INTRODUCTION

The Hydrometeorology of the Mackenzie River Basin during the 1998–99 Water Year

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1. Introduction

A Canadian contribution to the Global Energy and Water Cycle Experiment (GEWEX) is the Mackenzie GEWEX Study (MAGS). The purpose of MAGS is to understand and model the high-latitude water and energy cycles of the Mackenzie River basin (MRB) in order to contribute to the international effort, and to improve our ability to assess the changes to Canada's water resources, owing to climate variability and change (Stewart et al. 1998). Previous MAGS synthesis articles include Stewart et al. (1998, 2002), Rouse (2000), and Rouse et al. (2003a). These papers, plus those published in a special issue of *Atmosphere–Ocean* (2002, Vol. 40, No. 6), have outlined the major goals and objectives of MAGS, and the physical environment of the Mackenzie basin (1.8 million km^2). The scientific progress to date has emphasized the improved understanding of many of the important physical processes that were not sufficiently understood (e.g., snow accumulation and melt, blowing snow, lakes, clouds, precipitation), the gathering and analysis of appropriate basic datasets (e.g., elevation, vegetation, permafrost, climatology, etc.), and the development of the necessary coupled models. As an early step in understanding the interactions of the water and energy fluxes within this basin, Stewart et al. (2002), along with 10 other papers in the *Atmosphere-Ocean* special issue, describe preliminary analyses of the basin's, hydrometeorology for the 1994–95 water year. This work outlined both the internal and external factors controlling these fluxes during a period of extreme low discharge.

Given the success of the 1994–95 water year study (Stewart et al. 2002), and in order to have as broad a database as possible for the data poor Mackenzie basin, a major component of MAGS was an enhanced data collection period for the period from August 1998 to September 1999. This project was called the Canadian GEWEX Enhanced Study (CAGES), and the analysis of this dataset is the topic of the papers that follow in this special issue.

The CAGES strategy comprised the following three-phased approach to obtain information required for process studies, model initialization, and validation: 1) compiling available data from operational weather, upper-air, radar, and stream discharge networks, as well as from satellite and research basins; 2) augmenting the operational network where required; and 3) carrying out the following enhanced observations: atmospheric soundings, stream discharge, radar, aircraft and tower flux measurements, hillslope runoff, and additional surface stations, for example. Examples of the resulting datasets include the following (see MAGS Web site for additional information online at http://www.usask.ca/geography/MAGS/).

1) Surface observations: These include enhanced discharge estimates during the ice cover/breakup periods for the Mackenzie River and major tributaries; additional surface meteorological measurements for typical vegetation covers and lakes (Rouse et al. 2003b,c; Blanken et al. 2003; Spence et al. 2003); and surface observations, including sensible and latent heat fluxes for the National Water Research Institute research basins in the Inuvik region, and at sites in Wolf Creek near Whitehorse, Yukon, Canada (Pomeroy et al. 2003). In addition, basinwide monthly precipitation- and temperature-gridded datasets (50-km grid squares; MacKay et al. 2003) for the 1950–99 period were developed.
2) Satellite remote sensing: AVHRR images have been used to develop datasets of land and water surface temperatures at 1-km resolution over the MRB (Bussières and Schertzer 2003), and also have been combined with the Scanner for Radiation Budget

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(ScaRaB) (Feng et al. 2003) data to provide radiation maps during CAGES. Special Sensor Microwave Imager (SSM/I) Equal Area SSM/I Earth Grid (EASE-Grid) microwave radiometer images have been used to develop snow water equivalent (SWE; see MacKay et al. 2003) maps for the basin, and snow cover and lake ice characteristics for Great Slave (Schertzer et al. 2003) and Great Bear Lakes for the years 1987–99.

3) Aircraft and radar: Sensible and latent heat flux data were obtained using the National Research Council of Canada Twin Otter aircraft in order to better understand the dynamic evolution of surface–atmosphere fluxes of sensible and latent heat during and following snowmelt, and for the snow-free period in the Mackenzie delta area. A radar-based precipitation accumulation product was developed for Environment Canada's operational radars in the southern Mackenzie basin, while the IPIX radar was used to provide datasets on the detailed kinematic description (e.g., vertical structure, wind fields) of the cloud systems in the central MRB.
4) Numerical weather prediction: Gridded model data from the Canadian Global Environmental Multiscale (GEM) operational forecast model for the CAGES period were archived (MacKay et al. 2003). This archive included higher-resolution (10 km) reruns for the spring/summer portion of the CAGES period.

The nine papers included in this special issue address the following topics: 1) the role of lakes in the energy and water budgets of the Mackenzie basin (Bussières and Schertzer 2003; Schertzer et al. 2003; Rouse et al. 2003c; Blanken et al. 2003; Spence et al. 2003), 2) small-scale hydrologic or land surface processes (Pomeroy et al. 2003; Rouse et al. 2003c), 3) MRB radiation budgets (Feng et al. 2003), and 4) regional-scale modeling (MacKay et al. 2003).

2. Results

a. Lakes

Unlike most major river basins of the world, and certainly the other GEWEX Continental-Scale Experiments, a major feature of the Mackenzie basin is the more than 30 000 lakes covering its surface (Rouse et al. 2002). In addition to the large number of medium-sized to large lakes covering the eastern portions of the basin (dominated by the Canadian Shield), there are a number of very large lakes including: Great Bear Lake (31 328 km^2), Great Slave Lake (28 568 km^2), Lake Athabasca (7935 km^2), Lac La Martre (1776 km^2), and Lesser Slave Lake (1168 km^2). Bussières and Schertzer (2003) provide a map showing the location and shape of all lakes $\geq$10 km^2. Using a 1-km-resolution land cover classification, they showed that 8% of the entire MRB is covered by lakes greater than 1 km^2, with 113 lakes $\geq$100 km^2, and 799 $\geq$ 10 km^2. Rouse et al. (2002) noted that it is likely that the summed areal coverage of lakes less than 10 km^2 is large, and that this lake coverage contributes significantly to evaporation.

Prior to MAGS/CAGES, few studies had considered the energy balance and evaporation of the vast range of lakes in the MRB. As a result, little was known about the importance of these lakes to the water and energy fluxes of the MRB, and their effect was, therefore, not included in hydrologic or atmospheric models of the basin. For example, Schertzer et al. (2003) have used meteorological instrumentation deployed over Great Slave Lake to determine heat fluxes. These point-derived fluxes are found to be representative of lakewide bulk heat exchanges, and form the basis for estimating the influence of Great Slave Lake on the MRB's thermodynamic properties. These studies may be applicable to lakes in Finland and northern Russia.

Bussières and Schertzer (2003) document the duration, structure, and amplitude of the temperature evolution of various water bodies in the MRB from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer AVHRR satellite data. These values are shown for the primary water bodies of Lake Athabasca, and Great Slave and Great Bear Lakes. The authors have found very different seasonal cycles for each of these major lake systems. This finding may be helpful in defining the integrated seasonal cycle for the entire basin.

Rouse et al. (2003c) have quantified both the interannual and seasonal variabilities of surface energy fluxes in Great Slave Lake. They find that, during the period from ice melt in mid-June–August, that the net solar insolation is primarily used to heat the lake. During this period, the static stability is strong, and the sensible and latent heat fluxes are small. After late August, the absorption of solar insolation becomes small, and the static stability decreases markedly, and there is a temporal increase in the upward sensible and latent fluxes. Up to 90% of total evaporation occurs after August and increases markedly as the autumn progresses into early winter.

An analysis of turbulent exchange data for Great Slave Lake (Blanken et al. 2003) for 3 yr reveals the dominant role of episodic events in determining the total evaporation. The pulses, occurring on a timescale corresponding to that of synoptic-scale weather systems (2–4 days), produced over 50% of the total evaporation for the 3-yr period.

Spence et al. (2003) have analyzed the processes controlling energy flux amplitudes occurring between a small northern lake and the atmosphere. These processes, which are strongly seasonal, switch between net radiation control of evaporation during the period in which the lake is warming, to vapor pressure deficit control of evaporation during the lake's cooling period. The authors conclude that the small northern lakes in the MRB during CAGES did not have evaporation rates as large as those of the southern lakes, because radiation did not penetrate to the deeper waters. The dissolved organic carbons, common to these northern lakes, prevent the solar insolation from penetrating to deeper waters.

b. Small-scale hydrology and/or land cover processes

Given the large spatial variability in northern hydrologic processes, and the lack of incorporation of these processes and their variability into hydrologic and land surface models, MAGS has conducted a number of small-scale hydrologic process studies at research basins that represent a range of conditions typical of the MRB. One of these basins is the Wolf Creek basin near Whitehorse. Although this basin is outside of the MRB, it is typical of the lower-elevation cordilleran regions of the northwest portions of the MRB.

Pomeroy et al. (2003) consider the effects of topography on the subgrid square variability of snowmelt. This work clearly shows the dramatic differences in rates of snow ablation over varying slopes and aspects. For example, they suggest that along a single 700-m transect [i.e., only a small portion of a NWP or regional climate model (RCM) grid square], the range of snowmelt rates that exists over a north–south transect of the entire MRB can be found. They suggest that such subgrid square variability could be incorporated into land surface models by considering not only the relative occurrence of various vegetation types, but also terrain slope and aspect.

Rouse et al. (2003b) considered the seasonal variations in the surface energy balance of tundra in the lower MRB and note that the spring season is the most dynamic, with the timing of snowpack ripening and snowmelt related to interaction of the solar cycle, air temperature, and snowpack conditions. In addition, they note that the spring season is the most sensitive to regional changes in temperature because of these interactions.

c. Regional-scale modeling

MacKay et al. (2003) utilized a developmental version of the Canadian Regional Climate Model (CRCM), coupled with the third-generation physics package of the Canadian Centre for Climate Modelling and Analysis GCM, to consider the surface water budget of the MRB during CAGES. This model was run with a horizontal resolution of 51 km, with the boundary and initial atmospheric conditions specified from the Canadian Meteorological Centre operational global data assimilation system. The first task of this work was to utilize the CAGES datasets, plus an enhanced version of the gridded dataset for the Mackenzie basin developed by Louie et al. (2002) to evaluate the model performance. Among their many findings, the authors conclude that the CRCM produces basin precipitation 9% higher than suggested by the gridded observations. Comparison to the MRB evaporation estimate of Louie et al. (2002) suggests that the CRCM precipitation minus evaporation ($P - E$) of 225 mm was too large by no more than 25%. Streamflow was estimated by routing grid-square runoff using the channel-routing scheme WATROUTE and by driving the hydrologic model WATFLOOD by the CRCM temperature and precipitation. For the entire basin, annual total flow was within 1% of the observed, again suggesting that CRCM estimate of $P - E$ is reasonable. However, for individual basins, and for shorter time periods, both runoff estimates had significant errors. Such errors are likely due to changes in storage, which are not yet accounted for in the land surface scheme used in the RCM. Ongoing work using the WATFLOOD and WATCLASS models is aimed at addressing this issue.

d. MRB radiation budgets

Solar and longwave radiation at the top of the atmosphere (TOA) and at the surface is a major component of the energy balance of the MRB. Because surface observations are limited in the MRB, satellite observations were used to assess both the total radiation absorbed by the basin and the spatial distribution of these fluxes. To address this issue, Feng et al. (2003) derived TOA and net surface solar radiation from AVHRR satellite images for the period from 1 June 1998 to 30 September 1999, and estimated longwave fluxes from the ScaRaB instrument for the period from November 1998 to March 1999. Comparisons of these estimates to surface observations from a number of CAGES locations demonstrated that the method generally agrees with surface observations under both clear and cloudy skies, and for both snow-covered and snow-free surfaces. Mean differences between satellite-derived (*NOAA-12* and *-14*) estimates and surface observations were between -7 and $+5$ W m^{-2}. These results suggest that the satellite method of Feng et al. (2003) provides a reasonable estimate of net solar radiation for the MRB. Comparisons with the CRCM results of MacKay et al. (2003), showed that when the basin is snow free, the CRCM overestimated TOA-reflected flux by an average of 33 W m^{-2}, but by only 2 W m^{-2} when the basin is snow covered. CRCM also underestimated the TOA longwave flux during the winter months, likely because of an underestimation of surface temperature. Furthermore, the CRCM significantly overestimated the TOA-reflected flux over Great Bear and Great Slave Lakes, and Lake Athabasca. This is likely because the current version of the CRCM does not include these lakes.

A comparison of the cloud cover from the AVHRR data and from the CRCM shows that the CRCM overestimates the portions of clouds during the summer period (a reliable comparison could not be carried out for the period when the basin is snow covered). For the entire summer period, the CRCM cloud estimate was 0.69, while that from the satellite was 0.46. This overestimation of clouds is consistent with the overestimation of the TOA-reflected flux.

For the longwave fluxes, CRCM underestimated the TOA longwave flux by 6–12 W m^{-2}, with this probably due to either overestimation of cloud fraction and/or underestimation of the surface temperature.

3. Conclusions

The nine papers in this special issue report on results from MAGS/CAGES for the MRB 1998–99 water year. Taken together, these results contribute to an overall understanding of the water and energy balance dynamics of high-latitude land regions in the following areas:

1) The role of the vast number of lakes in the MRB on the energy and water fluxes of the MRB: Prior to MAGS, very little was known about the effects of these lakes on the atmosphere or on the hydrology of this region. The work reported in this special issue should motivate incorporation of better representation of high-latitude lake processes in both hydrologic and atmospheric models.
2) Hydrological and land surface processes dominating northern regions: This is a specific focus of MAGS, which is intended to lead to the development of physically based models that reflect the role of small-scale heterogeneity in northern environments. For example, results from Pomeroy et al. (2003), showing topographically related variations in snow processes, clearly suggest the need to consider subgrid-square variability in both hydrologic and atmospheric models.
3) Development of a suite of linked hydrologic and atmospheric models for modeling the energy and water fluxes of high-latitude river basins: MacKay et al. (2003) demonstrate both progress and shortcomings of the Canadian Regional Climate Model in its ability to represent land–atmosphere interactions over the MRB. MAGS data collection and process studies are expected to lead to better parameterizations in models such as the CRCM.

Ongoing CAGES studies will continue to incorporate process studies into MAGS models, test and validate these models under present conditions, and use these models to better understand the water and energy cycles of the MRB.

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