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These proceedings are also available on the MAGS website (under Publications and Publicity) at http://www.usask.ca/geography/MAGS/
The major objectives of the second phase of the Mackenzie GEWEX Study (MAGS-2) are to gain integrated knowledge of atmospheric and hydrologic cycles of the basin, and to develop a hierarchy of models for applications in scientific, environmental and social issues. The 8th Annual Scientific Meeting of the Mackenzie GEWEX Study (MAGS) was held in beautiful Jasper, Alberta on November 6-8, 2002. The purposes of the meeting were to present and to discuss new scientific results from MAGS research projects, and to collectively assess research progress for the program. As evident in the presentations given at the meeting, significant progress throughout all MAGS research themes have been achieved in year-2 of MAGS-2 to attain the project goals. In particular, we saw the completion of major research projects initiated during MAGS-1, significant advance on all fronts of MAGS modelling activities, and progress in research that endeavour to enhance our basic physical understanding of the basin’s hydroclimate.

It is noteworthy that this is the first MAGS annual scientific meeting that was held within the Mackenzie Basin. We greatly appreciate the attendance of our invitees, especially members from the International Advisory Panel, despite the rather inconvenient location of the meeting venue. We are also grateful to the Prairie and Northern Region of the Meteorological Service of Canada, particularly Mr. Bob Kochtubajda, for their logistic support in organizing the meeting. Ed Struzik (Edmonton Journal) is thanked for his special evening presentation on the history of the Arctic which was thoroughly enjoyed by all. Finally, we wish to thank Peter di Cenzo for the great effort he put in editing and publishing this proceedings.

Kit Szeto
Chair, MAGS Scientific Committee
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A. ATMOSPHERIC STUDIES
Precipitation and Weather Disturbance Evolution in the Mackenzie River Basin:
Its Interaction with the Global Circulation

J.R. Gyakum\textsuperscript{1}, M.K. Yau\textsuperscript{1}, I. Zawadzki\textsuperscript{1} and H. Ritchie\textsuperscript{2}

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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.
- To understand the role of these synoptic-scale disturbances in the modulation of the global atmospheric circulation.

2. Progress

A. The Ph.D. work of Marco Carrera on interhemispheric mass exchanges is now completed (Carrera, 2002), with Marco having successfully defended his thesis in January 2002. The study of this process, being surface anticyclogenesis, provides insight into the amplification of Available Potential Energy (APE), 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 moist 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. The first of the refereed publications is to be submitted to the \textit{Journal of Climate} by the end of October 2002 (Carrera and Gyakum, 2002). The abstract for this manuscript follows:

\textit{The various modes of atmospheric mass redistribution characterize the principal variations of the general circulation of the atmosphere. Interhemispheric exchanges of atmospheric mass occur with considerable regularity on intraseasonal time-scales. Observational evidence from previous studies indicates that anomalous and persistent regional atmospheric mass distributions (e.g., atmospheric blocking) may often be related to interhemispheric atmospheric mass exchange.}

\textit{Using the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis, we identify significant events when the northern hemisphere (NH) loses dry atmospheric mass on subseasonal time-scales during the boreal
winter from 1968 to 1997. A total of 25 events is found, with a preferred time-scale of 9 days. The NCEP reanalysis fails to conserve dry atmospheric mass with a mean annual cycle of 0.23 hPa in global dry atmospheric mass. Nonetheless, the linear correlation coefficient between the dry atmospheric mass anomalies for the NH and southern hemisphere (SH) is –0.91 for the 25 events, indicating very strong interhemispheric compensation.

Positive sea-level pressure anomalies are found over northern Eurasia, the North Pacific and the North Atlantic prior to the onset of the composite NH dry atmospheric mass collapse event. Over northern Eurasia the building of the Siberian high is found to be a statistically significant precursor to the events. The breakdown of NH dry atmospheric mass occurs in association with the decay of the positive atmospheric mass anomaly in the North Pacific as a cyclone deepens explosively in the Gulf of Alaska. Pressure surges over Southeast Asia and North America, associated with statistically significant positive atmospheric mass anomalies, are mechanisms that act to channel the atmospheric mass equatorward on a rapid time-scale (~4 days). The dry atmospheric mass increase in the SH is manifested as enhanced surface ridging over the South Pacific and South Indian Oceans.

Additionally, Marco Carrera is contributing to the CAGES special issue with a physical documentation of the large-scale atmospheric circulation during this water year.

B. Werner Wintels successfully defended his Ph.D. dissertation on APE in August 2002 (Wintels, 2002). The first refereed manuscript (Wintels and Gyakum, 2000) is being followed by a manuscript (in preparation) that focuses on 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. Richard Danielson's Ph.D. dissertation is to be completed by December 2002, with a defence planned for January 2003. 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). This process is illustrated in section 3.

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. Additionally, potential inversion techniques (Zhang et al., 2002) have been utilized to demonstrate that energy dispersion from the western region of the North Pacific positively impacts surface cyclogenesis in the eastern regions of the North Pacific. This latter cyclogenesis is typically responsible for water vapour transports into the MRB (Lackmann et al., 1998).

D. In collaboration with 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 Harold Ritchie of the MSC, we have submitted a manuscript discussing the ensemble forecast issues relating to ex-Hurricane Earl of 1998 (Ma et al., 2002). Additionally, we are collaborating with William Perrie and his group at the Bedford Institute of Oceanography on the problem of improving the parameterization of surface sensible and latent heat fluxes in the presence of high winds (greater than 20 ms\(^{-1}\)) and sea spray. This project offers the prospect of improving the modelling of fluxes and the consequent improvement in the simulation of surface cyclonic disturbances.

F. In collaboration with Isztar Zawadzki at McGill University, Florence Bocquet has completed her Master's Degree (Bocquet, 2002) that documents the large-scale atmospheric environments of severe convective weather that have been detected by the Canadian radar network. We intend to apply these results to a new research effort focusing on the MRB region.

G. In collaboration with Bob 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. Dorothy Durnford has begun her Ph.D. research on the predictability of surface cyclogenesis. The study focuses on improving initial analyses in data-sparse regions, such as the Pacific basin. Testing has begun on the utility of using total ozone data as a statistical proxy for atmospheric potential vorticity. A resulting improved analysis would serve as improved initial condition dataset for numerical simulations of cyclogenesis. Preliminary work has so far yielded promising results.
3. Results

Principal results are summarized above in section 2.

Figure 1 (taken from Richard Danielson’s Ph.D. thesis) shows the importance of the upstream eddy kinetic center in dispersing energy towards the eastern Pacific. The figure shows the strong cyclone after 84 hours of the 'Control Simulation' with eddy kinetic energy values approaching 7 MJm$^{-2}$. The bottom panel, in which the upstream perturbation was initially removed, yields a much weaker cyclone with eddy energy values reaching only 3 MJm$^{-2}$. This result has important implications for the MRB, as a key predecessor to eastern Pacific cyclogenesis may be an upstream energy source over the Asian continent.

![Figure 1](image)

Figure 1. Top panel: Control simulation with 500 hPa geopotential heights (5000, 5300, and 5600 m), surface cyclone track in red with dot indicating position at 1200 UTC, 11 March 1977, eddy kinetic energy (interval of 1 MJm$^{-2}$) with a geostrophic flux vectors plotted for values larger than 30 MWm$^{-1}$. Bottom panel: As above, except for the simulation with the potential vorticity perturbation in east Asia removed at the initial time.
4. 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.

- 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 3 above.

A. The completed 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.

Ongoing work of Marco Carrera defines the atmospheric structures during the CAGES period.

B. The completed 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, show 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. Surface cyclones accomplish these transports.

D. The research performed by Ron McTaggart-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 Dr. Harold Ritchie and Suhong Ma provides additional insight into the role of ETs in transporting water vapour into high latitude regions. The collaborative work with William Perrie will add to our understanding of energy transports into the MRB region.

F. The work with Dr. Zawadzki focuses on severe weather in the high latitudes and its role in transporting water vapour horizontally and vertically.
G. The collaborative work with Bob Kochtubajda enhances our knowledge of high latitude weather systems’ impact on the MRB environment within the context of a warming environment.

H. The Ph.D. research of Dorothy Durnford relates to our understanding of the cyclone's role in transporting heat and moisture into the MRB.

5. Networking and Collaboration

Seminars and Presentations

CWRP-CFCAS workshop on quantitative precipitation forecasting (Rimouski, QC) – May 20, 2002: “A study of heavy precipitation occurring in continental and marine environments”.

CWRP-CFCAS workshop on quantitative precipitation forecasting (Rimouski, QC) – May 21, 2002: “Orographic influences on the mesoscale structure of the 1998 ice storm”.

36th Congress of the Canadian Meteorological and Oceanographic Society (Rimouski, QC) – May 23, 2002: “Orographic influences on the mesoscale structure of the 1998 ice storm”.


36th Congress of the Canadian Meteorological and Oceanographic Society (Rimouski, QC) – May 25, 2002: “A study of heavy precipitation occurring in continental and marine environments”.

A two-week Winter Weather Course was developed and taught during February 2002 at COMET in Boulder, Colorado for the Meteorological Service of Canada. The enrolment was 20 students, including 6 from the US National Weather Service.

Participation in MAGS and/or non-MAGS Workshops

MAGS-CAGES Workshop – Edmonton, AB (March 2002)

CWRP-CFCAS Workshop on quantitative precipitation forecasting – Rimouski, QC (May 2002)

MAGS WEBS Workshop – Downsview, ON (May 2002)

36th Congress of the Canadian Meteorological and Oceanographic Society – Rimouski, QC (May 2002)

Networking Activities and Collaboration with other Researchers

Charles Lin (McGill) – initiation of collaborative research on relationship of weather in the MRB to large-scale circulation indices

Bob Kochtubajda (MSC) – collaborative research on forest fire relationship to weather and climate in the MRB

William Perrie (Bedford Institute of Oceanography) – collaborative research on ocean-air surface fluxes and their relation to tropical cyclogenesis

Richard Greatbatch (Dalhousie University) – collaborative research on ocean-air surface fluxes and their relation to tropical cyclogenesis

Aldo Bellon (McGill) – severe weather climatology study

6. Summary

Our research has linked global circulation parameters that include available potential energy, interhemispheric 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 extratropical cyclones, and their role in transporting heat and moisture to high latitudes.

7. Publications


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

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1. Objectives

The specific objectives of this study are:
1. to understand the role of convective processes over the Mackenzie River Basin through an examination of its spatial, temporal, and topographic distribution and their relation to atmospheric and surface forcing,
2. to validate numerical model output which resolves convection, and
3. to examine the impacts of convection and lightning on forest fires.

2. Progress

This year we expanded the lightning study in several directions. We were awarded a Northern Ecosystem Initiative (NEI) grant to further our climate-fire-forest ecosystem interaction studies. The objectives are to establish the necessary baseline connections between variations in the vertical structure of the atmosphere and wildland fire behaviour, and to examine the regional impacts of future climate change. Quality control of the extended upper air, surface weather, fire and area burned data sets are nearly complete. Statistical analyses are set to begin shortly. Efforts to determine the susceptibility of the forests in the basin to an altered fire regime due to climate change are underway. Presentations are scheduled for mid-January (2003) at the Aurora College Thebacha Campus in Fort Smith, (Mr. Kevin Antoniak, Head of the Natural Resources Technology Program) as part of our outreach activities and a final report to NEI is slated for the end of April 2003.

The Government of the Northwest Territories, Forest Management Division continues to provide us with lightning data from their lightning detection network. We now have data for the period 1994 to 2001. Data from the Large Fire Database ( Stocks et al., 2002 ) now includes the 1999 season.

A new initiative has recently been undertaken with Dr. William Burrows (Meteorological Research Branch, Toronto) to test a statistical lightning forecast model (Burrows, 2002) over the Mackenzie Basin. The model applies a tree-based non-linear regression technique, known as the Classification and Regression Trees (CART), to relate lightning to predictors derived from the
GEM model (Coté et al., 1997). Contours of probability of lightning occurrence in 3-hour periods up to 12 hours from 0000 UTC and 1200 UTC GEM model runs are then derived. These models will be used to give forecasts for a 24-hr period, and possibly a 48-hr period. The forecast model, built primarily with 2001 CLDN data, is being run to predict the probability of lightning on 8 randomly selected days during the summer of 2002. Comparisons against the observed lightning in the basin are underway and preliminary results are expected in time for the meeting.

Efforts were also initiated in 2002 to explore, identify and develop collaborative opportunities with CCRS. A seminar describing our lightning studies was presented during a visit to CCRS in April. Subsequent discussions with several staff members were very positive and several short-term and longer-term initiatives were identified for further development including:

1. Lightning and satellite-detected hotspots to investigate the possible delay in fire events after lightning; correlation between positive/negative lightning events and fire as indicated by hotspots. [Dr. Robert Fraser has sent us some hotspot data. We are very early in this project]

2. Satellite derived smoke data for significant fire events in 1994-1995, and maybe other years. These data will be useful to investigate the hypotheses of positive feedback between smoke and second lightning strike and fire.

3. Fire process modelling, to integrating the effects of lightning, fuel loading, fuel dryness, and other factors into fire process model (future direction).

4. The impact of climate change on fire regimes, and associated impact on ecosystem health, productivity, biodiversity, etc. (future direction).

Partner Involvement

We continue to broaden our collaborative partnerships. Discussions are underway with Parks Canada to work on a fire regime study over Wood Buffalo National Park. Discussions are also underway with Ms. Tracy Hillis, the recently hired Climate Change Biologist for the GNWT-RWED, to explore climate-fire-mammal ecosystem interactions.

References


3. Results

*Special MAGS 94-95 Water Year Issue*

Paper on the nature of lightning, convection and forest fire activity over the basin was published in the MAGS Special Issue of Atmosphere Ocean.

*Lightning-fire Regime of the NWT*

A study describing the fire regime of the Northwest Territories jurisdiction of the Mackenzie basin, between 1994 and 1999, will be presented at the 4th International Fire Research Conference in Luso, Portugal, November 18-21.

Lightning activity patterns during this study period (Figure 1) illustrate the seasonality and broad spatial variability. In the early part of the season, the region of lightning activity (densities less than 1 flash/100 km²) extends from the Peace-Athabasca region of Alberta northwards through Fort Smith in the south Slave region and westward to Fort Simpson in the Deh Cho region. Lightning densities intensify to 2-4 flashes/100 km² through the Sahtu region in July and by August the activity decreases southeast into the North Slave region. The maximum area of lightning activity extends from the wetlands region through the Cameron Hills of the Northwest Territories to the Clear Hills of the Peace River Basin in northern Alberta.

![Figure 1](image-url)  
*Figure 1.* The monthly spatial distribution of lightning activity (strikes/100 km²) averaged over the period 1994-99 for a) May, b) June, c) July, and d) August.
Historically, thunderstorm climatologies have been based on hearing thunder at weather stations. Such observations can be affected by a number of factors including the conditions through the atmosphere and barriers between the listeners and where the sound occurred. A thunderstorm day climatology based on the lightning network has been produced for the NWT (Figure 2). The NWT experiences more thunderstorm days than previously reported frequencies (Climatic Atlas, 1987).

![Figure 2. Mean Lightning occurrence days for period 1994-99 between May-Sept.](image)

4. Relevance

This work is enhancing our knowledge of the interactions between the atmosphere, devastating fires and their ecological impacts in the basin. The 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

A. Seminars and Presentations


B. Participation in MAGS and/or non-MAGS Workshops

MAGS CAGES and Data Management Workshop. Edmonton, March 22-23, 2002


C. Networking Activities and Collaboration with other Researchers

Drs. Dave Hudak, Brian Currie, Ron Stewart, Jason Burford, Normand Bussieres, and Peter Rodriguez [MSC and McMaster University] – collaborating with this team on a study characterizing significant cloud systems in the central Mackenzie River Basin.

Drs. Wayne Rouse and Jacqueline Binyamin [McMaster University] - surface weather data for Lake Evaporation studies

Dr. Suzanne Carriere, Ecosystem Management Biologist, Yellowknife, NWT [GNWT-RWED] – Tibbitt Lake Fire Study Camp

Dr. Faye Hicks [University of Alberta] – surface weather data for Ice break-up studies


Dr. Gerhard Reuter [University of Alberta] – monthly lightning statistics for fire regions in NWT (1994-2001] for an undergraduate honors project

6. Summary

Several parallel studies to assess climate-fire-forest ecosystem interactions are underway. Weather, ignition sources and the condition of the forest vegetation are factors that influence fire occurrence. A lightning derived thunderstorm day climatology shows that the NWT experiences more thunderstorm days than previously reported.

7. Publications


Whillans, S., R.E. Stewart, D.R. Hudak and B. Kochtubajda, 2002: Large accumulation rainfall events occurring over Edmonton during the CAGES water year. (submitted to Journal of Hydromet)

Conference Proceedings


1. Objectives

i. To evaluate the radiation fields that are being generated by the atmospheric models that are being used in MAGS.

ii. To study the sensitivity of processes that impact on the hydrology of the Mackenzie River Basin as they are simulated by WATCLASS to the uncertainty in the surface radiation forcing from atmospheric models.

iii. To develop new data sets of the radiation fields at the top of the atmosphere and the surface that can be used to test the transferability of the models and results from the Mackenzie to other northern regions.

2. Progress

- We have carried out an extensive comparison of the outgoing shortwave fluxes at the top of the atmosphere and the net solar flux at the surface from the RCM with values deduced from AVHRR measurements from the NOAA-12 and NOAA-14 satellites for the CAGES year.

- We have compared outgoing longwave radiation fluxes from the RCM with broadband measurements from ScaRaB flight module 2 on the RESSURS satellite for winter months of the CAGES year (the only period for which broadband measurements were available).

- We have carried out two sets of simulations for the CAGES year with WATCLASS driven off-line by output from GEM. Each set of simulations consists of two runs: one using the GEM output, and a second run in which the incoming solar radiation is modified to make it consistent with the solar radiation field deduced from the shortwave satellite measurements referred to above. The sensitivity of the energy and water fluxes to “uncertainties” in the solar radiation field from GEM has been assessed.

These points address the first two objectives. In last year’s proposal these first two objectives were subdivided into five sub-goals all of which were expected to be completed by the end of this year. We have met the targets with the exception that although we have compared cloud mounts from satellite data and from the RCM, and have investigated the impact of differences in cloud amount from the model and satellite retrievals on radiation budgets, we have not explicitly compared cloud forcing from the model and satellite data.
The third objective, as stated in last year’s proposal, is longer-term. We expected last year “to have made considerable progress in assembling the data sets by the end of 2002”. As it turns out that has not happened and this will be a part of our 2003 research.

3. Results

Comparisons of RCM Output with Satellite Retrievals

The outgoing solar and longwave fluxes at the top of the atmosphere from the RCM were compared with the fluxes from satellite retrievals. Broadband shortwave fluxes were deduced from AVHRR (narrowband) measurements from the NOAA-12 and -14 satellites for nine months of the CAGES period. No shortwave retrievals were carried out for the months of November through February because of large solar zenith angles and small fluxes over most of the basin. Retrievals of broadband longwave fluxes were carried out for the months of November through March, the period when broadband measurements were available from the ScaRaB FM2 instrument that was on the Russian RESURS 01-4 satellite.

It was found that for the months when the surface is snow-free, the CRCM overestimated the outgoing solar flux at the top of the atmosphere, at the times when values were deduced from the satellite data, by an average of 33 Wm⁻² (Figure 1). For the months when the surface was mostly snow-covered the mean difference was about 2 Wm⁻². In the longwave, fluxes the RCM underestimates the outgoing radiation by about 6-12 Wm⁻².

When comparisons between the outgoing shortwave radiation in the summer months are restricted to pixels that are clear both according to the RCM and the satellite retrieval, the RCM underestimated the outgoing shortwave flux by 6.5 Wm⁻² and overestimated the net solar flux at the surface by about 15 Wm⁻² (Figure 2). There is a tendency for overestimation of the clear-sky reflected flux over the western portion of the basin and the three major lakes (which are not resolved in the RCM) but underestimation over most of the rest of the basin.

Since the RCM outgoing solar flux generally agrees much better with the satellite retrievals for clear skies, the large overestimation of the outgoing solar flux under all-sky conditions is most likely due to the simulation of clouds in the model. Comparisons of the cloud amounts from the model and the satellite retrievals does suggest that the model over-predicts cloud amounts, which is consistent with the outgoing solar flux over-predictions.

Returning to the apparent good agreement between satellite and RCM for snow-covered conditions, it turns out that when we examine the spatial distribution of the differences we find that the RCM underestimates the outgoing solar radiation in the northern part of the basin (albedo is too small) and overestimates the outgoing solar radiation in the southern basin (albedo is too large). The nature of the surface in the basin is very complicated. Accurate representation of the surface albedo can be expected to be a challenge in forested regions where there is snow under and possibly on a forest canopy.
Figure 1. Comparisons of monthly basin averages of solar fluxes at the top of the atmosphere (TOA) and at the surface from the RCM and satellite retrievals. Solid and dashed lines are for the RCM and satellite values respectively. The triangles and circles are for the TOA and surface respectively.
Figure 2. Comparisons of solar fluxes at the TOA (plus signs) and surface (solid circles) under clear skies from the RCM and satellite retrievals.

In our evaluation of the version of the RCM that was used in the 1994-95 water year (see the MAGS Phase I final report) we found that the atmospheric absorption of solar radiation was significantly underestimated. In the current version of the RCM the bias in the monthly average absorption is reduced to between 2 and 12 Wm$^{-2}$. 
Sensitivity of WATCLASS to Incoming Solar Radiation

Two sets of two simulations with WATCLASS have been carried out for the CAGES period. Each set of two runs provided a measure of the sensitivity of the energy and water budgets, as simulated by WATCLASS, to uncertainties in incoming solar radiation from GEM of the magnitude that may be expected on the basis of satellite - GEM solar radiation flux comparisons. The WATCLASS simulations driven by the GEM solar fluxes had 36% more solar flux incident at the surface than the simulations that were more in accord with the satellite retrievals. The two runs are referred to as the GEM and SAT runs, respectively.

The two sets are distinguished by their different treatment of the surface. One set of simulations only allowed a single land surface type for the whole basin, while the second set included seven different land classes. Comparisons of the results from the two sets provided insight into the influence of the surface type on the sensitivity.

Both the energy and water budgets were sensitive to the change in incoming solar radiation. For instance, for the seven-land-class run, the higher incoming solar radiation resulted in a basin average annual temperature increase of 1.2°C, a 14% decrease in downward net longwave radiation, and increases in sensible and latent heat transfer to the atmosphere of 141% (Figure 3) and 18% respectively. The snowpack starts to erode earlier and disappears more quickly. Evaporation is increased by 21% and runoff is decreased by 10%.

![Sensible heat fluxes](image)

Figure 3. Monthly basin averages of sensible heat flux from the four WATCLASS simulations described in the text.
A caveat to these results is that because the atmospheric model (GEM) is not coupled to WATCLASS the atmosphere does not respond to the changes in the surface fluxes. In reality, atmospheric properties (e.g. temperature, humidity) will change and these changes will in turn feedback on the surface fluxes and the water budget.

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 present range of climate variability and climate change.

5. Networking and Collaboration

The work with WATCLASS is being done in close collaboration with Ric Soulis and his research group. Bruce Davidson, an M.Sc. student working with Ric Soulis, spent a few days at McGill collaborating with McGill M.Sc. student, Nathalie Voisin.

The comparisons of satellite data with the RCM are being carried out in close cooperation with Murray Mackay.

Normand Bussières prepared the AVHRR data that were used in this work. (Those data are in the CAGES archive.)

Bill Schertzer, Phil Marsh and Wayne Rouse kindly supplied surface radiation measurements that were used to test our retrievals of net solar radiation at the surface.

I participated in the CAGES Data Workshop in Edmonton and co-chaired with Geoff Strong the WEBS workshop in Toronto.

Nathalie Voisin presented a paper at the CMOS Congress in Rimouski and at the Eastern Snow Conference in Stowe, Vermont.

I was a co-author of a paper presented by Murray Mackay at the CMOS Congress in Rimouski.

6. Summary

Numerical models play an important part in understanding the energy and water cycles of the Mackenzie River Basin. Assessing the weaknesses of the models is an important process in their evolution and improvement. The present work points to potentially important problems in the simulation of clouds in the Canadian Regional Climate Model. We have also assessed the sensitivity of the WATCLASS land surface - hydrology model to uncertainties in incoming solar radiation as might arise for limitations in the simulation of clouds in atmospheric models.
7. Publications


– ◊◊◊ –
The Effect of Land Surface Schemes on the Simulation of Summer Precipitation and Surface Fluxes

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1. Objectives

1. To evaluate the sensible and latent heat fluxes simulated by the land surface schemes CLASS and ISBA in a stand-alone mode using CAGES data.

2. To compare RCM/CLASS and MC2/CLASS simulation of selected cases during the CAGES period.

3. To develop methodologies to compare model and radar-retrieved precipitation (in collaboration with Isztar Zawadzki).

2. Progress

2.1 We have examined the sensible and latent heat fluxes simulated by CLASS and ISBA at the Trail Valley Creek site, for a 90-day period (June-August 1999) during the CAGES period. Observed meteorological data were used to drive CLASS and ISBA in a stand-alone mode, and the simulated fluxes compared with observations. The motivation for this study is that the major coupled atmospheric/land surface models used in MAGS so far are RCM/CLASS, GEM/ISBA and MC2/CLASS. It is difficult to assess the effects of the two land surface schemes as they are coupled to different atmospheric models. A first step is thus the evaluation of the schemes in a stand-alone mode. This study has now been completed.

2.2 The next step in the evaluation of coupled models is the comparison of RCM/CLASS and MC2/CLASS using selected CAGES cases. It is important for MC2 and RCM to have the same land surface fields for CLASS. MC2, being a mesoscale model, works well at mesoscale resolution. RCM uses model physics that was originally designed for use at coarser GCM resolution, but is now run at mesoscale resolution. It is thus important to evaluate RCM performance against mesoscale models for MAGS. We have prepared the surface fields needed for this study, in collaboration with Murray McKay and Kit Szeto. We will start with the anticyclonic case study of 29 May 1999. Once this initial comparison is completed, cyclonic cases during the CAGES period will be examined. We note there has been some unexpected problems encountered with computing platforms. MC2/CLASS has been developed and tested on the MSC (Meteorological Service of Canada) supercomputer NEC SX4. This version has been used successfully to study the Saguenay flood. However, MSC is upgrading its supercomputer to SX5 and SX6, and our version of MC2/CLASS can no longer run on the upgraded computers. This is because the physics package of MC2 of our version of the coupled model can no longer compile on the new computers, as these packages have been upgraded by MSC. A new version of MC2 runs on the SX5 and SX6, but the
linkage of this version of MC2 to CLASS is not available. We have recently successfully implemented an in-house version of MC2/CLASS that can run on the SX5 at the Montreal research centre CERCA (Centre de recherche en calcul appliqué), thus giving a coupled model (MC2/CLASS) that is independent of MSC computers.

2.3 In collaboration with Isztar Zawadzki, we have developed a methodology based on Fourier and wavelet analysis to evaluate model and radar-retrieved precipitation as a function of spatial scale. The methodology is being tested using data from the McGill radar and composite data from the US radar network. The methodology is now ready to be applied to CAGES storms. Further details are described in the Zawadzki and Lin progress report.

3. Results

We show in Figure 1 the sensible ($Q_H$) and latent ($Q_E$) heat fluxes simulated in a stand-alone mode for the upland Trail Valley Creek site using CLASS and ISBA from project 2.1 above. Results from three models have been obtained: the standard version of CLASS (Verseghy, 1991, *Int. J. Climatol.* 11, 111-133), the peatland version of CLASS as developed by Nigel Roulet’s group at McGill (Letts *et al.*, 2000, *Atmosphere-Ocean* 38(1), 141-160) and the 3-layer version of ISBA (Noihlan and Planton, 1989, *Mon. Wea. Rev.* 117, 536-549). The results shown are the averaged diurnal cycle over the 90-day period from June to August 1999. We see that the peatland version of CLASS and ISBA perform about equally well, both being better than the standard version of CLASS. The errors are of order several tens of Wm⁻². This represents a lower bound on the land surface scheme heat flux errors, if we assume the observations are perfect. From the point of view of coupled atmospheric-land surface models, the errors are likely to be larger, as the radiative fluxes have significant errors due to inadequate treatment of clouds.

We have also examined the simulated soil moisture for the 90-day CAGES period. Comparison of the top layer soil moisture with observed values shows that CLASS tends to lose soil moisture too rapidly. The study sites are located near local depressions, and thus lateral flow is likely to be important. We have parameterized this in a simple manner in CLASS by restoring the top layer soil moisture to field capacity at each time step. The sensible and latent heat fluxes are then better simulated (results not shown). ISBA already has a similar restoring term for the top layer soil moisture.
Figure 1. The averaged diurnal cycle of sensible ($Q_H$) and latent ($Q_E$) heat fluxes simulated by CLASS and ISBA for the 90-day period from June to August 1999 compared with observed values.

MC2/CLASS has been installed at the NEC SX5 computer at CERCA. We have successfully tested the coupled model by repeating the Saguenay flood simulation that we had made earlier on the MSC SX4. We are now in the final stages of preparation to make a run simulating the May 29, 1999 anticyclonic case. All of the CLASS fields provided by Mackay and Szeto have been converted to the proper format. Analysis fields for defining the initial and boundary conditions have been obtained, and interpolated onto the experimental grid appropriate for comparison with RCM/CLASS.

The results of project 2.3 are described in the Zawadzki and Lin progress report (“Scale dependence of radar-retrieved and model precipitation”). In short, power spectra of model and radar precipitation have been computed using Fourier and wavelet analysis. This enables an evaluation of model precipitation as a function of scales.
4. Relevance

MAGS-2 concentrates on the modelling of the major components of the Mackenzie Basin physical system to improve our predictive capability for water resource problems. Our study is relevant to MAGS-2 goals as it provides verification of surface sensible and latent heat fluxes, which serve as the link between the land surface scheme (and hence hydrology) and the atmospheric component of coupled atmospheric-hydrological models. Precipitation is a key hydro-meteorological variable and its prediction remains a challenge. We have also developed a methodology based on Fourier and wavelet analysis of model and radar-retrieved precipitation. Finally, a recommendation of the 2001 Yellowknife Scaling Workshop is the comparison of MC2/CLASS and RCM/CLASS for selected CAGES cases to determine the adequacy of model physics and the ability of models to deal with heterogeneous land surfaces. We have prepared MC2/CLASS for such a comparison study.

5. Networking and Collaboration

- Project 2.3 is undertaken with Isztar Zawadzki as the principal investigator.
- We have obtained the ISBA code and programming help from T.Y. Gan’s group at the University of Alberta. Further networking will occur as both groups continue their work with ISBA.
- We have set up MC2/CLASS for comparison studies with RCM/CLASS in consultation with Murray Mackay and Kit Szeto. This consultation will continue as different CAGES case studies are examined.
- We have used CAGES Trail Valley Creek data to evaluate CLASS and ISBA in stand-alone mode. This has led to networking with the data collection groups of Phil Marsh and M.K. Woo.

6. Summary

We have compared the surface heat fluxes simulated by the land surface schemes CLASS and ISBA in a stand-alone mode, using observed forcing fields from CAGES. The heat fluxes are verified using observations as well. The fluxes are simulated with an error of several tens of Wm$^{-2}$. Parallel runs with RCM/CLASS and MC2/CLASS are being set up now for CAGES case studies, using common surface fields. We have also developed a methodology to evaluate model and radar-retrieved precipitation as a function of scale based on Fourier and wavelet analysis.

7. Publications

Rodgers, D., C.A. Lin, L. Wen and D. Chaumont, 2002: Validating Canadian Land Surface Scheme (CLASS) heat fluxes under subarctic tundra conditions. (submitted to Journal of Hydrometeorology, special CAGES issue)


– ⬤⬤⬤ –
1. Introduction

Considerable progress has been made with the Canadian Regional Climate Model since last year. A successful simulation of the CAGES water year has been achieved, and two detailed studies have been completed and submitted to the Journal of Hydrometeorology special issue for CAGES (MacKay et al. 2003; Feng et al. 2003). The results of these studies will not be duplicated here in their entirety: only key aspects requiring further investigation, or which shed deeper insight into the workings of the model are described here.

2. CAGES Water Year Simulation

A complete description of this simulation, along with a detailed evaluation against observed data and an analysis of the simulated surface water budget is presented in MacKay et al. (2003). The version of the model we use (CRCM 4.0-MAGS) makes use of the GCMIII physics parameterization package of the Canadian Centre for Climate Modelling and Analysis (CCCma). This package includes CLASS 2.7, and we also make use of the detailed land surface data set described in last year’s report. The most important findings of this study are summarized below.

2.1 Surface Climate Evaluation

Temperature

Compared with a monthly gridded climatology produced by the MSC (CANGRID), the Mackenzie Basin mean annual screen level (2 m) maximum and minimum temperatures were both too cold by 1.7°C. The simulated monthly average T$_{max}$ tended to be close to observed from March to May, but too cold otherwise. On the other hand, T$_{min}$ was too cold throughout the year with the exception (inexplicably) of December and January. The autumn cold bias contributed to a longer snow covered season and larger peak SWE than observed.

Precipitation

Mackenzie Basin annual precipitation was about 9% greater than observed, which may be within the uncertainty of the observed (CANGRID) estimate. Simulated hydrographs for the Mackenzie River at Arctic Red indicated total flow volumes for the 1998/99 WY within 1% of observed, also suggestive of realistic precipitation totals (or at least realistic P-E). On the other hand, simulated hydrographs further upstream (Athabasca River at Athabasca, Smoky River at Watino) indicate that orographic precipitation can be excessive. This is difficult to verify as conventional observations of precipitation in mountainous regions are scant and relatively unreliable.
Snow Cover

A cold, wet bias in October led to a longer and deeper snow cover period than was observed. However, two independently observed data sets suggest that snow accumulated in the model at a realistic rate over the Mackenzie Basin lowlands (below 800 m) from November 1 until at least January or February. The simulated snowpack grew at the rate of accumulated simulated precipitation until the spring melt: i.e. the model simulated no mid-winter ablation. The extent of mid-winter ablation in the Mackenzie Basin is currently unknown, but this study suggests an upper limit of about 20% of the peak simulated SWE (or about 20 mm).

2.2 Land Surface Initialization and Spinup

The land surface was initialized with climatological (atmospheric) temperatures and saturated (based on porosity) soil moisture conditions and spun-up for 18 months prior to the CAGES water year. While temperature appeared to equilibrate relatively quickly, numerous grid cells in the Liard sub-basin were still dumping large amounts of moisture in an attempt to reach equilibrium – even by the end of the simulation. This was evident in both the soil moisture budget and a simulated hydrograph. Clearly an 18 month spinup period is insufficient under these conditions: either a longer spinup should be allowed, or more realistic initial conditions for soil moisture (perhaps field capacity) considered.

2.3 Surface Runoff and Interflow

CLASS 2.7 does not include any representation of lateral flow. Grid cell water excess (runoff) from the simulation was routed offline using two different techniques. In the first, the runoff was instantaneously put into stream channels and routed (based on Manning’s equation) through the University of Waterloo’s channel routing scheme WATROUTE. In the second approach, simulated precipitation and temperature were used to drive WATFLOOD. In addition to using the WATROUTE channel routing scheme, WATFLOOD also represents sub-grid scale surface flow and interflow – both of which occur much slower than channel flow. Compared with observed hydrographs, the WATFLOOD hydrographs generally show much better timing than the WATROUTE hydrographs, which generally peak too early. We take this to indicate the importance of surface flow and interflow in the region.

2.4 Water Balance: CAGES WY

P = 496 mm, P-E = 225 mm, Q = 246 mm, S = -26 mm

Note that the 5 mm residual is the change in snow cover from October 1 1998 to October 1 1999. Also, the soil moisture change is excessive due to the spinup problem in the Liard. A more representative value (i.e. excluding the problematic grid cells) is closer to -14 mm.
2.5 Radiation Evaluation

An evaluation of top-of-atmosphere (TOA) solar and long wave radiation, and net surface solar radiation (NSSR) for this simulation was presented in Feng et al. (2003). Some key findings are:

Solar Radiation

A summary of the solar radiation bias found by Feng et al. (2003) is presented in Table 1. Results are summarized by season: Fall (Oct); Winter (Nov-Feb); Spring (Mar-Apr); Summer (May-Sept). The most significant bias occurs during summer, where excessive simulated outgoing solar radiation at the TOA is seen to occur largely at the expense of NSSR. This deficit in summertime NSSR is likely contributing to the significant summertime cold bias (-2.1ºC) in T$_{\text{max}}$ simulated in the CRCM. During the spring the deficit in simulated NSSR is small, and the corresponding bias in T$_{\text{max}}$ is only +0.6ºC. On the other hand, even though the bias in NSSR during October is positive, there is a significant cold bias in both T$_{\text{max}}$ (-2.2ºC) and T$_{\text{min}}$ (-3.5ºC).

Table 1. Solar radiation bias (CRCM - OBS) summarized by season (from Feng et al., 2003).

<table>
<thead>
<tr>
<th>Season</th>
<th>NSSR (Wm$^{-2}$)</th>
<th>TOA (Wm$^{-2}$)</th>
<th>Atm. Absorbed (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall (Oct)</td>
<td>11.2</td>
<td>-0.2</td>
<td>-11.0</td>
</tr>
<tr>
<td>Winter (Nov-Feb)</td>
<td>No Data</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td>Spring (Mar-Apr)</td>
<td>3.8</td>
<td>2.8</td>
<td>-6.6</td>
</tr>
<tr>
<td>Summer (May-Sept)</td>
<td>-33.4</td>
<td>31.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Excessive Summer Cloud Cover

There is considerable evidence to suggest that the model simulated excessive cloud cover during summer. Summertime simulated outgoing TOA solar radiation was excessive by 31 Wm$^{-2}$ compared with satellite estimates. At the same time, the summer TOA solar flux under clear sky conditions had a bias of -6 Wm$^{-2}$ on average – much smaller and in the opposite sense. This suggests that excessive cloudiness, which of course has a relatively high albedo, was responsible for the excessive outgoing flux. Cloud cover estimates based on AVHRR brightness temperatures also suggest the model is excessively cloudy, though these observed estimates are somewhat uncertain. May-August monthly average diurnal cycles indicate that the bias in both TOA outgoing solar flux and NSSR peaked during mid day and were small in the early morning and early evening. This is suggestive of excessive convective rather than stratiform cloud.

Long Wave Radiation

Satellite estimates of TOA outgoing long wave radiation were available for November 1998 to March 1999: results are summarized in Table 2. While the night time bias remains more or less steady, the daytime bias steadily improves after the winter solstice with increasing sun angles over the basin. An examination of Basin averaged T$_{\text{max}}$ and T$_{\text{min}}$ during this period shows that while T$_{\text{min}}$ indicates a more or less constant cold bias (all year, in fact), T$_{\text{max}}$ improves dramatically from
March until June. This pattern is consistent with the LW flux bias, and may be reflecting a known night time cold bias within CLASS 2.7 (e.g. Delage et al., 2002) – a problem that has been addressed in CLASS 3.0. Note that the TOA LW bias may be a result of too much (high) cloud being simulated in the model, or surface temperatures that are too cold, or a combination of both. While there is no clear evidence for the former, the latter has certainly been demonstrated above. Also, assuming an emissivity of 1, a cold bias of 1°C on an average temperature of -10°C would lead to a LW bias of -4 Wm\(^{-2}\), roughly consistent with the March results.

<table>
<thead>
<tr>
<th>Year</th>
<th>Nighttime LW Bias (Wm(^{-2}))</th>
<th>Daytime LW Bias (Wm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>9811</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>9812</td>
<td>-14</td>
<td>-10</td>
</tr>
<tr>
<td>9901</td>
<td>-10</td>
<td>-8</td>
</tr>
<tr>
<td>9902</td>
<td>-13</td>
<td>-7</td>
</tr>
<tr>
<td>9903</td>
<td>-11</td>
<td>-5</td>
</tr>
</tbody>
</table>

Table 2. Long wave radiation bias (CRCM - OBS) for November 1998 to March 1999. (from Feng et al., 2003).

Albedo

Clear sky TOA solar radiation flux can be used to examine surface albedo characteristics. Results for June-September 1999 show excessive TOA fluxes over the mountainous western part of the Basin, suggesting surface albedo must be too high there. This could be the result of excessive simulated snow cover, or the incorrect characterization of land cover (i.e. vegetation). The clear sky June-September flux bias also clearly indicates the three great lakes in the basin. In this simulation, in the absence of a lake model, we have simply “filled in” the lakes with nearby soil and vegetation which have a much higher albedo than open water. The monthly average surface albedo at 21 UTC (all sky conditions) for March suggests values of 0.3-0.4 over much of the Basin. This appears to be somewhat too high over the boreal forest, where values around 0.2 are typically observed throughout the winter, and perhaps somewhat too low over more northerly tundra regions. The problem may again be connected with an incorrect characterization of land cover.

3. Land Surface Characterization

Analysis of this CAGES Water Year simulation highlights a number of issues related to our characterization of the land surface. Figure 1a shows our estimate for the first soil layer of CLASS based on our 1 km resolution land surface data set aggregated up to the 51 km resolution grid of this simulation. In order to be used in CLASS 2.7 a number of modifications had to be made, which warrant some discussion here. First of all, as no inland lake model was run for this simulation, all lake points were simply “filled in” by nearest neighbour interpolation for both soil
texture and vegetation cover. Work is currently underway to represent both resolved (indicated in Figure 1) and sub-grid scale lakes in the CRCM, and we hope to report some progress on this next year. Figure 1 also suggests significant areas of surface rock. It is certainly unlikely that large areas (1 grid cell represents 2600 km²) can be covered with unbroken shield, and even locally (as any visit to the area will attest) large trees can be seen springing up through cracks in the surface rock. However, CLASS handles rock as impermeable and unvegetated. To get around this limitation, rock has been removed from the first soil layer and replaced by nearest neighbour interpolation as was done for the lakes. Finally, a considerable fraction of the land surface shown in Figure 1 is characterized by organic soils. Organic soils have considerably different thermal and hydraulic properties than mineral soils, and the addition of an organic module to CLASS 3.0 is a major enhancement to previous versions. However, CLASS 2.7 (the current version in the CRCM) handles organic soils poorly. As with surface rock, some of the problem is related to the relatively coarse resolution of 51 km. Organic soil is deemed capable of supporting surface ponded water to much greater depths than mineral soil. However, it is unlikely that such large areas as even a single grid cell will not have some outlet somewhere for this surface water – yet this is not represented in CLASS 2.7. The result is large areas of standing water throughout much of the year. Figure 1b indicates this for August 1, 1999. Such large areas of standing water can certainly be expected to perturb the surface climate, though the extent to which this has influenced our current simulation has not been assessed.

Figure 1. First layer soil texture and moisture characteristics for the CRCM: (a) 51 km resolution soil type aggregated from the CRB land surface database; (b) August 1, 1999 surface soil moisture content from the CAGES WY simulation. In (b), moisture contents in excess of the depth of the first soil layer (10 cm) represent surface ponding.
4. References


The Foothills Orographic Precipitation Experiment (FOPEX):
Introduction and Preliminary Results

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Summary

The foothills region of Alberta is a significant source of spring runoff for the Prairie Provinces and the Mackenzie Basin. Unfortunately, this region is poorly instrumented and therefore represents a gap in our observations and knowledge of precipitation east of the Rocky Mountain barrier. The installation of six surface stations along an elevation transect in the Alberta foothills will hopefully lead to a better understanding of foothill precipitation accumulations and processes. The FOPEX transect is located between Caroline and Limestone Mountain at elevations ranging between 1070 and 2120 metres above sea level. Final installations were completed in October 2001. Preliminary results show a general increase in precipitation with elevation at an average rate of 40 mm/1000 metres in elevation. However, since site installation, precipitation has been below normal for 7 out of 14 months with a precipitation deficit of 108 mm over the course of the 2001/2002 Water Year (WY). Monthly and seasonal precipitation accumulations have been used to assess the quality of GEM Quantitative Precipitation Forecasts in the region. Results for the 2001/2002 WY suggest that GEM is underestimating cold season precipitation but overestimating warm season precipitation.

1. Introduction and Site Description

Orographic precipitation and precipitation processes east of the Rocky Mountains are inadequately measured, poorly modelled, and not well understood. Although precipitation and precipitation processes are better understood on the windward side of the Rocky Mountains (i.e. Barry, 1981), less attention has been paid to lee phenomena. Precipitation in the foothills of Alberta is a significant contributor to stream discharge that eventually flows across the Prairie Provinces via the Saskatchewan River Basin or through the Mackenzie River Basin. Quantifying and understanding precipitation in this region is therefore important to flood and water resource forecasters in Alberta, Saskatchewan, Manitoba, and the Northwest Territories.

One of the ways to estimate and distribute precipitation in the foothills for the purpose of hydrological models is the use of gridded Quantitative Precipitation Forecasts (QPFs) derived from the GEM operational forecast model (i.e. Strong et al., 2002). QPF forecasts from GEM are relatively easy to verify in non-mountain regions as there tends to be more precipitation gauges, but this task becomes more difficult in complex terrain where gauging is sparse and usually limited to valley locations. A better understanding of the relationship between precipitation and elevation may improve QPFs and the ability to accurately distribute precipitation in complex terrain.
The objectives of FOPEX include:

1. quantify precipitation at various elevations in the foothills,
2. develop a relationship between precipitation and elevation (at various time scales),
3. assess the quality of Quantitative Precipitation Forecasts at various elevations in this region, and
4. assess the impact of regional phenomena such as upslope atmospheric flow on precipitation accumulations.

Some ancillary objectives include examining spring snowmelt processes in the foothills, addressing moisture sources for precipitation, and modelling the hydrological cycle of small watersheds within the study region.

The FOPEX study region is located southwest of Rocky Mountain House, Alberta, near the southern boundary of the North Saskatchewan River Basin (Figure 1). The sites are distributed over the elevation range 1070 to 2120 metres above sea level (masl) at roughly 200 m elevation intervals (Table 1). The distance between the highest and lowest stations is roughly 45 km. The sites were located based on elevation, exposure to the east/north-east, and accessibility.

Figure 1. Location of the FOPEX transect in south-central Alberta.
Table 1. FOPEX site locations and elevations.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Site</th>
<th>Latitude (decimal degrees)</th>
<th>Longitude (decimal degrees)</th>
<th>Elevation (m.a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caroline</td>
<td>AB0</td>
<td>52.09253°</td>
<td>114.86697°</td>
<td>1070</td>
</tr>
<tr>
<td>Clearwater Ranger Station</td>
<td>AB1</td>
<td>51.98742°</td>
<td>115.24074°</td>
<td>1280</td>
</tr>
<tr>
<td>Marble Mountain East</td>
<td>AB2</td>
<td>51.90136°</td>
<td>115.18771°</td>
<td>1440</td>
</tr>
<tr>
<td>Marble Mountain West</td>
<td>AB3</td>
<td>51.90530°</td>
<td>115.22595°</td>
<td>1640</td>
</tr>
<tr>
<td>Limestone Ridge East</td>
<td>AB4</td>
<td>51.88597°</td>
<td>115.37246°</td>
<td>1950</td>
</tr>
<tr>
<td>Limestone Ridge</td>
<td>AB5</td>
<td>51.91647°</td>
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<td>2120</td>
</tr>
</tbody>
</table>

The sites are named according to their relative elevation with AB0 being the lowest in elevation and AB5 being the highest in elevation. Meteorological equipment is identical at AB1, AB2, AB3, AB4, and AB5 with the exception of a Vaisala surface pressure sensor at AB1, AB3, and AB5. Each site is equipped with a Geonor accumulating precipitation gauge, a Hydrological Services tipping bucket rain gauge, a SR50 sonic snow depth sensor, a HMP35 temperature and humidity sensor, and a RM Young wind monitor (installed at gauge height). AB1 and AB5 are equipped with a modem and cell phone for data retrieval. The AB0 site has less instrumentation than the others but is equipped with a Belfort high capacity accumulating precipitation gauge, a cup wheel anemometer at gauge height, a SR50 snow depth sensor and a Campbell 107F temperature probe. Snow surveys were performed periodically during the 2001/2002 accumulation period and will be performed monthly during the 2002/2003 accumulation period.

Several of the FOPEX sites were installed in July 2001 but installation was not fully completed until October 2001. Since initiation, all sites have been fully operational with the exception of AB2 that experienced some vandalism during the summer of 2002. The data collected to date allow for the analysis of one complete WY (Oct-2001 through Sept-2002).

Conveniently, Alberta Forestry operated a climate station at the Clearwater Ranger Station (co-located with the AB1 installation) nearly continuously during 1961-1990. Although some gaps occur in the data set, this provides the 1961-1990 climate normals for comparison with current data sets. This station is still operated for forest fire weather purposes but is only maintained and archived during the critical forest fire period.

2. Preliminary Results

Monthly precipitation at each of the six sites is shown in Figure 2. Note that the bars are plotted from left to right in order of descending elevation with the last bar (black) representing the Clearwater Ranger Station 1961-1990 normal precipitation. Missing bars represent missing data and not zero precipitation (i.e. AB4 and AB2 in August 2001, and AB2 from July through September of 2002). Direct comparisons can be made between the Clearwater Ranger Station
normal precipitation and the AB1 observed precipitation. Precipitation measurements shown are currently uncorrected for wind-induced under catch. This phenomenon will affect the higher elevation sites more than the more sheltered lower elevation sites. It is estimated that corrections will result in an increase in cold season accumulated precipitation at AB4 and AB5 by up to 20-30%. Wind correction curves for the Geonor T-200 accumulating precipitation gauge are currently in development.

The graph shows the monthly precipitation at the FOPEX sites and the 1961-1990 normal monthly precipitation at the Clearwater Ranger Station.

Examination of Figure 2 shows that precipitation in the region has been below normal from August through December of 2001, returning to normal or above normal between January and May of 2002. Drier than normal conditions persist through June and July of 2002 with normal or above normal precipitation occurring between August and September of 2002. Normal precipitation over the course of the water year (October through September) at the Clearwater Ranger Station is 652 mm with only 544 mm (measured at AB1) received in the 2001/2002 WY (83% of normal).

From Figure 2, the increase in precipitation with elevation is often prominent (i.e. March, April, and May 2002) but this is not always the case (i.e. December 2001, June-July 2002). Although below normal precipitation is also of interest, current analysis has focused on months with normal or above normal precipitation. With the exception of November 2001, precipitation generally increases with elevation (Figure 3). The average increase (excluding November) is 40 mm/1000 m elevation (35 mm/1000 m when November 2001 is included). There seems to be
a marked difference in slope between cold months (November 2001, January-March 2002) and warm months (April, May, August, and September 2002). This difference is likely due to gauge undercatch of snow that is dependent on wind (Goodison et al., 1996). Since the higher elevation sites (AB4 and AB5) are more exposed, undercatch will be more significant. Correction of these accumulations will increase the slopes of the monthly precipitation-elevation relationship which should approximate warm season values near 50 mm/1000 m elevation change. This can only be verified after correction curves have been applied to the precipitation data. It also needs to be determined if the relationship is non-linear. There is a strong possibility that precipitation increases with elevation but then plateaus or decreases with increasing elevation. This can only be determined with a longer collection period. All slopes have to be considered approximate until more precipitation data is collected.

Figure 3. Relationship between elevation and FOPEX monthly precipitation (months shown have precipitation above or equal to 1961-90 normals).

Monthly observed precipitation totals were compared with accumulated GEM 12-Hour QPFs for the 2001/2002 WY (Figure 4). A transect of three GEM grid cells was selected in the proximity of the FOPEX sites to represent the same elevations as AB1, AB3, and AB5. The elevations of the grid cells matched closely to the FOPEX site elevations. However, it should be noted that the model elevations represent an average cell elevation while the FOPEX sites represent a spot elevation. Generally, GEM underestimates precipitation during the cold seasons and overestimates precipitation during the warm seasons at all elevations. Looking at three-month seasons for the 2001/2002 WY, summer (June-July-August) is the only period of overestimation, and along with spring (March-April-May), are the only periods where the bias clearly increases with elevation. The strong dry bias in spring has implications towards spring snow pack assessment, snowmelt, and runoff and needs to be explored further.
Figure 4. Monthly bias in GEM QPFs as compared to FOPEX observations at AB1, AB3, and AB5 (Bias = FOPEX – GEM).

For the 2001/2002 WY, annual GEM precipitation was 687, 601, and 499 mm (highest elevation to lowest elevation) while observed precipitation was 749, 634, and 544 mm (highest elevation to lowest elevation). This represents a dry bias in the model of 5 to 8% with no clear relationship with elevation.

3. Future Direction

With a year of data collected for FOPEX, preliminary analysis has provided some interesting insight into the elevation-precipitation relationship. It has also provided an indication as to the performance of GEM QPFs in complex terrain, although more data and analysis is required to make conclusive statements. As the project progresses, the analysis discussed above will be updated and relationships modified as required.

Some exploratory analysis has been undertaken to examine the role of upslope atmospheric flow on enhancement of precipitation, using GEM gridded wind data cross-referenced with 12-hr or 24-hr observed precipitation accumulations. This analysis is in its infancy and will be the subject of future discussions.

Other future directions of FOPEX include hydrological analysis of some of the smaller watersheds in the vicinity of AB3, possibly involving WATFLOOD. University and inter-departmental partners, with data support from the Climate Research Branch, have expressed
interest in this work. Other potential research interests not yet pursued include identifying and quantifying source regions of moisture available for foothills precipitation and developing atmospheric moisture budgets for the study area. The importance of spring snow melt to water resources and flooding events warrants examination of snowmelt processes. This work will be undertaken in conjunction with work on the smaller watersheds.

4. References


Climate System, Cloud and Precipitation Studies

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1. Objectives

The objectives of this study are:

• to document the nature of clouds and precipitating systems over the Mackenzie basin and better understand their role in the climate system, and

• to 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 special IPIX observations made at Fort Simpson during CAGES as well as 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 have utilized data from the Carvel radar, geostationary satellite, and surface weather stations. The Saskatchewan basin studies have utilized the 1948-2001 NCEP/NCAR re-analysis dataset. Comprehensive studies of the Mackenzie climate system were completed earlier and they now serve as benchmarks for the Saskatchewan studies.

3. Results

A number of results were obtained over the last year on different aspects of this work.

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, and they cover on average about 60% of the sky. The IPIX radar observations made during CAGES are being used to examine the statistical characteristics of clouds over the Fort Simpson area and to assess model capabilities. For example, during the observing periods, multiple-cloud layering was present for about 20-25% of the time and individual layers ranged up to 8 km thick.
Rainfall Events

The seven largest rain-producing systems that occurred during the spring and summer of 1999 within the southern Mackenzie Basin and in the vicinity of Edmonton were examined. First of all, and as typical, these seven events made up about 50% of the region’s annual rainfall. For this particular period, the storms were almost all banded, produced rainfall mainly through stratiform processes, and typically had very small anvil regions. The storms occurred under conditions of weak wind shear and were generally linked with moisture entering the region from the south. The Global Environmental Multiscale (GEM) model was able to simulate some aspects of these storms but had considerable difficulty with the flow fields occurring within them.

Saskatchewan Basin

Given that progress has already been made on better understanding the Mackenzie basin climate system through the 1994/95 water year and other efforts, the emphasis has now shifted to the Saskatchewan basin. The NCEP/NCAR reanalysis data are being used for initial studies. It was found, for example, that very low water vapour transport occurred into the Saskatchewan basin during the winter of 2000/01. It is suggested that the subsequent lack of storms and snowfall (and the ensuing reduction in runoff) contributed to the drought conditions experienced during the summer of 2001. Over the 2000/01 water year, the Prairies actually experienced the greatest reduction in precipitable water (integrated water vapour content) of any part of the continent (Figure 1). Preliminary work has started on the examination of RCM information over this region but comprehensive results will not be available until 2003.

![Figure 1. Precipitable water anomalies (mm) for the period of 1 September 2000 to 31 August 2001 over North America as deduced using the 1948-2001 NCEP/NCAR re-analysis information.](image-url)
4. **Relevance**

These issues are directly relevant to MAGS overall objectives. 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 one can properly handle these then one cannot properly address longer time scales either. And, 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**

This work is being carried out in consultation with, in particular, David Hudak, Bob Kochtubajda, Kit Szeto, Murray MacKay and Brian Currie.

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 tremendously and their vertical structure has been documented and is being better understood through the special measurements made during CAGES. Episodic precipitation events are one of the features of the long-term climate that must be well-handled; typically about seven or so of these account for 50% of a region’s annual rainfall. And, there are fundamental differences in the water fluxes affecting the Mackenzie and Saskatchewan River basins; more of the moisture for the Saskatchewan basin comes from the Gulf of Mexico and this (as well as other factors) leads to many differences in the water vapour and precipitation features of the two basins.

7. **Publications**

*Journal Articles*

Liu, J., R.E. Stewart and K.K. Szeto, 2002: Moisture transport and other hydrometeorological features associated with the severe 2000/01 drought over the Canadian Prairies. (submitted to Journal Climate)

Whillans, S., R.E. Stewart, D.R. Hudak and B. Kochtubajda, 2002: Large accumulation rainfall systems occurring near Edmonton during the CAGES water year. (submitted to Journal of Hydrometeor.)


Liu, J. and R.E. Stewart, 2002: Water vapour features over the Saskatchewan River basin. (submitted to Journal of Hydrometeor.)

Conference Papers


Atmospheric Enthalpy Budget for the Mackenzie River Basin

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1. Objectives

1. To calculate and document the basin-scale atmospheric enthalpy budget, as well as its mean seasonal and inter-annual variability for the Mackenzie River Basin (MRB).

2. To investigate the large-scale and local processes responsible for the occurrence of anomalous warm/cold episodes or seasons over the Mackenzie basin from the perspective of the atmospheric enthalpy budget.

The study of the atmospheric enthalpy budget for the MRB is important because: (a) the enthalpy term is the largest component in atmospheric energy budgets; (b) the basin is one of the major heat sink regions in the global heat budget during the winter; (c) in association with 'b' the basin is a source region of cold continental polar (cP) air mass; and (d) a strong warming signal has been observed over for MRB, especially during the cold season. The study of the enthalpy budget is therefore important for both the basin-scale and global water and energy budget studies, in regards to 'a' and 'b'. The budget study will also allow physical insights to be gained on processes that govern the large-scale atmospheric thermodynamics of the basin, and thus a better understanding of the cold air mass development and associated anticyclogenesis, as well as the nature of the observed warming signals. We are particularly interested in the effects of the interactions between the large-scale atmospheric flow and the basin’s physical environment in affecting the atmospheric thermodynamics of the basin.

2. Progress

Calculation of Enthalpy using NCEP Reanalysis Dataset

The atmospheric specific enthalpy $H$ is defined by $H = Cp T$, where $Cp$ is the specific heat capacity and $T$ is temperature. The equation governing the change of (vertically-integrated) $H$ over an atmospheric column is obtained by applying the first law of thermodynamics to the column:

$$\int \frac{\partial H}{\partial t} dp = \frac{1}{g} \int \left( -u \frac{\partial H}{\partial x} - v \frac{\partial H}{\partial y} - \omega \frac{\partial H}{\partial p} + \alpha \omega + Q \right) dp \quad (1)$$

where $u$, $v$, $\omega$ are x-, y- and pressure velocities, $\alpha$ is specific volume and $p$ is atmospheric pressure. The first two terms within the integral on the RHS represent horizontal advection, the third term is vertical advection, the fourth term is the adiabatic effect associated with vertical
motions and the fifth term represents diabatic effects. The vertical advection and adiabatic terms will be combined into a single term (called the “vertical” term) in the following discussion. The 6-hourly and 2.5º resolution National Center for Environmental Prediction (NCEP)/NCAR reanalysis dataset was used to calculate the basin-averaged and vertically-integrated $H$, as well as the individual budget terms in Equation 1 for the period 1970-1999.

**Studies of Anomalous Warm/Cold Winter Seasons and Episodes**

The warmest and coldest winters (DJF) for the MRB during the study period were identified and H-budgets for these anomalous seasons were examined. Physical processes responsible for the occurrence of these anomalous winters were investigated by examining the corresponding large-scale atmospheric circulations affecting the basin, as well as their correlation with low-frequency climate modes (e.g. PNA, ENSO). In addition to the study of anomalous winters, the occurrence of extended extreme cold/warm winter periods and their associated H-budgets were also examined to gain insights on the processes affecting the formation of these extreme winter thermal conditions within the basin.

**3. Results**

**H-budget Climatology**

The mean seasonal variability of the vertically-integrated and basin-averaged $H$ is presented in Figure 1. As expected, the basin-average $H$ correlates well with the mean surface temperatures and both exhibit strong seasonal dependence for a high-latitude continental basin like the MRB.

![Figure 1. 30-year normal monthly variation of surface temperature and enthalpy over the Mackenzie River Basin, 1970-99.](image)
The seasonal atmospheric heat balance for the basin is illustrated in Figure 2 which shows the 30-year mean individual budget terms for the different seasons. During most of the year (except during the summer), the basin gains atmospheric enthalpy through net horizontal transport of sensible heat into the basin by the mean westerly and the adiabatic warming associated with the net sinking over the lee side of the Rockies, and loses heat through radiative loss to space. During the summer (JJA), the basin actually gains net radiation which is balanced mainly by the net cold advection into the basin.

![Figure 2. Mean seasonal variation of H-budgets.](image)

The mean H-budget for the basin basically echoes some previously know facts in atmospheric general circulation and energy balance studies that the Earth receives net radiation at lower latitudes; the general circulation transports this energy poleward and this energy is lost back to space in the form of long-wave radiation at higher latitudes. On the regional scale, the atmospheric heat balance could be affected significantly by the local environmental conditions and their effects on the large-scale flow. This is particularly true for the MRB due to its location which is immediate downstream of a major mountain range (i.e., the Rockies) and its relative proximity to the Pacific Ocean. The combined land/sea contrast and mountain blocking effects induce significant disturbance to the mean westerly flow, especially during the winter. In particular, they produce a stationary long wave pattern with a ridge over the west coast of North America and a trough over eastern North America (which is part of the well-known wave number 2 pattern that characterizes the mid-latitude boreal winter atmosphere). The MRB is therefore under the influence of a mean westerly which transports warmer air into the region from the North Pacific, and a mean northerly flow which transports colder air into the region from the high Arctic (Figure 2).
The blocking effect of the mountain range also affects significantly the vertical motion of the mean flow. In particular, the air is forced to rise (sink) on the windward (lee) side of the mountain. Associated with this rising/sinking motion is the adiabatic cooling (warming) on the windward (lee) side of the mountain. Within the MRB, the results (Figure 2) show that the adiabatic warming effects play an important role in the basin’s heat balance (i.e. its magnitude is bigger than the net horizontal advection). Note that there would have been no net heat gain in the atmosphere if the flow was totally adiabatic (e.g., if there were no net condensation, i.e. precipitation, occurring in the rising air). However, there will be a net heat gain in the air flow traversing the mountain if precipitation results from the upslope flow.

These results lead one to hypothesize that both the advection of warm moist oceanic air into the continent and condensation at the windward side of the mountains would be enhanced (reduced), and hence producing anomalously warm (cold) periods over the basin when the flow entering the continent is strengthened (reduced). It should however be noted that the magnitude of the stationary long-wave ridge at the west coast (and hence the cold air advection by the mean northerly flow) also has a direct relationship with the magnitude of the low-level onshore/upslope flow, and thus complicating the effects of large-scale atmospheric flows on the heat balance of the basin, as shown in the results from the study of H-budgets for the basin during anomalous winter presented below.

Anomalous Warm/Cold Winters

The composite enthalpy budget anomalies for the 5 warmest and 5 coldest winters (extremes in basin-average DJF surface T) for the basin are given in Figure 3. It can be noted that anomalous cold winters in the basin are characterized by a slight decrease in warm advection into the basin by the mean westerly, a large decrease in the cold air advection into the basin by the mean northerly, a substantial decrease in the subsidence and associated adiabatic warming over the basin, and an increase in radiational loss from the basin. The net anomalous cooling associated with the latter two processes overcompensated the warming effects associated with the weaker cold advection into the basin and produced the anomalous cold conditions for the basin. Examination of the large-scale conditions associated with these cold winters show that the anomalous cold winters were results of weakened onshore/upslope flows into the continent that could be attributed to a weakened Aleutian Low over the N. Pacific Ocean which occurred frequently during periods of low PNA index.

On the other hand, anomalously warm winters over the basin are characterized by enhanced (reduced) warm (cold) air advection into the basin by the mean westerly (northerly) which together produced a weak net cooling effect compared to normal conditions, enhanced sinking and adiabatic warming over the basin, and an increase in radiation loss from the basin. The increase in subsidence/adiabatic warming effects overcompensate the net cooling effects of the enhanced radiational loss and produced the anomalous warm conditions over the basin. Examination of the large-scale conditions associated with these warm winters show that the anomalous warm winters were results of enhanced onshore/upslope flows into the continent that could be attributed to a strengthened Aleutian Low over the N. Pacific Ocean which occurred frequently during periods of high PNA index.
Figure 3. Composite anomalous H-budgets for five warmest/coldest winters.

**Anomalous Warm/Cold Episodes and Anticyclogenesis**

Extreme and extended warm/cold winter periods for the basin (defined as periods that have basin average surface temperatures that are 7°C above/below normal for at least 7 consecutive days) were identified and the H-budgets for these anomalous periods were examined (not shown). The biggest changes in the H-budget terms for the cold extreme periods are in the “vertical” term. In particular, the mean subsidence and associated adiabatic warming over the basin reversed into mean uprising and associated adiabatic cooling during the development of these cold episodes. Examination of the synoptic conditions for these events shows that a weak ridge building into the basin from Alaska was coupled with a weak low located over the west coast of Canada to produce an easterly gradient wind that went up the eastern slope of the Rockies, and producing the adiabatic cooling in the heat budgets. Such a situation is quite similar to “cold air damming” events that have been observed quite frequently over southern regions. The adiabatic cooling effects act together with radiational cooling to produce a large pool of cold air along with pressure rise (anticyclogenesis) over the basin. The sequence of events observed during the development of cold air mass over the basin was compared to those hypothesized in earlier theories (e.g. Wexler, 1936 and Curry, 1984) and found that earlier theories do not give an accurate account of the development in general. These discrepancies reflect the neglecting of the important roles played by the interactions between the large-scale flows and the basin topography in the development of these features in earlier theories.

H-budgets for the extreme warm events echo those of warm DJF in general except with larger magnitude anomalies. The synoptic conditions associated with these events are typified by a strong low located just south of Alaska, which along with the semi-persistent ridge located over the southern Rockies, forced a strong onshore/upslope flow across the Canadian west coast. Lee
troughs are often produced when the strong flow crossed the mountains along with extreme warming over the basin.

4. Relevance

The present research is relevant to the overall MAGS objective to better understand and model the energy and water cycles in high latitude as well as their response to climate change. The work also contributes to MAGS Water and Energy Budget Studies (WEBS).

5. Networking and Collaboration

Collaboration will be initiated with Profs. P. Yau and J. Gyakum who had investigated anticyclogenesis and anomalous winters over the basin by using different approaches. In addition, the PL had organized and lectured for the Model Cross-Training Workshop, being the local organizer and participated in the WEBS workshop, participated in the CAGES/Data Workshop and MAGS Annual Meeting.

6. Summary

The basin-scale atmospheric enthalpy budgets, as well as its mean seasonal and inter-annual variability for the MRB, were investigated with the NCEP reanalysis data. The large-scale and local processes responsible for the occurrence of anomalous warm/cold episodes or winters over the basin were studied from the perspectives of atmospheric enthalpy budgets. It is found that the large-scale atmospheric circulations can interact with the physical settings of the MRB, namely its proximity to the Pacific Ocean and the presence of continuous mountain barriers to its west, to amplify the atmospheric thermal response of the basin to changes in large-scale atmospheric conditions. Results from this study also enhance our understanding of the physical processes involved in the development of cold air mass over the basin.

5. Recent Publications


Szeto, K.K., 2002: Atmospheric enthalpy budgets for the Mackenzie River Basin. Part I: Applications to understanding the inter-annual variability of basin’s winter temperatures. (in preparation for Journal Climate)
Szeto, K.K. and H. Tran, 2002: Atmospheric enthalpy budgets for the Mackenzie River Basin. Part II: Applications to understanding extreme winter temperature events of the basin. (in preparation for Journal Climate)


MacKay, M., K. Szeto et al., 2002: Surface water and energy balance during the CAGES water year from the Canadian Regional Climate Model. (submitted to the Journal of Hydromet., CAGES special issue)


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Anticyclones, Winter and Summer Time Precipitation Systems over the Mackenzie River Basin

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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. A secondary objective is to study anticylogenesis often associated with blowing snow in the Canadian Arctic. Our approach is through the development and use of mesoscale models with realistic representation of microphysical processes and the analysis of the global dataset.

2. Progress

In accordance with the time line set out in our MAGS-2 proposal, we will complete the extension of the microphysics scheme to a double moment scheme in MC2 and begin the simulation of precipitation systems in high latitudes by the end of 2002. This step has been completed together with progress in other areas. Specifically,

1. we have completed the implementation of a double moment microphysics scheme in MC2,
2. we have completed a simulation of a CAGES hailstorm and modelled the growth of hailstones within the storm,
3. we are beginning the analysis and modelling of severe summer rainfall events over the Mackenzie River Basin (MRB) for the cases of 20-22 July 2000 and 27-29 July 2001,
4. we completed a first study of the large-scale mass balance effects of blowing snow and surface sublimation using the ECMWF re-analysis (ERA15) dataset, and
5. we are beginning a compilation of a global climatology of anticyclones using ERA15.

3. Results

Development of Double-moment Microphysics Scheme in MC2

Microphysical processes affect the water budget of precipitation systems at high latitudes. In numerical models, these processes are parameterized. Schemes that predict only the mass mixing ratio of the hydrometeor categories are called “single-moment” bulk schemes. Although they are computationally efficient, there are some severe limitations imposed by diagnosing, rather than predicting, the total number concentration. Ph.D. student Jason Milbrandt has developed a double-moment approach which allows both the mass mixing ratios and the total number
concentrations of each hydrometeor type to be predicted. The scheme includes six distinct hydrometeor categories: cloud, rain, ice, snow, graupel and hail. The scheme was first tested in the context of a two-dimensional kinematic model where the air flow is prescribed and resulted in realistic distribution of modelled precipitation. The scheme has been incorporated into MC2 and will be applied to the simulation of high-latitude precipitation systems.

Simulation of a CAGES Hailstorm and Hail Growth Processes

Yau et al. (2002) simulated the 11 May 1999 high-latitude hailstorm observed during the CAGES (Canadian GEWEX Enhanced Study) field experiment using MC2 with a grid size of 10 km. Even though there was dynamic forcing associated with the passage of a shortwave trough, the amount of convective available potential energy (CAPE) was small and it was found that the hailstorm cannot be simulated realistically without improving the surface properties through the introduction of another soil type. The result demonstrated the importance of surface processes in the production of summer precipitation over the MRB.

To gain further insight into the mechanisms that allowed pea-sized hail to form in the shallow storm, Reuter and Brimelow used the HAILCAST model, which combines a time-dependent hailstone model with a steady-state one-dimensional cloud model. The growth of hail starts with hail embryo introduced within the storm updraft. The embryo has an initial diameter of 300 µm, originating from the shedding of water from the surface of melting hail already present in the cloud. The rate of accretion is determined by the mass and heat budgets of the hailstone, which depend on the hailstone's size and cloud conditions (such as updraft speed, cloud liquid water content, and temperature).

Results from the HAILCAST model suggest that the observed pea-sized hail grew mostly by dry growth, i.e. the hailstone collects supercooled droplets, which freeze on impact. Wet growth was important only near the cloud base. The low tropopause, low CAPE convection was found to be very sensitive to fluctuations in surface temperature and humidity values. The size of the maximum hail depends crucially on the combination of temperature and dew point values. With the continued improvement of mesoscale models, it should soon become feasible to feed model forecast soundings into a hail growth model like HAILCAST to obtain the maximum expected hail size.

Analysis and Modelling of Severe Summer Rainfall Events over the MRB

During summer months, the hydrological cycle of the MRB is largely affected by rainfall. Gerhard Reuter identified 18 severe rainfall events over the MRB with accumulated rainfall exceeding 150 mm between 1921 and 2001. Reuter, Dupilka, and Brimelow analyzed the synoptic regimes for two such major rainfall events that resulted in flooding over northern Alberta and significant discharge in the MRB. The synoptic setting differed: a quasi-stationary mesoscale convective complex (MCC) developed in the July 2000 case, interspersed with intermittent convection which was triggered by the interaction of the outflow boundaries. In contrast, the 2001 case was a classic example of lee cyclogenesis with strong synoptic forcing. Using the HYSPLIT, software available from the NOAA website, trajectories were calculated to identify the source regions of
the moisture. It was found that the Pacific Ocean was not the source region in both cases; instead
the moist air came in from the east. For the 27-29 July 2001 case, the moisture-laden air likely
originated from the Gulf of Mexico. A strong southerly jet carried the maritime air from the Gulf
via Texas and Kansas to the Dakotas several days prior to the heavy rainfall event. Heavy
downpours occurred first over the Dakotas before the moisture-laden air moved on to Manitoba,
Saskatchewan and Alberta and precipitated over the MRB catchment area. It is indeed intriguing
that moist air is carried from the tropical ocean waters to the midlatitudes by the wind, causing
rain in the MRB, and ends up in the Arctic Ocean.

Yau and M.Sc. student Shih-Li Jou performed a simulation of the 27-29 July 2001 case using
MC2. A 96 hour simulation captures the development and the movement of the synoptic weather
system, with good timing and location of the lee cyclogenesis. A higher resolution 24 hour
simulation yields wind and pressure fields similar to those analyzed. The modelled rainfall
accumulation indicates good agreement with the spatial distribution of rainfall obtained from rain
gauges and as estimated from the Carvel radar. Work is underway to merge the MC2 flow field
with the HYSPLIT software to refine the trajectories of moist air parcels.

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

Dery and Yau (2002) conducted a surface mass balance study of the polar regions with an
emphasis on several cold season processes. The water budgets were computed using the ECMWF
re-analysis data (ERA15) for the years 1979-1993 inclusive at a horizontal resolution of 2.5º. The
results demonstrate that both surface (11 mm a⁻¹ SWE) and blowing snow sublimation (4 mm a⁻¹
SWE) are two important processes on global scales. On smaller scales, the Antarctic continent
and the MRB lose mass on the order of 29 mm a⁻¹ SWE through these processes, disposing 17-
20% and 7% respectively of the total annual precipitation over these regions. Although the first of
its kind, the study provides only a first-order estimate of the contribution of surface sublimation
and blowing snow to the surface mass balance because of limitations with the dataset and some
uncertainties in the blowing snow process.

**Climatology of Anticyclones**

Motivated by the findings of Dery and Yau (1999) that blowing snow events near Yellowknife are
often associated with anticyclones and lee cyclones, Evangelia Ioannidou is compiling a global
climatology of anticyclones using the ERA15 dataset. A sophisticated model was used to track
anticyclones through their lifetime over different parts of the globe to yield characteristic
properties like the speed of motion, intensity, and growth rate. Analysis was also made on the
distribution of tracks and the frequencies of anticyclogenesis and anticyclolysis. By using mean
sea level pressure (MSLP) as a defining criterion and by decomposing the MSLP field into
contributions from different wavelength bands, it was found that the MRB represents one of the
preferred regions in northern latitudes for the development of anticyclones. As an example,
Figure 1 shows that for the winter (December, January, and February) of 1980-1981, the MRB
represents one of the regions with a distinct maximum in anticyclonic activity – with intense
anticyclones approximately 25 percent of the time (Figure 1a), 5-6 anticyclogenesis events
occurred during the winter (Figure 1b), and the mean intensity of the identified anticyclones is around 1038 hPa (Figure 1c).

A significant issue that emerged from the ERA15 climatology is the interannual and intraseasonal variability in the intensity and the distribution of anticyclonic activity in the MRB. This issue will be studied further in the next year.

Figure 1. Climatology of large scale (6500-3000 km) anticyclones for the winter of 1980-1981: a) Percentage of time that an anticyclones occurred over a 106 km² surface area (the numbers should be divided by 3.6 to arrive at the actual percentage), b) number of genesis events per 106 km² surface area, and c) mean intensity of anticyclones in mean sea level pressure (hPa) above the climatological mean. For the Mackenzie region, the climatological mean is 1022 hPa.
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 are starting to collaborate with Charles Lin to study the effect of surface schemes on a CAGES hailstorm. Both Reuter and Yau attended the March 22-23, 2002 CAGES and Data Workshop in Edmonton. A number of presentations were made at the 36th Congress of CMOS in Rimouski.

6. Summary

We made progress in developing better representation of microphysical processes to model winter and summer time precipitation over high latitudes. We have found that the property of the surface was important in the initiation and development of summertime precipitation systems and hail over the MRB. We are beginning to study the water budget associated with several severe rainfall events that affected the basin. We obtained a first order estimate of the effect of blowing snow and surface sublimation over the MRB. We have initiated a climatological study of anticyclones which contribute to blowing snow events.

7. Publications

Refereed Journals


Cao, Z., R.E. Stewart and M.K. Yau, 2002: Revisiting the physical processes associated with the clear-sky greenhouse effect over high latitudes. (submitted to Meteoro. Zeitschrift)


*Conference Presentation*

Scale Dependence of Radar-Retrieved and Model Precipitation

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1. Objectives

The objectives of this project are:

- to examine the scale dependence of radar-retrieved and model-simulated precipitation for the Mackenzie Basin, and
- to compare such dependence in radar and model data to obtain a better characterization of precipitation.

2. Progress

The first goal of the project is to produce radar precipitation maps and establish the precision of these measurements. We have developed a number of algorithms that eliminate the contamination of precipitation measurements from ground clutter and overestimation by melting particles. A first procedure for extrapolation to ground of measurements at the height of the radar beam has been implemented. We are well advanced now on a second version of the algorithm for extrapolation to ground that is based on the optimal estimation of the vertical profile of reflectivity.

Error structure is determined by real time simulation of measurements at far range (and aloft) from the observed structure of radar reflectivity at short range. The comparison of the simulated measurement extrapolated to ground and the actual value at ground gives the error.

A procedure for radar calibration using disdrometric information was developed and is being evaluated by a comparison with the calibration obtained by polarimetric radar information. This test is made on the McGill S-band radar (the only Canadian radar with polarimetric capability).

The development of the software for the above tasks was made on the McGill radar first. Then we obtained high-resolution data from the King Radar (of which the Carvel and Spirit River radars are clones) to test our algorithm on systems as those covering the Mackenzie basin before the software can be implemented on the Carvel and Spirit River radars.

Evaluation of the attenuation at C-band (the frequency of the radars covering the MAGS region) was made and methods of correction for attenuation in rain and on the radar radome were developed and will be tested in the near future.
In collaboration with Charles Lin, work is being done on the question of model validation. This requires a proper solution to the problems of optimal estimation of precipitation from radar. But it also involves a number of specific questions to consider: what are the scales for which we should expect models to be capable of giving reliable results (not overly dependent on model parameters such as size of the domain, grid spacing, etc.). Only information on the reliable scales should be validated. Thus, comparison of radar data with models should be made as a function of scale.

The first task is to develop and test methods of scale decomposition appropriate for the precipitation fields. Two alternative techniques have been extensively explored: Fourier decomposition and Wavelet decomposition. For the former a fast Direct Cosine Transform (DCT) algorithm was used. DCT, as opposed to a fast Fourier Transform, has the advantage of mitigating the problem of lack of periodicity in the observed precipitation fields. However, sharp gradients will produce the Gibbs effect and ripples far away from the precipitation regions are generated. Using a logarithmic precipitation scale, which tends to result in gradients that are linear in space, can diminish this effect. Nevertheless, the Gibbs effect is not totally eliminated.

Wavelet transform, on the other hand, can be applied to fields that have very sharp gradients and consequently a linear scale of rainfall can be used. If the Haar wavelet is used as the base of scale decomposition the interpretation of the associated filter is simple: it is the running mean over a two dimensional window (as opposed to a periodic wave filter).

In anisotropic fields, such as often occur in precipitation, particularly at the larger scale, Wavelet Transform also permits to some extent taking the anisotropy into account by using rectangular Haar wavelets.

At this stage we are inclined to concentrate of the wavelet scale decomposition as the most appropriate method of analysis.

3. Results

Figure 1 shows an example of a radar precipitation expressed in dBZ (proportional to log R) filtered by the two methods to roughly equivalent resolutions. The filtered images produced with WT are of much lower spill-off as compared with the DCT filter due to the periodicity of the base functions in the DCT.

If the model is run at a grid spacing of say 3 km its precipitation outputs should be compared with the radar images as filtered above (taking the average over five model grid points as the minimal averaging for which we can expect a meaningful model result).

Figure 2 shows the power spectrum of the case shown in Figure 1. This is perhaps the most basic information from radar patterns against which model outputs can be validated.
Figure 1.
Left image: 2km-CAPPI map with a 2x2 km resolution on a 240x240 km domain from the CARVEL radar
Left bottom image: same with scales smaller than 16x16 km filtered out by WT.
Right bottom image: same with wavelengths smaller than 22 km filtered out by DCT.

Figure 2. Wavelet power spectrum of log R for the precipitation pattern shown in Figure 1. The horizontal coordinate was chosen from large to small scales as customary in Fourier power spectra.
First model-radar comparisons were made using the US composite maps, of which Figure 3 is an example for two situations. The choice of US composites as the test bed for our development of work methodology is the unavailability at this stage of a digital composite that includes the Canadian network. The motivation for using large-scale composites is the possibility of large phase errors in the model outputs that must be corrected before a comparison of model and radar can be made at the scale of a single radar.

Figure 3. Left: radar precipitation patterns at the continental scale. Right: the same precipitation patterns as simulated by the GEM model (24h forecast). These cases occurred on 2 June 1999 and 25 May 2001, both at 1:24 AM.

4. Relevance

MAGS-2 concentrates on the modelling of the major components of the Mackenzie Basin physical system to improve our predictive capability for water resource problems. Our study is relevant to MAGS-2 goals as precipitation is a key hydrometeorological variable and its prediction remains a challenge.

Beside the critical importance for MAGS, our study of error structure of radar precipitation measurements will benefit the entire Canadian radar network by providing algorithms that will be incorporated into the operational software for quantitative precipitation estimates (QPE).
The project greatly benefited from work done funded by other grants, particularly the project funded by CFCAS related to radar data assimilation that require the detailed knowledge of the radar data error structure.

5. Networking and Collaboration

Collaboration with Charles Lin and John Gyakum is ongoing throughout the project. We are in close relationship with researchers from the Meteorological Service of Canada in all matters of QPF.

6. Summary

Techniques to describe the scale dependence of the structure of precipitation have been developed. These techniques are applied to radar data and model outputs so that model validation can be made scale dependent.

The two methods of analysis studied were Direct Cosine Transform (DCT) and Wavelet Transform (WT). Given the large dynamic range of rain rate values and the lack of periodicity in precipitation fields WT appears to be the technique of choice.
B. LAND SURFACE STUDIES
1. Objectives

The goal of this project is to use the CAGES AVHRR database to develop a better understanding of the MAGS energy and water balance. The AVHRR database consists of 2200 scenes covering June 1998 to September 1999. The current project objectives are:

1.1 Develop AVHRR derived time series of water temperatures. The time series are to be used jointly with investigators engaged in quantifying the role of lakes and surface moisture in the Mackenzie River Basin water and energy cycle.

1.2 Continue previous work on the estimation of land surface temperature in relation with elevation, latitude, land surface type, soil moisture and lake water distribution. Knowledge of these fields and their variability has impacts on the resulting aggregated datasets used in model initialization.

1.3 Expand AVHRR work to evaluate the land surface temperature maps produced by TERRA/MODIS. This methodology can be applied to comparative studies with other research basins.

1.4 Update documentation on the website and increase the accessibility and usability of the CAGES data set.

1.5 Increase the synergetic use of MAGS data with other researchers and participate in joint publications.

2. Progress

- AVHRR time series of water temperatures were derived for April 1999 to September 1999 for 52 of the water bodies of size larger than 100 km² and a few smaller ones. Results were submitted for publication (Bussières and Schertzer, submitted 2002). [Objectives 1.1 and 1.5]

- Representativity of weather station air temperature observations was studied as function of land cover (Bussières, 2002a). An update was also presented at the MAGS WEBS meeting (Bussières, 2002b). [Objective 1.2]

- Website documentation and data access were produced. See section 4 below (Networking and Collaboration) for details. [Objectives 1.4 and 1.5].

- Determination of the "cloud/no cloud" mask continued. The cloud mask is now determined for the periods July-September 1998 and April-September 1999. See section 4 below (Networking and Collaboration) for details. [Objective 1.5]
2. Results

- The seasonal temperature trends of the water bodies over the Mackenzie basin were described using a quadratic function of time. Figure 1 shows these seasonal trends in 1999 for lakes ranging from Great Bear lake (area of 30,764 km²) to smaller lakes like Lake Prelude (18 km²). The characteristic times (e.g. the estimated time when water is completely free of ice) and amplitude for each water body were determined from the fitted curves to the quadratic equation. There is quite a variety of characteristic times and amplitudes for the MAGS water bodies studied so far. The most important factor affecting amplitudes and their time of occurrence is latitude. Size and depth were not very significant factors. Because of the difficulty to determine simple empirical relationships, data assisted physical modelling of water bodies should be encouraged.

- For the first time ever, the seasonal temperature cycle of Great Bear Lake was determined. From the seasonal trend curve of Great Bear Lake, the maximum fitted temperature is 6.8°C, compared to 13.7°C for Great Slave Lake as a whole. Actual fluctuations up to 7°C above these values are observed in the unfitted data time series.

- Figure 2 compares the distribution of maximum AVHRR land surface temperatures ($T_s$) for 1994 with maximum air temperatures ($T_a$) at the available weather stations inside the Mackenzie basin. The AVHRR $T_s$ values sampled at the stations are higher by a few degrees than the $T_a$ values measured at stations. The histogram in Figure 2 allows us to evaluate the effect of spatial sampling at the station locations. The thick line for the distribution of AVHRR $T_s$ has a small amplitude and a larger spread than the dashed line which represents information from air temperature stations alone. The large spread in the AVHRR data is an indication of the larger variety of elevation ranges and types of land covers represented with AVHRR. The distribution of AVHRR $T_s$ is also smoother than the distribution of station $T_a$ because of the large number of AVHRR samples. Studies of the data spatial distribution of data should be useful in assessing the accuracy of other $T_s$ dependent variables, such as evapotranspiration.

- The use of maximum $T_s$ values was proposed as a benchmark for modelling and MODIS validation (Bussières, 2002a). One possible benchmark is the linear relationship between elevation and maximum AVHRR-derived $T_s$ over the MAGS region in 1994. The slope of this relationship is $-4.5^\circ$K km$^{-1}$. This slope was matched in RCM runs. Analysis of the CAGES data (1998 and 1999) is not completed yet but initial results suggest an AVHRR-derived slope of $4.0^\circ$K km$^{-1}$ for 1998 data and $-5.4^\circ$K km$^{-1}$ for 1999 data.
Figure 1. Seasonal (1999) AVHRR water temperature curves plotted from the coefficients for the water bodies (Bussières and Schertzer, submitted, 2002). Triangles indicate the peak temperature in each curve.

Figure 2. Histograms of maximum temperature (land and air) for the 1994 warm season over the MAGS region.
3. Relevance

- The AVHRR-based land surface temperatures (LST) should serve in intercomparisons with the recently released TERRA-MODIS land surface temperature product, and in model validations. Since LST is intrinsic to the energy balance, the knowledge of the spatial variability of LST as observed with AVHRR or MODIS is useful to understand and quantify the variability in the energy budget terms like heat and water vapour fluxes.

- The AVHRR-based lake water temperature data should serve in the near future in the initialization and validation of the MAGS coupled models (RCM/CLASS/WATFLOOD plus lake model). Lake components of the model will enable the computation of the water vapour fluxes from the Mackenzie water bodies. The temperatures can also serve as one of the inputs to water vapour flux computations made using Granger's lake model. The water flux is one of the components of the MAGS water and energy and water balance computations.

- AVHRR-derived cloud information as obtained with this project will serve MAGS cloud and synoptic studies.

4. Networking and Collaboration

- Existing website documentation on the CAGES AVHRR database and the CAGES AVHRR data products were rewritten. CAGES AVHRR cloud thumbnails were produced. MAGS data secure access to the AVHRR cloud thumbnails was arranged in cooperation with the MAGS Data Manager. MAGS data secure data request capability for the digital values of all the 2200 scenes was also arranged in cooperation with the MAGS Data Manager. Colour composite images of various scenes were provided on request to other investigators who used them in presentations and publications.

- Work on the AVHRR temperature estimates for water bodies is in collaboration with work from scientists engaged in direct observation and modelling of various lakes (Schertzer, Rouse, Oswald, Granger, Spencer).

- Joint publication efforts are underway (Hudak, Stewart, Burford) using the CAGES AVHRR cloud mask and cloud top temperature information as one of the experimental datasets.

- Collaboration in the use of AVHRR data are expected to develop further with the RCM/CLASS/WATFLOOD modelling effort (Verseghy, MacKay, Szeto).

- A proposal was made to collaborate with GAME scientists on topics related to lake water temperatures.
5. Summary

The hydrological basin of the Mackenzie River is a 1.8 million km$^2$ region that extends over parts Yukon, North Western Territories, British Columbia, Alberta and Saskatchewan. Except for its southernmost tip, where the town of Jasper is located, most of the Mackenzie basin is located north of 55ºN. Most Canadians do not visit these parts and do not have a chance to grasp the immensity of the Mackenzie basin. As part of on-going efforts to understand and predict the Canadian and the global climate, Canadian climate scientists have been busy determining precisely the interaction of water, snow and ice with climate. They have set up observations sites in remote areas. They also use satellites to observe the heat loss from the surfaces (thermal infrared). This current exploration work has shown the large variability over the Mackenzie basin of environmental factors like the surface temperatures of land and lakes.

For the first time ever, the seasonal temperature variation of the very large and remote Great Bear Lake was observed. The observations suggest that Great Bear Lake, which is the third largest Canadian Lake, is probably the coldest lake of the whole basin, and with the shortest ice-free season. Great Bear Lake is a deep lake, with a maximum depth near 413 m. It is quite remote and there are just a few settlements and lodges around the lake. It is not surprising that only satellite data could be used to describe the temperature variation of the lake. Research continues to determine the role of lakes of various shapes, sizes and location in the Mackenzie basin play in affecting local weather and moisture contribution to the atmosphere, and how these lakes interact with climate.

6. Publications


Using an Off-line Surface Model for Water and Energy Budget Studies and for Coupling with an Atmospheric Model in Various Configurations

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1. Objectives

The objectives of this project are to develop and test an off-line surface model to handle the vertical exchanges of water and energy between the atmosphere and the underlying surface at various horizontal resolutions, and to test various ways to couple this model with an overlying atmospheric model.

2. Progress

The off-line surface model with the ISBA scheme has been upgraded to work on a more general configuration and to accept cumulative fluxes as inputs. The model has been tested to reproduce the results obtained in a fully coupled run of GEM/ISBA. Experiments were performed to compare the outputs of the surface model at a resolution of 3 km with those of a 30 km run over the entire North America. Work was done to contribute to version 3.0 of CLASS, which is to be implemented in the surface model.

3. Results

The first important result of the study was establishing the importance of forcing the surface model with cumulative radiative fluxes and precipitation in order to reproduce in the off-line model the results obtained during a full run of GEM/ISBA. With cumulative fluxes, the time interval between successive atmospheric inputs can be as large as six hours. This produces results of equivalent quality to those obtained with a one hour forcing with only instantaneous fluxes.

The preparation of geophysical data and the derived model parameters as inputs to the land surface model were also found to be of great importance. In preparing the geophysical fields of vegetation and soil types at various resolutions, we found that the source of these data, the algorithm for aggregating these data at a desired resolution and the recipes to translate these into the parameters used by the ISBA model each had a sizable impact on the results of the model at certain times and locations. We realized that care must be given to choosing the best land surface descriptors and to identifying the sensitivity of the surface model to its parameters before engaging into a study of the impact of horizontal resolution of the model itself. In one of our examples presented at the Physics Parameterization Workshop in Montreal, two different software packages were used to prepare the vegetation types for input to the surface model. Over Wisconsin, one indicated ‘long grass’ while the other indicated ‘mixed wood forest’. It so happens that the ‘long grass’ category is associated in ISBA with a 30% vegetation cover while...
most other types have much larger percentages. The combination of this difference in the vegetation type and the assignment of a low value to an important parameter of ISBA resulted in very different thermal regimes for the case that we studied, one with large evapotranspiration and one with large sensible heat flux.

4. Relevance

Although this study is not dedicated to the MAGS area, we believe that it is relevant to MAGS objectives in providing tools to be used in a land data assimilation system presently in construction at MSC-Dorval. As presented at the MAGS WEBS Workshop in Toronto, a land data assimilation system is a very valuable tool to estimate the surface water and energy budgets over the MAGS region. This study will also allow us to estimate uncertainty in the budgets due to land descriptor and model deficiencies (for both CLASS and ISBA).

5. Networking and Collaboration

- Collaboration with Diana Verseghy in preparing CLASS 3.0 and in making it available to the MAGS community through the GEM and CMC/RPN library.

6. Summary

Work in using off-line surface models to interact with atmospheric models and to prepare a land data assimilation system is in progress. A few factors having impacts on the quality of the results have been identified. The high resolution experiments planned should be of interest to the MAGS community since they include the Mackenzie River basin. The land data assimilation system in construction could within a few years serve to improve the current estimates of the water and energy budgets.

– ◊◊◊ –
Multi-Objective Parameter Optimization of Land Surface Models 
applied to the Mackenzie River Basin

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1. Objectives

The objective of this study is to develop a simplified land surface scheme (LSS) out of ISBA 
(Interactions Soil–Biosphere–Atmosphere; developed by Noilhan and Planton, 1989), and 
possibly BATS (Biosphere Atmosphere Transfer Scheme; Dickinson et al., 1986, 1993), that 
addresses the northern environment issues of the Mackenzie River Basin.

2. Progress

In January 2002, we upgraded the SGI workstation Octane II, initially set up in 2001, with a 
72 GB hard drive, and we were able to get S. Belair of MSC in Montreal to provide us the codes 
for ISBA. Unfortunately we couldn’t get the codes to work, partly because they were designed 
for LINUX instead of for UNIX platforms. In April, through the MOPEX meeting at Tucson, 
Arizona, we met Ms. Florence Habets of Meteo France who kindly provided us the stand-alone 
ISBA codes. Using these codes we set up ISBA for stand-alone tests with data from CAGES, 
similar to those we did with BATS in 2001.

By May 2002, we got some encouraging results by forcing ISBA with the 1999-00 CAGES data 
of Fort Simpson, NWT. The three ISBA simulations were: (i) 1-layer snow cover with force-
restore temperature variation, (ii) 3-layer snow cover with force-restore temperature variation, 
and (iii) 3-layer snow cover with heat diffusion. The 1999-00 winter season had a significant 
warm spell in late December, e.g., +14°C on December 23. The simulated snow depth followed a 
similar pattern as the observed snow depth with the exception of the response to the ablation 
event. In terms of predicted versus observed snow depth, the 1-layer snow model predicted much 
shallower snow depths than the 3-layer model because the 1-layer model predicted much higher 
snow densities (297 kgm⁻³) than the 3-layer models (both 155 kgm⁻³). Since ISBA uses snow 
density to estimate other quantities, these differences can have a significant impact on the timing 
of spring runoff.

We also set up ISBA for stand-alone tests with data of the Paddle River Basin (PRB) of central 
Alberta, located at the southern tip of Mackenzie River Basin. To calibrate the a priori 
parameters of ISBA and BATS with respect to PRB data and to evaluate model sensitivity to the 
chosen parameter values, we incorporated the Multi-Objective Complex Evolution Algorithm 
(MOCOM) into ISBA and BATS. MOCOM was developed by Yapo et al. (1998) as a multi-
objective extension of the Shuffled Complex Evolution Algorithm of Duan et al. (1994). 
Calibration runs for both BATS and ISBA were performed using data from the 1998-99 snow 
season of PRB. For BATS, 27 parameters were optimized simultaneously, and 22 parameters 
were optimized for ISBA. The objective functions minimized were near-surface soil temperature
(\(T_g\)) HMLE and runoff HMLE. Because ISBA took approximately 10 times longer than BATS to simulate a given time period, we executed the BATS runs using an initial population of 300 while the ISBA runs used a population of 50. ISBA was run with interactive vegetation, sub-grid runoff, three soil layers, and the three-layer snow option. The simulated snow water equivalent (SWE) was compared with observed SWE.

Some preliminary sensitivity tests on some \textit{a priori} parameters of ISBA were also conducted. So far, the lack of observed data such as SWE and \(T_g\) prevented us from extending the sensitivity tests and parameter calibrations to other stations such as Macmillan Pass, Lindberg Landing, Lower Carp Lake, Fort Good Hope, Dease Lake, and Watson Lake.

We have not yet modified ISBA algorithms with regard to northern processes such as permafrost, snow interception by canopy, sublimation, and blowing snow partly because in the last few years, ISBA has already been extended to include an interactive vegetation scheme (Calvert \textit{et al.}, 1998), a sub-grid runoff scheme (Habets \textit{et al.}, 1999), a third soil layer (Boone \textit{et al.}, 1998), and a multi-layer snow scheme (Boon and Etchevers, 2000), and partly because of the initial difficulty we encountered with the ISBA codes of S. Belair, MSC. We are currently extensively testing ISBA of Meteo France using some of these options.

3. Results

Summaries of the final parameter statistics for BATS and ISBA are shown in Tables 1 and 2 respectively. In both cases, most of the parameters fall into relatively tight ranges, with the ISBA parameters tighter than the BATS parameters (15 out of 22 ISBA parameters and only 3 out of 27 BATS parameters have a coefficient of variation CV less than 3%). The final results of the MOCOM optimization in objective space for BATS and ISBA are shown in Figure 1. The BATS calibrations matched the observed ground temperature about 10% better than the ISBA calibrations, but ISBA was much better at simulating runoff. Figure 1a shows how runoff accuracy must be sacrificed in order to reduce Near-surface Soil Temperature (\(T_g\)) HMLE from 0.52 to 0.515. Figure 1b does not show such a strong trade-off, partly because the initial population of ISBA was much smaller than that of BATS, and thus the parameter space was not as thoroughly searched.

For each LSS, a single set of parameters was selected midway along the objective space solution curve (the 150th point in Figure 1a for BATS, and the 25th point in Figure 1b for ISBA). Figures 2a and 2b show the variation in observed and simulated \(T_g\) for BATS and ISBA respectively. For both LSSs, \(T_g\) falls well below freezing during the winter months, even though the observed temperatures never fall more than a few degrees below 270ºK. This is probably due to a combination of three factors: (i) the use of the force-restore method, (ii) how the LSS models the soil-snowcover relationship, and (iii) that LSS links \(T_g\) too closely to the current air temperature. For ISBA, this can be seen in the very strong variation during the autumn of 1998 and the spring of 1999, and is partly to do with how ISBA treats surface soil. Unlike BATS, the depth of the top layer of soil is not an input parameter but is fixed at 1 cm. The weaker variation of \(T_g\) in BATS during the autumn and spring is due to the fact that the top layer is much thicker than in ISBA. The cold soil temperatures predicted by both LSSs during the winter months is also due to the
use of the force-restore method, where $T_g$ is continually restored towards the deep-soil temperature. The deep-soil temperature is usually assumed to be the long-term average air temperature, which becomes problematic when the snowcover insulates the soil. As a result, even though ISBA includes an explicit snow scheme, the surface soil still gets cooled to the long-term air temperature. For ISBA, the temperature variation is almost non-existent during the winter months when ISBA’s use of an explicit snow cover scheme effectively insulates the soil. BATS, however, assumes that the snow temperature is equal to $T_g$, and so it cannot have an insulating effect. The soil temperature is therefore free to vary with air temperature. These problems can be addressed by using an explicit snow layer, diffusive heat flux instead of the force-restore method, and by using ground heat flux instead of ground temperature to calibrate the LSSs.

Figure 2c and 2d show the time variation of observed and predicted daily average runoff. BATS fails to simulate both the flood peaks and the timing and volume of the spring runoff due to its inability to simulate a realistic snowcover. ISBA, which partitions its outflow into surface runoff and gravity drainage, simulated the long-term runoff accurately, but cannot produce either of the two spring peaks partly because it requires that the soil column be fully saturated (Habets et al., 1999). Despite the inclusion of sub-grid variation in soil capacity, ISBA runoff is still dominated by gravity drainage (Habets, personal communication), which is a much slower process than surface runoff. This can be fixed by changing the range of various parameters (e.g., increasing maximum clay content and the maximum $\beta$ parameter), increasing the initial population size in MOCOM, or by changing the way surface runoff is managed by ISBA.

Figures 2e and 2f show the time variation of observed and predicted SWE for BATS and ISBA. The SWE data was not used to calibrate the LSSs. BATS is incapable of properly simulating the evolution of the snow cover primarily because the force-restore method tends to keep the soil temperature low, causing MOCOM to search for the easiest way to warm up the soil. This turned out to be maximizing the snow free area, which would allow the soil to warm up faster during the occasional warm spell. Since the snow temperature is assumed to be equal to the soil temperature in BATS, this would also lead to higher mid-season snowmelt. As a result, BATS never develops a significant snow cover and therefore fails to simulate the spring runoff. Because ISBA has an explicit snow cover, it does not suffer from this defect.

The inability of BATS to adequately calibrate a single snow season demonstrates its shortcomings in northern environments and the importance of using an explicit snow cover scheme. The failure of ISBA to match the observed winter soil temperatures demonstrates the limitations of using the force-restore method without deep-soil temperature forcings, and thus the importance of using a diffusive heat flux scheme.
Table 1. Summary statistics of parameter values for MOCOM-BATS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>$\bar{x}$</th>
<th>S.D.</th>
<th>CV (%)</th>
<th>Solution Range</th>
<th>Optimization Range</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td>vegc</td>
<td>Maximum vegetative cover</td>
<td>0.73</td>
<td>0.018</td>
<td>2.53</td>
<td>0.64 0.86</td>
<td>0.62</td>
</tr>
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<td>seaf</td>
<td>Seasonal variation of veg cover</td>
<td>0.35</td>
<td>0.018</td>
<td>5.02</td>
<td>0.27 0.42</td>
<td>0.20</td>
</tr>
<tr>
<td>rough</td>
<td>Roughness height (m)</td>
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<td>0.805</td>
<td>10.62</td>
<td>3.15 8.92</td>
<td>0.00</td>
</tr>
<tr>
<td>displa</td>
<td>Displacement height (m)</td>
<td>3.62</td>
<td>0.421</td>
<td>8.13</td>
<td>2.63 6.87</td>
<td>2.40</td>
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<td>rsmin</td>
<td>Minimum stomatal resistance (sm$^{-1}$)</td>
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<td>7.943</td>
<td>7.99</td>
<td>54.21 140.7</td>
<td>40</td>
</tr>
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<td>xla</td>
<td>Maximum LAI</td>
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<td>0.235</td>
<td>4.57</td>
<td>1.22 3.26</td>
<td>1.00</td>
</tr>
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<td>xai0</td>
<td>Minimum LAI</td>
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<td>0.199</td>
<td>7.56</td>
<td>1.75 2.95</td>
<td>1.50</td>
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<td>Stem area index</td>
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<td>0.099</td>
<td>4.03</td>
<td>1.50 2.95</td>
<td>1.50</td>
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<tr>
<td>sqrdi</td>
<td>Inverse square root of leaf dimension (m$^{0.5}$)</td>
<td>6.98</td>
<td>0.270</td>
<td>3.87</td>
<td>5.90 8.85</td>
<td>5.50</td>
</tr>
<tr>
<td>fc</td>
<td>Light dependence of stomatal resistance (m$^{2}$W$^{-1}$)</td>
<td>0.05</td>
<td>0.002</td>
<td>4.83</td>
<td>0.03 0.065</td>
<td>0.03 0.065</td>
</tr>
<tr>
<td>depuv</td>
<td>Depth of upper soil layer (mm)</td>
<td>170.1</td>
<td>3.609</td>
<td>2.12</td>
<td>157.8 197.5</td>
<td>130</td>
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<tr>
<td>deprv</td>
<td>Depth of root soil layer (mm)</td>
<td>1737</td>
<td>85.02</td>
<td>4.90</td>
<td>1020 2018</td>
<td>1000</td>
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<tr>
<td>deptv</td>
<td>Total depth of soil (mm)</td>
<td>7985</td>
<td>304.5</td>
<td>3.81</td>
<td>6502 9647</td>
<td>4000</td>
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<tr>
<td>albvgs</td>
<td>Vegetation short wave albedo</td>
<td>0.19</td>
<td>0.025</td>
<td>12.92</td>
<td>0.06 0.35</td>
<td>0.05</td>
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<tr>
<td>albvgl</td>
<td>Vegetation long wave albedo</td>
<td>0.41</td>
<td>0.031</td>
<td>7.70</td>
<td>0.20 0.57</td>
<td>0.05</td>
</tr>
<tr>
<td>rootf</td>
<td>Ratio of roots in upper soil to root layer</td>
<td>0.62</td>
<td>0.035</td>
<td>5.62</td>
<td>0.39 0.70</td>
<td>0.30</td>
</tr>
<tr>
<td>xmpor</td>
<td>Soil porosity</td>
<td>0.65</td>
<td>0.031</td>
<td>4.68</td>
<td>0.39 0.70</td>
<td>0.30</td>
</tr>
<tr>
<td>xmosuc</td>
<td>Minimum soil suction (mm)</td>
<td>137.7</td>
<td>6.730</td>
<td>4.89</td>
<td>89.46 177.2</td>
<td>85</td>
</tr>
<tr>
<td>xmoahyd</td>
<td>Maximum hydraulic conductivity (mms$^{-1}$)</td>
<td>0.15</td>
<td>0.007</td>
<td>4.54</td>
<td>0.12 0.17</td>
<td>0.085</td>
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<tr>
<td>xmwol</td>
<td>Wilting point</td>
<td>0.39</td>
<td>0.018</td>
<td>4.50</td>
<td>0.28 0.47</td>
<td>0.25</td>
</tr>
<tr>
<td>xmach</td>
<td>Ratio of field capacity to saturated water content</td>
<td>0.65</td>
<td>0.018</td>
<td>2.69</td>
<td>0.54 0.75</td>
<td>0.50 0.80</td>
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<tr>
<td>bee</td>
<td>Clapp and Hornbereger 'B'</td>
<td>5.52</td>
<td>0.622</td>
<td>11.27</td>
<td>4.58 10.24</td>
<td>2.00</td>
</tr>
<tr>
<td>skrat</td>
<td>Ratio of soil heat conductivity to that of loam</td>
<td>1.64</td>
<td>0.091</td>
<td>5.56</td>
<td>1.16 2.16</td>
<td>0.90</td>
</tr>
<tr>
<td>solour</td>
<td>Soil albedo</td>
<td>0.06</td>
<td>0.008</td>
<td>12.85</td>
<td>0.04 0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>ssw</td>
<td>Initial soil water content in upper layer (mm)</td>
<td>76.39</td>
<td>3.488</td>
<td>4.57</td>
<td>45.84 87.71</td>
<td>40</td>
</tr>
<tr>
<td>rsw</td>
<td>Initial soil water content in root layer (mm)</td>
<td>449.0</td>
<td>36.44</td>
<td>8.12</td>
<td>349.3 784.1</td>
<td>300</td>
</tr>
<tr>
<td>tsw</td>
<td>Initial total soil water content soil (mm)</td>
<td>3678</td>
<td>164.8</td>
<td>4.48</td>
<td>2522 4180</td>
<td>2500</td>
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Table 2. Summary statistics of parameter values for MOCOM-ISBA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>( \bar{x} )</th>
<th>S.D.</th>
<th>CV (%)</th>
<th>Solution Range</th>
<th>Optimization Range</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>clay</td>
<td>Clay content of soil</td>
<td>0.46</td>
<td>0.0033</td>
<td>0.73</td>
<td>0.44</td>
<td>0.46</td>
</tr>
<tr>
<td>sand</td>
<td>Sand content of soil</td>
<td>0.30</td>
<td>0.0067</td>
<td>2.25</td>
<td>0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>emis</td>
<td>Soil emissivity</td>
<td>0.96</td>
<td>0.0029</td>
<td>0.30</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>d3</td>
<td>Total soil depth (m)</td>
<td>7.43</td>
<td>0.088</td>
<td>1.18</td>
<td>6.91</td>
<td>7.52</td>
</tr>
<tr>
<td>rsmin</td>
<td>Minimum stomatal resistance (sm (^{-1}))</td>
<td>91.99</td>
<td>0.461</td>
<td>0.50</td>
<td>90.46</td>
<td>93.44</td>
</tr>
<tr>
<td>d2</td>
<td>Depth of root layer (m)</td>
<td>1.18</td>
<td>0.034</td>
<td>2.90</td>
<td>1.14</td>
<td>1.38</td>
</tr>
<tr>
<td>rgl</td>
<td>Surface resistance parameter</td>
<td>111.1</td>
<td>2.619</td>
<td>2.36</td>
<td>105.9</td>
<td>121.5</td>
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<tr>
<td>cv</td>
<td>Vegetation heap capacity parameter</td>
<td></td>
<td></td>
<td></td>
<td>6.22E-06</td>
<td>5.76E-07</td>
</tr>
<tr>
<td>lai</td>
<td>Maximum LAI</td>
<td>5.36</td>
<td>0.154</td>
<td>2.88</td>
<td>4.62</td>
<td>5.65</td>
</tr>
<tr>
<td>bslai</td>
<td>Ratio d(biomass)/d(lai)</td>
<td>0.27</td>
<td>0.014</td>
<td>5.28</td>
<td>0.251</td>
<td>0.357</td>
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<tr>
<td>htree</td>
<td>Tree height (m)</td>
<td>4.35</td>
<td>0.174</td>
<td>4.00</td>
<td>4.14</td>
<td>5.34</td>
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<tr>
<td>sefold</td>
<td>E-folding time for senescence (days)</td>
<td>21.83</td>
<td>0.449</td>
<td>2.06</td>
<td>19.78</td>
<td>22.73</td>
</tr>
<tr>
<td>veg</td>
<td>Vegetative cover fraction</td>
<td>0.80</td>
<td>0.0072</td>
<td>0.89</td>
<td>0.76</td>
<td>0.81</td>
</tr>
<tr>
<td>laimin</td>
<td>Minimum LAI</td>
<td>3.36</td>
<td>0.040</td>
<td>1.19</td>
<td>3.12</td>
<td>3.41</td>
</tr>
<tr>
<td>wgi2</td>
<td>Initial deep soil ice content</td>
<td>0.0062</td>
<td>0.0009</td>
<td>14.48</td>
<td>0.0041</td>
<td>0.0091</td>
</tr>
<tr>
<td>wg3</td>
<td>Initial deep soil moisture content</td>
<td>0.062</td>
<td>0.0003</td>
<td>0.41</td>
<td>0.061</td>
<td>0.063</td>
</tr>
<tr>
<td>wg2</td>
<td>Initial root layer moisture content</td>
<td>0.035</td>
<td>0.0040</td>
<td>11.27</td>
<td>0.022</td>
<td>0.046</td>
</tr>
<tr>
<td>wg1</td>
<td>Initial upper layer moisture content</td>
<td>0.12</td>
<td>0.0014</td>
<td>1.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>zt2</td>
<td>Initial deep soil temperature (K)</td>
<td>275.7</td>
<td>0.129</td>
<td>0.05</td>
<td>275.0</td>
<td>275.9</td>
</tr>
<tr>
<td>runoff B</td>
<td>Runoff parameter ( \beta )</td>
<td>1.96</td>
<td>0.030</td>
<td>1.53</td>
<td>1.92</td>
<td>2.12</td>
</tr>
<tr>
<td>wdrain</td>
<td>Gravity drainage parameter</td>
<td>0.056</td>
<td>0.0023</td>
<td>4.19</td>
<td>0.050</td>
<td>0.064</td>
</tr>
<tr>
<td>albedo</td>
<td>Vegetation albedo</td>
<td>0.29</td>
<td>0.017</td>
<td>5.94</td>
<td>0.24</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Figure 1. Relationships between minimizing the HMLE of generated runoff and the HMLE of near surface ground temperature ($T_g$) for the 1998-99 snow year in the Paddle River Basin using (a) BATS with an initial population of 300 (left panel), and (b) ISBA with an initial population of 50 (right panel).

Figure 2. Comparison between observed and modelled near-surface temperature from (a) BATS and (b) ISBA, daily runoff from (c) BATS and (d) ISBA, and snow water equivalent from (e) BATS and (f) ISBA for the 1998-99 snow year in the Paddle River Basin.
4. **Relevance**

ISBA and BATS can serve as an alternative to CLASS to better model the water and energy cycles of Mackenzie River Basin. The results show that calibrating the \textit{a priori} parameters of ISBA and BATS can improve model performance, but it also shows the need to modify ISBA and BATS, to incorporate northern features of Mackenzie River Basin.

5. **Networking and Collaboration**

- Dr. Al Petroniro (NWRI, Saskatoon), Sal Figliuzzi (Alberta Environment, Edmonton), Ross Herrington (Environment Canada, Regina), Jim Bryne (University of Lethbridge) – a proposal entitled “Future Water Availability in the South Saskatchewan River Basin under the Potential Impact of Climate Change” was submitted to CCAF, Natural Resources Canada.

- Drs. L. A. Bastidas, Hoshin V. Gupta, and Soroosh Sorooshian (SAHRA, University of Arizona) – Applying their Multi-Objective Complex Evolution Algorithm (MOCOM) to calibrate the \textit{a priori} parameters of ISBA and BATS.

- Dr. Charles Lin (McGill University) – Interactions on implementing the stand-alone ISBA code to Mackenzie River Basin.

- Dr. Ric Soulis (University of Waterloo) and Dr. Alain Petroniro who provided us re-analysis data of GEM archive. We provided Dr. Soulis the stand-alone ISBA codes for adding to WATFLOOD.

- Dr. Gerhard Reuter (University of Alberta) and Prof M. Shiiba (Kyoto University, Japan) – Modeling the the June 1998 Mei-yu in the Huai-he Basin in East China using the Pennsylvania State University/National Center for Atmospheric Research Fifth-Generation Mesoscale Model (MM5).

- Dr Kaz Higuch and Amir Shabbar of Meteorological Service Canada, Downsview, Ontario – a proposal entitled “Seasonal Prediction of Hydroclimatic Variables of Western Canada by Linear and Nonlinear Statistical Models” was submitted to CFCAS.

- Dr. Xu Liang (UCB) – Collaboration on hydrologic modeling and land surface scheme (VIC-3L) using MOPEX data of NOAA-AVHRR.


- Non-MAGS, MOPEX Workshop, University of Arizona, Tucson, April 8-10, 2002.


- Non-MAGS Conference, the 13\textsuperscript{th} ADP-IAHR Conference, Singapore, August, 2002
6. Summary

Two land surface schemes, ISBA and BATS were tested as simplified alternatives to CLASS to better model the water and energy fluxes of the Mackenzie River Basin. The a priori parameters of ISBA and BATS were automatically calibrated for the 1998-99 snow season of Paddle River Basin located at the southern part of the Mackenzie River Basin using the Multi-Objective Complex Evolution Algorithm (MOCOM) of Yapo et al. (1998). The performance of ISBA and BATS was assessed in terms of near surface soil temperature, daily runoff and snow water equivalent.

7. Publications


Singh, P.S. and T.Y. Gan, 2002: A semi-distributed, modified temperature index approach for snowmelt modeling in the Canadian Prairies using near surface soil and air temperature. (submitted to Journal of Hydrometeorology, CAGES Special Issue, AMS)


8. References


Modelling Surface Water Fluxes in Boreal, Tundra and Alpine Areas of the Lower Mackenzie Region


1National Water Research Institute, Saskatoon, Saskatchewan
2Simon Fraser University, Burnaby, British Columbia
3University of Saskatchewan, Saskatoon, Saskatchewan
4National Research Council, Ottawa, Ontario
5Colorado State University, Ft. Collins, Colorado

1. Objectives

The long term objectives of this study are to improve the understanding and representation of surface and near-surface processes involving the flux, phase change and redistribution of water/snow in appropriate climate and hydrologic models, and to utilize these improved models to consider the impacts of climate change on surface hydrology and related aquatic systems. This will be accomplished through the following tasks:

- define and measure the sub-grid processes controlling the fluxes of sensible and latent heat, radiation and snow melt over heterogeneous cold regions surfaces,
- test and validate a variety of hydrologic and atmospheric models, and
- consider the effect of various GCM and RCM scenarios of future climate on the hydrology of the lower Mackenzie Region.

2. Progress

During the past year we have focused primarily on:

- continued development of a consistent nine-year database of daily water balance values (snowmelt, rainfall, runoff, evaporation, and storage, plus air temperature, wind, humidity, radiation, soil heat flux) for the runoff period at both Trail Valley (TVC) and Havikpak Creeks (HPC) in the lower Mackenzie Basin near Inuvik,
- analysis and comparison of both tower and aircraft measurements of sensible and latent heat fluxes for TVC and HPC, and
- modelling the spatial variability in the radiation, latent and sensible heat fluxes over the TVC basin, with an emphasis on the spring melt period.

The following sections 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 CCAF, 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 Dataset

Preliminary results were reported in our 2001 report. We have ongoing studies aimed at improving the consistency of these data, and we plan to publish these results as both a comparison of results from Wolf Creek and the Ft. Simpson area as part of our CFCAS work, and in a comparison of water balance data from the circumpolar area as a component of an NSF funded project lead by D. Kane at the University of Alaska Fairbanks.

Comparison of Tower and Aircraft Measurements of Sensible and Latent Heat Fluxes

Analysis of the tower and aircraft measurements for both TVC and HPC are ongoing. During the last year, considerable effort has been put into carrying out a reanalysis of the aircraft data. This has included an analysis of the 1-second data, and in dividing the flight lines into shorter, 2 km, segments. Analysis of these data, and comparison to tower measurements at four sites within TVC, and comparisons to other modelling efforts will be completed over the next year. We also plan to consider the July aircraft measurements, and carry out a more detailed comparison with the results from evaporation studies by W. Rouse.

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 within a 16x16 km region that contains TVC. This spatial variability has implications to both the return of energy to the atmosphere and to the surface hydrology. The following sections outline ongoing research aimed at understanding the spatial variability of radiation and of sensible heat flux over the study areas, with a long term objective to develop appropriate modelling strategies to properly consider this variability.

Radiation

A simple radiation model, following the approach of Ranzi and Rosso (1991), is used to distribute incoming radiation by slope and aspect over the study area. In order to consider the effect of model scale, DEMs of 40 m and 400 m grid size were used.

The model was run for each hour from sunrise to sunset for 33 days during the snowmelt period from May 5 to June 6, 1999. Figures 1 and 2 demonstrate that the model provides reasonable prediction of both incoming clear sky global radiation and incoming diffused radiation for a horizontal site. Figure 3 provides an example of the modelled distribution of radiation over the basin at 04:00, 12:00 and 16:00 on May 27, 1999. In the early morning (Figure 3a), large shadowed areas can be seen to the west of the ridges, while peak radiation occurs on the east facing slopes. By midday the south facing slopes receive maximum radiation and only a very small fraction of the area is shadowed due to the high sun angle and the fairly low topography. Figure 3c shows afternoon conditions with increased radiation values on SW to W facing slopes.
The radiation values over the basin are normally distributed, with the modal class increasing from near 200 Wm\(^{-2}\) at 04:00 to 710 Wm\(^{-2}\) at 12:00, and then decreasing to 550 Wm\(^{-2}\) at 16:00. Throughout this period, the range of values is in excess of plus or minus 100 Wm\(^{-2}\).

Figure 1. Hourly values of modelled (\(G_m\)) vs. observed incoming (\(G_o\)) clear sky global radiation for 5 clear days during the spring of 1999.

Figure 2. Hourly values of modelled (\(D_m\)) vs. observed (\(D_o\)) incoming diffuse radiation.
Figure 3. Modelled radiation in Wm$^{-2}$ for May 27, 1999: (a) at 04:00 solar time. Solar Elevation = 9.8°, Solar Azimuth = 54.9°, (b) 12:00, Elevation = 42.5°, Azimuth = 180.0°, and (c) 16:00, Elevation = 30.4°, Azimuth = 249.4°.
The importance of the small scale variability during the spring can be assessed by comparing the amounts of potential snowmelt for high and low radiation locations. Potential snowmelt values were calculated using a measured average albedo of 0.65 for the snow cover over the entire 33 day melt period (Figure 4). The radiation values at opposite ends of the 2S radiation range differ in their incoming radiation amounts from 176,512 Wm$^{-2}$ to 186,783 Wm$^{-2}$. This translates to a difference of 3,595 Wm$^{-2}$ in solar energy absorbed by the snow cover and therefore available for snowmelt. Expressed in mm of snow water equivalent (SWE) this would mean a difference of 39 mm of melt over the entire domain, and 53 mm within the TVC basin. A 1S range would still lead to a difference of 10 mm (13 mm within TVC). Considering that the average end of winter SWE for open tundra areas varies from about 50 to 80 mm SWE, these differences in potential melt represent significant spatial variability in melt, with implications to the development of a patchy snow cover and runoff. Areas of late lying snow in and around TVC, which covered 4% of the basin on June 11, also have a large range in radiation with late lying snow patches on south facing slopes receiving over 20,000 Wm$^{-2}$ more radiation than those on north slopes, resulting in over 60 mm SWE of additional melt. All of the late lying snow patches had much higher than average winter snowpack since they are the remnants of slope drifts that formed in the lee of ridges during blowing snow events (Essery et al., 1999). As noted by Marsh and Pomeroy (1996), these snow patches may hold up to 33 % of the entire TVC end of winter snow.

Figure 4. Spatially distributed incoming solar radiation as difference to overall 33-day mean in Wm$^{-2}$ and as difference to potential snowmelt to overall mean in mm SWE for the original DEM (40x40 m)

An example of the effect of changing modelling scale is shown in Figure 5. In this example, a 400 m DEM was used. The general pattern of spatially distributed radiation is the same as with the 40 m DEM (Figure 4), but the range in values is decreased (Figure 6). Ongoing work is considering the impact of this on the hydrology and the implications for modelling.
Figure 5. Spatially distributed incoming solar radiation as difference to the overall 33-day mean in Wm\(^{-2}\) and as difference to potential snowmelt to overall mean in mm SWE for the resampled DEM (400x400 m)

Figure 6. Histograms for total incoming solar radiation as difference from the mean, for two resolutions (40x40 m and 400x400 m)
Wind and Sensible Heat Flux

Two wind models were used in this study, a simple wind model described by Liston and Sturm (1998) and a more complex model developed by Warmsley and Taylor (also known as the MS3DJH/3R) and applied to the TVC area for blowing snow studies by Essert et al. (1999).

The Liston model uses empirical wind-topography relationships to modify an initially uniform windfield, with wind weighting factors computed for each grid cell of the DEM from calculations of slope and curvature for that cell. This model assumes that lee and concave slopes have reduced wind speeds, and windward convex slopes have reduced wind speeds. The model was run for 8 principal wind directions for a period of 33 days (JD 125 - JD 157, May 5 to June 6). The Warmsley-Taylor Model is a linear model, developed from theoretical analysis of neutrally stratified boundary-layer flow over low hills, which generates output of distributed normalised windspeeds for 8 principal wind directions. In order to test the appropriateness of these models, a simple experiment was set up during the spring and summer of 1992, with 6 wind speed and direction stations set up around a typical hill located in the TVC basin (Figure 7).

Significant differences in the wind speed due to the topography of the hill were evident from the field measurements, with wind weighting factors ranging from 1.0 (at the top of the hill) to as low as 0.6 for leeward locations at the base of the hill (Figure 7). In all, the anemometer at the top of the hill recorded the highest average windspeed over the spring and summer periods for all wind directions. Clear differences were found for locations on the slope of the hill depending on whether they were on the windward or the leeward side of the hill.

The Liston Model overall compares fairly well to observed wind speeds (Figures 8 and 9). This is especially true for the pattern of the windward-leeward differences which are well captured. The model has problems defining the locations of highest wind speeds on the hill, as the model assumes them to be on the steepest convex part of the windward slopes while the experiment shows that the hilltop has the highest wind speeds. The Warmsley-Taylor model is also fairly similar to the observations (Figure 8).
Figure 8. Comparison of observed and modelled wind weighting factors for eight different wind directions at location 5.

Figure 9. Comparison of observed and modeled (Liston Model) wind speeds at location 5.

Figure 10 illustrates the spatially variable wind speed as estimated from the Liston model for the TVC domain. In this example, for a 45º wind direction, the wind weighting factor varies from 0.55 in the lee of slopes, to over 1.2 on hill crests. When run for the entire period of record, with temporally variable air temperature, the potential snowmelt due to sensible heat flux varies by approximately +/- 50 mm of melt (Figure 11). Again, given the shallow and variable snowcover, this is a substantial variation in melt, which has implications to the development of patchy snowcovers.
Figure 10. Basin map showing wind weighting factors for 45º wind direction.

Figure 11. Potential snowmelt due to sensible heat flux over entire 33-day model period in mm SWE as difference from the mean.
The above sections illustrate two processes resulting in variable energy fluxes and therefore melt rates over the snowmelt period. Ongoing work will integrate the effects of a variable snow pack, wind speed, air temperature, and incoming solar radiation, in order to consider the integrated 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.

References


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 and Dr. I. Macpherson on analysis of aircraft flux data
- Organization of CAGES Special Issue of the Journal of Hydrometeorology. In addition I am continuing to work with J. Gyakum on a synthesis article.
- Participation in both the 94/95 WY and the MAGS-1 synthesis articles (see reference list).

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 the importance of sub-grid square processes to both the hydrology and the atmosphere, and will result in improved model algorithms.
7. Publications

Pohl, S., P. Marsh and A. Pietroniro: Spatial variability in solar radiation during the spring melt period Inuvik, NWT. (submitted to Journal of Hydrometeorology)

Pohl, S., P. Marsh and G. Liston: Spatial variability in wind speed and sensible heat flux during the spring melt period Inuvik, NWT. (in preparation for Hydrological Processes)


—◊◊◊—
1. Objectives

General Objectives

- To fully understand and model the role of lakes in the energy and water-balance in northern Canada.
- To forecast the role that these 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
  - lake area, volume and latitude,
  - lake abundance in a geographical area, and
  - the longevity of the ice-free period for the lakes.
- To scale energy and water balance modelling from individual lakes to local, regional and macro-scales.
2. Progress

Schedule of Activities from Previous Proposal (October, 2001):

1. • Initiate documentation of lakes. Work up field data. Begin work on lake models. • Assemble NOAA AVHRR (1.25 and 5 km) skin temperature and albedo data. Fall and Winter 2001-02

2. • Continue measurements at Yellowknife lake sites. • Field measurement campaign on shallow lakes in Old Crow Flats for testing/improvements of CLIMo. • CLIMo testing and begin improvements (snow and heat flux from sediments) at several sites on GSL and other sized lakes in Mackenzie basin and Old Crow Flats Spring, Summer, Fall 2002

3. • Work up summer field data. Complete documentation of lake coverage. • Continue work on lake thermal models. • Publish results of measurement programs. • Begin analysis of temporal coherence in freeze-up and break-up dates (1.25 km AVHRR data) for lakes of various sizes. • Begin analysis of water skin temperature and albedo (1.25 km AVHRR data) for lakes of various sizes Fall 2002 Winter 2003

Actual Activities to Fall 2002:

1. Fall and Winter 2001-02

• A documentation of lake size and distribution has been initiated (Oswald, 2002).
• The consolidation of field data is well in hand with a target of spring 2003 for completion of analysis for all measurements made to date.
• The application of a 1-D model of lake thermal and energy balances has been initiated and a radiation transfer model has been successfully tested for both incoming short-wave and long-wave radiation arriving at the lake surfaces that is applicable at any high latitude location (Binyamin, 2002 – Poster presentation at MAGS 8th Annual Scientific Meeting, Jasper).
• A third year of radiation and energy balance measurements has been completed for our four research intensive lakes. These data are ready for analysis.
2. *Spring, Summer, Fall 2002*

- Conducted simulations of lake ice phenology with CLIMo and compared with *in situ* ice observations in Back Bay, Hay River, and Charlton Bay on Great Slave Lake (GSL) over a 30-year period. Results of Ménard are currently in press (Hydrological Processes).
- Compared CLIMo simulation results in the main section of GSL with SSM/I-derived freeze-up/break-up dates.
- Simulated ice normals (1961-1990) in Back Bay with CLIMo.
- Investigated the impact of climate change on ice phenology in Back Bay under various scenarios of increases and decreases in air temperature and snowfall (Ménard, 2002 – Poster presentation at MAGS 8th Annual Scientific Meeting, Jasper). Results currently being written by Ménard for journal publication.

3. *Fall 2002*

- Working up summer field data has begun and work is continuing on lake thermal modelling (Binyamin, 2002 – Poster presentation at MAGS 8th Annual Scientific Meeting, Jasper).
- Results contained in theses of Oswald (2002) and Worth (2002) are in review (Worth and Rouse, 2002) or currently been written for journal publication.
- Water skin temperatures are currently being analysed but work has not yet begun on comparison to AVHRR analysis. The latter will commence in winter 2003.
- Began assembling a surface albedo and surface temperature NOAA AVHRR time series (1.25 and 5 km resolutions) for both morning and afternoon overpasses. Data from 1995 to 2001 have been assembled to date. 1981 to 1994 will be completed by the end of 2002. This component of the project was delayed due to unforeseen technical problems at NSIDC, from where we get the original data.
- The acquisition of ENVISAT data has begun but we have not yet received any images. This will happen later this fall. Some funding has been obtained from the Canadian Space Agency to conduct a field validation campaign on GSL and other smaller lakes in the vicinity (March or April 2003).
- Chris Spence took some snow and ice measurements on GSL and other lakes last winter. He is still working up some of the winter 2001-2002 data from the meteorological stations.

3. **Results**

*The Energy Balance and Thermal Regimes of Large Lakes in the Mackenzie River Basin*

The initial phases of this research have concentrated on measurement on Great Slave Lake (GSL). In the ice-free period, we have found that the interannual variability in evaporation and heat fluxes from GSL is large and, in a very warm year when the lake ice melts early, can be as large as from the Laurentian Great Lakes. (Blanken *et al.*, 2000; Rouse *et al.*, 2002a, in review). Heat fluxes from the lake are small during the stable atmospheric period that lasts into mid-August but accelerate into the fall and winter season reaching a maximum prior to final freeze-up. This is shown for the evaporative flux in Figure 1. Evaporation is not in phase with the solar cycle but
rather is episodic being driven by meteorological processes such as storm events that both stir the lake surface waters bringing heat to the surface and entrain warm dry air into the surface boundary layer (Blanken et al., 2002). Cross lake variability in the thermal regime and fluxes is considerable. Melting proceeds from the shore areas in early summer and heating commences in these regions but there is a considerable lag into the mid-lake regions. The process reverses during winter freeze-back, the inshore areas freezing first and the mid-lake regions last. There is good agreement between lake heat storage calculated as a residual in energy balance calculations and determined from thermistor strings in a series of cross-lake buoys (Rouse et al. 2002a; Schertzer et al. 2002).

Figure 1. Evaporation rates on Great Slave Lake during three years of measurement. The data plotted are 3 day moving averages and the trend lines are 2nd order polynomials. From Rouse et al. (2002a, in review).

Modelling the Ice Cover of Great Slave Lake

The one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model or CLIMo) was used to simulate ice phenology on GSL. Model simulations were validated against freeze-up and break-up dates, as well as ice thickness and on-ice snow depth measurements made in situ at three sites on GSL (Back Bay near Yellowknife, 1960-1991; Hay River, 1965-1991; Charlton Bay near Fort Reliance, 1977-1990). Freeze-up and break-up dates from the lake ice model were also compared to those derived from SSM/I 85 GHz passive microwave imagery over the entire lake surface (1988-1999). Results show a very good agreement between observed and simulated ice thickness and freeze-up/break-up dates over the 30-40 years of observations, particularly for the Back Bay and Hay River sites. CLIMo simulates the ice thickness and annual freeze-up/break-up dates with a mean error of 7 cm and 4 days, respectively. However, some limitations have been identified regarding the rather simplistic approach used to characterize the temporal evolution of snow cover on ice. Future model improvements will therefore focus on this particular aspect through linkage or coupling to a snow model.
CLIMo was also used to evaluate the response of the ice phenology of GSL (Back Bay) to climate change. Daily climatic normals, derived from meteorological observations (1960-1991) obtained at the Yellowknife Airport weather station, were used to simulate ice normals and then modified in order to reproduce climate changes. Thus, air temperature and snow on the ground were either increased or decreased from the normals.

The results show a good agreement between the simulated ice thickness normals produced with CLIMo and the mean ice thickness observations made in Back Bay (Figure 2). The mean absolute difference (MAD) between simulated and observed ice thickness is only 5 cm. The model also does well at reproducing on-ice snow depth normals with a MAD of less than 3 cm. However, for both simulated ice thickness and snow depth normals, the results suggest that the model reproduces these less accurately during the melt season. The simulated ice cover melts more rapidly than the observations and, inversely, the simulated snow cover melts after the observations. However, in terms of the length of the ice season, the model gives very good results. Indeed, the ice cover duration (normals) is very well reproduced by the model. The simulation gives an ice-cover duration of 214 days, which corresponds to the mean duration observed at the Back Bay site.

Figure 2. Comparison of observed and simulated ice thickness and snow depth on the ice for Back Bay.

The impact of changes in air temperature and snow depth normals on ice cover duration is shown in Figure 3. The effect of deviation in the air temperature is particularly noticeable. For each degree increase or decrease in mean air temperature normal, the ice cover duration changes by six days almost linearly. The results suggest that ice cover duration is as much influenced by climatic warming than cooling. The influence of snow depth is, however, less obvious. The length of the ice season varies only by one day for each 25% increment of snow depth from the normal.
Results from the simulations made to test the sensitivity of maximum ice thickness to changes in air temperature and snow depth are shown in Figure 4. The deviation in air temperature is less significant for the maximum ice thickness than it was for ice cover duration. The deviation induces only 3 cm of difference in the ice thickness for each increase or decrease of one degree. Snow depth, on the other hand, plays a significant role in the evolution of ice thickness. A decrease in the amount of snow increases the maximum ice thickness by 17 cm for each 25% increment from the normal.
Comparative Energy Balances of different-sized Lakes in the Mackenzie River Basin

Different-sized lakes have thermal and flux characteristics ranging from those of shallow lakes and ponds, in which heat storage is small and short-term and the ice-free energy balance cycle follows the solar cycle, to large-sized lakes that are smaller than Great Slave Lake and that display intermediate characteristics to their shallow and very deep brethren (Oswald, 2002; Rouse, 2002b). On a seasonal basis, small lakes evaporate the least water and deep lakes the most and their cycles are lagged so that when small lakes are freezing in early winter, deep lakes are achieving their maximum evaporation rates (Figure 5). The heating of beneath-surface lake waters in spring and summer is primarily due to absorbed solar radiation in the photosynthetically active band (PAR). Measurements indicate that Canadian Shield lakes in the vicinity of Yellowknife tend to have small absorption coefficients for PAR (Figure 6) because both dissolved organic matter and turbidity are small. An exception is GSL where a major particulate plume from the Slave River feeds into the main body of the lake in late summer and fall. This strongly increases the absorption coefficients (Worth, 2002). It also appears to be responsive in part to releases from the Bennett Dam on the Peace River.

Figure 5. Cumulative evaporation (E) in 2000 beginning on 19 June (Day 171) and extending to the end of the respective measurement periods for different sized lakes (average depth): Gar Lake (GR: 0.5 m), Skeeter Lake (SK: 3.2 m), Sleepy Dragon lake (SD: 12m) and Great Slave Lake (GS: 32 m). (from Oswald, 2002)
Figure 6: A: Averaged attenuation coefficients for Long Lake (LO), Skeeter Lake (SK), Sleepy Dragon Lake (SD), and Great Slave Lake (GS). The linear trend line shows the increase in \( k_{par} \) for LO. Range bars represent one standard deviation. B: Secchi disc depths for LO (diagonal lines), GS (black), SD (clear), SK (shaded). (from Worth, 2002)

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 2002

- N. Bussières, Meteorological Service of Canada (MSC), on testing AVHRR-derived lake surface temperatures against measured values on different-sized lakes.
- M. Mackay, Meteorological Service of Canada (MSC) – interfacing lake models with Canadian Regional Climate Model.
- D. Swayne, University of Guelph, on lake energy balance and thermal modelling.
- P. Blanken, University of Colorado on flux measurements from Great Slave Lake.
- J. Jasper, Environment Canada, Northern Division, and R. Reid, Department of Indian and Northern Affairs, Yellowknife, on water balance of lakes in the Canadian Shield.
- 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.
- M. Jeffries and K. Morris, Geophysical Institute, University of Alaska Fairbanks, on modelling of ice from small lakes.

Conferences and Workshops – 2002

Rouse
- Jan. 11, McMaster University, Small lakes modelling workshop.
- Mar. 21-24, Edmonton, Alberta. MAGS CAGES Workshop.
- May 27-29, MSC Downsview, Ontario. MAGS WEBS Workshop.
- Sep. 20, University of Guelph, Ontario. Lake thermal modelling workshop.

Duguay
- May 22-25, Rimouski, Québec. Annual CMOS Conference. Author in presentation Sensibilité du couvert de glace de certains lacs du basin du Fleuve Mackenzie aux changements climatiques.
6 Summary

Different sized northern lakes have highly variable energy exchange characteristics. In shallow lakes, in which heat storage is small and short-term, the summer energy balance follows the solar cycle, whereas very large lakes, such as Great Slave Lake, show large thermal lag. Seasonally, small lakes evaporate the least water and deep lakes the most, and cycles are lagged so that when small lakes are freezing in early winter, deep lakes are achieving their maximum evaporation rates. Mid-sized lakes display intermediate characteristics. Lake heating is primarily due to absorbed solar radiation. Lakes in the vicinity of Yellowknife are relatively transparent because both dissolved organic matter and turbidity are small. An exception is Great Slave Lake where a major particulate plume from the Slave River feeds into the main body of the lake in late summer and fall, thereby strongly decreasing transparency.

Model simulations of ice thickness and depth of snow on the lake ice accurately depict the observations for Back Bay on Great Slave Lake. It is evident from model results, that while both air temperature and snow thickness exert influences on lake ice duration, the longevity is especially sensitive to anomalies in air temperature increasing and decreasing in fairly linear fashion as temperatures become cooler and warmer, respectively. In contrast, maximum ice thicknesses are highly and non-linearly sensitive to changes in snow depth, with ice thicknesses increasing rapidly when the overlying snow cover becomes thinner than normal, but responding minimally when the snow cover becomes thicker than normal.

7. Publications


Interannual Variability and Preliminary Thermal Modelling of Great Slave Lake

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²School of Geography and Geology, McMaster University, Hamilton, Ontario
³University of Colorado, Boulder, Colorado, USA

1. Objectives

Primary objectives of this research are the following:

• To develop compatible and consistent databases required for evaluation of lake-atmosphere fluxes and lake thermal characteristics.

• To assess the interannual variability of meteorology, radiation, lake thermal characteristics, and heat and mass exchanges from large deep northern lakes.

• To assess the predictive capability of lake thermal models applied to large deep lakes when forced with measured data, with data from Objective Analysis (one-way coupling), and to develop a coupled lake/atmosphere scheme for application in CLASS and the Canadian Regional Climate Model (CRCM).

• Collaboration with MAGS researchers.

2. Progress

2.1 Measurement Program: FY2002

The investigation on Great Slave Lake includes year-round observations in support of heat and mass exchange computations, thermal modelling and for applications in collaborative research. The FY2002 field observations consist of a winter program (September 2001-June 2002), a summer program (June 2002-September 2002), and the winter program (from September 2002 and extending into spring 2003). Summer observations are conducted at all sites indicated in Figure 1 and include meteorology, radiation and lake temperature observations from the meteorological buoys, thermistor moorings and from Inner Whaleback Island. The winter programs have thermistor observations at the ODAS and NWRI-2 sites and meteorology and radiation is observed at Hay River near the coast guard station. Meteorology and radiation is recorded at 10-minute intervals and thermistor observations are recorded every 20 minutes. These data are formed into hourly and daily values. The FY2002 databases combined with the FY1998 to FY2001 databases form the basis for evaluation of heat and mass exchanges, thermal response, lake heat storage and waves. The data have been used extensively in collaborative research (see section 5 on Networking and Collaborations).
2.4 Modelling the Thermal Structure of Great Slave Lake

A number of thermal models have been applied to the Laurentian Great Lakes (e.g. Lam and Schertzer, 1987; McCormick and Lam, 1999; Boyce et al., 1993). In this initial phase of analysis, the Dynamic Reservoir Model (DYRESM) will be used to simulate the 1-D temperature structure of Great Slave Lake. Briefly, the standard DYRESM model simulates temperature and total dissolved solids on a daily basis over the water column of a lake or reservoir. Basin geometry and hydrology and surface meteorology are the principal model inputs. The model is initialized with field observations and then is run over the simulation period. Although the model is based on a one-dimensional diffusion equation for temperature, \( T \), the model design philosophy has been to incorporate in parametric form higher dimensional processes affecting the distributions of heat and matter in the water body.

\[
\frac{A \frac{\partial T}{\partial t}}{\partial t} = \frac{\partial}{\partial z} \left( AK \frac{\partial T}{\partial z} \right)
\]

The model was originally developed for reservoirs (Fischer et al., 1979; Imberger and Patterson, 1981) and extended to lakes by Patterson et al. (1984) and the reader is referred to these sources for details. Later, Patterson and Hamblin (1988) added to the model the ability to simulate ice cover and snow cover. Rogers et al. (1995) modified the ice formation routine to better model temperate zone ice formation which has been implemented by McCord et al. (1998). The model DYRESM, despite being restricted to variation in the vertical direction, has received a wide application to lakes and reservoirs throughout the world; for examples of recent applications, see McCord and Schladow (1998) and Boyce et al. (1993).
References


3. Results

Interannual Variability of Over-lake Meteorology, Radiation, and Heat Storage

Over-lake observations of meteorology (atmospheric pressure, air temperature, surface water temperature, wind speed, relative humidity, vapour pressure), and radiation (solar and longwave radiation) have been formed into hourly and daily averages over Great Slave Lake. Initial evaluation of interannual variability has been conducted using the 1998 and 1999 database. Table 1 shows a statistical summary of variability in lake-wide averaged meteorological components for Great Slave Lake. The year 1998 was influenced by an intense El Nino. This is reflected by higher mean over-lake air temperatures, and higher surface water temperatures. In addition, 1998 was also characterized by a longer ice-free season (Walker et al., 2000) and significantly higher heat storage (2.543 x 10^{19} J in 1998 compared to 2.159 x 10^{19} J in 1999). Databases for FY2000 to 2002 are nearing completion and will be applied to the analysis of interannual variability for this lake.

Table 1. Statistical summary of selected meteorological components measured over-lake during CAGES.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Year</th>
<th>Mean</th>
<th>Max.</th>
<th>Min.</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>ºC</td>
<td>1998</td>
<td>12.9</td>
<td>23.5</td>
<td>0.3</td>
<td>4.8</td>
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<tr>
<td></td>
<td></td>
<td>1999</td>
<td>9.7</td>
<td>18.4</td>
<td>-2.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>ºC</td>
<td>1998</td>
<td>12.9</td>
<td>20.5</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999</td>
<td>9.3</td>
<td>16.9</td>
<td>0.14</td>
<td>3.8</td>
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<tr>
<td>Wind Speed</td>
<td>m s^{-1}</td>
<td>1998</td>
<td>6.8</td>
<td>15.6</td>
<td>1.5</td>
<td>2.9</td>
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<td></td>
<td></td>
<td>1999</td>
<td>6.7</td>
<td>13.7</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>%</td>
<td>1998</td>
<td>79.2</td>
<td>94.3</td>
<td>61.4</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999</td>
<td>77.7</td>
<td>91.9</td>
<td>57.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>Wm^{-2}</td>
<td>1998</td>
<td>161.5</td>
<td>328.2</td>
<td>12.3</td>
<td>89.8</td>
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<tr>
<td></td>
<td></td>
<td>1999</td>
<td>176.0</td>
<td>345.7</td>
<td>4.2</td>
<td>99.6</td>
</tr>
</tbody>
</table>

Comparison of Bulk Heat Exchange and Observations

Daily heat storage computed for Great Slave Lake based on thermistor observations applied over a 2 x 2 km grid were used to derive a 5-day mean bulk heat exchange between the lake and the atmosphere. The bulk heat exchange generally varied between 282 Wm^{-2} (spring) and -225 Wm^{-2} (fall) in 1998 compared to a smaller range 171 Wm^{-2} (spring) to -202 Wm^{-2} (fall) in 1999. Comparison of the bulk heat exchange derived from lake heat content models compares favourably with heat flux determined from Inner Whaleback Island (Schertzer et al., submitted to J. Hydrometeor.).
Thermal Modelling

One-dimensional (1-D) thermal models are representative of lake-wide average vertical temperature. Consequently, temperature observations from the thermistor moorings have been applied to a 2 x 2 km grid to derive an annual lake-wide averaged observed temperature isotherms. Figure 2 shows an example of the lake-wide average temperature isotherms and vertical temperature profiles for year 1999. Simulations from the 1-D thermal model DYRESM will be verified against the observed isotherms and profiles.

Figure 2. An example of observed 1999 lake-wide averaged isotherms and vertical temperature profiles derived by applying station temperature observations over a 2 x 2 km grid bathymetry for Great Slave Lake.

Thermal modelling of Great Slave Lake is in progress. Initial simulations will be conducted for the ice-free period and then extended over the entire year using the ice model routine within DYRESM (Patterson and Hamblin, 1988). Through collaboration with Claude Duguay, data from this investigation will be used to further develop and verify a lake ice model. These results can then be compared to the DYRESM 1-D ice simulations.

4. Relevance

This investigation builds upon ongoing research conducted to understand the processes controlling heat and mass exchange from large and small northern lakes. The lake component of MAGS-2 includes both an observational and modelling program based on collaborative university and government research. The observational program is focussed on deriving a longer-term meteorological, thermodynamic and hydrodynamic database. These data will support evaluation of interannual variability and also provide initial boundary conditions and a critical model verification dataset for models of the surface heat fluxes and thermal structure. Initial
modelling is in 1-D mode, however, research will continue with application of 3-D lake hydrodynamic model. The modelling research benefits from significant technology transfers (heat flux and thermal models) from work being conducted simultaneously on the Laurentian Great Lakes. The primary goal of this phase of our investigation is to add to MAGS-2 modelling efforts by developing a coupled lake-atmosphere model for integration with CLASS – current schemes do not include large or small lakes. Inclusion of lakes within the regional climate model is critical for reducing uncertainties in climate predictions.

This investigation has worked in close collaboration with both university and other government researchers to contribute to MAGS-2 and to achieve goals related to assessing heat and mass exchange contributions from large and small lakes. The investigation has provided detailed over-lake meteorology, radiation fluxes, and limnological components which are critical for understanding the response of lakes and for development and verification of models. There are significant ongoing collaborations as evidenced through the CAGES special issue submissions (see below) and there are numerous potential modelling collaborations that can add to achieving the MAGS goals. Participation in MAGS-2 has been made possible through funding received from the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) which contains MAGS lakes within one of its modelling components.

5. Networking and Collaboration

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

Surface temperature measured at buoy sites have been used to verify the dates of ice break-up through SSM/I (Walker, MSC) and also to help in the development and verification of lake-wide surface temperature (Bussieres, MSC). During FY2002, collaborations continued with the co-authorships on two CAGES papers submitted to the J. Hydrometeorology (see section 7: Schertzer et al.; Bussieres et al.) Temperature observations from FY2002/03 summer and winter programs will be used to further collaborations contributing to MAGS.

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 the Hay River sites, 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, McGill U.). During 2002, lake radiation data were summarized as an appendix to the MAGS-WEBS Workshop held at MSC, Downsview. Both solar and longwave radiation data continue to be collected for Great Slave Lake. It is anticipated that further collaborations with Dr. Leighton will continue.
Ice Model Development and Verification (Great Salve Lake Bathymetry)

Development and verification of ice models on Great Slave Lake are planned by Claude Duguay (U. of Alaska). During FY2002, data will be transferred to Dr. Duguay for preliminary runs of his ice model. Collaboration will continue on the testing and verification of the ice model with observations and with other lake model simulations.

Networking of Research on Lakes for MAGS through Funding from the Canada Foundation for Climate and Atmospheric Sciences (CFCAS)

Progress is being made on development and application of lake models on Lake Ontario, Lake Erie, Great Slave Lake and small lakes of the Mackenzie basin. This investigation is being funded by the Canadian Foundation for Climate and Atmospheric Sciences. A major goal is to develop a coupled lake / atmosphere model for use in CLASS and the regional Climate model. Work is continuing with collaborations between Schertzer (NWRI), Rouse (McMaster U.), MacKay (MSC), D. Lam (NWRI) and C. McCrimmon (NWRI) and D. Swayne (U. of Guelph) including others.

Hydrological Components from WATFLOOD (Advective Component for Great Slave Lake Heat Flux-Thermal Models)

Based on discussions held at the MAGS Model Cross-training Workshop at York U., there is the possibility that a first approximation of advective components based on hydrological exchanges (major inflow, major outflow, water level, runoff and precipitation) from the WATFLOOD model many be incorporated within the advective term in lake surface heat flux computations. At present there are no estimates for this component in the Great Slave Lake thermal calculations. It is anticipated that this collaboration will proceed in 2003

Data Processing and Archiving

Data collected in this study are processed in standard formats used at NWRI and which have been forwarded to the GEWEX archives in Phase I activities. Observations from the FY2002 field season are currently being processed and will be transferred to the GEWEX archives.

6. Summary

Detailed observations of over-lake meteorology, radiation fluxes and limnological components are being conducted to support analyses of interannual variability and modelling of lakes as part of the Mackenzie GEWEX Study (MAGS). Analyses of heat and mass transfers conducted during the Canadian Enhanced GEWEX Study (CAGES) in 1998/99 showed that large deep lakes such as Great Slave Lake can be significantly impacted by climatic variability. Warmer conditions in 1998 associated with an intense El Nino resulted in earlier ice melt and a longer ice-free season. This allowed greater lake heating with significantly higher heat storage than in 1999 that did not exhibit such warm conditions. The warmer conditions in 1998 also lead to higher evaporation that approached the amounts observed in some of the Laurentian Great
An understanding of the susceptibility of water resources to climate variability and change is becoming an important issue in Canada and this investigation helps to reduce uncertainty in the response of lakes to such variability. Research in FY2002 is in the initial stages of application and verification of thermal models on the MAGS lakes. This research will lead to parameterizations for development of coupled lake/atmosphere models for application in CLASS and improvement in Regional Climate Model simulations.

7. Publications and Presentations

Publications and Reports


Authored and Co-authored CAGES Submissions to J. Hydrometeor. in FY2002.


Blanken, P.D., W.R. Rouse, W.M. Schertzer and A.D. Culf, 2002: On the enhancement of evaporation from a large northern lake by the entrainment of warm, dry air. (submitted to Journal of Hydrometeor.)


Proposals Funded in FY2001-02 which include a Research Component on MAGS Lakes

Swayne, D., W.R. Rouse, W.M. Schertzer and D.C.L. Lam – Cross-evaluation of the Canadian Regional Climate Model (CRCM) and Lake Thermal Models using Observations and Objective Analysis.

Successful submission for funding to the Canadian Foundation for Climate and Atmospheric Sciences. Research to include modelling of Mackenzie Basin Lakes (Great Slave Lake and smaller lakes).

Conference Presentations


Workshop Presentations


*Workshop Attended*

MAGS Model Cross-training Workshop: York University, September 5-6, 2002.

– ◊◊◊ –
Modelling and Parameterization of Blowing Snow and Limited Fetch Evaporation

P.A. Taylor\textsuperscript{1} and J. Wilson\textsuperscript{2}

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\textsuperscript{2}Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta

1. Objectives

a) Blowing Snow

We believe that there is still considerable uncertainty concerning modelled blowing snow sublimation rate, which needs to be resolved before we can accurately assess the importance of this process for the Mackenzie basin. Our PIEKTUK model has been extensively tested against the two other size-distributed blowing snow models developed elsewhere (UK and Holland) and against Antarctic and US field data. The comparisons with field data need to be finalised and written up for journal publication. In addition, our current work with an Inertial Particle – Lagrangian Simulation model is leading to a better understanding of effective settling velocities and eddy diffusivities. These lessons will be used to refine our PIEKTUK model and improve its predictions of transport and sublimation rates. This will lay the foundation for applications of the model to the development of a blowing snow treatment within the Canadian Land Surface Scheme (CLASS), and work on this will be continued.

b) Evaporation from Lakes

Work with the modified Guidelines model will be extended to include calculations of evaporation from small lakes and extensions to the Guidelines to non-neutral stratification will be investigated. We will also use a more complex Reynolds average equation model with second order closure to represent internal boundary layer growth in these non-neutral situations and a diffusion-advection model in use at University of Alberta will be evaluated for application to these studies.

Relation to MAGS Objectives

The redistribution and sublimation of blowing snow can be an important factor for water budgets in high latitude locations such as the Mackenzie basin. The work already completed has raised doubts about earlier blowing snow models and should allow us to make a better assessment of the significance of these processes within the MAGS context. Parameterization of these processes within CLASS will provide an effective way to apply our improved capacity to model blowing snow to mesoscale meteorological and climate issues in the Mackenzie.
2. Progress

Work with Lagrangian Simulations of dispersion of heavy, inertial particles continued and led to the submission and acceptance of a paper describing our basic model and results for small particles with linear drag (Taylor et al., 2002). Subsequent work has focused on larger particles with a non-linear drag law. This formulation is giving particle concentration profile results which agree, at least qualitatively, with the shape of observed profiles of blowing snow particles, and with some of Businger’s (1965) arguments. We have still not managed to find time to write up the comparisons between PIEKTUK and published field data (reported last year in Jingbing Xiao’s thesis) for journal publication, but recent results from our Lagrangian simulation work may be directly relevant to this issue and will lead to a more complete study.

We have put considerable effort over the past year into tests of the Canadian Land Surface Scheme (CLASS version 2.7, see Verseghy, 1991; Verseghy et al., 1993) and its treatment of snow. This proved rather more complicated than we had expected, at least in part because CLASS 2.7 was rather susceptible to problems with small fractional areas, and porting the code from a UNIX machine to a PC (with shorter word length) caused a number of problems, mostly involving small water budget errors. These have been resolved and modifications suggested and documented which make the code more robust. Tests against 15 years of data from Goose Bay (Labrador) were completed satisfactorily. Tests against data from Resolute (Nunavut) have caused more difficulties. Although this may be due in part to overestimates of albedo, the sublimation of blowing snow (a frequent winter occurrence in Resolute) is also a potential mechanism for snow removal. Simple parameterizations of blowing snow sublimation have been developed and are being tested, together with the scheme proposed by Déry and Yau (2001). Further tests of CLASS are planned against data from Trail Valley Creek and the SHEBA site on the Arctic ice.

Largely as a result of an interview with The Weather Network concerning our work on blowing snow, contact was made with an environmental group at the Dufferin County Museum. This led to us discovering an area in Ontario (near Hornings Mills, just north of Shelburne) with a significant frequency of blowing snow events, and we established a pilot study there in winter 2001/2002. Using mostly borrowed equipment we established an automatic monitoring station (wind profile, temperatures and snow depth) and also attempted in situ measurements of blowing snow with a “replicator” borrowed from the Desert Research Institute in Nevada (via MSC). This was ultimately unsuccessful, but the automatic station data have been carefully studied and confirm the potential of this site for blowing snow research. An unsuccessful proposal was submitted to the Canadian Foundation for Climate and Atmospheric Science to expand on this work, at a number of sites across the country. Undeterred we submitted a modified proposal to the New Initiative Fund of Search and Rescue Canada and are now awaiting a decision on that (due 1 April 2003).

Some progress has been made on internal boundary layers and modelling evaporation from lakes within the framework of our “guidelines” model (Walmsley et al., 1989). A poster describing this work was presented at the American Meteorological Society symposium in July 2002 (Saveliev and Taylor, 2002). We have not, so far, managed to undertake the modelling work planned.
3. Results

3.1 Lagrangian Simulation Modelling

A 3-D Inertial Particle - Lagrangian Stochastic model for heavy particles in turbulent flows has been constructed. In this model, fluid velocities are calculated in the vicinity of a particle satisfying a 3-D Langevin equation based on Thomson's "simplest" solution (c.f. Rodean, 1996) in which, as in 1-D, the Lagrangian correlation timescale for the fluid velocities along a particle trajectory is reduced relative to that along a fluid trajectory. Unlike our 1-D model which only adopts a linear drag law, particle velocities in our 3-D model can be computed from the governing equations with a non-linear drag law.

We first tested our 3-D model on neutrally buoyant non-inertial particles. By reversing the vertical and streamwise velocity components upon reflection at both upper and lower boundaries as suggested in Wilson and Flesch (1993), our 3-D model has been able to generate a well-mixed concentration profile.

Next we have applied our 3-D model, with a linear and a non-linear drag law, to inertial particles without settling velocity. Compared with our 1-D model results, the inclusion of streamwise velocity fluctuations computation in our 3-D model with a linear drag law has reduced the magnitude of the mean vertical velocity component as well as the effect of turbophoresis in the region close to the lower boundary. With the use of a non-linear drag law, our 3-D model has shown that such reductions are even more pronounced.

Finally, we have also run our 3-D model with a non-linear drag law to heavy particles with settling velocity \( w_g = -0.5 \text{ ms}^{-1} \). In Figure 1, dimensionless concentration from our model results are shown. For comparison, results with a linear drag law from 1-D and 3-D are also presented in Figure 1. From Figure 1, it is quite clear that both the inclusion of the streamwise velocity fluctuations and the use of a non-linear drag law have an independent effect on the particle concentration profile. While the former has increased (decreased) the particle concentration in the lower (upper) region, the latter has predicted the opposite effect. It is this latter effect which should move our model predictions into better agreement with field observations – but we would caution that there are very few field observations currently available.
3.2 CLASS

Verseghy et al. (1993) constructed the CLASS model for a UNIX computing environment. Our group at York is using smaller capacity computers in a LAHEY FORTRAN 95 computing environment. Double precision can be used, but single should be enough. In the basic version of the 1-D code 4 run-time errors were initially identified. Modifications to the code circumvented these problems. More details, and code changes required, are available from kirsimon@yorku.ca or pat@yorku.ca.

Our initial tests were based on data from Goose Bay and Resolute.

The Goose Bay runs. Using 1969-1984 hourly data obtained from Ross Brown (and used in the “Snowmip” project) we set up input variables to specify surface composition, roughness, initial conditions, reference measurement height, etc. A comparison of outputs indicated a near perfect correlation of the LAHEY FORTRAN 95 run with the UNIX run. Differences between the outputs from the UNIX and the LAHEY FORTRAN 95 runs should be generally insignificant.

The Resolute runs. The problem here, initially, was that net long wave data were used as input since these were available. CLASS has an option (ILW = 2) which allows net long wave radiation as input, but when run in this way with the Resolute data we found surface temperatures dropping to 0K. These were resolved by using an estimate of incoming long wave radiation as input in place of the net. In the basic version of CLASS, however, without any parameterization of blowing snow sublimation, there appears to be too much snow lasting too long into the summer (see Figure 2).

Figure 1. Concentration profiles predicted by Lagrangian simulation for inertial particles with \( w_g = -0.5 \text{ ms}^{-1} \).
Blowing Snow Parameterization

Based on a very rough initial fit to PIEKTUK model results we assume that the vertically integrated sublimation rate \( F_{\text{sub}} \) can be represented as:

\[
F_{\text{sub}} = A[\exp(U/U_t - 1) - 1][(1-R_{\text{hice}})\rho_a q_{\text{s}}(T)U_t]
\] (1)

Where \( q_{\text{s}} \) is the saturation specific humidity at air temperature (T) and \( \rho_a \) is air density. \( U \) and \( U_t \) are wind speed and threshold wind speed at ZREF, respectively. For ZREF = 10 m we take \( A = 0.01 \) initially. In “typical” blowing snow conditions (\( U_t = 7 \) ms\(^{-1} \), \( R_{\text{hice}} = 0.9 \), T = -15ºC (\( q_{\text{s}} = 1.03 \times 10^{-3} \)) this formula gives \( F_{\text{sub}} = 2.1 \times 10^{-5} \) kg m\(^{-2}\) s\(^{-1}\) (= 1.8 mm SWE/day) when \( U = 15 \) ms\(^{-1}\), and \( F_{\text{sub}} = 1.19 \times 10^{-4} \) kg m\(^{-2}\) s\(^{-1}\) (= 10.2 mm SWE/day) when \( U = 25 \) ms\(^{-1}\).

Figure 2 illustrates the effect of this parameterization in a part of the Resolute run. In black and white, the lower curve is the run with sublimation. Compared with observations we still have too much snow but our parameterization may be conservative and we should also consider modifications to the snow albedo.
The parameterization proposal above provides an estimate of snow removal, but there are also implications for the heat and moisture budgets. In the 1-D stand alone Resolute CLASS 2.7 run, with ZREF = 1.5m in the data supplied to us we have assumed that the input data on temperature and relative humidity already reflect the input of moisture and removal of heat associated with blowing snow sublimation. So we have not dealt with these effects but in a full model situation they need to be taken into account. We also need to look at horizontal fluxes of blowing snow and redistribution issues.

3.3 Blowing Snow Experiment

Blowing snow is an intermittent occurrence, not always easy to predict. In order to get a statistically significant number of observations of blowing and drifting snow and remain within a reasonable budget, researchers have to rely upon automated weather stations. We tested an experimental instrumentation setup at a site near Hornings Mills throughout January to March 2002 and are assessing its ability to provide reliable information on snow related processes. Some sample data measured during five days in early February 2002 are depicted in Figure 3. On the top panel one can see air temperature values together with information on synoptic situations as derived from surface analysis maps provided to us by Meteorological Service of Canada.

Air temperature influences the rate of snow pack aging and thus the possibility for drifting snow events to occur. Relatively warm air was advected into the region on Julian Day 41 with the passage of a cyclone and caused melting of the snow surface. Snow depth diminished by 3 cm (see bottom panel) and a crust formed on the snow surface. Another curve on this panel shows the standard deviation of the snow depth within 15 minute averaged values. In our opinion these parameters can be very informative.

Surface analysis maps show snow showers all around the region but the standard deviation values allow us to conclude that no snow fell at the site up to the afternoon of Julian Day 43 when both parameters indicate snow fall. The second from the bottom panel depicts wind speed measured at different heights together with gust values. The thicker line corresponds to the 10 m wind and a horizontal line shows the value of wind speed at 7 ms\(^{-1}\) which is considered to be a tentative threshold value for the onset of blowing and drifting snow. During the snowfall on late JD43 the wind speed was well above this threshold and snow that fell was immediately removed by the wind. In the early morning of JD44 the wind subsided and the snow depth increased by approximately 3 cm. The standard deviation of snow depth then shows an absence of snow fall and the snow depth stayed almost unchanged until the wind again increased above the threshold and quickly removed all fresh snow down to the old crust at the end of JD44. One can see that automated weather stations equipped with Ultrasonic Depth Gauges are able to register data that can be interpreted in terms of snow history and blowing-drifting snow events. This work is currently being written up as a part of Sergiy Savelyev’s MSc thesis. We would like to repeat the experiment in the coming winter if resources allow.
4. Relevance

Basic studies of blowing snow transport and sublimation, and of evaporation from lakes remain 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. As we research the blowing snow issues it has become clear that there are still a number of uncertainties in the behaviour of heavy inertial particles (including blowing snow) in turbulent boundary layers which need to be resolved.
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 the sublimation of snow, both in blowing snow situations and from tree canopies. The use of CLASS within the Regional Climate Model is an appropriate “vehicle” for these assessments. 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. Again we are planning to apply these ideas within CLASS.

5. Networking and Collaboration

I have been in frequent contact with John Wilson on our joint Lagrangian Modelling study. We have cooperated with Diana Verseghy, Ross Brown and Yves Delage of MSC on the CLASS applications. In addition, the MAGS Model Cross-Training Workshop (September 2002) and the MSC Physics Parameterization Workshop (September 2002) provided excellent opportunities to network with other users and developers of CLASS. We hope to collaborate with Wayne Rouse (McMaster) and Bill Schertzer (NWRI) on lake evaporation studies once we have our models finalised and need data for validation. We are in communication with US researchers involved in the SHEBA Arctic experiment and plan to test CLASS against their data for snow covered ice, and continue to exchange ideas and information with Stephen Déry (now at Lamont Doherty) on blowing snow, and with Anton Beljaars (ECMWF) on land surface representations in NWP models.

6. Summary

Work is now progressing well on applying our findings on blowing snow within the CLASS land surface scheme. We have 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. Further work with this model, now extended from 1-D to 3-D, and allowing non-linear drag (appropriate for larger particles) has also progressed. A pilot field experiment was conducted on blowing snow. Work on evaporation from lakes is on hold at present, but we do plan to study that within the CLASS context over the coming year.

7. Publications and Presentations

Journal Articles


Conference Proceedings


Other Conference Presentations


Workshop Presentation


8. References


1. **Objectives**

The objectives of this research include:

- development of an improved model for the retrieval of surface spectral and broadband properties and solar radiation budget for the MAGS region from historical, current and future satellite instruments;

- studying the influence of variable surface properties on the solar energy budget and cloud-radiation interactions; and

- producing the digital maps/database with retrieved parameters for the purposes of climate change monitoring as input data for modelling.

2. **Progress**

- In addition to datasets prepared last year we added to our database newly available data for 2001-2002 from the AVHRR, VGT narrowband sensors, and CERES broadband data. Methodology for combining multiple-satellite data sets from the above sensors and EOS/Terra (MODIS and MISR) is under development (Trishchenko et al., 2002g,h; Cihlar et al. 2002a,b). Validated and processed data will be made available through the CCRS public archive.

- Improved models for atmospheric correction and surface retrievals based on improved spectroscopy database were developed for operational polar-orbiting and geostationary satellite missions (Trishchenko et al., 2002e,f).

- Effect of spectral response function on surface and cloud reflectance and vegetation indices was quantified for operational satellite sensors (Trishchenko et al., 2002a,b).

- Improved methods of thermal calibration for AVHRR/NOAA were developed (Trishchenko, 2002c, Trishchenko et al., 2002d).
3. Results

Since satellites provide frequent and global observations of atmospheric and terrestrial environments, attempts have been made to use satellite data for long-term monitoring of land reflectances, vegetation indices and clouds properties. Although the construction and characteristics of spaceborne instruments may be quite similar, they are not identical among all missions, even for the same type of instrument like AVHRR. Consequently, the effect of varying spectral response may create an artificial noise imposed upon a subtle natural variability.

We conducted a detailed study on the sensitivity of the Normalized Difference Vegetation Index (NDVI) and surface and cloud reflectance to differences in instrument spectral response functions (SRF) for various satellite sensors. They include AVHRR radiometers onboard NOAA satellites NOAA-6 to NOAA-16, the Moderate Resolution Imaging Spectroradiometer (MODIS), the VEGETATION sensor (VGT) and the Global Imager (GLI). We also analyzed the SRF effects for several geostationary satellites used for cloud studies, such as GOES-8 -12, METEOSAT-2 -7, and GMS-1 -5. The results obtained here demonstrate that the effect of instrument spectral response function cannot be ignored in long-term monitoring studies that employ space observations from different sensors. The SRF effect introduces differences in observed reflectances and retrieved quantities that may be comparable or exceed the range of natural variability and possible systematic trends, the contribution from the calibration, atmospheric and other corrections.

Modelling results were validated against satellite observations employing AVHRR/NOAA-14, -15 and MODIS, with very good agreement (Figure 1). It is shown that for identical atmospheric states and similar surface spectral reflectance, the NDVI and spectral reflectances are sensitive to the sensor’s SRF. Relative to a reference SRF for AVHRR/NOAA-9, the differences in reflectance among the AVHRR radiometers range from -25% to +12% for visible channel (red), and from -2% to +4% for NIR channel. Absolute change in NDVI among various AVHRRs ranged from -0.02 to +0.06. The most significant difference was observed for the AVHRR/3 radiometer. Consistent results were obtained with the AVHRR sensors aboard the following afternoon satellites: NOAA-9 -11 and -12, whereas important discrepancies were found for other AVHRRs aboard NOAA-6 and -10 and especially those launched more recently (NOAA-15, -16).

Reflectance and NDVI measured by MODIS channels 1 and 2 also exhibit significant differences (up to 30-40%) relative to AVHRR. GLI and VGT have some specific features that should be taken into account when inter-comparing surface or top of the atmosphere reflectance as well as NDVI. Sensitivity of the SRF effect to variable atmospheric state (water vapour, aerosol, and ozone) was also investigated. Polynomial approximations are provided for bulk spectral correction with respect to AVHRR/NOAA 9.
Atmospheric correction of satellite measurements is a major step in the retrieval of surface reflective properties. It involves removing the effect of gaseous absorption as well as correcting for the effect of atmospheric molecular and particulate scattering. Significant advance in our knowledge of the absorbing properties of various atmospheric radiatively active gases has been achieved in the past few years. We used the latest version of MODTRAN-4 combined with updated HITRAN 2001 database (Rothman et al., 2001) to estimate the impact of these improvements on atmospheric correction of the signal in the solar domain for various satellite sensors. The objectives of our study where: (i) to develop a fast, but accurate, semi-analytical atmospheric correction scheme suitable for implementation in operational data processing of satellite narrowband observations, (ii) to estimate the impact of improved molecular spectroscopy on atmospheric correction and surface reflectance retrievals, and (iii) to derive sensor specific model parameters for narrowband satellite sensors such as the AVHRR/2 and AVHRR/3 radiometers aboard NOAA spacecrafts, VEGETATION sensor aboard SPOT, GOES imager, Landsat TM and ETM+, and selected MODIS channels using comprehensive radiative transfer modelling employing MODTRAN-4.
Use of the improved molecular spectroscopy database resulted in more atmospheric absorption especially in the NIR region where the correction may reach up to 12% relative to the computations based on obsolete, but still popular spectroscopic data. This may lead to the biases in NDVI up to 10% or more (Figure 2). Similarly, this effect leads to decrease of water vapour amounts retrieved from satellite observations in the NIR region, when improved spectroscopy is implemented. Operational atmospheric correction model was developed and validated against MODTRAN-4 with the updated HITRAN 2001 molecular database. The reflectance calculated from this model is mostly within ±0.01 relative to MODTRAN-4. Coefficients of the model were produced for all narrowband shortwave channels of AVHRR/2-3, Landsat TM, Vegetation/SPOT, GOES and selected MODIS channels.

Figure 2. The water vapour transmittance computed by MODTRAN-4 and 6S code (version 4) for NOAA-14 AVHRR visible (a) and near-IR (b) channels. The solid and dotted lines in (a) and (b) represent the corresponding calculation by the semi-analytical model. Panel (c) shows the difference in the water vapour transmittance between MODTRAN-4 and 6S for the visible (solid line) and near-IR channel (dotted line). Panel (d) shows the estimated bias in the retrieved AVHRR near-IR surface reflectance for different surface albedo.
Newly available broadband satellite data from CERES/Terra show a significant anomaly in broadband albedo over the MAGS area in wintertime (Figure 3). The anomaly is especially strong in clear-sky observations. Further investigations are required to explain this phenomenon.

![Graphs showing all-sky and clear-sky albedo over MAGS area](image)

**Figure 3.** Anomalous all-sky and clear-sky albedo in winter time is observed over the MAGS area from broadband data available from new CERES/Terra radiometer relative historical observations from ERBE and ScaRaB.

Satellite measurements from the infrared (IR) channels of AVHRR/NOAA have been used to derive many important atmospheric, cloud and surface parameters for weather prediction, climate modelling and a variety of environmental studies. Calibration accuracy of the satellite data directly affects accuracies of the derived parameters. So far, very limited attention has been given to the calibration uncertainties of the IR channels. We analysed the calibration data of AVHRR radiometers onboard polar orbiting satellites NOAA-9 to NOAA-16. We utilized Global Area Coverage (GAC) data, approximately one orbit per month throughout the lifetime of the instruments, available from the NOAA Satellite Active Archive (SAA). The overall budget of uncertainties has been evaluated using an in-flight calibration system that includes four thermal platinum resistance thermometers (PRTs) to monitor the ICT temperature. The measurement noise was found to vary from 0.03ºK to 0.3ºK at 300ºK depending on the channel and radiometer, and it increases significantly as temperature decreases. Systematic degradation of the radiometric sensitivity of the IR detectors was observed during the lifetime of a radiometer, although the annual rate of degradation is rather small (typically below 1% per year). The degradation of a sensor’s radiometric sensitivity reduces the radiometric resolution of the AVHRR measurements and expands the upper limit of the measured brightness temperature. PRT measurements are subject to significant orbital variation (up to 7ºK) and inconsistency for some AVHRR radiometers. The inconsistency was especially large for the AVHRR onboard NOAA-12 (up to 4ºK) and NOAA-14 (up to 3ºK), but it is less than 0.5ºK for NOAA-15 and -16. The inconsistency may signify the presence of a thermal gradient across the ICT. Some systematic
differences between PRT measurements may also indicate inaccurate characterization of the PRT sensors, for example for AVHRR/NOAA-11 and -14. The impact of the varying thermal state of the AVHRR environment on the accuracy of AVHRR in-flight thermal calibration was assessed. We found this impact to be significant (up to 0.5°K and more), and proposed a physical model to explain it (Figure 4). We recommend this model for AVHRR operational in-flight calibration, especially during solar radiative contamination events. Estimates of the PRT thermal response time constant were derived and found to vary between 0.5 and 1.5 minutes among AVHRR radiometers.

![Figure 4. Variation in channel 4 gain $G_4$ and ICT temperature derivative. Uncorrected (dashed) and corrected (solid line) values of gain $G_4$ are plotted for NOAA-9 (a), NOAA-12 (b), NOAA-14 (c), NOAA-15 (d), and NOAA-16 (e). Derivative $T'(t)$ is plotted as dash-dot line.](image-url)

4. Relevance

The project contributes towards the following MAGS research activities: *Integration and synthesis of processes, scaling of data and processes, model development and evaluation.*

5. Networking and Collaboration

- Presentation at WEBS workshop (Toronto, May, 2002)
- Collaboration with McGill University (Prof. H. Leighton) with regard to AVHRR processing and radiation budget research
- Participation in the US Atmospheric Radiation Measurement (ARM) Program
- Invited presentation at CloudSat Science Team Meeting
- Research grant from Canadian Climate Change Action Fund (CCAF) was received to support our work in the area of retrievals and modelling of surface albedo over Canada landmass (Dr. S. Wang serves as Co-PI)

6. Summary

- In addition to datasets prepared last year we added to our database newly available data for 2001-2002 from the AVHRR, VGT narrowband sensors and CERES broadband data. Validated and processed data will be made available through the CCRS public archive.
- Improved models for atmospheric correction and surface retrievals based on improved spectroscopy database were developed.
- Effect of spectral response function on surface and cloud reflectance and vegetation index was quantified.
- Improved methods of thermal calibration for AVHRR/NOAA were proposed that are useful for water and land surface temperature retrievals in MAGS area.
7. Publications


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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

The main goal of this investigation is to improve our capability to characterize the spatial and temporal variability of snow cover (esp. snow water equivalent) and lake ice over the MAGS region, with particular emphasis on the use of new satellite sensors (e.g. EOS platforms) that are planned for launch in the next few years. The new microwave radiometer AMSR was launched on the NASA EOS Aqua satellite in May 2002 and offers enhanced spatial resolution (10 km vs. 25 km) from 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.

Since AMSR data will not be available for scientific use until May 2003, our MAGS research activities during 2002 were focused on continued analysis of data from the current satellite microwave radiometer, SSM/I, for which we now have 15 years of data. A specific objective for this year was the evaluation of the SSM/I snow water equivalent (SWE) retrievals over the basin for the CAGES time period. Investigation of the potential extension of passive microwave derived snow cover and lake ice information back in time to 1979 with Nimbus-7 SMMR data in the same grid format as SSM/I was also a focus of our 2002 MAGS activities.

2. Progress and Results

A major activity for 2002 was the evaluation of SWE information over the basin as derived from SSM/I data using CRB open and forest land cover algorithms for the CAGES time period. This evaluation was conducted using conventional snow course measurements as the comparison data set, supplemented with snow depth observations from climate stations and SWE measured during special CAGES snow surveys conducted by other MAGS investigators (e.g. Marsh, Pietroniro). Snow course data for the 1998/99 winter were acquired directly from DIAND (Yellowknife).
The compiled snow cover data set for the 1998/99 winter was limited in both temporal and spatial coverage, with most data available for end of winter/early spring. Evaluation of the SSM/I derived SWE values was conducted for low elevation areas (<1000 m) due to the limitations of algorithm performance in mountainous terrain. Two aspects of the derived SWE information were assessed: (i) the length of snow cover season (in weeks) was compared with station data and gridded snow extent data derived from NOAA weekly snow cover maps (derived using AVHRR data), and (ii) the magnitude of the derived SWE values was compared with the conventional SWE measurements.

The results of the comparison in snow season length for the CAGES 1998/99 winter season is summarized in Table 1. The AVHRR derived snow extent product tends to overextend the snow cover season relative to the station data. This may be a function of snow cover being absent at the point station location, but still present over greater than 50% of a large NOAA grid cell. The SSM/I data identify a snow cover season similar to that characterized by the station data.

Table 1. Comparison of snow-on and snow-off dates (weeks) derived from station snow depth measurements, NOAA snow extent charts and SSM/I derived SWE for the 1998/99 winter season.

<table>
<thead>
<tr>
<th>Station</th>
<th>Snow-On Date (week)</th>
<th>Snow-Off Date (week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td>NOAA</td>
</tr>
<tr>
<td>Fort Smith</td>
<td>Nov. 9 - 15</td>
<td>Nov. 9 - 15</td>
</tr>
<tr>
<td>Grande Prairie</td>
<td>Nov. 9 - 15</td>
<td>Oct. 26 – Nov. 1</td>
</tr>
<tr>
<td>Norman Wells</td>
<td>Sept. 28 – Oct. 4</td>
<td>Oct. 5 – 11</td>
</tr>
<tr>
<td>Yellowknife</td>
<td>Oct. 26 – Nov. 1</td>
<td>Oct. 26 – Nov. 1</td>
</tr>
</tbody>
</table>

Results of the evaluation of the magnitude in derived SWE from SSM/I as compared with conventional snow course measurements conducted as snow survey sites within the basin are presented in Figure 1. Since the snow course SWE is essentially a point-based measurement while the SSM/I derived SWE represents an average over a 25x25 km grid cell, an absolute comparison of SWE values was not conducted. Instead, the distribution of snow course SWE measurements, and the SWE retrievals from the passive microwave grid cells nearest each snow course location through the CAGES snow cover season are compared. Both datasets contain a bimodal distribution of SWE values, with peaks located near 90 and 130 mm for the snow course measurements, and 40 and 80 mm for the passive microwave derived estimates. This affirms a consistent passive microwave underestimation of SWE across the basin (with a spatial basis to where snow course information is available in the basin), with a bias of approximately 50 mm. The narrow range in SSM/I derived SWE as compared to the conventional measurements can be
explained due to underestimations in dense forest cover and high SWE areas (Walker and Silis, 2002).

![Graph](image)

Figure 1. Distributions of snow course SWE measurements (top) and passive microwave derived SWE estimates (bottom) for the CAGES snow cover season.

The potential to extend the passive microwave derived snow cover and lake ice time series back to 1979 with Nimbus-7 SMMR data available in EASE-Grid format was another major area of investigation during 2002. Our analysis of a combined derived SWE time series from SSM/I and SMMR data sets for the Canadian prairie region has revealed a significant underestimation bias in derived SWE values for the SMMR time period related to brightness temperature differences between the two instruments (Derksen et al., in press). Methods to correct for the inconsistencies between the SMMR and SSM/I brightness temperature data sets are currently being investigated. The identification of lake ice freeze-up and break-up events in the SMMR data has been initiated to extend the Great Slave and Great Bear lake ice time series back to 1979. Since these events are identified by changes in brightness temperature, there is minimal impact of the inconsistencies between the SMMR and SSM/I data records on the ability to extend the lake ice freeze-up and break-up time series. An analysis of the interannual variability in timing of freeze-up and break-up for the two lakes over the 1979 to 2002 time period (23 years of combined SMMR and SSM/I data) is planned as the next step in the lake ice component of the investigation.

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 the relationship with the behaviour of the whole system (esp. short term climate variations, e.g. El Nino) thus contributing to the MAGS-2 objective of developing a predictive capability for impacts on the climate-hydrological system.

4. Networking and Collaboration

• Contribution of SSM/I lake ice freeze-up and break-up information (images and dates) to support research conducted by other MAGS investigators during 2002 – Dr. Bill Schertzer, Claire Oswald (student of Dr. Wayne Rouse), Anouk Utzschneider (student of Dr. Claude Duguay).

• Collaboration with Dr. Bill Schertzer on the preparation of a CAGES special issue paper on seasonal characteristics (e.g. thermal properties, heat content) Great Slave Lake during 1998/99 (see section 6).

• Collaboration with Dr. Murray Mackay on the evaluation of RCM derived snow cover fields for the CAGES time period. Contribution of satellite derived snow extent and SWE data sets and conventional snow course measurements to the RCM evaluation. Co-authorship (A. Walker) on CAGES special issue paper by Murray Mackay (see section 6)

• Participation in the MAGS WEBS Workshop held at Downsview in May 2002, including an oral presentation by A. Walker on “Contribution of Satellite-derived Snow Cover and Lake Ice Information to Understanding the MAGS Energy and Water Cycles”.

• Presentation of SSM/I Great Slave and Great Bear lake ice freeze-up and break-up research results at IGARSS’02 (International Geoscience and Remote Sensing Symposium) held at Toronto in June 2002. Oral paper presentation by A. Walker entitled “Use of SSM/I Passive Microwave Data for Investigating Ice Variations over Large Lakes in Canada”.

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


C. HYDROLOGIC STUDIES
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, approximately starting at Peace Point and ending at the mouth of the Peace. 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: a) to identify and quantify the hydro-climatic parameters that are conducive to ice-jam flooding, b) to 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

Field Data Collection

Field data collection continued this year including:

- Channel bathymetry measurements between Peace Point and Sweetgrass Landing, to characterize channel hydraulics in this, not previously surveyed, reach. This will facilitate modelling applications that involve the entire reach between Peace Point and the mouth.

- Ice thickness measurements during the fall and winter periods, including an early-spring data set, intended to document decay processes.
- Continuous water-level monitoring at selected stations in the Delta reach (Sweetgrass Landing to mouth) during the ice season.

- *In-situ* ice-breakup observations and measurements.

Review and assessment of existing data pertaining to the PAD (e.g. Water Survey of Canada Records at Peace Point; meteorological data) as well as relevant material from other rivers that can be used to corroborate methods developed for the PAD.

**Data Analysis and Interpretation**

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

- Application of the calibrated RIVJAM model to assess the efficacy of water releases at the Bennett dam in augmenting ice-jam flood stages at the Delta and their potential use as non-structural adaptation strategy to help restore floodwater to the local ecosystem.

- Delineation of hydro-climatic conditions that must be fulfilled for ice-jam floods to occur in the PAD reach of the Peace River.

- Assessment of WATFLOOD model requirements for implementation on Peace River basin, and suitability of using GCM/RCM output to drive the model.

3. **Results**

**In-Situ Measurements and Observations**

The PAD reach of the Peace River is largely inaccessible by road. Consequently, very limited information exists about local ice processes, in general, and ice breakup and jamming, in particular. Of necessity, the present analysis is mostly based on historical hydrometric data that are being collected by Water Survey of Canada at the Peace Point gauging station. This approach is being corroborated with field measurements and observations in the entire study reach (Peace Point to Peace River mouth), using winter-road and snowmobile access, fixed-wing aircraft, boats, or special-purpose vehicles on loan from Parks Canada. Without the logistical assistance provided by the Fort Smith and Fort Chipewyan offices of this agency, the field program would be limited to mainly qualitative aerial observation. Important supplementary information and occasional field support are provided by the Yellowknife office of Water Survey of Canada.

In addition to bathymetric and slope surveys that are normally carried out in the summer or early fall, ice thickness evolution and river water levels are monitored at selected locations throughout the ice season. An equally important component of the field program is *in-situ* documentation of breakup and jamming processes. Since the start of the project, however, breakup events have been of the thermal type, which is characterized by in-place disintegration of the ice cover and absence of significant ice jams. Thermal events are typically associated with low spring runoff; the opposite typifies the mechanical breakup event, which does result in ice jams that can cause flooding.
This year, snowpack conditions at the end of winter indicated that a mechanical event might be possible. This expectation was reinforced in April by the considerable flows that were recorded at upstream gauges, such as the one at the town of Peace River. Consequently, a field program was initiated by NWRI, with the assistance of Parks Canada. Ice conditions and water levels were monitored for about two weeks by means of aerial observation and ground access at a few locations along the Delta reach. Despite high flows (over 4000 m$^3$s$^{-1}$) the ice cover remained in place and eventually disintegrated in thermal fashion. Though this outcome was not what had been hoped for, important data regarding the evolution of the process were obtained for the first time, not only in the study reach but well upstream. This information is now being processed and analyzed in order to explain why a mechanical breakup did not materialize, despite the high runoff. Two factors that may have contributed to this occurrence are the high stage during the preceding freeze-up and a cold snap in late April - early May.

High freeze-up stages occur frequently, owing to the high winter flows produced by regulation. The lower reach of Peace River is very flat (slope less than 1x10$^{-4}$), and one would ordinarily expect the ice cover to form by surface juxtaposition of ice floes and outward expansion of smooth border ice (Andres, 1995). However, analysis of historical freeze-up stages and flows has indicated that this type of cover formation is the exception rather than the rule. Usually, the data suggest considerable thickening of the cover, sometimes attaining the condition of an equilibrium jam that is formed by internal collapse and shoving (Beltaos, 1995). This deduction was confirmed during reconnaissance in November 2000: long stretches of the river were covered by a rough, unconsolidated cover, while the water-level transducers indicated a rapid rise of about 2 m. The same was recorded at the Peace Point gauge, where channel bathymetry and slope are known in sufficient detail to permit calculation of ice-jam stage as a function of discharge. Figure 1 compares this function with the 2000 freeze-up event and points to equilibrium-jam conditions when the freeze-up stage crested. The thickness of the jam at the corresponding flow of 1600 m$^3$s$^{-1}$ is calculated as 1.4 m, some seven times the visually estimated thickness of the ice blocks comprising the jam.

![Figure 1. Stages at Peace Point during the 2000 freeze-up event versus flow discharge. Visual evidence of a collapsed and thickened cover is consistent with the proximity of the peak stages to those of an equilibrium ice jam.](image-url)
Ice Thickness Decay and Spatial Variability

Thermal decay occurring prior to the spring breakup reduces both the thickness and the strength of the ice cover and renders it more amenable to dislodgment by the rising hydrodynamic forces. Ideally, strength should be measured repeatedly during the pre-breakup period, however ice cover access at that time is problematic and often hazardous. At the same time, it is difficult to calculate the degree of strength reduction with certainty, even though it is known to be caused by absorption of short-wave radiation (e.g. see Prowse et al., 1996). For the 2002 event, a late-season cold spell and snowfall may have postponed the onset of strength decay.

Thickness reduction has been empirically tied to the degree-days of thaw above a base temperature of -5°C (Bilello, 1980). Based on numerous measurements of river ice thickness in Alaska and Northern Canada, Bilello proposed the following relationship:

\[ h = h_o - \varepsilon S_5 \]  

in which \( h \) = ice cover thickness in metres; \( h_o \) = ice thickness just prior to the beginning of thaw in metres; \( S_5 \) = accumulated degree-days of "thaw" with respect to a base of -5°C, which was recommended for river-ice conditions; and \( \varepsilon \) = site-specific empirical coefficient, varying between 0.004 and 0.010 m per °C/day.

Figure 2 indicates a large degree of scatter when the data points for the lower Peace are plotted in the form suggested by Eq. 1, and suggests that air temperature, alone, does not adequately explain ice thickness reduction. If, as a first approximation, a linear fit through the origin is forced through the data points, the slope works out to be 0.0015 m per °C/day, about three times less than the lower limit of Bilello’s range. Preliminary indications for the 2002 event are that the rate of thickness loss as of May 7 was near 0.0015 m per °C/day; extrapolation would then indicate a total thickness reduction of 0.25-0.30 m prior to the disintegration of the ice cover.

Figure 2. Ice thickness decay as a function of degree-days of thaw. Diamonds: from Water Survey of Canada records for Peace Point hydrometric station. Circles: spring 2000 at Rocky Point and Moose Island.
Hydroclimatic Conditions leading to Ice-jam Flooding

As discussed in the previous progress report (Beltaos et al., 2002), flooding of the Delta when a major jam is in place requires a Peace-Point flow of at least 4000 m$^3$s$^{-1}$. However, significant ice jams can only form during mechanical breakup events. Consequently, the question of whether a breakup event will be thermal or mechanical is of central importance in this study. This question was answered empirically (Beltaos et al., 2002) for a preliminary assessment of climate-change impacts, which indicated further reductions in ice-jam flood frequency. However, for consideration of adaptation/mitigation methods, and for transferability to other rivers, it is important to have physics-based criteria for the occurrence of mechanical events. This objective is continuously being pursued as part of the analysis and interpretation activities.

Using recent advances regarding the onset of breakup on a variety of river sites, it has been possible to derive a simple threshold equation:

\[
(H_B)_L \approx H_F + kh_o
\]  

(2)

in which \((H_B)_L\) = limiting value of the breakup onset stage, \(H_B\), such that higher onset stages are associated with mechanical events and lower values with thermal ones; \(H_F\) = stage during the preceding freeze-up; and \(k\) = dimensionless coefficient that depends on local hydraulics and morphology. For details and theoretical background, see Beltaos (2002). For Peace River at Peace Point, Figure 3 shows that the available data are delineated by means of Eq. 2, using \(k = 1.35\).

![Figure 3. Separation of mechanical from thermal breakup events by means of the threshold equation (Eq. 2).](image-url)
Spring flow can be readily identified as a major factor via Eq. 2. The higher the flow, the higher the stage $H_B$, hence a mechanical breakup will be more likely to occur. Equation 2 also illustrates the importance of the freeze-up level: other things being equal, higher values of $H_F$ make it less likely that a mechanical breakup will occur. In principle, therefore, an increase in spring flow and/or a reduction in freeze-up level, via modified regulation procedures, would contribute to increased ice-jamming frequency. However, this would have to be accomplished without serious impacts on riverside communities or on power generation during the winter, a season of peak energy demand.

Flow Releases to Restore Floodwater to the Delta Ecosystem

As a means of enhancing the potential of the 1996 ice-jam flood event, B.C. Hydro released an extra flow of $500 \text{ m}^3 \text{s}^{-1}$ at the Bennett dam from April 25 until May 3 (Prowse et al., 2002). The effect of this release on Peace Point flows was estimated by means of a hydrodynamic model. Application of the calibrated RIVJAM model, with and without the extra flow during the period of ice jamming in the Delta reach, indicated a small ($\approx 0.27 \text{ m}$) but ecologically significant increase in water level. Had the extra flow arrived when the jam was at its maximum extent, a rise of $0.55 \text{ m}$ would have been attained (Prowse et al., 2002). This approach does show promise, therefore, and might even have been beneficial during this year’s event. The timing of the release is a critical issue, because it has to be consistent with peak flows and ice conditions in the Delta reach while ensuring that upstream communities are not adversely affected.

Implementation of WATFLOOD Hydrologic Model

Numerous runs with WATFLOOD have been carried out for the Peace and Athabasca Rivers using current-climate and future-climate data based on perturbation of the six IPCC GCM runs. The accuracy of WATFLOOD on the upstream tributaries for the current climate runs is presently being evaluated. We have also run the CAGES and 94/95 WY precipitation and temperature forcing from the RCM through WATFLOOD with mixed success (for details please contact Dr. Alain Pietroniro).

3. Relevance

The research presently in progress contributes to both of the overall goals of MAGS:

1. to understand and model the high-latitude water and energy cycles that play roles in the climate system, and

2. to improve our ability to assess the changes to Canada’s water resources that arise from climate variability and anthropogenic climate change”.

Building upon the achievements of 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 present work 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).
4. 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 data base components that are presently being developed (Environment Canada: Water Survey of Canada and other operational groups);

- securing crucial logistical and personnel assistance for field operations under difficult access conditions (Parks Canada, First Nations);

- obtaining supplementary field data and hydrograph-related information (BC Hydro, Alberta Environment); and

- developing improved understanding of ice-instigated surges and other breakup processes through: informal links to the MAGS-2 study led by Prof. F. Hicks; and field measurements in New Brunswick Rivers under an ongoing joint NWRI-NB Environment study (Beltaos et al., 1998).

The study leader attended the 2001 Annual Scientific meeting of MAGS where he presented his 2001 progress report and chaired one of the sessions. In his capacity as Vice President of the CGU Hydrology Session, he also organized the CGU Hydrology Annual Science meeting that was held at Banff, May 18-21, 2002. Several MAGS-related presentations were made at that meeting.

5. Summary

The objectives if the study are being addressed using a combination of archived data, process studies, field data collection, and numerical modelling. Last year’s findings, partly based on empirical criteria, indicated that global warming is likely to reduce the frequency of ice-jam floods, and thence exacerbate the drying trend of the PAD ecosystem. To refine this approach and facilitate assessment of adaptation strategies, physics-based hydro-climatic criteria for ice-jam flood occurrence are presently being developed. As a first step, the incidence of mechanical versus thermal breakup events was investigated in terms of current knowledge of the breakup process. Freeze-up stage and ice cover thickness were shown to be among the governing factors: increases in either one of these quantities render mechanical breakup less likely. The opposite effect is expected from increases in spring flows. This was documented and quantified for the extra-flow release during the 1996 ice-jam flood event by means of hydrodynamic and ice models.
6. Publications


Beltaos, S., 2002: Threshold between mechanical and thermal breakup of river ice cover. NWRI Contribution No. 02-024. (submitted to Cold Regions Science and Technology)

Beltaos, S.: Climate impacts on the ice regime of an Atlantic river. NWRI Contribution No. 02-025. (submitted to Nordic Hydrology)


7. References


Beltaos, S., 2002: Threshold between mechanical and thermal breakup of river ice cover. NWRI Contribution No. 02-024. (submitted to Cold Regions Science and Technology)


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Modelling the Interaction of Climate, Hydrology, and River Ice Hydraulics

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1. Objectives

The objectives of this research project are:

- to 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, AB, where ice jams occur frequently;

- to develop and validate a deterministic numerical model which integrates the interactive effects of climate, hydrology, and river ice processes; and

- to use this model to quantitatively assess the potential impact of climate change on basin hydrologic response in the Mackenzie basin and other high latitude regions.

Timeline for the 5-Year Project:

Year 1: Initiate field program; develop model framework based upon historical records documenting meteorological and hydrological influences on breakup in study basin.

Year 2: Continue field program of ice jam monitoring and the development of the deterministic model of dynamic ice jam processes. Integrate the cdg1-D finite element hydraulic flood routing model with the basin hydrologic models (developed by Soulis et al., MAGS-1).

Year 3: Continue field program of ice jam monitoring and the development of the deterministic model of dynamic ice processes; commence work on integrating the deterministic model of dynamic ice processes into the existing hydraulic model.

Years 4 and 5: Model completion, verification, application; possible additional field work.

2. Progress

2.1 Field Data Program

Eight remote water level monitoring stations were installed along the Athabasca River upstream of Fort McMurray (Figure 1). 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 breakup. They also capture the propagation of ice jam surge releases through the study reach during breakup. Five of the eight remote stations are interactive: data can be downloaded on a real time basis and they are also equipped with alarms, which call out 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.

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

2.2 Development of the Deterministic Model of Ice Processes

Preliminary development of the model framework is to be based upon historical records documenting meteorological and hydrological influences on breakup in the study basin. To facilitate that, we have completed the development of an extensive archive of hydro-meteorological data pertinent to river ice processes at the Fort McMurray site, dating back to 1972 (Robichaud, 2002). This includes: basin snow course data (from Alberta Environment); meteorological data: air temperature, hours of bright sunshine, and precipitation (from Environment Canada, our station, and from Golder Associates); digitized water level records based on strip charts obtained from the Water Survey of Canada (WSC) at 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).
Hydraulic models form the basis of the deterministic modelling approach and also support the hydrologic modelling effort of other MAGS researchers (e.g. Soulis et al.). In addition to existing hydraulic flood routing models of the Peace (Blackburn and Hicks, 2002), Slave and Hay Rivers, we have now completed two additional hydraulic flood routing models (Underschultz, 2002): the Athabasca River from Whitecourt to Embarrass; and the Mackenzie River from Great Slave Lake to Arctic Red River.

3. Results

3.1 Field Data Program

We have now completed two years of field observations of river ice breakup on the Athabasca River at Fort McMurray. This included documentation of: ice thickness, winter/spring discharge and water levels prior to breakup (three additional winter discharge measurements were funded by WSC); continuous automated and manual water level measurements during breakup; daily observational flights (partially funded by Alberta Environment) monitoring ice cover deterioration and major ice movements, and water levels from the remote network capturing surge propagation events. We also completed additional hydrometric (cross section) surveys of the Athabasca River in the 35 km study reach upstream of Fort McMurray in July 2002.

Our meteorological station measuring precipitation, solar insolation, air temperature, and barometric pressure now operates continuously throughout the year at Fort McMurray. A sunshine ball is also in use at the site in order to facilitate development of a local relation between hours of bright sunshine and solar insolation.

Most Significant Observations in 2002

During breakup 2002, a 17 km long ice jam formed approximately 10 km upstream of Crooked Rapids. On April 26, this ice jam released, sending a large surge of ice and water down through the study reach. This surge was measured by the remote monitoring station at G140 (location shown in Figure 1) and also by Alberta Environment observers camping at the site. Figure 2 shows the data obtained from these two sources, in which it can be seen that the water level rose 4.3 m in just 15 minutes, as the surge front passed. This is probably one of the largest events of this type ever measured, and the fact that the water level sensor survived the passage of this wave and the associated large competent ice floes is quite remarkable.

As the water level peaked, the probe at G140 shifted on the river bed to a deeper spot. Figure 2 also presents the corrected probe record, adjusted based on the manual observations. This surge of water and ice propagated down through the study reach, and was measured by the recorders at stations G135 and G130. These data are presented in Figure 4. The surge of ice then came to an abrupt halt, forming a new 8 km long ice jam with the toe located just upstream of station G105. As the ice run arrested, it scoured gravel on the bed, forming a large gravel bar at the jam toe. This gravel buried the water level sensor at station G105, destroying it. However, before this, the sensor did capture the wave peak showing the water escaping under the intact downstream ice
cover (i.e. the ice was arrested, but water continued to propagate downstream under the intact ice cover). Figure 3 shows this, along with data collected further downstream at station G95 by manual observers working for the Regional Municipality of Wood Buffalo.

There were three additional (non-communicating) water level recorders (at the recording stations indicated in Figure 1) which were intended to provide intermediate stage hydrographs for such events. These recorders could not be safely retrieved until remnant ice in the river channel had melted out. In July 2002 one was retrieved sitting on the bank (the ice run had pushed it out of the water) and another one had been ripped off the end of its anchor cable (the most upstream one). The third one was retrieved from the water. The two that survived provided intermediate data to supplement that illustrated in Figure 3.

The data in Figure 3 is quite unique, and probably represents the most detailed observations of the propagation of an ice jam release surge obtained to date. Probably of greatest scientific value is the documentation of the attenuation of the wave peak amplitude and speed as it propagated over this 35 km long reach. The average speed of the surge was 4.05 m s⁻¹ (14.6 km h⁻¹) from stations G140 to G135, 3.3 m s⁻¹ (11.9 km h⁻¹) from G135 to G130, and 2.5 m s⁻¹ (9 km h⁻¹) from G130 to G105. These data will be used in the validation of our ice jam surge release model and will also be valuable in addressing pressing scientific questions regarding the influence of ice on ice jam surge release propagation.
Figure 3. Surge measured at remote stations during ice jam release event, 2002.
Because of the dynamic nature of breakup on this river, numerous smaller release events were documented propagating down through the study reach over the ensuing breakup period. These were all measured by the remote stations as shown in Figure 4. Two, smaller waves, approximately 30 cm high passed through the reach without disturbing the jam poised upstream of the town of Fort McMurray. The third, 50 cm high, wave cause the ice jam to release resulting in a 2 hour run of ice through Fort McMurray. Based on the speed of propagation of the events through the upper reach, we were able to forecast the arrival of this peak at the town, and were able to notify town officials of the likelihood of ice jam release.

![Figure 4. Smaller waves measured at the remote stations during breakup, 2002.](image)

Normally breakup occurs at the town of Athabasca, located approximately 250 km upstream of the study reach, well in advance of breakup at Fort McMurray. Alberta Environment has long suspected that the waves resulting from the breakup at Athabasca were pivotal in instigating the dynamic breakup in the Fort McMurray reach and might be associated with major ice jam events at the town. As Figure 4 shows, water levels in the study reach rose approximately 1 m as the wave associated with the breakup at the town of Athabasca arrived in the study reach. Had the progression of breakup been typical in 2002 (i.e. Athabasca preceding Fort McMurray), it is possible that more severe jamming may have resulted at Fort McMurray, given the height of this wave. These data are extremely valuable for validation our hydraulic flood routing model for the Athabasca River and contributes to our understanding of the nature of breakup progression on north flowing rivers.
3.2 Deterministic Model of Ice Processes

Conceptual-Empirical Model of Breakup Ice Processes

The data archive was first used to develop a conceptual-empirical model for forecasting the risk of breakup ice jam occurrence at Fort McMurray, with the ultimate goal of identifying the significant hydrometeorological parameters to be considered in the deterministic modelling efforts (Robichaud, 2002). One of the key findings of this study was that the peak water level observed at Fort McMurray during breakup in any given year ($H_B$) can be forecast based on a regression model employing the following key hydrometeorological parameters:

- $T_{10}$: degree-days accumulated in the 10 days prior to breakup
- $S_4$: total solar heat input received in the 4 days prior to breakup
- $SWE\text{ (Mar)}$: snow water equivalent for the Upper Athabasca River Basin on Mar.1
- $SWE\text{ (Apr)}$: snow water equivalent for the Upper Athabasca River Basin on Apr.1
- Soil Moisture Index: based in total daily precipitation for preceding summer (May 1 to Oct. 15)
- $H_i$: ice thickness
- $\Delta H/\Delta t$: rate of increase in water level at the WSC gauge below Fort McMurray during the later winter period (surrogate for discharge)

Figure 5 shows the comparison between the observed peak breakup water levels at Fort McMurray and those predicted by Robichaud’s (2002) multiple linear regression model based on the variable listed above ($R^2 = 0.80$). It is of interest to note that the model is applicable for all record years, including: extremely dynamic breakups involving ice jam events; non-eventful thermal breakups; as well as for unknown breakup conditions. In addition, this model has low enough error to be operationally useful for short-term flood forecasting of extreme events. Ph.D. candidate, Chandra Mahabir, has been investigating the use of Fuzzy Logic for providing long lead time ice jam risk forecasts, confirming the validity of these same hydrometeorological indicators (Mahabir et al., 2002). Her preliminary results to date indicate that this has very promising potential for ice jam flood risk forecasting. In addition, her model has the capability of assessing the impact of climate change on the frequency of ice jam occurrence.

Hydraulic Modelling

The hydraulic flood routing model of the Athabasca River from Fort McMurray to Embarrass was successfully used to accurately route historical floods, based on a single calibration parameter (roughness), applicable to a range of events, as reported on 2001. The extension of the Athabasca River model upstream of Fort McMurray to Whitecourt (Underschultz, 2002) involved developing the geometric database (from maps and available survey data) calibrating the channel roughness in the model, and conducting verification runs (using WSC data). This reach was particularly challenging to model hydraulically because of the significant drop in bed elevation through the Grand Rapids (a drop of 10 m over approximately 3 km).
Figure 5. Comparison of water levels obtained with the multiple linear regression model, to the observed values measured on the Athabasca River just upstream of the Clearwater River confluence (Robichaud, 2002).

The development of a hydraulic flood routing model of the Mackenzie River from Fort Providence (outlet of Great Slave Lake) to Arctic Red River (Underschultz, 2002) involved developing the geometric database from maps and available survey data, calibrating the channel roughness in the model, and conducting verification runs (using WSC data). Figure 6 shows the results obtained at Fort Simpson for a 1996 simulation, while Figure 7 presents the results obtained at Arctic Red River.

As Figure 6 shows, the model tends to over-predict the flows at Fort Simpson, and this can likely be attributed to the poor accuracy of the inflow hydrographs available at the Fort Providence WSC gauge site. The outflow hydraulics at Great Slave Lake are complex and subject to wind effects and, to date, the lake outlet hydraulics have never been accurately defined.

As Figure 7 shows, the model under-predicts flows at Arctic Red River. Given that the model predicts the timing of events accurately, these results imply ungauged inflows are responsible for the differences between modelled and observed values. In fact, few Mackenzie River tributaries are actually monitored by WSC, illustrating the importance of the basin hydrologic model (of Soulis et al.) which will quantify these lateral inflows. Additional simulations were conducted using WATFLOOD data as input for the ungauged contributions; however these efforts are still at the preliminary stage (Underschultz, 2002).
Figure 6. Hydraulic model results for the Mackenzie River at Fort Simpson, 1996 simulation (Underschultz, 2002).

Figure 7. Hydraulic model results for the Mackenzie River at Arctic Red, 1996 simulation (Underschultz, 2002).
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 important 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**

- Participation in MAGS-2 meetings: Montreal, Spring 2001; Hamilton, Fall 2001; Edmonton, Spring 2002; York Univ., Fall 2002

- Our flood routing model development efforts on the Athabasca and Mackenzie Rivers are in direct response to specific discussions with/requests by R. Soulis.

- A meteorological station has been established at Fort McMurray which provides real time data, which is available to all MAGS researchers.

- We have established an extensive data archive of hydrometeorological data pertinent to river ice processes at this site, dating back to 1972, which will be provided to the MAGS Data Archive.

- Field data taken in relation to our study of river ice breakup at Fort McMurray from 2000, 2001 and 2002 (including discharge determination during the breakup period) will also be provided to the MAGS Data Archive.

- We continue to collaborate with Alberta Environment on the river breakup monitoring program at Fort McMurray.
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 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 totaled several million dollars during a single event in 1997. In this study, using sophisticated instrumentation and modern communications technology, we have established an automated ice jam monitoring network along the Athabasca River upstream of Fort McMurray, AB. In addition to providing unprecedented data on the dynamic aspects of river ice breakup (critical to developing a scientific understanding of ice jam events), this network also provides a flood warning system for the people of Fort McMurray, which will facilitate evacuation planning 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 give year, based on the severity of the preceding winter and the weather occurring during spring breakup. This model can also assess the influence of climate change on the potential for increased risk of ice jam occurrence.

7. Publications


Research Objective

The overall objective of this research project is to improve the understanding and representation of surface and near-surface processes involving the flux, phase change and redistribution of water/snow in the Canadian Regional Climate Model (CRCM) land surface scheme WATCLASS, with specific concern for Canada's cold regions. This is being accomplished through four inter-related research tasks. These tasks involve both field and modelling studies at several representative biophysical site types within Canada's cold regions, including Wolf Creek near Whitehorse, Yukon; the lower Liard River valley near Fort Simpson, NWT; and the Havikpak and Trail Valley Creek basins near Inuvik, NWT. This report presents the progress of each research task for the period September, 2001 to June, 2002.

Task 1: Measure and Describe Sub-grid Processes Controlling the Fluxes of Sensible and Latent Heat and Radiation over Heterogeneous Surfaces

Summarising and Publishing of Archived Data

Data collected during the 1999 CAGES (Canadian GEWEX Enhanced Study) field experiment included tower and aircraft (NRC Twin Otter) measurements of sensible and latent heat, solar radiation, and surface temperature. Initial work has shown that: a) aircraft measurements over both tundra and forest sites, are in close agreement with tower measurements, suggesting that the tower sites are representative of a broader area, and that the aircraft measurements can be used to consider the spatial variability in energy fluxes over the larger study area, and b) during the spring melt period there is a strong relationship between the fluxes of sensible heat, latent heat, reflected solar radiation, surface temperature and snow-covered area. Ongoing analysis is breaking the eight 16 km aircraft flight lines into 2 km transects in order to allow further analysis of various methods for determining spatial averages over this complex natural terrain, and a consideration of various techniques for modelling sub-grid scale variability in both atmospheric and land surface models. A journal paper is in production (Marsh et al., 2002a).
At Wolf Creek the CAGES data archives for 1999 are being reanalysed to determine the known effects of complex terrain on net radiation, sensible heat and latent heat during the snow ablation period. The measurements permit estimation of the major terms of the snowmelt energy budget at a point on a north and south-facing slope and valley bottom. The 1999 melt commenced in mid-April, driven primarily by short-wave radiation associated with clear skies. In this early period, there were substantial differences in melt rate between slopes with almost complete ablation of the snow pack on the south-facing slope while the north-facing slope snow pack cooled. In May, temperatures warmed permitting a larger sensible heat flux, however ablation rates varied only slightly amongst slopes and valley reflecting the reduced role of direct short-wave and increasing importance of sensible heat. Sensible heat had a much lower spatial heterogeneity than did short-wave radiation.

Data collected continuously since 1993 at the three main experimental sites within the Wolf Creek basin are being summarised and prepared for publication. These sites represent the main landscape types within the basin: boreal forest, brush taiga and alpine tundra. The data, along with basin, site and sensor descriptions, are being prepared for presentation as monthly summaries in tabular form. Brief descriptions of other projects and sites within the basin are also provided. These summaries will be posted on an Environment Canada web site dedicated to the Wolf Creek research basin. A written report is also being prepared in the form of a National Water Research Institute contribution.

Field Studies

In 2002, field studies commenced at all study sites in March with late-winter snow surveys. At Havikpak and Trail Valley, field studies concentrated on: a) installation of 6 wind speed/direction sensors at locations of high to low wind speed for the purpose of validating the wind models, b) carrying out detailed snow surveys for determination of end of winter snowcover for the purpose of snowcover energy balance simulation, and c) selection of, and preliminary instrumentation of, shrub sites for studies of snow accumulation/melt. This dataset will complement existing data for similar studies in tundra and forest environments in the Inuvik area. At Wolf Creek, field activities concentrated on determining: a) the extinction of shortwave and emission of longwave in vertical profiles through a spruce forest canopy, b) the surface temperatures of exposed shrub vegetation, rocks and bare patches during melt of a patchy tundra snowpack, c) the lower boundary layer characteristics over a patchy open snowfield and the potential for advection and mixing in the lowest few metres above the surface; and during the snow-free period, and d) the effect of sloped surfaces on the turbulent transfer of sensible and latent heat.

Development of New Observational and Analytical Methodologies

The role of surface slope and aspect on the variability in solar radiation is being considered using a version of the Ranzi and Rosso radiation model, implemented within a GIS system. This research will consider the spatial and temporal variability in solar radiation over 16 x 16 km study area. Initial work has validated the accuracy of this model at a point by comparison with measured clear sky incoming radiation, and measured diffuse radiation under cloudy conditions. In addition, the model has been validated by comparing modelled reflected shortwave radiation to that measured by the NRC Twin Otter along a 6 km transect.
Spatial variability of sensible heat flux, and the effect on snowmelt, has been considered through the implementation of a simple, rough terrain wind model (Liston et al.) linked to a snowpack energy balance model. The first step in this analysis demonstrated that the simplified Liston model provided similar results to a more complex wind model (Wamsley/Taylor), and compared well with wind measured at three sites. This demonstrates that the Liston wind model is sufficiently accurate for the gently rolling terrain of the study area. To date, a preliminary analysis of the effect of spatially variable sensible heat flux on snowmelt has been carried out.

In the calculating of the melt of a patchy snowcover, the energy advected from bare to snow surfaces is an important consideration. This additional energy flux cannot be calculated using traditional boundary layer flux-profile relationships, since these are based on the assumption of a constant flux layer. A new approach is being investigated, in which boundary layer integration and blending height theories are combined to provide a means of calculating the amount of energy removed by the snow patch surface as warmer air moves over it.

The influence of vegetation on snowmelt energetics is substantial as canopies extinguish shortwave radiation and emit longwave. Measurement of the surface temperature of complex vegetation surfaces (pine canopies, deciduous shrub stalks, needles, trunks, etc.) has remained difficult and collecting sufficient surface temperature samples to characterise the longwave radiation flux to the snow surface all but impossible. A portable thermal infrared digital imaging radiometer has been rescaled so that it can collect measurements in the range -30 to 90°C and modified so that it will work in cold remote environments. This radiometer features a variable emissivity setting and includes image processing software to carefully determine the surface temperature/thermal IR emission of complex surfaces.

**Task 2: Develop Physically-based Algorithms to Estimate Soil Moisture and the Volume and Timing of Subsurface Drainage of Organic Soils**

*Summarising and Publishing of Archived Data*

For the Fort Simpson region, the CAGES data collected at wetland and woodland sites, in addition to discharge data from the Water Survey of Canada (WSC) for the major drainage basins of the lower Liard River valley, and data from Environment Canada on extensive snow surveys in this region, has been compiled into a single comprehensive dataset. At Wolf Creek, the CAGES data has also been compiled, and a comprehensive dataset that includes stream flow and snow survey data from Indian and Northern Affairs is presently being compiled.

*Field Studies*

At the Scotty Creek and Granger Creek basins, tracer tests were conducted on 10 x 10 m hillside plots at each study site immediately following the snow melt season, and then again in late August, in order to define the water transmission properties near the top and the bottom of the organic layer, and other measures needed for the development of the mass flow algorithm. The measurements needed for the development of a thermal algorithm were also made at each site. Soil cores containing the entire thickness of the peat layer extracted from each site in order to provide data needed for the
solution of the thermal and hydraulic formulae. Soil pits were excavated and instrumented in order to monitor water level, and the volumetric liquid water content and soil temperature at closely spaced depth increments. Thermal infrared sensors were also installed at each site in order to monitor the ground surface temperature. These data enabled the monitoring of changes in thermal properties and active layer thaw. Soil blocks were also sampled from these locations. They will be used in experiments at the University of Calgary cold temperature laboratory designed to elucidate frost table dynamics.

Additional soil moisture measurements were made at Granger Creek in order to provide an initial evaluation of surface (0-10 cm layer) soil moisture patterns over an extensive grid network that includes approximately 900 points. These measurements will help to determine: a) how soil moisture controls the transfer of water from hillslopes to the stream network, and b) how patterns of soil moisture on hillslopes changes from melt to freeze-up and how this affects hydrologic fluxes.

At both Wolf Creek and Scotty Creek, field studies aimed at increasing the understanding of basin-scale water flux and storage processes were also initiated. In order to determine the relative contributions of the major terrain units within these drainage basins, and the relative contributions of event (snowmelt and rainfall) and pre-event (storage) water to stream hydrographs, baseline oxygen and hydrogen isotope values for precipitation, streamflow and soil water for the major landscape units within the Wolf Creek and five representative drainage basins of the lower Liard River valley, including Scotty Creek. At Scotty Creek, water level, and where possible, discharge measurements were made at nodes along the drainage way between the head waters and the outlet in order to measure the propagation of the flood wave through inter-connected channel fens. In Scotty Creek, high resolution (4 x 4 m) Ikonos satellite imagery was used in combination with aerial and ground verification surveys to classify the land cover, and to delineate the wetland area connected to the drainage system in these drainage basins. At both Scotty and Wolf Creek, low-altitude aerial photographs have been purchased. This will serve as a basis for the development of a Digital Elevation Model.

*Development of New Observational and Analytical Methodologies*

A horizontal mass transfer algorithm has been developed to form the basis of the hydraulics of the hillslope subsurface drainage system. It is based on the results of field studies on the effects of variations in soil hydraulic properties and the position and thickness of the saturated layer on lateral water movement. From an examination of the ground surface temperature, soil thermal properties, heat flux into the ground and the seasonal thaw of the soil, a heat transfer algorithm was also developed for estimating the elevation of the lower boundary of the saturated layer (i.e. the frost table) needed to estimate mass transfers during ground thawing. The mass and energy algorithms were coupled with the procedure describing subsurface lateral flow suggested by Colbeck. The module was then incorporated into the Cold Regions Hydrological Model. The performance of the runoff module is presently under evaluation using observations at each of the study sites.
Soil moisture and the relationship between its variability and other hydrological components is a key CFCAS research issue. Programs to analyse the geostatistical properties of soil moisture variability have been implemented, allowing the determination of characteristic length scales at different hydrological time periods (i.e. melt, post-melt, mid-summer and pre-freezeback). Additionally, methods to relate soil moisture at the hillslope-scale to both lateral and vertical moisture fluxes are being explored.

Algorithms for the classification of landcover have been developed for Scotty Creek. These algorithms, developed from extensive ground observation surveys, were used to classify the lower resolution Landsat image (30 x 30 m) image for the lower Liard River valley. This enabled comparisons of the hydrological characteristics of five basins in the Lower Liard valley in relation to wetland abundance and connectivity. This information is needed to properly represent storage and routing processes in WATCLASS.

Task 3: Develop Appropriate Up-scaling Techniques to Represent Sub-grid Processes in Tasks 1 and 2 at the RCM Scale

Work is underway for developing appropriate up-scaling techniques to represent sub-grid processes discussed in Task 1 and 2 at the RCM scale. We have established a framework for archiving historic datasets that will be used for this phase of the project. We are also actively encouraging all the CI's and PI's to collate any new information and data into a GIS for each of the three research sites. An M.Sc. student (Mr. John Bastien) from the University of Waterloo has been assigned to this project through a collaborative arrangement with Dr. E.D. Soulis, Department of Civil Engineering, University of Waterloo. Student salary is being covered by Dr. Soulis and should be considered an in-kind contribution to this project. This student will be assisting with field data collection at all three research sites. These data will be used as forcing and input data into the WATCLASS model. Operationalizing the model is currently underway and will be completed by the end of this summer. This requires detailed physiographic information, land-cover information, digital elevation models and appropriate forcing variables. Much of these data are already in place. Testing and evaluation will commence this fall.

The majority of this year's resources are going towards field data collection. Mr. Bastien, along with two field technicians from the National Water Research Institute conducted snow surveys in March, 2002 throughout the Fort Simpson region, and while there serviced existing equipment and retrieved logged data. Mr Bastien then proceeded to the Wolf Creek and Inuvik research sites where he assisted with snow surveys and other data collection with the other PI's. A graduate student (Mr. Dean Shaw) was hired as a Research Assistant for the 2002 summer period in order to help develop the GIS for all the datasets and interface this GIS with CRHM.
Task 4: Test and Validate the CRCM Land Surface Scheme for a Variety of Cold Region Landscapes.

Development of the GIS interface for the CRHM is in progress. This interface is an arc/info based routine designed to segment the basin into fundamental hydrological response units. This interface uses automatic sub-basin delineation derived using the Topographic Parametrization (TOPAZ) package developed by Martz and Garbrecht (2001). A prototype for the Wolf Creek basin is under development.

Research Collaboration

CFCAS funding of this study has enabled extensive research collaboration among several Canadian universities and government departments. This has brought together a wide range of internationally-recognised scientists and other experts, and has resulted in the extensive sharing of data and resources. Without this degree of scientific collaboration, the complex, multi-disciplinary research tasks of this study could not be properly addressed.

Publications

Journal Papers

Carey, S.K., S. McCartney and W.L. Quinton: Snowmelt runoff processes in a subarctic basin: isotopic, geochemical and hydrometric approaches. (in preparation)

Carey, S.K. and W.L. Quinton: The isotopic evolution of a late-lying snowpack and its contribution to streamflow in a subarctic basin. (in preparation)

Carey, S.K., M.K. Woo: Freeze-up of subarctic hillslopes, Wolf Creek basin, Yukon. (submitted to Can.. J. of Hydromet.).


Hayashi, M. and W.L. Quinton: Hydraulic conductivity and water-retention properties of shallow peat soils. (in preparation)
Hayashi, M., W. Quinton and A. Pietroniro: Hydrological functions of interconnected wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. (submitted to Journal of Hydrology)


Marsh, P., C. Onclin, M. Russell, P. Schuepp, I. MacPherson: Spatial variability of surface fluxes during the spring melt period at the arctic treeline during CAGES. (in preparation for Journal of Hydrometeorology)


Pietroniro, A., W. Quinton, M. Hayashi, J. Gibson, N. Kouwen and E. Soulis: Modelling the Hydrological Response of the Lower Mackenzie System in the Zone of Discontinuous Permafrost/Wetland Zone. (submitted to Hydrometeorology)

Pietroniro, A., W. Quinton, M. Hayashi, J. Gibson, R. Soulis and N. Kouwen: Modelling the Hydrological Response of the Lower Mackenzie System in the Zone of Discontinuous Permafrost/Wetland Zone. (submitted to Journal of Hydrometeorology)


Quinton, W.L., M. Hayashi, and A. Pietroniro: Connectivity and storage functions of channel fens and flat bogs in northern basins. Hydrological Processes. (in press)

Quinton, W., and J. Pomeroy: The influence of runoff pathways on the ion chemistry of water draining from arctic tundra basins. (submitted to Hydrological Processes)
Quinton, W. and D.M. Gray: Lateral subsurface flow coupled with a snowmelt percolation routine - Evaluation of the Cold Regions Hydrological Model at Wolf Creek, Yukon. (in preparation)

Quinton, W., M. Hayashi, A. Pietroniro and B. Toth: Multi-year water balance of wetland dominated, northern basins from observed and modelled data. (in preparation)

Conference Presentations


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1. Objectives

The objective for this project is to produce the integrated modelling system for MAGS. This involves the development of a model strategy and the incorporation of process studies. An important part of this system is WATCLASS. The particular goal for this year was to develop WATCLASS such that it is usable by other MAGS investigators, and that it generates credible test output data sets for application studies.

2. Progress

This was the year for consolidation in preparation for the application work anticipated for the coming year. The elements of WATCLASS had been assembled in prior years and the goal for this year was to gain experience with the algorithms and produce reliable hydrographs through an extensive testing program.

The primary task was the selection of parameters for the soil moisture algorithms. Although a manual optimization method produced both reasonable hydrographs and soil parameter estimates, the mix of soil parameters is not typical of a naturally occurring soil. This raises the question whether a single generic soil type is appropriate for each land class type or whether vegetation/soil sub-classes are necessary (e.g. coniferous forest/sand, coniferous forest/clay). Furthermore, Snelgrove (2002) found soil type to be strongly related to slope and elevation as well as to vegetation. This suggests that landscape units should have a series of attributes that reflect vegetation, soil and topography.

As an interim measure, we selected soil parameters based on water balance considerations. Default values for layer one hydraulic conductivities were set to approximately 3 times the mean annual storm intensity, and third layer conductivities were set to that of the mean annual rainfall. This gives values of $10^{-6}$ ms$^{-1}$ and $10^{-8}$ ms$^{-1}$ for the layers, respectively, which are typical of consolidated soil conductivities.

The calibration process is proving to be a challenge. WATCLASS still requires a significant amount of time to run, and the fine-tuning of the landscape parameters is tedious. This year, a pre-screening system was developed using a simple version of the model for preliminary parameter identification. A formal, gradient based calibration scheme is then used for final parameter selection.
The testing program focused on the Mackenzie River Basin but also involved tests using existing data sets from other research watersheds. The BOREAS data set continues to be the most complete data set for testing process algorithms. In this data set, summer hydrographs are well modelled but spring hydrographs are problematic. This can be partially attributed to problems with algorithms relating to the melt and the accumulation of a partial snow pack. The snowcover depletion algorithm only allows for the exposure of ground during melt but does not properly account for development of new snowcover when the pack is refreshed. The D100 model for snowcover depletion was extended to include a D100 accumulation depth to track the recovery of the pack during a new snowfall. This has a significant impact on the snow energetics and we are currently evaluating the resulting hydrographs.

Improper infiltration to and drainage from cold ground is also corrupting the spring hydrographs. This requires a major effort to resolve. Movement of water in cold soil is affected, among other things, by: preferred occupation of small pores by ice, reduction of pore connectivity due to ice, and increases in viscosity at cold temperatures. As a first step, the Clapp-Hornberger soil physics model was modified to include the ice fraction in estimation of the effective saturation ratio and the saturated conductivity.

These two changes produced more realistic spring hydrographs by allowing more movement both vertically and horizontally through the soil. However, spring freshet hydrographs are still too early and too high. Further investigation of the hydraulics of cold soil is warranted. A Ph.D. student, Cindy Cai, has begun to address this problem.

WATCLASS forcing data sets for Southern Ontario were developed. These include field observations of soil moisture from a previous study (Seglenieks et al., 1998). Both the soil moisture and hydrographs were reasonably simulated, confirming that the model is transferable and state variables can be simulated.

High quality data sets for the current MAGS research basins are being assembled by a Masters student, Jon Bastien, currently at NWRI in Saskatoon, Saskatchewan. The drainage layer databases have been completed for a number of watersheds. We are currently in the process of assembling the forcing data sets and developing the required interpolation algorithms to grid the station point data. This work is in collaboration with Phil Marsh, Lawrence Martz and Al Pietroniro.

3. Results

The key results are the successful simulation of the Mackenzie River Basin using WATCLASS with multiple land classes. Results for the CAGES year are shown in Figure 1. Major improvements are in the simulation of baseflow and in the consistency of the results between northern and southern basins. Significant problems remain, including routing in the main stem of the Mackenzie River and prediction of the spring freshet.
Figure 1. WATCLASS Hydrographs for CAGES. (thick line is observed, thin line is simulated)

References


4. Relevance

This work is an essential part of the integrated modelling task. Land surface scheme testing for the model physics as well as parameter identification and the associated scaling issues can only be resolved in the stand alone modelling tests such as were conducted this year.

5. Networking and Collaboration

The primary objective this year was to create a system robust enough to make WATCLASS usable by the rest of the MAGS team. To date, it has been used in radiation budget studies by Henry Leighton; inflows have been provided to Faye Hicks for routing the main stem of the Mackenzie; and the code has been transferred to NWRI for use in a CFCAS study. Most importantly, the code has been transferred to Environment Canada for use in CLASS 3.0. Furthermore, coupled modelling with the RCM has begun.

We have taken part in all MAGS workshops and meetings, and represented MAGS with presentations at CGU, CMOS, and CWRA.

6. Summary

One of the major goals for MAGS is to provide the tools to predict how changes in the atmospheric conditions will affect the water resources of the Mackenzie River Basin. This year we made a major step forward with the completion of WATCLASS 2.7. This is a model that takes precipitation, temperature, and other information and uses it to simulate the river flows and water levels at various points in the watershed. The model is much more detailed and rigorous than earlier models. We will continue to improve it as we learn more but, in the meantime, we can review and revise our understanding of the basin’s response to climate change. The first step will be to determine the vulnerability of critical points in the river such as ferry crossings and navigation hazards.

7. Publications

Refereed Journal Publications


*Refereed Conference Proceedings*


*Other Publications*


*Non-Refereed Contributions*

Conference Proceedings:
   CWRA 2002 – 1

Conference Presentations:
   CMOS 2002 – 2
   CGU 2002 – 4
   CGU-Student Conference – 2

Workshops Presentations:
   MAGS Cross-Training Workshop – York University
   MAGS CAGES Workshop 2002 – Edmonton
   MAGS Annual Scientific 2002 – Jasper

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Hydrological Modelling of Subarctic Canadian Shield Rivers

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²Northwest Territories Power Corporation, Yellowknife, Northwest Territories
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⁴University of Saskatchewan, Saskatoon, Saskatchewan
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⁶Meteorological Service of Canada, Downsview, Ontario

1. Objectives

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

2. Progress

The partnership with the Northwest Territories Power Corporation continues to flourish. Expanded monitoring in the Snare River Basin (Figure 1) meant to address spatial data gaps has worked well to date. SLURP has been parameterized using two schemes discussed below. Simulations for 1999 and 2000 are complete producing interesting results. WATFLOOD has been parameterized in partnership with the National Water Research Institute and simulations are forthcoming. Applications of CLASS using MAGS-1 field data collected at Lower Carp Lake are beginning. Problems with premature termination of the model have prevented comparison of model output to field measurements of the energy budget. Troubleshooting of this problem continues.

3. Results

SLURP was configured using many small scale sub basins (678 ASA’s) in an attempt to force the model structure to mimic the runoff processes identified during MAGS-1. SLURP was also configured using large scale sub-basins (17 ASA’s) to compare against the small scale scheme and determine any scale effects. The output statistics from the January 1 to December 31, 1999 calibration runs of both the large scale method and the small scale method (Table 1) and the resulting hydrographs (Figures 2a and 3a) were promising and merited validation runs. The validation hydrograph (Figure 2b) and statistics (Table 1) of the large scale method were good compared with the optimization results. The large scale approach produced an accurate hydrograph but the large discrepancies in the vertical water budget (Table 2) suggests that the match was forced by exaggerating other parameters and constants in the model, most notably, river routing coefficients. The small scale scheme yielded a poor hydrograph simulation (Figure 3b) but the annual mean error and deviation of volume were still good, at 1.1 m³ s⁻¹ and 2.0%, respectively. The accurate runoff volume from the small scale scheme is a result of a well
reproduced vertical water budget (Table 2). Constraints within SLURP on river routing coefficients prevent a well simulated hydrograph. The use of an external river routing method could improve the hydrograph, rendering the small scale model good in both its ability to represent both the vertical water budget and the timing of the high order streamflow.

Figure 1. The Snare River Basin including land cover, basin outline and important monitoring sites.
Figure 2. Large scale configuration: a) calibration and b) validation hydrographs.
Figure 3. Small scale configuration: a) calibration and b) validation hydrographs.
Table 1. SLURP output statistics for both the large scale and small scale modelling method for the Snare River Basin.

<table>
<thead>
<tr>
<th>SLURP output statistics</th>
<th>Large Scale</th>
<th></th>
<th>Small Scale</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Validation</td>
<td>Calibration</td>
<td>Validation</td>
</tr>
<tr>
<td>Mean computed streamflow (m³s⁻¹)</td>
<td>81.709</td>
<td>52.258</td>
<td>83.496</td>
<td>55.688</td>
</tr>
<tr>
<td>Mean measured streamflow (m³s⁻¹)</td>
<td>82.283</td>
<td>54.595</td>
<td>82.283</td>
<td>54.595</td>
</tr>
<tr>
<td>Mean error (m³s⁻¹)</td>
<td>-0.5743</td>
<td>-2.3366</td>
<td>1.2126</td>
<td>1.0939</td>
</tr>
<tr>
<td>Largest daily error (m³s⁻¹)</td>
<td>114.07</td>
<td>36.847</td>
<td>93.797</td>
<td>66.526</td>
</tr>
<tr>
<td>Nash-Sutcliffe criterion</td>
<td>0.79934</td>
<td>0.73048</td>
<td>0.78281</td>
<td>0.1912</td>
</tr>
<tr>
<td>Deviation of volume (%)</td>
<td>0.69796</td>
<td>4.2799</td>
<td>-1.4737</td>
<td>-2.0036</td>
</tr>
</tbody>
</table>

Table 2. Water budgets (1999) and Muskingum coefficient K calculated from the two model configurations and observed at Lower Carp Lake. P is precipitation, M is snowmelt, R is runoff, ET evapotranspiration and ΔS, change in storage.

**Large scale model configuration**

<table>
<thead>
<tr>
<th>Month</th>
<th>P</th>
<th>M</th>
<th>R</th>
<th>ET</th>
<th>ΔS (calc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>10.8</td>
<td>0.2</td>
<td>1.4</td>
<td>0</td>
<td>9.6</td>
</tr>
<tr>
<td>May</td>
<td>23.4</td>
<td>42.1</td>
<td>1.5</td>
<td>3.6</td>
<td>60.4</td>
</tr>
<tr>
<td>June</td>
<td>14.1</td>
<td>250.7</td>
<td>24.5</td>
<td>9.3</td>
<td>231</td>
</tr>
<tr>
<td>July</td>
<td>10.6</td>
<td>122.5</td>
<td>31.0</td>
<td>5.5</td>
<td>96.6</td>
</tr>
<tr>
<td>August</td>
<td>21.3</td>
<td>0.1</td>
<td>20.9</td>
<td>2.9</td>
<td>-2.4</td>
</tr>
<tr>
<td>Sept.</td>
<td>33.1</td>
<td>6.8</td>
<td>16.7</td>
<td>0.6</td>
<td>22.6</td>
</tr>
</tbody>
</table>

Muskingum K coefficient: 1.36

**Small scale model configuration**

<table>
<thead>
<tr>
<th>Month</th>
<th>P</th>
<th>M</th>
<th>R</th>
<th>ET</th>
<th>ΔS (calc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>10.8</td>
<td>5.2</td>
<td>2.4</td>
<td>1.5</td>
<td>12.1</td>
</tr>
<tr>
<td>May</td>
<td>23.4</td>
<td>99.9</td>
<td>37</td>
<td>18.8</td>
<td>67.5</td>
</tr>
<tr>
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<td>8.6</td>
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Muskingum K coefficient: 1.46

**Observed**

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Muskingum K coefficient: 14.73
4. Relevance

The SLURP model results to date show the importance of capturing the correct hydro-meteorological processes at the scale at which a model is applied. The results imply that simulations must be performed at a small scale to correctly model streamflow as well as water and energy exchanges between the subarctic Canadian Shield landscape and the atmosphere. This has significant implications on how MAGS might meet its research goals.

5. Networking and Collaboration

A partnership has been formed between Environment Canada and the Northwest Territories Power Corporation to improve hydrometric and meteorological monitoring and streamflow forecasting in the Snare River Basin. Environment Canada, McMaster University and the University of Saskatchewan are collaborating in the incorporation of MAGS-1 results into the hydrological models being applied to the Snare Basin. Parallel modelling exercises with WATFLOOD are being performed at the National Water Research Institute. Staff from MSC-Downsview are assisting in tests of CLASS using MAGS-1 field data from Lower Carp Lake.

6. Summary

A promising configuration of a hydrological model has been developed for the Snare River in the subarctic Canadian Shield. Exercises with configurations at different scales show the importance of operating the model at a scale appropriate for the conceptualized hydrological processes in the model. With work, the hydrological model may prove useful in running predictive scenarios, linking with atmospheric models and expanding knowledge of the movement of water through meso-scale Canadian Shield basins. Such a tool would improve water resource management on the Snare River in particular, increasing efficiencies at hydropower facilities subsequently reducing reliance on expensive diesel generators and energy costs to the consumer.

7. Publications


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1. Objectives

For MAGS investigations, the cold climate environment and limited availability of data render it important to assess the inclusion of relevant processes in the hydrological models and to improve the parameterization and spatial representation aspects in hydrological modelling.

Research in 2002 was carried out with the objectives:

1. to improve the model representation of processes of importance to the high latitude environments, and
2. to improve the spatial representation and horizontal linkage of basin components in support of upscaling and to examine the transferability of model parameters.

2. Progress and Results

2.1 Process Representation in Modelling

This aspect of research includes two components: a) application of a one-dimensional frost model, and b) evaluation of model complexity appropriate to several spatial and temporal scales.

a) Frost algorithm

A one-dimensional heat conduction model with phase change was used to calculate ground freeze. It is based upon Stefan’s equation (Jumikis, 1977), assuming that latent heat is the principal heat source to be overcome before the freezing front propagates downward. The equation takes the form of

\[
\frac{dz_f}{dt} = \frac{k_f D_f}{(\lambda \theta z)}
\]

where \(dz_f/dt\) is the rate of freezing front descent (m s\(^{-1}\), to be multiplied by 86,400 to convert into daily rate), \(k_f\) is the thermal conductivity of the frozen soil (J m\(^{-1}\)s\(^{-1}\)K\(^{-1}\)), \(D_f\) is the freezing degree-day (converted into degree-second or s K\(^{-1}\)), \(\lambda\) is the volumetric latent heat of fusion (J m\(^{-3}\)), and \(\theta\) is the volumetric fraction of soil moisture content.

The model was applied to four experimental slopes in Wolf Creek basin (Woo et al., 2000) for the winter of 1998-99. The initial soil moisture contents were estimated from profile measurements that were made a number of days before the freeze-up. Figure 1 compares the simulated freeze-
back with the 0° isotherm based on ground temperature measurements, for the north and south facing slopes. For the slopes tested, the modelled frost table position generally agrees with the descent of the freezing front, indicating that:

1. conduction is the predominant heat transfer mechanism during freeze-up,
2. latent heat is the principal factor controlling frost front descent, and
3. discrepancies between the observed and modelled values suggest that lateral flow can retard significantly the frost penetration because of heat advection.

Figure 1. Ground temperature isotherms and modelled frost table (grey lines) during the freeze-back period for two slopes in Wolf Creek basin, Yukon.

b) Model complexity

Different levels of model complexity are needed in hydrological investigations at various temporal and spatial scales. The number of physical processes and their representation are important considerations, but data availability imposes a serious limitation for modelling the Mackenzie basin, especially its western, mountainous terrain. We examined the effects of increasing the complexity of a simple model towards the improvement of runoff simulation for mountainous environments, using the Liard Basin (227,100 km²) and two of its sub-basins as examples. The sub-basins are the Fort Nelson Basin (22,800 km²) on the high plateau and the more rugged Kechika Basin (22,700 km²) with large relief. This work is part of doctoral research by Sandra van der Linden at the University of Utrecht (van der Linden and Woo, 2003a).

A simple model (herein named LIARDFLOW) based on the RHINEFLOW model developed for large basins (Kwadijk and Middelkoop, 1994) was systematically rendered more complex by adding or replacing its basic algorithms with those from SLURP, a model previously evaluated for a mountainous region and for the Mackenzie (Kite et al., 1994). The LIARDFLOW is a simple, GIS-based model that demands minimal amounts of input data: only air temperature and
precipitation. DEM data for the basins are stored in a GIS at 1 km grid size and water balances are preformed daily for each grid cell. Air temperature is used to partition precipitation into rain and snow, and for calculating snowmelt using a fixed snowmelt factor. Evapotranspiration is calculated based on the Thornthwaite equation. The model has only one subsurface storage, with rainfall and snowmelt either entering this storage or being discharged directly depending on a pre-specified separation coefficient. Subsurface storage is released as delayed runoff through a recession coefficient. Catchment runoff is obtained by summing the runoff generated in all the grid cells. Since no routing procedure is used, the simulated daily values have to be aggregated over 10-day and one-month periods to satisfy the assumption that all water generated by the cells will reach the outlet during these periods.

LIARDFLOW and SLURP were calibrated using the 1985-88 data. The parameters thus obtained were used in running the 1981-84 data. These runs provide the reference output sets. Then, LIARDFLOW was systematically rendered more complex by adding or replacing one or more process representation using algorithms from SLURP. The modified versions include LIARDFLOW-E (evapotranspiration: with the Spittlehouse equation replacing the Thornthwaite equation), LIARDFLOW-E/S (evaporation and snowmelt: with the Spittlehouse equation and a variable snowmelt factor that changes during the year), LIARDFLOW-E/S/P (evaporation, snowmelt and precipitation: with precipitation increasing by 5% per 100 m elevation), LIARDFLOW-E/S/P/I (similar to previous version, with single storage replaced by soil water and groundwater storages), and LIARDFLOW-All (all of the E/S/P/I modules are possible candidates and replacement is made in a stepwise fashion, first replacing the module that yields the largest improvement to the Nash and Sutcliiffe R2, followed by the module that yields the next highest R2, and so on, so long as the new R2 is higher than that in the previous step.

Results show that more process replacement is needed for the smaller basins. On a 10-day basis, both evapotranspiration and snowmelt functions have to be replaced and for the rugged Kechika basin, replacement of the precipitation routine further improves model performance. In general, the upgrading of only a limited number of critical processes is sufficient to model runoff satisfactorily because at a particular spatial and temporal scale, runoff may be sensitive to only a certain number of processes. This is an encouraging outcome for the data sparse Mackenzie basin because a compromise can be struck between the model demand and data requirements in producing simulation results adequate for particular time scales and basin sizes.

2.2 Scaling and Parameterization Procedures

Research in 2002 proceeded on two fronts with a) the development and assessment of flow pattern aggregation techniques, and b) the examination of model parameter transferability.

a) Flow Pattern Aggregation

Ongoing research in this area has the general objective of developing improved methods of upscaling land surface parameters for regional hydrologic modelling. It focuses specifically on techniques for aggregating detailed flow pattern data extracted from DEM to larger spatial units suitable for representing the hydraulic and routing characteristics of large basins such as the
Mackenzie. It is undertaken in collaboration with other research teams and serves to strengthen the MAGS network structure.

Earlier research (Armstrong and Martz, 2002) examined the impact of changing grid cell size on basin delineation and flow pattern definition in the Mackenzie and Mississippi River basins and their major sub-basins. One of the objectives was to determine if regional flow patterns could be reliably represented while increasing the size and decreasing the number of spatial elements in a DEM by the aggregation of elevation values through simple, linear averaging. It demonstrated that such techniques have a profound impact on the determination of basin boundaries and flow patterns and that they cannot be used to generalize flow pattern data in a reliable fashion.

This led to an examination of the potential for automating the manual methods of topographic parameterization developed for use with the WATFLOOD hydrologic model as an alternative method of deriving flow pattern data for macro hydrological modelling (Shaw et al., 2002). The fundamental approach was to aggregate flow pattern data (and other topographic data) extracted from fine resolution DEM using the TOPAZ digital terrain analysis model (Garbrecht and Martz, 2000) to the much coarser GRU cells used in the WATFLOOD hydrological model. This study has demonstrated that a WATFLOOD-like, expert system approach is much superior to a simple elevation aggregation approach for flow parameterization for macro or regional scale hydrological modelling.

This research has produced a new parameterization method implemented using the Arc/Info macro language (AML) to create an interface between the TOPAZ and WATFLOOD models. This new interface software (WATPAZ) uses output raster data from TOPAZ as the source of flow path, slope and channel parameters for WATFLOOD grouped response units (GRU); the spatial elements of the model. An additional benefit of this work was the replacement of the slope index parameterization method of WATFLOOD with a more conceptually valid method based on a statistical summary of slope values calculated from elevation data.

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 2).

Comparative analysis was done over a range of spatial scales and DEM resolutions using available data for the Wolf Creek, Peace-Athabasca and Mackenzie basins. Work has also been initiated on a discharge-weighted, vector resultant approach that may improve on the WATFLOOD-like, expert system approach. Such a technique could yield more objective and consistent results with less operator dependence, and could have considerable value in the parameterization of models for large basins such as the Mackenzie.
The automated flow aggregation technique WATPAZ is fully operational and has been made available to other MAGS research groups. It is now being applied in regional scale hydrologic studies of the Great Lakes of Canada.

Figure 2. Drainage patterns for the Mackenzie basin using: (a) coarse resolution elevations aggregated from fine, and (b) WATFLOOD-like aggregation of flow pattern data for fine resolution elevations.

b) Parameter Transferability

In areas with limited data, we frequently apply parameters calibrated for a large basin to simulate the runoff of its sub-basins (or using sub-basin parameters for large basin simulation). The implication of such parameter transfer has not been evaluated adequately. This study performs such an assessment by comparing the SLURP-simulated hydrological outputs obtained by using the locally calibrated and the transferred parameter values. The Liard and its two sub-basins of Fort Nelson and Kechika are again used as examples. The calibration period is 1985-88 and the model is run for 1981-84. Full results, as part of a doctoral thesis for van der Linden, are reported in van der Linden and Woo (2003b).

Daily evaporation, snowmelt and soil water storage for the two sub-basins, calculated using parameters derived: a) for the Liard basin, and b) for the local basins are compared. With the Liard parameters, the simulated evaporation is similar to those using the sub-basin sets but the Liard parameters yield a shorter melt season and exaggerated melt rates. Soil water storage is similar for the Fort Nelson basin but the Liard parameters generate much higher storage than the Kechika set. In terms of runoff, neither sets of parameters produce the high peaks of Fort Nelson River but the sub-basin parameters give higher flows than the Liard set. For the Kechika basin, runoff simulated by the locally-derived parameters out-performs the Liard parameters in matching the observed runoff.
From these results, it is cautioned that the transferability of parameters depends on basin characteristics, climatic conditions and compatibility of scale, a view paralleled by that of Beven’s (2001) that parameter values are usually valid for the conditions for the basins from which it is derived.

References


3. Relevance

This project is concerned with the integration and modelling of the hydrological processes important to the cold climate setting. 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. The models, when completed and tested, 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 contributed substantially to the model cross-training initiative. They have also been active in presenting MAGS research results at other national and international conferences. Some of the research activities – particularly, the development of the WATPAZ of flow pattern aggregation system – have been undertaken in collaboration with other research team members and have been transferred to other applications outside of the MAGS study area.

5. Summary

The issue of scaling in hydrological modelling involves the considerations of incorporating the principal physical processes, providing appropriate parameterization, and defining the major land units and their drainage to permit proper integration of the basin runoff. Our findings in 2002 relate to the process representation, parameter transfer, and flow pattern aggregation aspects.

1. A one-dimensional frost model was tested by applying it successfully to the Wolf Creek freeze-up data obtained during the CAGES period.

2. Model improvement through incorporating various hydrological processes at different scales of investigation was evaluated, with the results showing that the upgrading of only a limited number of critical processes may be sufficient to model runoff satisfactorily.

3. An assessment of parameter transferability demonstrates that its feasibility depends on basin characteristics, climatic conditions and compatibility of scale.

4. An automated flow aggregation technique (WATPAZ) is now fully operational to facilitate the coupling of hydrologic models with RCM/GCM atmospheric models.

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 (since 2000)


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D. INTERNATIONAL REPORTS
Water Resource Applications Project (WRAP)

Lawrence W. Martz
Chair, Water Resource Applications Project Committee

WRAP (Water Resource Applications Project) is a working group of GEWEX Hydrometeorological Panel (GHP) with the mandate to establish dialogue with the water resource community on the development and application of GEWEX products for management and planning purposes. WRAP currently includes representatives from all of the GHP continental scale experiments (CSE) and continental scale associates (CSA), the International Satellite Land Surface Climatology Project (ISLSCP), Hydrology for the Environment, Life and Policy (HELP), World Water Assessment Programme (WWAP), International Association of Hydrological Sciences (IAHS), and the World Meteorological Organization (WMO).

WRAP Background and Development

1. GHP 5: 15 to 17 September 1999, Geesthacht, Germany
   An ad hoc committee was struck to develop a water resources applications proposal.

2. SSG 12: 31 January to 4 February 2000, Honolulu, Hawaii
   Water Resources Application Project (WRAP) proposal submitted to GEWEX Scientific Steering Group (SSG).

3. WRAP 1: 29 to 30 August 29 2000, IRI, Columbia University, New York
   First meeting of the Water Resources Application Project (WRAP) working group

4. GHP 6: 12 to 15 September 2000, Angra dos Reis, Brazil
   WRAP members present workshop proposals to GHP.

5. SSG 13: 29 January to 2 February 2001, Barcelona, Spain
   WRAP report and workshop proposal presented to SSG.

6. WRAP 2: 5 September 2001, Paris, France
   WRAP committee met at UNESCO to review progress and to plan future activities.
   WRAP report to GHP.

7. WRAP 3: 9 September 2002 at Columbia University, New York
   WRAP committee annual planning meeting.
Recent WRAP Activities

GEWEX-IAHS Workshop:
The Application of GEWEX Scientific Research to Water Resources Management

The WRAP Committee and the IAHS/WMO Working Group on GEWEX organized this workshop which was held on 24 July 2002 in conjunction with the 3rd International Conference on Water Resources and Environment Research (ICWRER) at the Dresden University of Technology (Dresden, Germany, 22-26 July 2002). The broad objective of the meeting was to initiate a dialogue with water managers on their needs and the GEWEX data/model products that are available to address those needs. This was intended to: (1) identify useful forecast/modelling products for water managers; (2) understand how these are used in decision-making, and (3) determine preferred product delivery mechanisms.

The Workshop program consisted of three keynote presentations, six presentations on water resource applications in GEWEX Continental Scale Experiments (CSE) and a panel discussion with the keynote speakers from the Workshop and the ICWRER Conference. The keynote presentations were:

- GEWEX and Water Resources Applications Project Overview, Lawrence Martz, Chair WRAP
- Relevance of Predictions (short-, medium-, long-term) of Water Availability for Water Resources Management, Martin Kaupe and Mathias Schmitt, Wassergewinnung (W), GEW RheinEnergie AG, Germany

The CSE presentations were:

- Toward Water Resources Assessment and Management in Thailand with GAME-T Datasets, Shinjiro Kanae (GAME)
- GEWEX Related Water Resources Applications in the Baltic Sea Drainage Basin - Contribution from BALTEX, Sten Bergström (BALTEX)
- The Value of Seasonal Climate Forecasts for Reservoir Management, Aris Georgakakos
- Application of Seasonal Climate Forecasts to Water Management in the Tennessee River, Ruby Leung (GAPP)
- Hydro-meteorological data availability issues in west Africa: a challenge to understand the African Monsoon; Christian Depraetere (CATCH)
- Restoring Ice-Jam Floodwater to a Drying Delta Ecosystem, Terry Prowse, presented by Lawrence Martz (MAGS).

The Panel Discussion component of the Workshop involved the Workshop keynote speakers (with Gert Schultz substituting for Kaupe and Schmitt) and keynote speakers from the ICWRER Conference – Uri Shamir (Israel), PeteLoucks (USA) and Keith Hipel (Canada). The panel discussion was wide-ranging and touched on the following issues:

- the uncertainty of forecasts and the need for measures to describe this uncertainty
- the relative value of characterizing and of reducing uncertainty in forecasts
• integration of hydrological and climate models to reduce complexity and model parameterization requirements
• water managers find it difficult to respond to high levels of uncertainty
• as water becomes more scarce, reliable water supply together with the opposite problem of flood protection are seen as key issues
• ecological issues and water quality are becoming important drivers of water management decisions and are equally affected by climate.
• climate data are more plentiful than hydrological data hence more use should be made of
• more robust water management systems may be a better response to climate change and variability than more accurate global/regional forecasts
• hydropower was seen as the most tradable commodity and even a 1% improvement in operations can yield huge economic benefits
• the potential value of the Global Soil Wetness products and the Prediction of Ungauged Basins (PUBS) initiative
• the value of hydrological observations to CEOP
• a demonstration project to show the use of water resource forecasts from climate information in larger basins
• the use of RCM using land data assimilation systems to establish initial water and temperature conditions for water management decisions
• one day workshops with water managers and water scientists at regional/local/basin scale by the CSEs as a way of developing greater use of GEWEX products.

WRAP Meeting at GHP-8

The third WRAP committee meeting was held on 9 September 2002 at Columbia University, New York, one day in advance of the main GHP-8 meeting. The meeting developed the following activity plan for the upcoming (2002-03) year:

• Submit report on Dresden ICWRER workshop to GEWEX and IAHS newsletters (Hall/Martz)
• Provide background on GEWEX Hydrometeorology Panel and WRAP to 1st World Water Assessment Report (Lawford/Martz)
• Organization of IUGG workshop (Hall)
• WRAP web site (Mantz)
• Collaboration with WWAP to review scientific indicators for global water resources assessment (Manton and others)
• CSE-based user workshops and transfer of knowledge between CSEs (all)
• Journal article on demand for GEWEX hydroclimatological inputs to water resource management (Lawford/Martz)

GEWEX has produced a variety of soil moisture and other hydrologic variable products and has enhanced hydrologic expertise/models that can be made available to the water resource community. WRAP is expanding the GEWEX interactions with the water resource community through a series of CSE-based and international workshops and is forging partnerships with other agencies and programs.
Upcoming WRAP Activities

The major upcoming event coordinated by WRAP is the special workshop entitled *The Role of GEWEX Hydrometeorological Science in Improved Water Resources Management* (Session JWH02) to be held on Friday, 4 July 2003 in conjunction with the IUGG General Assembly in Sapporo, Japan. The workshop is convened jointly by IAHS and IAMAS.

MAGS and Water Resource Management and Planning

MAGS has gained a good understanding of the atmospheric and hydrologic system of the Mackenzie basin. Its research has given insights into the energy and water balance behaviour in basin which, as we know, is experiencing a distinct warming trend. Currently, MAGS is concentrating on the modelling of the Mackenzie system so that it will have the capability to handle scientific, environmental and water resource problems.

As part of MAGS Yellowknife Workshop held in June 2001, a public forum was held for local scientists, water managers and the general public to identify issues of concern that MAGS research might be able to help address. Issues of concern that were raised included:

- the effects of changing climate on economic activities such as hydro-electric generation, mining, barge traffic;
- information needed for informed decision making regarding issuing water rights, mining regulations; and
- the possible effects of climate change and climate variability on traditional lifestyle sustainability.

MAGS research has generated the expertise and datasets that allow it to make significant contributions to the dialogue about issues of concern in northern regions. The MAGS research program has reached the point in its agenda that it is seeking collaboration with users of its scientific outputs. MAGS Users’ Advisory Group (UAG) has been set up to facilitate collaboration between MAGS scientists and users of MAGS results and will be holding a “User’s Session” as part of this workshop to identify potential users of MAGS research. UAG Chair, David Milburn, will present a report on this session and future UAG activities during the closing session of this annual meeting.

WRAP is pleased to see that MAGS is actively pursuing linkage between science and operations and hopes that there are opportunities in the future for WRAP interaction and participation in these efforts.

WRAP Website

Information on WRAP and on recent and upcoming activities is now available on the WWW at http://ecpc.ucsd.edu/projects/ghp/Wrap_web/.

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GAME Status and Cooperation with MAGS

Tetsuo Ohata

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Frontier Observational Research System for Global Change, Yokohama, Japan

1. GAME Status

GAME (GEWEX Asian Monsoon Experiment, Chairman: Tetsuzo Yasunari, Nagoya University) finished its first phase in March 2002, and has started its second phase which will continue for at least three years. Phase 2 is primarily a synthesis phase with a very small observational component. The major focus in Phase 2 will be on:

1. **Land Surface Processes/ABL/AAN**
   J. Chan (China), A. Sugita (Tsukuba University, Japan), J. Kin (Korea), T. Nakajima (University of Tokyo, Japan)

2. **Precipitation Processes**
   A. Fujiyoshi (Hokkaido University, Japan), UEDA (Nagoya, University, Japan)

3. **Monsoon System Study**
   J. Chan (China), Satomura (Kyoto University, Japan)

4. **Monsoon System Modelling**
   Kimura (Tsukuba University)

5. **Re-Analysis**
   Yamazaki (MRI, Japan)

6. **Satellite Utilization**
   K. Nakamura (Nagoya University, Japan), T. Koike (University of Tokyo, Japan)

7. **GAIN (GAME Information Group)**
   Takahashi (MRI, Japan)

8. **Siberia**
   T. Ohata (Hokkaido University, Japan), T. Ohta (Nagoya University, Japan), A. Georgiadi (Russia)

9. **WEBS (Water Energy Budget Study)**
   K. Matsuda (FRSGC, Japan), B.J. SOHN (Korea)

10. **WRAP (Water Resource Application Project)**
    T. Oki (RIHN, Japan)

Among these components, the topics related strongly to Siberia (or Tibet) are 1, 4, 8, and 9.
The Siberia regional study will continue its activities (observational components will be implemented in other projects) for 1-2 years in this framework to finalize the results. Other regional experiments (Tropics, Tibet, Huaihe River) will not be studied explicitly.

GAME will hold domestic and international workshops under the initiative of these WGs during the first three years, and a final conference is planned for 2004.

The GAME International Science Panel (GISP) Meeting was held recently on November 6-7, 2002 at NASDA, Tokyo, Japan.

2. Results from the Siberia Regional Study 1997-2001

The main tasks of this regional study are to produce results from five years of observations (1997-2001) including the year 2000 intensive observation period. Results are being published in Hydrological Processes, Journal of Hydrometeorology, the Japanese Journal of Water Resources and Hydrology and other journals. The final project report for Siberia, apart from the whole GAME, is planned to be published in 2003.

The main findings from the regional study are:

1. There are relatively high sublimation rates for snow in the Lena Basin Area (Tiksi, Tynda).
2. The snow-melt refreezing process in frozen ground is very important in regards to seasonal and interannual variation of runoff.
3. Deforested areas exhibit non-uniform evaporation rates. The reason for this is related to the history of the deforested area and initial permafrost conditions.

Verification, application and improvement of patch-scale physically-based heat/water exchange models, land-surface schemes of regional and global climate models, and hydrological models are being done.

3. Schedule of Siberia Group and Future Issues

The Siberia Group (Ohta and Georgiadi) presented recent findings at the GAME-ISP Meeting. The Group will hold a domestic workshop on November 29-30, 2002 at Hokkaido University to discuss further outcomes, and hopes to publish a Project Report within one year. The Russian Group is planning an monograph concerning their contributions.

There are several shortcomings in the Siberia Regional Project, which cannot be resolved in the next 1-2 years, and needs to be treated in the future. We have not yet developed a large scale hydrological model which can run only using land surface parameters and meteorological inputs. We have not yet understood the present condition of cryospheric, hydrological, meteorological, land surface components in the context of the long-term climate change which is occurring strongly in this region.
One issue for Siberia Group is to start a comparison study of Lena and Mackenzie Basin of Canada (ACSYS/Clip SSG Meeting) in cooperation with the Mackenzie GEWEX Study (MAGS) in order to develop and generalize the understanding of large northern rivers.

The Siberia Group will be distributing a CD-ROM, including all data obtained up to 2000, by the middle of 2003.

4. Follow-on Observational Studies of GAME-Siberia

Follow-on observational studies are being started and planned. The two main succeeding projects of GAME-Siberia at the moment are:

1. Basic measurements at the GAME observational area are being maintained by FORSGC: the basic meteorological and hydrological (some biological) observation system, such as drainage and patch scale heat/water budget measurements at Tiksi (71ºN); three forest tower and spatial surface soil moisture/temperature measurements around Yakutsk (62ºN) are being continued and managed by the Frontier Observational Research System for Global Change (Yokohama, Japan). Two sites (Tiksi, Yakutsk) have been registered as CEOP sites. The southern-most site (Tynda) has finished its two-year observation period and investigations at this site are complete.

The main focus of the study at FORSGC is to understand the annual variations of water/energy exchange and obtain and archive verification data for models for different climate years. It should be noted that it was an exceptionally dry year in 2002, drier than the previous 5 years, with a huge forest-fire burnt area (30,000 km²) which was one of the largest in history. Also, winter land surface processes which were not intensively investigated in the GAME Project will be given more focus. The PI of the study at FORSGC is T. Ohata.

2. A study on parameterization of forest processes in relation to the hydrological cycle (funded November, 2002). As a follow-on of GAME-Siberia, this project is directed to better understand the structural and physiological character of the boreal forest system and to improve land surface parameterization for regional and global climate models. Observational studies are planned at Yakusk (Russia), Kamchatka, and Hokkaido and Nagoya (Japan). This study is planned for five years, and the PI of this project is Takeshi Ohta of Nagoya University, Japan.

5. Cooperative Research with MAGS

5.1 Past Discussions

Cooperative research between MAGS and GAME was discussed during the 2nd GAME-MAGS Joint International Meeting held in Sapporo in October 2001. Cooperative research was planned for 2-3 years. Through discussion on collaboration, main topics were identified: hydrological model application to the Lena and Mackenzie basins (whole drainage and tributaries); similarity and difference in local scale phenomena (forest, tundra and others); atmospheric studies.
It was decided at the meeting that proposals for cooperative research be exchanged by end of 2001, and the possibility was raised of holding a third joint workshop in the fall of 2003. Proposals from MAGS side were received by Ohata in December 2001. Unfortunately, GAME was unsuccessful in securing funding, and the start of collaborations is delayed.

The research topics identified from the MAGS proposals as being possible collaborative projects include the following:

1. Comparison of leaf area index and evapotranspiration between MAGS-Mackenzie Basin and GAME-Siberia Study area.
   MAGS: Chen, Fernandes, Leblancm, Wang, Cihlar
   GAME: Suzuki, R, Masuda

   MAGS: Marsh, Quinton, Macpherson, Pohl
   GAME: Kodama, Ishii, Ohata, (Yabuki, Hirashima)

3. Comparison of the hydrology of boreal and mountain environment in Western Canada and Siberia.
   MAGS: Woo, Carey, Martz, Janowitz
   GAME: Ohta, Hiyama, Kubota

4. Comparison of hydrologic model performance at regional and small basin scales in the Mackenzie and Lena River Basins.
   MAGS: Martz, Pietroniro, Soulis, Kowuen, Woo
   GAME: (Ma)

5.2 Future Activities

GAME-Siberia is applying for funds to support this work for the fiscal years 2003-2005, and it will be clear in April 2003 if funding is forthcoming. GAME is also investigating the possibility to start with small funding from several projects.

Other collaborative actions planned the distribution of a GAME dataset (this will be made available in first half of next year) and to organize a meeting for the specified topics at some time next year, perhaps in conjunction with the IUGG Sapporo, June-July 2003. Scientist exchange may be another way of cooperation, and GAME will seek possibility for next year.
6. Information on GAME-Siberia

For more information on GAME, please contact one of our project offices:

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GAME Publications are available on the WWW at:
   http://www.suiri.tsukuba.ac.jp/~ game/list/thesis.html

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E. STATUS AND UPDATES
MAGS Progress and Activities

Kit Szeto
Chair, MAGS Scientific Committee

MAGS Goals

- To better understand and model the high-latitude water and energy cycles
- To improve our ability to assess the changes in Canada’s water resources that arise from climate variability and human-induced climate change

MAGS-2 (2001-2005)

- Shift in research focuses from data acquisition and experimentation to modelling and prediction
- Major MAGS-2 Objectives
  - Integrate knowledge of atmospheric and hydrological cycles into a unified system
  - Develop hierarchy of models for use over a range of spatial and temporal scales
  - Apply improved predictive ability to environmental and social issues

MAGS-2 Timeline

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<th>Theme</th>
<th>Objective</th>
<th>Components</th>
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Highlights of Past Year (2002)

MAGS Workshops:

*CAGES (1998-99 WY) Workshop:*
- Edmonton Workshop (March) to present and discuss CAGES data analysis and modelling results
- ~15 articles submitted to CAGES Special Issue of *J. Hydrometeorology* (Marsh and Gyakum, editors)
- Synthesis article under preparation

*MAGS Data Workshop:*
- Held in conjunction with the CAGES Workshop
- Assessed data gaps
- Refined data policies
- Developed the blueprint for MAGS legacy datasets

*WEBS Workshop:*
- Toronto workshop (May) to assess present MAGS WEBS status and to map out future activities
- There are various MAGS research activities related to the study of water and energy budgets from local to basin scale by using observations, analysis or model results
- The synthesis of individual results into an organized dataset and scientific article remain to be done
- SWAT team approach to lead and coordinate future MAGS activities

*Model Cross-Training Workshop:*
- Held at York University, Toronto (September) for hydrologists to educate atmospheric scientists on hydrologic models and *vice versa*
- Enhanced communication and collaborations between PLs with different backgrounds and helped to streamline the application of different models or model results in MAGS projects

Scientific Progress:

*Completion of 1994/95 WY Project:*
- Provided overall perspective on basin climate system over 1994-95 water year using operational observation networks and analysis data.
- Highlighted critical gaps in data and understanding to define future research directions
- Special issue of *Atmosphere-Ocean*
  - June 2002 (R. Stewart, editor)
  - 10 articles plus synthesis paper
- Data CD is being produced
Atmospheric Processes:
- Enhanced understanding of large-scale atmospheric processes (e.g. moisture and energy transport) affecting the climate and weather of the basin
- Starting to gain insights on the linkage between the short-term climate variability of the basin and low frequency climate variability in upstream regions

Integration:
- New and improved physics are being incorporated into CLASS, WATFLOOD etc.
- Incorporation and testing of blowing snow parameterizations in models
- Developments of new submodels (e.g. lakes) and their integration into coupled models

Scaling:
- Processes (e.g. snow, lake effects) and data scaling studies
- Intercomparison of CRCM and MC2 to assess downscaling capability of the CRCM
- Field and model studies of snow processes and their scaling for model and remote-sensing applications (MAGS-PLs led CCAF project)

Modelling:
- Modelling activities span from sensitivity experiments with simple and not so simple models of all kinds (e.g., LSS, ground frost, river ice, lake and hydrologic models), weather case studies with cloud models to WY simulations with coupled models and their validation
- MAGS now has intermediate coupled models (CRCM-CLASS and WATFLOOD-CLASS) which were run with CAGES data producing good results for surface temperature and precipitation

Networking
- MAGS Model Cross-Training Workshop
- NSERC PI and SC Chair meeting with government and university PLs (May) to assess research progress and gaps
- Structured, both top-down and dynamic, grass root networking
- International Linkages
  - GHP
  - CSEs
  - CEOP
  - GHP/CEOP WEBS
  - Transferability
  - WRAP
  - Water Sources
  - Extremes

Users/Applications
- Initiated communications between UAG and scientists.
- Identification of new users.
- User Session at Annual Meeting
Publicity and Outreach

- Provided weather station to Samuel Hearne High School (SHHS), Inuvik to give students an opportunity to work with scientific instruments and climate data
- Public presentations by the Network and Information Managers (Aurora College in Inuvik, CGU and CMOS conferences etc.)
- MAGS sponsored and participated in CWRA workshop “Bridging Science and Operations”.
- Updated MAGS website:
  ⇒ French Translation
  ⇒ New user-friendly interface

MAGS Progress – Technical-Logistical Criteria for CSE Assessment

| NWP centre atmospheric and surface data assimilation and estimates of hydro-meteorological properties. | F |
| Suitable atmospheric-hydrological models and numerical experimentation and climate change studies. | F |
| Mechanism for collecting and managing adequate hydrometeorological data sets. | F |
| Participate in the open international exchange of scientific information and data. | F |
| Interactions with water resource agencies and related groups to address the assessment of impacts on regional water resources. | I |
| Evaluation of GEWEX global data products | I |
| Contributions to CEOP and transferability data bases. | I |

*F = Functioning, I = Initiating*

MAGS Progress – Scientific Criteria for CSE Assessment

| Simulate the diurnal, seasonal, annual and interannual cycles. | Pr |
| Close water and energy budgets. | Pr |
| Determine and understand climate system variability and critical feedbacks. | Pr |
| Demonstrate improvements in predictions of water-related climate parameters. | Pr |
| Demonstrate the applicability of techniques and models to other regions. | B-Pr |

*Pr = Progressing, B = Beginning*
MAGS Annual Statement

It has become tradition for an annual statement to be prepared by the chair of the Scientific Committee summarizing activities and progress over the previous year. Following is a summary statement for 2002.

In year 2 of MAGS-2, we see the completion of some major projects initiated during MAGS-1, the advance of research in the integration, scaling and modelling themes, the flourishing of research collaborations and networking at the grass root level, as well as the beginning of users/application activities.

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The second phase of MAGS has a number of themes, each of which addresses major components required to meet the final objectives of MAGS. The first theme addresses the issues of undertaking necessary process studies, and the integration of these into the MAGS integrated models. Specifically, the objectives of Theme I are:

1. To extend the process studies to encompass the important physical processes not covered comprehensively in MAGS-1, and

2. To consolidate knowledge of the atmospheric-hydrological system of the Mackenzie basin in a unified framework.

The MAGS-2 NSERC proposal noted the following examples of processes that are required: orographic precipitation, convective processes, diurnal water vapour variations, evaporation, blowing snow, overall contribution of lakes to water and energy balance, basin storage, groundwater, river ice formation and breakup effects on water level and river flow and channel storage, while the Integration Workshop (Montreal March 2001) noted that “the outstanding factors that need to be incorporated into the MAGS-2 modelling effort include the roles that infiltration into frozen ground, permafrost, river ice jams, wetlands, and lakes play in the transfer of water and energy”.

The majority of the studies contributing to Theme I are directly funded by either NSERC, or NWRI, MSC, and CCRS. Funding from these organizations includes Abase, plus funding from other projects such as PERD, CCAF, CFCAS for example. Other studies are being carried out by university and international partners with other funding sources. For example, Quinton et al. is supported by CFCAS.

The following is a brief outline of the process studies continued or initiated in MAGS-2:

**Orographic Precipitation** (C. Smith)
- considering orographic precipitation in the leeward areas of the western cordillera

**Evaporation** (R. Granger, W. Rouse, W. Chen, P. Marsh)
- point measurements, work required on basin scale evaporation
- in MAGS-1 we had studies using remote sensing to provide snapshots of basin wide evaporation
- there is a great need for basin wide estimates of evaporation to compare to output from models (RCM or WATFLOOD/WATCLASS) and products such as CANGRID
- continuation of work using the NRC Twin Otter flux aircraft will allow determination of evaporation rates in the northern edge of the Mackenzie basin
Blowing Snow (P. Taylor, J. Pomeroy)
- continuing debate concerning the magnitude of sublimation during blowing snow and from snow in forest canopy
- previous field studies in the Mackenzie Region suggest that sublimation rates are high. However, there is a need for further field studies to confirm its magnitude and to reconcile different modelling approaches

Lake Water and Energy Balance (W. Rouse, B. Schertzer, C. Spence)
- studies of both GSL as well as small shield lakes
- given the large number of lakes in the Mackenzie this is an important field of study, which is unique to the MAGS region
- this is definitely one of the significant success stories of MAGS

Basin Storage (P. Marsh)
- one of the few studies considering this topic, but is limited to one small region of the Mackenzie (not representative of the entire basin)

Snowmelt (P. Marsh, J. Pomeroy)
- ongoing studies considering the spatial variability and the role of different vegetation types, and the role of patchy snowcovers

River Ice (F. Hicks, S. Beltaos, T. Prowse)
- river ice breakup (F. Hicks, S. Beltaos)
- role of channel storage during ice covered period (T. Prowse)

Wetlands (B. Quinton, M. Hayashi)
- wetlands cover a large area of the Mackenzie basin
- ongoing work in the Ft. Simpson area
- given the importance of this - not sufficient work to date
- no MAGS funding or from any of the original MAGS-2 partners, but funded entirely by other projects

Even though significant progress has been made in the above processes, little or no progress has been made in the following areas.

Convective Processes and Diurnal Water Vapour Variations
- G. Strong was working on this aspect during MAGS-1
- Little current activity in MAGS or in related studies

Groundwater
- no activity within MAGS on this issue
An important component of Theme I is the consolidation of the above process knowledge into the major MAGS models. Examples of this consolidation include the following.

**Infiltration into Frozen Ground and Permafrost** (Woo, Martz, Carey)
- development of frozen ground model
- needs to be incorporated into landsurface scheme/hydrologic model

**River Ice Jams** (Hicks, Beltaos)
- plans are to incorporate the models under development into the hydrologic models used in MAGS

**Wetlands** (Quinton, Hayashi, Pietroniro)
- objective of this CFCAS funded study is to test land surface schemes used in MAGS, and suggest where improvements are needed
- testing of peatland version of CLASS (Lin)

**Lakes** (Rouse, Schertzer, Mackay, Lam, McCrimmon, Swayne)
- develop a coupled lake / atmosphere model for use in CLASS and the Regional Climate Model (RCM)

**Blowing snow** (P. Taylor, P. Yau, J. Pomeroy)
- working on incorporation of various blowing snow models (i.e. PBSM, PIEKTUK) into landsurface schemes
- however, there are still important discussions/tests needed to verify these models

**Snow processes** (P. Marsh, J. Pomeroy)
- ongoing studies aimed at testing snow algorithms in CLASS, WATCLASS and RCM
- and incorporating algorithms developed in the process studies (i.e. advection, melt, effect of vegetation, runoff)

**Evaporation** (C. Lin, W. Rouse, P. Marsh, R. Granger)
- ongoing tests of CLASS and ISBA
- further need to bring together the various process studies carried out in MAGS-1 and BOREAS

An important component of MAGS was CAGES, a case study of a single water year (1998-99). As part of the ongoing CAGES analysis a workshop was held in Edmonton in March 2002. Following this workshop, MAGS investigators have worked on producing a special issue of the Journal of Hydrometeorology. The editors of this special issue (P. Marsh and J. Gyakum) have solicited a number of papers. These have been submitted to JHM, and are undergoing the normal JHM review process. It is expected that this issue will be finalized in the spring of 2003, with publication to follow.
To conclude, Theme 1 is on track, with many of the major issues outlined previously under way including: orographic precipitation, evaporation, blowing snow, lakes, river ice, wetlands, and snow processes. In terms of the integration of process results into the MAGS models, the following are well underway, including: frozen ground/permafrost, river ice, wetlands, lakes, blowing snow, snow processes, evaporation. A CAGES Special Issue of the Journal of Hydrometeorology is in preparation, and it is expected to be finalized in the spring of 2003, with publication following. The CAGES data set is a “gold mine”, and we would expect analysis of it to continue for a number of years, with another MAGS/CAGES special issue in the future.

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The first MAGS-WEBS Workshop was held at MSC-Downsview, May 27-28, 2002. There were 28 participants at this meeting. The goals of the workshop were to: evaluate the progress and success in closing energy and water budgets; document various approaches for closing budgets; and identify specific actions needed to understand and model the water and energy budgets.

On the first day Geoff Strong and Kit Szeto gave overview presentations on the water and energy budgets, respectively. The overview presentations were followed by 14 individual project presentations covering the full range of MAGS-WEBS activity. The second day started off with two parallel breakout sessions, one dealing with water budgets and the other with energy budgets. The participants then returned to a plenary session to discuss the current state of knowledge and future plans.

On the water budget side, Strong argued that there was almost closure of the water budget on the monthly and annual time-scales, with about a 10% difference between the annual basin atmospheric and hydrologic water budgets. He emphasized the importance of assessing the uncertainties in all of the water (and energy) budget terms. Strong presented his estimates of the uncertainties associated with the various quantities. Szeto reported that energy budget studies are behind water budget studies and small-scale studies are ahead of large-scale studies. There is a lack of information on long-term variability. Our understanding is based more on modelling studies than observational studies, there being many well-recognized gaps in the observations. Szeto emphasized that the water and energy cycles are coupled and we must integrate our water and energy budget studies.

The breakout sessions were primarily devoted to completing tables that detailed the current state of knowledge of the Mackenzie basin water and energy budgets from both modelling and observations studies.

In the plenary session, plans were discussed as to how best meet the MAGS-WEBS goals. After the workshop it was agreed that Kit Szeto would lead MAGS-WEBS activities. One of the first priorities was the preparation of a MAGS-WEBS article. Other important tasks are to prepare a MAGS-WEBS legacy data set and to participate in the preparation of the GHP WEBS synthesis paper.

A detailed summary of the MAGS-WEBS Workshop is available through MAGS website (http://www.usask.ca/geography/MAGS/) under “Meetings/Events”.

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F. REPORTS AND COMMENTS
The pressure on the NSERC budget for the 2003 Discovery Grants competition is significant with over 900 new applicants not previously funded through this program. NSERC continues its efforts to obtain a significant budget increase and is optimistic that there will be additional funds allocated in the February 2003 Federal Budget.

The earth sciences community (represented in the Solid and Environmental Earth Sciences NSERC Grant Selection Committees) did not receive funds at the level requested in the recent reallocations exercise. Of the approximately $2M contributed to the reallocations fund, $1.3M was reallocated to the two grant selection committees. Partial funding was provided to support and strengthen research capacity in targeted areas and for field research. Funding was not approved to develop a concept and proposal for a Canadian Earth Institute. Comments on the reallocations submissions can be found on the NSERC website.

**Year 2 Progress Report – Summary of the Comments of the Original Site Visit Committee and the Research Networks Selection Committee**

The Site Visit Committee and Research Network Selection Committee members who reviewed the progress report judge that this is a well-managed research network that is making significant scientific progress towards its objectives. Active networking is taking place and excellent training opportunities are being provided. Communication with the user community has begun and progress in this area is expected to accelerate in the future. Continued funding for the network is recommended.

Review Criteria:

*Achievements of the Objectives of the Network*

The reviewers are in agreement that significant progress has been made towards the objectives of the network. Several notable achievements were highlighted by the reviewers for specific university projects. These achievements include substantial progress in development, diagnosis and sensitivity testing of individual component models and some progress towards integration. The main work of integrating the various models into a coherent set to simulate the climate and hydrology of the Mackenzie basin remains to be done and is the principal focus for the next 2 years.

Details of the progress of government projects are not included in this report. The government projects are reviewed annually by the Scientific Advisory Committee to assess their level of contribution to the MAGS network and to identify ways in which this could be enhanced.
Network Management and Budgeting

The reviewers commented that the progress report indicates a well-articulated committee structure and a good division of responsibilities between the Science Advisory and Management Committees.

The management of the budget is judged to be appropriate.

Networking and Partnerships

The reviewers commented that clearly there is meaningful networking taking place among the various university research groups. Because the progress report does not specifically cover the interactions between the university and government researchers, it was difficult for the reviewers to get a complete picture of this aspect. However, from attendance at the annual scientific meetings, the Program Officer reports that there is significant collaboration taking place between the academic and government groups. In addition to the specific scientific collaborations, the reviewers noted that the annual scientific meetings and a series of targeted workshops provide further opportunities for networking.

Internationally, networking with other GEWEX programs appears to be primarily with the GAMES-Siberia (Japan) project. It was noted that members of MAGS are prominent members of the GEWEX-Global Hydrometeorology Panel where major international connections are made. Strengthening of the international collaboration is further encouraged.

Accessibility of Results to Partners and Users

The annual scientific meetings, workshops, annual reports, journal publications and the website provide ample opportunity for access to results. The reviewers noted that the research results are readily accessible to hydrological and meteorological scientists through rapid publication in leading journals, including two special issues. Communicating results to the appropriate government agencies is not problematic as they are active partners in the network.

There have been some initial activities undertaken to engage the private sector and northern communities (Yellowknife Public Forum, 2 weather stations set up in Yellowknife and Inuvik high schools) but this outreach still needs extension. One reviewer commented that this is not a project that could have benefited greatly by local information inputs in the early stages but as the program moves toward its conclusion, it will be important to broadcast results more widely. This will require more user and community contact and advice. This reviewer suggested that to fully realize the value of this network in northern communities of the Mackenzie Basin, consideration should be given to adding collaborators who are able to interpret results in terms that are meaningful to the needs of the communities. Another reviewer commented that involvement of partners from the socio-economic sciences and the climate change research and adaptation study communities needs to be strengthened.

Training

The training was viewed to be one of the strongest elements of the MAGS network.
Neither Professor Ohata nor I were able to attend the first day of the meeting, so these comments are based on presentations made on the 7th and 8th, and discussions we had with various MAGS scientists during that period. Overall, we think that MAGS-2 is proceeding well at what is nearly the midpoint of the project. We were favourably impressed with the success to date of the “networking” concept that is central to MAGS-2. We believe that it has fostered improved interaction between the disciplines involved in MAGS (especially hydrology and atmospheric sciences), as well as between the field and modelling groups.

Based on our understanding of presentations, posters, and discussions with MAGS scientists, we make the following observations and recommendations. We note that in some cases, actions may already be underway to implement some of these suggestions.

1) The WATCLASS effort appears now to be over the major hurdles involved in merging the WATFLOOD hydrologic model and the CLASS soil-vegetation-atmosphere scheme. We believe that this project now must enter a new phase, and that model testing should be carried not only by the development team, out also by interested scientists within the MAGS and broader land-atmosphere community. Specifically, we suggest formation of an informal WATCLASS application and evaluation team. Participation in the team would be open, both within and outside the MAGS community, but would presuppose land-atmosphere modelling experience, i.e., the development group should not be expected to provide consulting to unsophisticated users. On the other hand, it should be possible to provide the model source code, demonstration data sets, and other information required to implement the model from a web site sufficient to allow experienced users to run the model. Inherent in this recommendation is that a version of the model suitable for “off-line” application should be provided. The WATCLASS development team should view the formation of an evaluation/application team as an integral part of the model testing and diagnosis process that will lead to model improvements. Some mechanism, perhaps web-based, or perhaps occasional workshops, should be provided for exchange and discussion of results.

2) The pathway for implementation of MAGS-supported land surface model upgrades, like the WATCLASS effort and cold season improvements in ISBA, into operational weather forecast models, and the Canadian climate model, remains unclear. We are not convinced that there is adequate interaction with the Canadian operational weather forecast community, which was virtually unrepresented in Jasper. A high level meeting may be required to make progress on this issue.
3) We believe that there may be an opportunity for a demonstration project linking the WATCLASS hydrologic forecasting (either coupled or uncoupled) with the MAGS river and ice jam forecast effort. The latter seems now to have good predictive skill given accurate boundary conditions, which essentially consist of upstream hydrologic information. Forecast lead times based on direct observations are limited to the time of propagation of the flood wave through the channel system. However, it should be possible to develop probabilistic forecasts at lead times out to a few weeks or more using ensemble forecast methods, and knowledge of initial conditions over the watershed(s) draining to the upstream points – precisely the type of information that WATCLASS is designed to provide, in either coupled or uncoupled mode. Such a demonstration project could have important benefits to MAGS in terms of its technical outreach efforts.

4) Surprisingly little was said in Jasper about MAGS involvement in the GEWEX Coordinated Enhanced Observing Period (CEOP), even though we are aware of MAGS involvement in CEOP planning. As a GEWEX Continental Scale Experiment, it is important that MAGS maintain a high profile in GEWEX activities like CEOP, which we believe will provide opportunities for model evaluation globally that might not otherwise be available. Furthermore, even though MAGS has a cold region/season emphasis, models like WATCLASS that are intended for use in GCMs must be able to perform well globally. We suspect that CEOP’s low profile in Jasper may have resulted from key people being unable to attend the Jasper meeting. We were encouraged by discussions of MAGS participation in other GEWEX activities like the Water and Energy Balance Synthesis (WEBS), but we think it is important to emphasize the need for MAGS to retain a high profile in activities at the international GEWEX level.

5) There were several papers, and a good bit of discussion about sublimation, blowing snow, and snow redistribution, and its implications at regional scales. It appears that some progress is being made in gaining an understanding of the reasons for discrepancies in estimates of sublimation from different models and at different spatial scales. One question, though, is whether enough attention is being given to forest hydrology and forest-atmosphere interactions. In forest environments, the dominant winter interactions have to do with snow accumulation and redistribution from canopies – there is much less action under the canopy. Given the apparent convergence on relatively low(er) estimates of sublimation from snow surfaces and from re-suspended snow in tundra environments, there is a question of how much larger these values are in forested environments where remobilization of snow from the canopy is a dominant mechanism. We are aware of work done in boreal forests by several MAGS investigators, but it is unclear whether this work has been integrated into model parameterizations, and its implications interpreted at regional scales.

Both Professor Ohata and I would like to express our appreciation for inviting us to Jasper. We wish all our MAGS friends and colleagues a prosperous and productive 2003, and we will look forward to seeing you at the next MAGS science conference next fall.

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MAGS Users Advisory Group

David Milburn
Chair, MAGS Users Advisory Group

Objectives of MAGS-2

- Move to modelling and prediction
- Apply improved predictive abilities to environmental and social issues

Purpose of Users Advisory Group

- Provide advice to GEWEX Scientific Committee on users’ needs
- Critically assess results of MAGS-2 from users perspective
- Assist in identifying funding sources
- Represent a broad spectrum of users in the study area
- Serve as a link between MAGS Scientific Committee and the public

Who is affected by Climate Variability and Climate Change?

Oil and Gas Industry
- Permafrost degradation - drilling sumps
- Shorter seasons for seismic and exploration activities
- Increased costs of exploration
- Pipeline design concerns for permafrost degradation

Mining Industry
- Increased evaporation leads to water balance adjustments for tailings ponds
- Effects on “frozen core” dams and other infrastructure
- Reduced winter road seasons
- Increased costs of mining

Forest Industry
- Drier summer seasons
- Reduced forest growth
- Increased lightning strikes and fires

Commercial Fishing
- Loss of near shore habitats and fishery potential
- More frequent summer storms
- Changes in ecosystem structure
Communities
- Predominantly aboriginal
- Water supply and drinking water quality
- Affects traditional ways of life - hunting, fishing, trapping

Hydroelectric Utilities
- Reduced inflows leads to greater reliance on fossil-fuels
- Reduced ice season affects winter operation
- Reduced magnitude of spring breakup and ice jamming but increase in mid-winter jams

Transportation
- Longer barging seasons but lower water levels
- Greater maintenance costs on “land” roads
- Greater construction costs for roads that once relied on permafrost for structural integrity

Recreation
- Warmer summers bring more vacationers
- Reduced big game hunting in some areas
- Lower water levels affect canoeing and boating

Renewable Resources
- Changes will affect reproduction, survival, migration and distribution of wildlife populations
- Changes in plant species, abundance for forage and distribution of species

Water Resource Managers
- Uncertainty in decisions for environmental assessments and regulatory reviews for long-term projects
- Public health and safety issues - flood forecasting, source water quality
- Transboundary water management issues - water withdrawals

Observations from Users Session at this MAGS Meeting
- MAGS-2 research is relevant to users
- Users feel they can contribute to ongoing MAGS-2 research

BUT

- Not all MAGS-2 research will be relevant to users and not all users’ needs can be met by MAGS-2
- Therefore, we need to find the common ground and find means to work together
Ongoing Role of Users Advisory Group

- Fully identify users’ needs
- Identify “indicators” of warming trends and effects on particular sectors
- Determine if MAGS-2 is providing research results for these indicators
- Communications with MAGS-2 researchers

MAGS-2 Users and Researchers Workshop

- Edmonton, June 17-18, 2003
- To develop structure to bring users and researchers together to fulfil goals and objectives of both groups
Next year is the mid-point of Phase 2 of MAGS. All our activities, including scientific, administrative and outreach efforts, are proceeding according to the overall five-year plan. It is useful to recall our Program goals as we plan for Year 3.

**Overall Goals for MAGS**

(1) to understand and model the high-latitude energy and water cycle that play roles in the climate system, and

(2) to improve our ability to assess the changes to Canada’s water resources that arise from climate variability and climate change.

**Themes in MAGS**

We are progressing very well in fulfilling the objectives of Theme 1 (Integration) and Theme 2 (Scaling). While we shall be continuing our research to complete the tasks pertaining to these themes, we shall accelerate our research in Theme 3 (Modelling) and initiate activities under Themes 4 and 5. The objectives under these themes are as follows.

Focussing on Year 3:

- **Model Development**
  - investigate processes, synthesize results, develop algorithms
  - hierarchy of models, including atmospheric, hydrologic, linked and coupled models
  - to be followed by model evaluation and application

- **Scientist-user Interactions**
  - increase user awareness and scientist involvement
  - enhance outreach activities
  - leading to user contribution and utilization of scientific results

- **Prediction of Climate-hydrologic System**
  - maintain priorities on water and energy balance study
  - apply knowledge gained from process studies and modelling to investigate climatic change effects on the Mackenzie system
Mechanisms to Facilitate the Attainment of the Objectives

We shall make use of thematic workshops and a new vehicle of ‘workgroups’ to facilitate our initiatives. Workshops will perform the functions of raising issues and providing a forum for discussions; networking among investigators and users; and providing opportunities to seek partnership and new research directions. The workshops proposed for 2003 are targeted on two aspects:

- Modelling Workshop - 27-28 March 2003, Ottawa
- Scientist-User Workshop - 17-18 June 2003, Edmonton

MAGS has reached the stage when collaboration and integration of results based on particular aspects of research will advance the overall Program. To assist in such networking, the idea of workgroups arose and was well received and approved by the Management Board. The policy for Workgroups is:

- each Workgroup will identify the problem, define its objectives and indicate the relevance of the study in terms of attaining the overall goals of MAGS
- MAGS investigators are encouraged to initiate Workgroups and can invite other MAGS and non-MAGS investigators to participate; for non-MAGS investigators, a brief introduction is needed to indicate who they are and why they are involved
- each Workgroup should notify the Science Committee of their formation by submitting a brief document indicating the milestones, the deliverables and its expected contribution to the MAGS goals
- A Workgroup can apply to the Science Committee for limited funding support (up to $3,000) to facilitate networking expenses such as teleconferencing, supplies, travels, consultation etc.

We encourage Workgroup initiatives to address issues of MAGS interest.
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Missing:
Jian Fang, Barry Goodison, Edward Hudson, Masaki Hyashi, Dean Shaw, Ed Struzik,
Jack VanCamp
Participants of MAGS 8th Annual Scientific Meeting. Key for the group photo is located on opposite page.