the applicability of techniques and models to other regions.</em></td>
<td>B-Pr</td>
</tr>
</tbody>
</table>

The technical-logistical criteria are presented in Table 2. Each criterion is rated as functioning (F), initiating (I) or planned (P). Italicized entries have been upgraded in the past year.
Table 2: Technical-logistical criteria for CSE assessment.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Status</th>
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<tbody>
<tr>
<td>NWP centre atmospheric and surface data assimilation and estimates of hydro-meteorological properties.</td>
<td>F</td>
</tr>
<tr>
<td>Suitable atmospheric-hydrological models and numerical experimentation and climate change studies.</td>
<td>F</td>
</tr>
<tr>
<td><em>Mechanism for collecting and managing adequate hydrometeorological data sets.</em></td>
<td>F</td>
</tr>
<tr>
<td>Participate in the open international exchange of scientific information and data.</td>
<td>I-F</td>
</tr>
<tr>
<td>Interactions with water resource agencies and related groups to address the assessment of impacts on regional water resources.</td>
<td>I-F</td>
</tr>
<tr>
<td>Evaluation of GEWEX global data products</td>
<td>I</td>
</tr>
<tr>
<td>Contributions to CEOP and transferability databases.</td>
<td>P</td>
</tr>
</tbody>
</table>

It became a tradition through MAGS-1 for an annual statement to be prepared by the chair of the Scientific Committee summarizing activities and progress over the previous year. This has proven to be an excellent technique for focussing on critical issues and should continue through MAGS-2. Following is a summary statement for 2001.

**MAGS has successfully completed the transition to a second, 5-year phase.** This included such specific activities as focused integration and scaling workshops, the publication of special journal edition on the 94-95 water year, a synthesis article on MAGS-1 scientific achievements, and planning of a transferability test over the Saskatchewan River basin. MAGS is on target with regard to its overall scientific plan and is well-positioned to initiate the next phases of research in the scaling, integration and model development themes, and to support the international GEWEX effort.

I would like to thank the MAGS community for the opportunity to serve as the chair of the Scientific Committee through the final year of MAGS-1 and the first year of MAGS-2. It has been an exciting and gratifying experience, largely because of the outstanding individuals with whom I have worked. These include the members of the MAGS Secretariat, Scientific Committee, Management Board, Users’ Advisory Group and International Advisory Panel. I would like to extend a special thanks to those with whom I worked most closely - the principal investigators Ming-ko Woo and Wayne Rouse, and the Secretariat managers Geoff Strong and Peter di Cenzo.
MAGS Program

Ming-ko Woo
MAGS Program Leader

The Program

MAGS is a Partnership Program that consists of a number of projects. MAGS has its distinctive attributes which contribute greatly to its success.

MAGS Science Committee provides the direction for scientific research.
• Partners offer direct and in-kind support.
• Administrative body and MAGS secretariat facilitate scientific activities.
• Investigators, including scientists, students and technicians, carry out research along the general direction of MAGS but we emphasize the ‘grass-root’ approach in which investigators propose their projects for approval and are not ‘directed’ from the top down.

Maintaining Scientific Excellence

• MAGS has a definite science plan as detailed in the MAGS-2 Proposal approved in 2000 (contents of which can be viewed at our website); this we follow with some degree of flexibility to ensure that our studies are in the forefront of research.
• Regular internal and external reviews of our work will enable us to assess our strengths and weaknesses, gauge our progress and identify gaps in our research endeavour. The mid-term review of our Program will be in 2003 but we invite members of our International Advisory Panel and representatives from NSERC to our Annual Meetings to update them on our activities and seek their views on our effort.
• To facilitate interactions among investigators and to discuss particular major issues or themes of MAGS, workshops are organized in which scientific debates are encouraged. The thematic workshops proposed for 2002 include:
  (1) CAGES and Data Workshop to be held in Edmonton in March
  (2) Water and Energy Balance Study Workshop
  In addition, we shall have a Training Workshop and our Annual Meeting.
• For a cross-disciplinary Program like MAGS, investigators are exposed to subject areas outside their own disciplinary training and to facilitate scientific communication, a Training Seminar/Workshop on modelling is proposed for September 2002. A glossary of terms commonly used by the MAGS community is also being prepared.

Review of University Proposals

The Natural Sciences and Engineering Research Council (NSERC) has entrusted the Science Committee to conduct annual reviews of the university proposals and to recommend funding. It is agreed that the following criteria are used in the review of the university projects:
• Relevance to MAGS themes
• Excellence of the proposals
• Performance of the Projects as indicated by the reports and presentations at the Annual Meeting
• Expenditure justifications
• Networking and participation of the investigators, a consideration much emphasized by NSERC for its Network grants
• Training of qualified personnel, including students, post-docs and technical staff

Collaboration

In the last year, there is a sense that collaborative activities are growing at several levels.

• Among individual researchers, the number of collaborative projects is increasing as complex questions are being addressed by research groups.
• Institutional participation has expanded as new partnership is forged with the Canada Centre for Remote Sensing and tangible support is provided by such user partner as the Northwest Territories Power Company towards the initiation of new projects. Effort has to be made to maintain existing partnerships.
• International linkage is important as MAGS is one of the Continental Scale Experiments (CSE) of GEWEX. We share similar scientific concerns with other CSEs including BALTEX (Baltic Sea Experiment), GAME (GEWEX Asian Monsoon Experiment) and GAPP (GEWEX America’s Prediction Project) and international collaboration is natural. As an example, the Second MAGS-GAME (Siberia) Workshop held in Sapporo (October 2001) is expected to lead to comparative studies in the future.

Outreach and Publicity

Our outreach and publicity, though increasing, is not commensurate with the success of our Program. Besides fulfilling the obligation to disseminate our findings to the public which ultimately is our funding source, public awareness of our scientific work is crucial to the later parts of our science agenda in which model applications is our major deliverable. Further benefit can be reaped by investigators conducting research under the MAGS label when seeking external funding from agencies that are acquainted with and favourably impressed by our work.
Comments from NSERC on MAGS and Research Partnerships Program

Doris Braslins
NSERC Program Officer

MAGS Research Network

- A particular strength of the MAGS Network application to NSERC was the plan for networking and collaborative research activities among university and government researchers and the network is to be commended for its effort in this area.
- Outreach activities have been undertaken to raise the profile of the network and the Yellowknife Workshop was very successful.
- Dr. Rouse’s presentation on MAGS-1 to NSERC staff in Ottawa was extremely interesting and much appreciated, particularly by staff members who have not yet had the opportunity to work with a Network.
- NSERC staff is also looking forward to Dr. Woo’s Bacon and Eggheads presentation on Parliament Hill.

Research Partnerships Program

There are research funding opportunities under the Research Partnerships Program. This is a group of programs that encourages links between universities and the public and private sectors through collaborative research projects. These programs build on NSERC’s primary role of support of university research and training.

- The Strategic Projects Program funds project research in target areas of national importance and in emerging fields that are of potential significance to Canada.
- The Research Networks Program funds large-scale, complex research proposals that involve multi-sectorial collaborations on a common research theme.
- Collaborative Research and Development Grants support well-defined projects undertaken by university researchers and their private-sector partners.
- The Research Partnership Agreements aims to build strong linkages between universities, the private sector and Canadian government laboratories.
- Industrial Research Chairs Program provides funding for infrastructure, equipment, general research expenses and the salary of the chair holder.
- Technology Partnerships Program supports partnerships between post secondary institutions and small and medium-sized Canadian companies.
- Intellectual Property Management Program provides funding in partnership with universities to support activities related to managing intellectual property and interacting with industry.
Challenges

Some of the challenges facing NSERC in the administration of these programs include:

- Adjustments to the Industrial Research Chairs Program in the context of the Canada Research Chairs.
- Co-ordination of peer review and funding with other government agencies.
- Pressure on program budgets as a result of the increased number of new applicants to the Research Grants Program.
- The need for outreach to industry (especially SMEs) to encourage participation in NSERC programs.

Reorganization of Research Partnerships Division

The Research Partnerships Division has been reorganized into three sector-based teams to better serve the needs of the university research community. The new teams are:

- Information, Communications and Manufacturing Sectors
  (Margaret Caughey, Director)
- Food and Bio-Industries Sectors
  (Krystyna Miedzybrodzka, Director)
- Environment and Natural Resources Sectors
  (André Isabelle, Director)

The detailed staff list is available on the NSERC web site; Doris Braslins will continue to act as the NSERC contact for the MAGS Network.

Lightening the Load

NSERC staff has undertaken to explore ways to “lighten the load” on the research community in terms of the demands of the application process and the peer review system. The results of this project will be known in 2002.
I appreciate the opportunity to attend the recent MAGS Science Meeting in Hamilton, and to participate in the open discussions following presentations, and more informal discussions at breaks and over dinner. I found the presentations stimulating, and I was quite impressed with the progress made to date. Unfortunately, I was only able to attend the Wednesday afternoon and Thursday sessions, so it should be understood that my comments are based solely on presentations made during those sessions. Furthermore, other members of the IAP were unfortunately not in attendance, so these comments represent my views only, and not those of the entire IAP. Given those qualifications, I summarize a few of my impressions below:

1) MAGS is the cornerstone of GEWEX efforts to better understand and predict cold seasons and cold regions land processes in the climate system. The networking concept that is the theme for MAGS-2 is unique among the GEWEX Continental Scale Experiments, and this concept appears to be enjoying considerable success. Nonetheless, the successes appear to be somewhat greater across the MAGS land surface activities, and in incorporating process research into land surface models, than vertically across the primarily land surface and primarily atmospheric modelling and observation activities. More effort is needed, especially in the atmospheric community, to incorporate results from MAGS land surface research. In some cases, this might be accomplished by near-term testing of “end points” rather than waiting for completed development and coupling of the newest version of CLASS, which eventually should integrate most of the land surface research. As one example, results of field activities that have estimated evaporation for lakes of different sizes within the MAGS region could be tested in coupled models, via appropriate simplifying assumptions, now – rather than waiting for a version of CLASS that has a fully functioning lakes submodel. I believe that there should be a possibility for testing the climatic implications of field and modelling sublimation estimates as well.

2) It is important that the project maintain a focus on the processes that have been identified as being central to MAGS-2 (lakes, snow sublimation and redistribution, frozen soils), and upscaling of field data and local scale models to the Mackenzie domain. Identification of mechanisms for testing sensitivity of surface water and energy budgets to appropriate process representations should be an integral part of the project, and is an area where the networking concept is critical. Modelling results showing minimal effect of sublimation on the regional water budget appear to be inconsistent with field results indicating the importance of sublimation of intercepted snow from forest canopies on the evolution of winter snowpacks. This is an area where a more collaborative approach could be taken, drawing from field observations, as well as coupled and off-line hydrologic model simulations.
3) There is a need for a stronger focus on archiving of data sets that are beginning to become available from MAGS-2. These include both model output data and/or analysis fields, and project level field data. The MAGS policy for data release and access should be made explicit. Among the data sets that I believe deserve particular attention are the MAGS contribution to the GEWEX WEBS (water and energy balance synthesis) activity. The WEBS data sets comprise the surface energy and moisture flux and storage terms, for an appropriate (ideally a decade or more) time period, and temporal and spatial resolution, sufficient to close the water and energy budgets both at the land and for the atmosphere. A commitment to complete the MAGS WEBS contribution in the reasonably near future (e.g., over the next year) would be highly desirable.

4) In most cases, the contribution of individual projects to the overall MAGS-2 goals and objectives was clear from the presentations. For a few projects or components thereof, however, there have been changes in project objectives for a variety of reasons, such as unavailability of data that had been anticipated at the time the project was proposed. Especially in these cases, the viability of the project, and its overall contribution, may need to be revisited. This is a task that I expect that the Science Committee will undertake. In any event, I think that it is important that participating scientists in all of the projects be able to give a concise statement of how their work contributes to MAGS-2 goals and objectives.

Again, thanks for inviting me to participate on behalf of the IAP. I wish all my MAGS friends and colleagues a productive 2002, and I will look forward to seeing you at the next MAGS science conference next fall.

– ○○○ –
Closing Remarks – MAGS 7th Annual Scientific Meeting

John Stone
Chair, MAGS Management Board

Thank you very much for giving me the opportunity to say a few words at the close of this meeting.

I have been impressed with what I see to be many positive things about MAGS and GEWEX:

- First, and most importantly, the science is being advanced;
- MAGS is clearly making a very positive contribution internationally, and is recognized for this;
- Judging from the attendance at this meeting, the MAGS and GEWEX family is growing;
- We are getting good publicity for your work and outreach to the users is encouraging;
- Finally, on the administrative side, things are going very well;
- Overall, the Management Board is extremely satisfied. On their behalf I would simply like to say, Thank you.

Let me say a few words about the science and policy linkages:

GEWEX is primarily a physics project, but we need to be aware that we are dealing with science that has great potential for application to operations and policy. Scientists sometimes give sweeping general comments which leaves the impression that all is well in hand, however, this is not the case:

- When I was involved in setting up GEWEX, I realized that we were dealing with a huge scientific problem. Fresh water input to the Arctic Ocean is very important but we still do not know well the magnitude and its interannual variability. It is very important to understand this better for it is a key determinant in the climate system in the Arctic and this is where we expect climate change to be greatest. This is a considerable challenge and we are making progress, but there is still a lot to learn, especially if we are to make this understanding transferable to other Arctic-flowing rivers.

- It is general knowledge that the prairies have been receiving less precipitation recently, often resulting in local areas of drought conditions. Politicians are paying greater attention to this and the work you are doing has the potential to be very useful to them. It is hoped that your knowledge, incorporated into models, will be used to project future conditions (especially in the prairies) resulting from natural variations and human-induced changes in the climate.

- Bulk water export continues to be an issue for this country. What is the scientific basis for this issue? My sense is that our policy is determined more by sentiment than science. To my mind the key science question is: to what degree are our fresh water resources renewable? It seems to me that one can only answer this question on a basin scale. Thus my challenge to you is: can you estimate this fraction for the Mackenzie Basin.
The work we are doing in the MAGS is extremely important but is far from being complete. There is still much to do (don’t let others tell you anything else), and lots of good science still to be done.

MAGS is doing good work, we need to keep up the excellent effort.

– ☽ ☽ ☽ –
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Key for Group Photo:
53. Frank Seglenieks.

Missing:
Doris Braslins, Toni Gasparini, Murray Mackay, David Rogers, John Stone, Fred Wrona.
Participants of MAGS 7th Annual Scientific Meeting. Key for the group photo is located on opposite page.