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Sensitivity of the Mackenzie River Basin Hydrology to Solar Radiation Uncertainties

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ABSTRACT

One of the goals of the Mackenzie GEWEX Study (MAGS) is to model the critical components of the water and energy cycles that affect the climate of the Mackenzie Basin. The hydrological model WATCLASS is used to simulate the energy and water transports at and below the surface. Atmospheric input to WATCLASS is provided by the output from the atmospheric model GEM. There may be significant uncertainties in the GEM incoming solar radiation due largely to difficulties in simulating cloud radiative properties. The question that we address is how these uncertainties affect the energy and water budgets of this northern river watershed.

To assess this sensitivity, two WATCLASS model runs are compared. Both runs are driven by atmospheric data from GEM for the 1998-99 water year but in the second run shortwave radiation fluxes retrieved from satellite measurements replace the GEM fluxes. Preliminary results show that the atmospheric model overestimates the incoming solar radiation field by 36%. This results in an increase in the basin annual average surface temperature of 1^{o}C and overestimates in net longwave radiation, and sensible and latent heat fluxes. Snowmelt starts earlier with a decreased first snowmelt peak in runoff hydrograph.

Keywords: WATCLASS, MAGS, solar radiation, hydrology sensitivity

INTRODUCTION

In the face of climate change, there is an international effort through GEWEX, the Global Energy and Water Cycle Experiment, to understand, and better model, moisture and energy transports (Stewart et al. 1998). The Canadian contribution to GEWEX is through the Mackenzie basin GEWEX Study (MAGS). The Mackenzie River basin is situated in northwestern Canada and is one of the great river basins of the world. Located at high latitudes (~60^{o}N), the basin is expected to be very sensitive to climate change, and has recorded an obvious warming in the last few years (Stewart, 1998). The Mackenzie River basin is of all the more interest since it is the main North American freshwater source into the Arctic Ocean, which regulates the thermohaline circulation, and hence to a certain extent global climate.

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One of the important objectives of MAGS is the coupling of an atmospheric-land surface scheme and a hydrologic model on monthly and longer time scales, so as to simulate the moisture transport into and through the Mackenzie Basin to the Arctic Ocean. The Canadian Land Surface Scheme CLASS (Verseghy, 1991) version 2.6 has been coupled with the distributed hydrological model WATFLOOD (Kouwen et al., 1993) to build a new model, WATCLASS (Soulis et al., 2001). Eventually WATCLASS will be coupled with an atmospheric model. However, before undertaking this step one needs to test the atmospheric model against observations and to assess the sensitivity of WATCLASS to the uncertainties in the atmospheric fields that drive WATCLASS: errors in the future atmospheric-WATCLASS model could arise either from WATCLASS limitations of from errors in the atmospheric model simulations.

A major component of the surface energy budget is incoming solar radiations. Feng (2002) showed that there is an underestimation of outgoing solar radiation at the top of atmosphere, as simulated by the atmospheric model GEM (Global Environmental Multiscale model) (Cote et al., 1998) compared to satellite observations. There is a corresponding overestimation of GEM net solar radiation at the surface. However, there is a very good agreement between satellite retrievals and model under clear sky conditions, suggesting that the impact of clouds in GEM on the solar radiation budget is underestimated.

The objective of this paper is to assess the sensitivity of the water balance and energy budget of the Mackenzie River basin, as simulated by WATCLASS, to uncertainties in incoming solar radiations, as simulated by the atmospheric model GEM.

The next section describes the data and methodology. The following section presents preliminary results on the energy budget and on the water balance, with emphasis on the snowmelt period. The concluding section discusses future work.

DATA AND METHODOLOGY

The following GEM-simulated atmospheric fields drive WATCLASS: specific humidity, wind speed, sea-level pressure, precipitation, temperature, downward longwave radiation, and incoming shortwave radiation. In order to assess the sensitivity of the Mackenzie River watershed hydrology to incoming solar radiation, WATCLASS is run for a one water-year period, from October 1998 to September 1999 with two different sources for the incoming solar radiation fields. The first run is driven by incoming shortwave radiation simulated by GEM, the second run is driven by incoming shortwave radiation fields retrieved from satellite observations at the top of atmosphere. The difference between the GEM and satellite- retrieved incoming solar radiation provides an estimate of the potential errors in the simulation of incoming solar radiation at the surface.

The archived GEM solar radiation fields available for this study are net and incoming solar radiation at the surface accumulated over three hours, from which we deduce hourly average solar radiation fluxes. The land surface scheme used in the GEM simulations is the simple force-restore method. The satellite-observed fields are AVHRR narrowband visible outgoing solar radiances at the top of atmosphere (TOA), from satellites NOAA12 and NOAA14. The visible solar radiances are converted into broadband outgoing fluxes using narrowband to broadband conversion (Feng et al. 2002), and an angular distribution model (Suttles et al, 1988). Net surface solar radiation fluxes are derived from the Li et al. (1993a) algorithm. This algorithm has been verified against surface observations by Li et al., 1993b and more recently against observations in the Mackenzie basin by Feng (2001), in both cases showing good agreement.

Depending on the time of the year, there may be a total of as many as six daytime passes over the Mackenzie Basin by the two satellites. Data at some missing hours is filled by interpolation and extrapolation of the satellite data. At all locations and times, the satellite net solar radiation field, F_{sat}, is transformed into an incoming solar radiation $F^{\downarrow}_{sat}$ defined by

$$F^{\downarrow}_{sat} = F^{\downarrow}_{GEM}\overline{\left[\frac{F_{sat}}{F_{GEM}}\right]}$$

where $F^{\downarrow}_{GEM}$ is the corresponding downward solar radiation at the surface from the GEM model, F_{GEM} is the net solar radiation at the surface from GEM (calculated with the surface albedo from GEM), and the over-bar indicates the basin monthly average. The result of this procedure is that the field $F^{\downarrow}_{sat}$ has the same spatial distribution as the field of downward solar radiation from GEM but normalized to correspond to difference in the average flux absorbed at the surface as deduced from the satellite data and GEM. Inherent in this approach is that assumption that differences in the basin averages of F_{sat} and F_{GEM} are due to differences between the atmospheric transmissions from GEM and the implicit transmission in the satellite retrieval, and not to surface albedo differences. This assumption is consistent with our observation that the differences in F_{sat} and F_{GEM} are small for clear skies. This procedure will also fill in data for pixels at times where there is no satellite data.

Figure 1 shows the basin daily mean incoming solar radiation fluxes (ISRF) from the satellite and from GEM: there is an obvious GEM overestimation, especially during spring and summer. There is a 36% error in the annual accumulated ISRF of GEM relative to the satellite ISRF, with a 23% GEM overestimation for the summer months (July to October), and 40% for spring months (April-June). In absolute terms the differences are often more than 50 $W.m^{-2}$. These two sets of data provide the solar radiation inputs to WATCLASS.

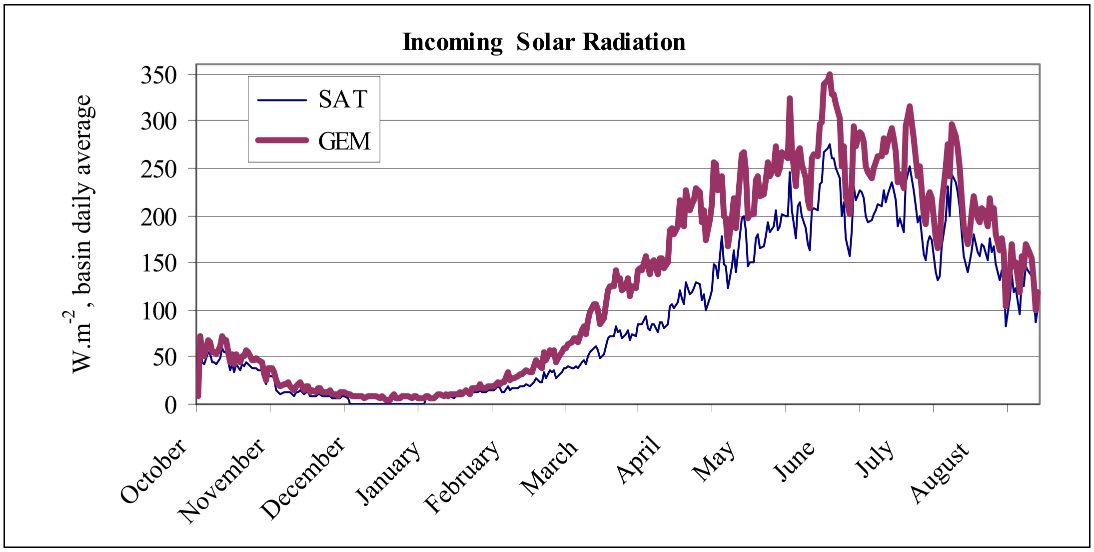

Figure 1. Incoming solar radiation field, averaged over the basin.

PRELIMINARY RESULTS AND DISCUSSION

The following results are from 342-day runs, starting October 1, 1998, to September 7, 1999. Only one land class (100% evergreen needle leaf) is included in the simulations.

The different results show first the changes into the energy budget and its different components, and then the water balance with its components. In the following section we call ‘GEM simulation’ the WATCLASS run driven by GEM incoming solar radiation, and similarly the ‘SAT simulation’ the WATCLASS run driven by the satellite retrieved incoming solar radiation.

Energy Balance

Solar radiation fluxes are an important component of the energy budget, all the more so for a sensitive high latitude northern watershed such as the Mackenzie River Basin; the energy balance is negative in wintertime because of low solar radiation input, and positive in summertime. The energy balance evolution, Figure 2, shows small differences in the two simulations, most importantly in the spring. The large positive values at this time are an indication of the energy available for melting snow, and occur slightly earlier and have larger magnitudes in the GEM simulation.

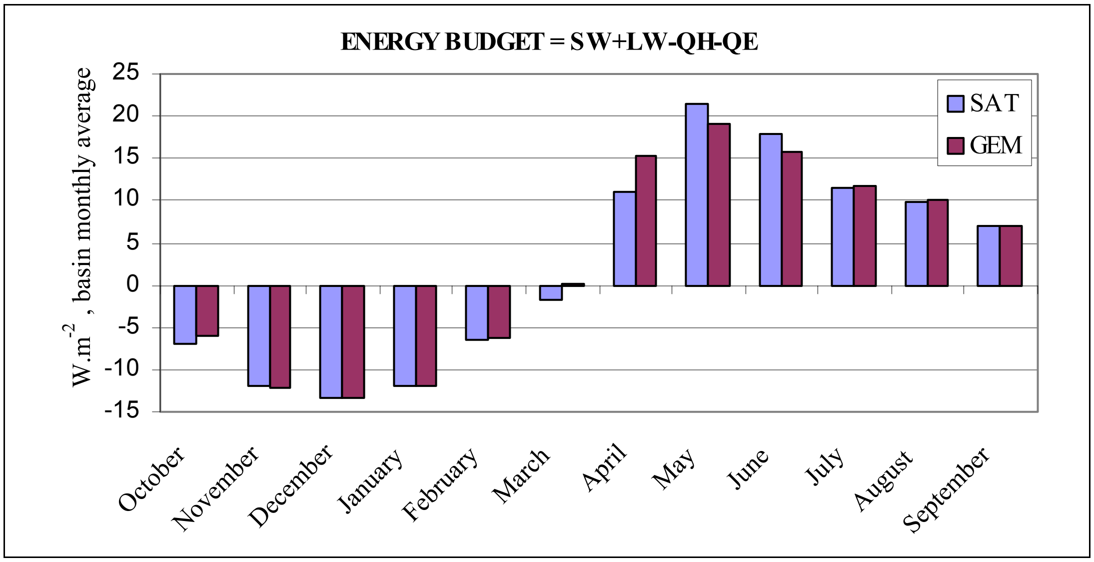

Figure 2. Basin monthly average energy budget.

Figure 3 shows the corresponding variation in net solar radiation. Since the land surface is the same, except for some induced differences in snow cover, the same differences as in the ISRF are observed, with a larger GEM simulation overestimation in spring and summer, and an annual overestimation of 37%.

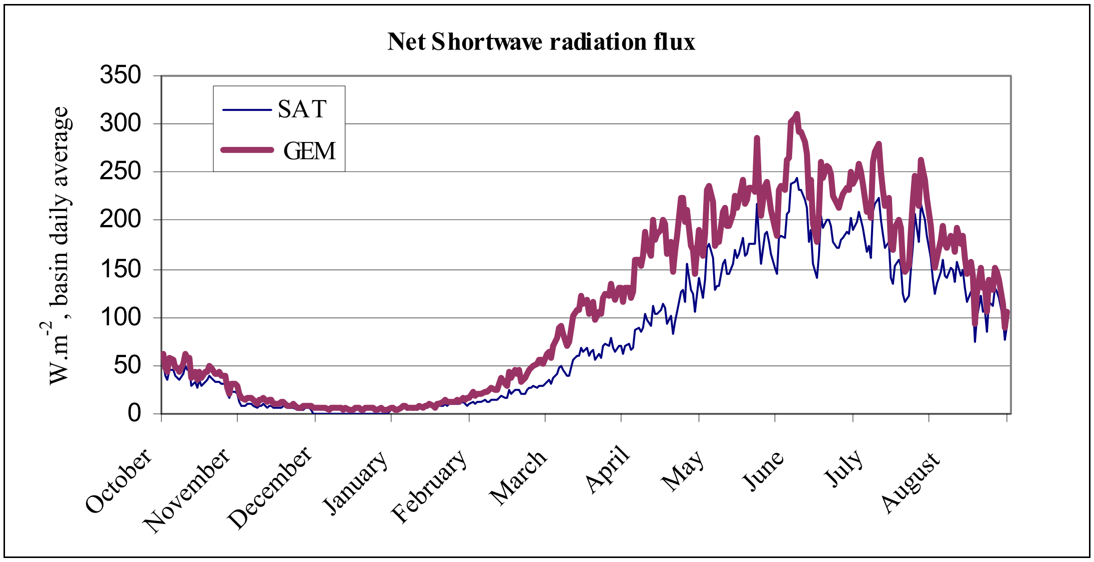

Figure 3. Basin daily average net solar radiation.

Figure 4 indicates the variations in the net longwave radiation fluxes. The GEM simulation overestimation is of the order of 1-3 W.m^{-2}, with the largest values in the spring. The net longwave radiation fluxes are indicative of the surface radiative temperature.

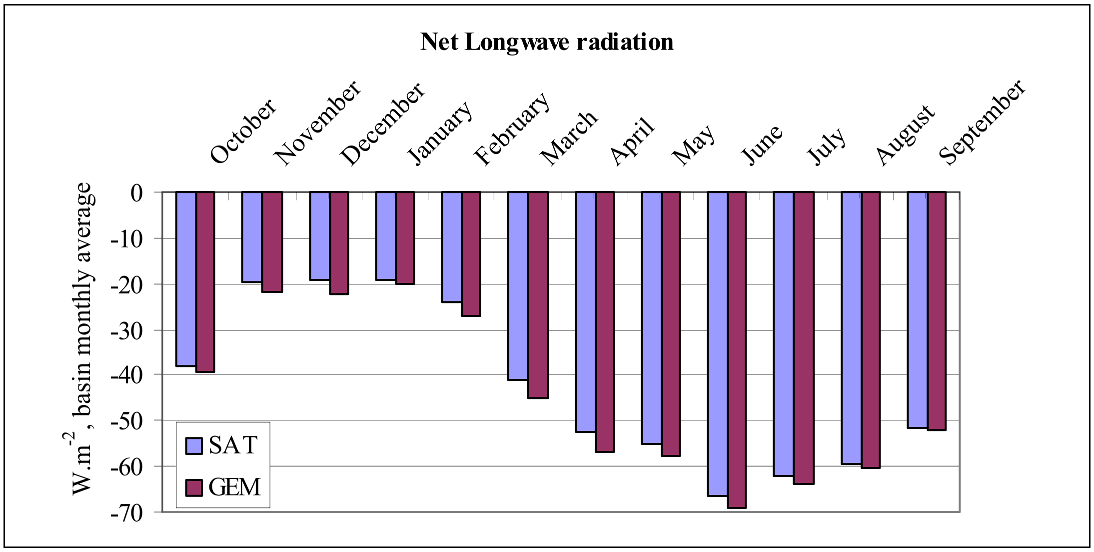

Figure 4. Basin monthly average net longwave radiation.

Figure 5 shows the changes in average surface temperature. The surface temperature difference reaches a maximum value of 1°C in April. The small value in January is a result of the very few satellite observations available at that time. As explained earlier in the section of data and methodology, the January SAT simulation incoming solar radiation input field is quite similar to that for the GEM simulation.

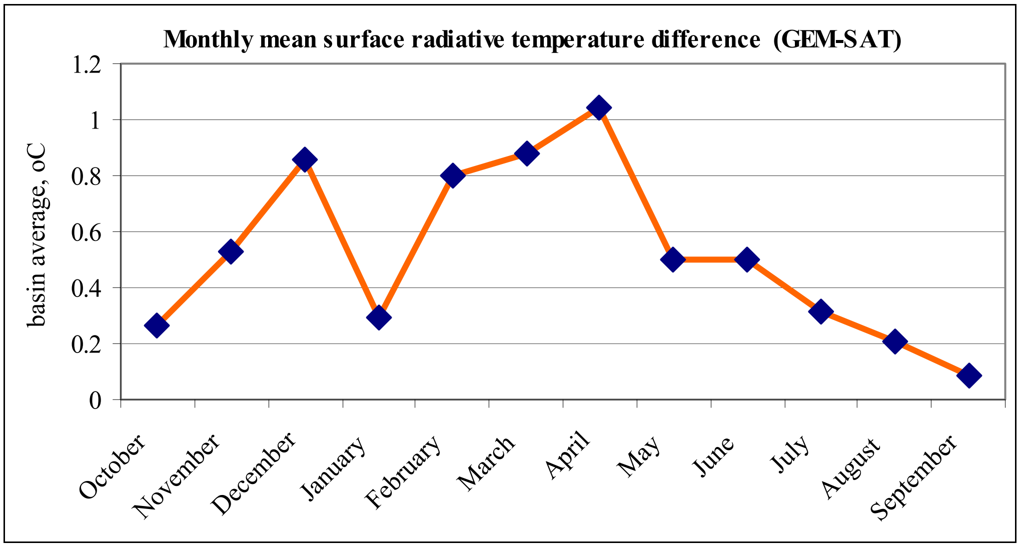

Figure 5. Basin monthly average surface radiative temperature difference.

Figures 6 and 7 show the sensible and the latent heat flux variations. As expected, the differences are more significant in spring and summer. The changes in the sensible heat flux in the two simulations are larger than those in the latent heat flux. During the period where the surface is largely snow-covered this must be due to efficient sensible heat loss from the canopy.

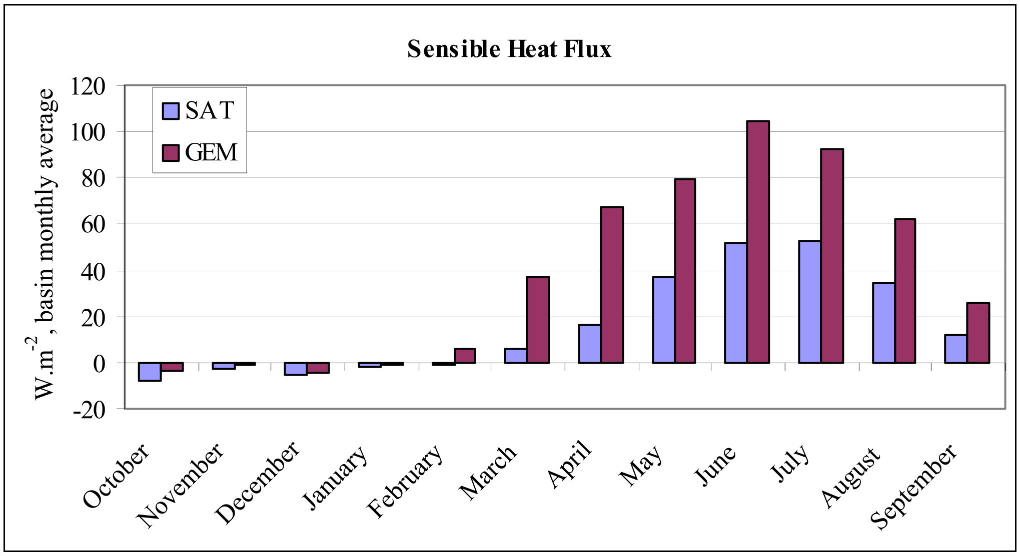

Figure 6. Basin monthly average sensible heat flux.

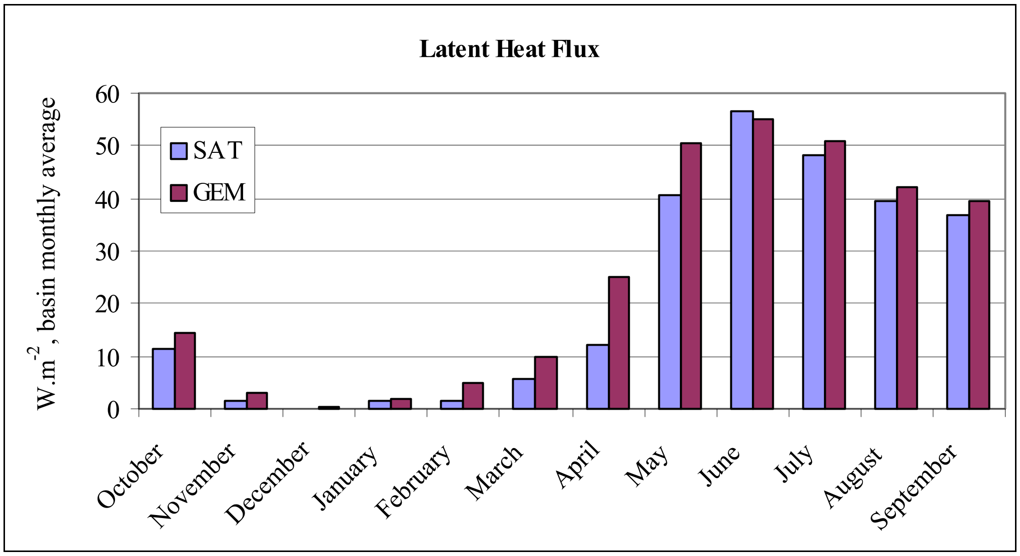

Figure 7. Basin monthly average latent heat flux.

Figures 8 and 9 compare the energy used for snowmelt in the two runs. There is a 6-day delay in the onset of snowmelt in the satellite simulation compared to the GEM simulation in March, but as discussed below, this delay is less significant in terms of the hydrological consequences. There is good agreement in terms of the seasonal average snowmelt energy (0.2 W.m^{-2} GEM simulation underestimation), but a significant different energy distribution between the two runs. The agreement in total energy used is expected since both runs have the same amount of precipitation and the same amount of snow.

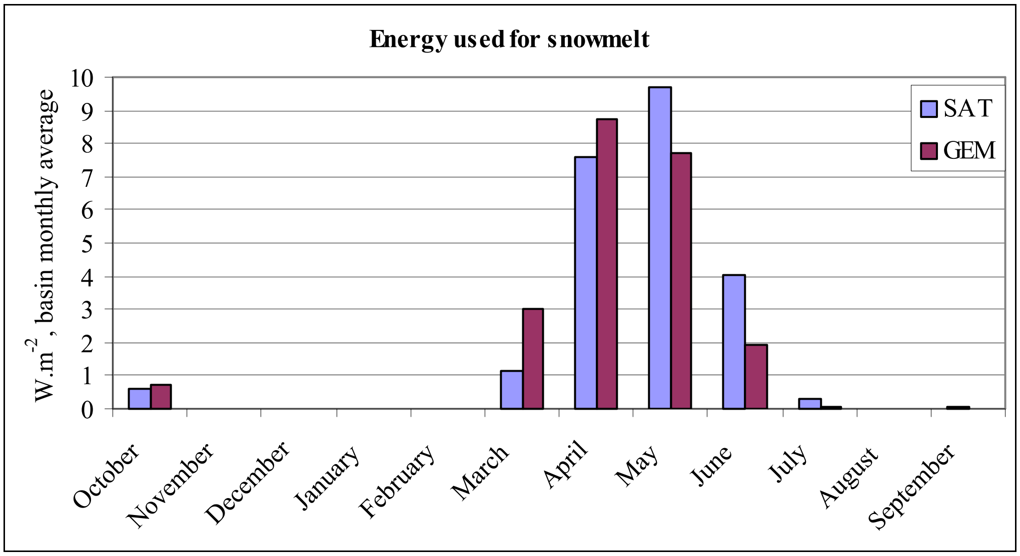

Figure 8. Basin monthly average energy used for snowmelt.

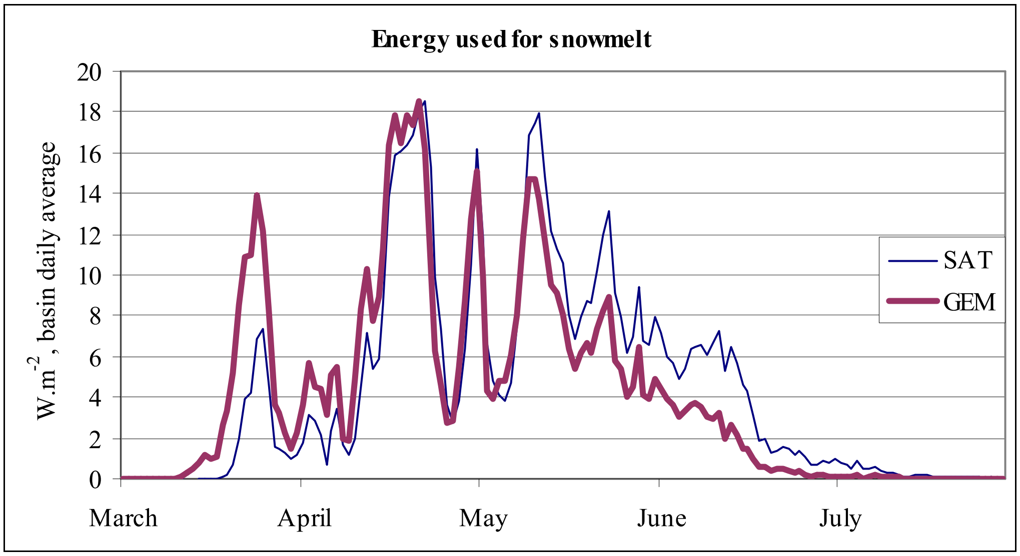

Figure 9. Basin daily average of energy used for snowmelt in spring and early summer.

The snow accumulation in the two runs (Figure 10) is not the same because of the increased rate of melting in the spring in the GEM simulation, and possible increases in the sublimation and evaporation of the snow intercepted by canopy.

In summary, there is an extra 29 W.m^{-2} annual average energy input through the net solar radiation fluxes. 8% of this energy is used to increase the net longwave radiation fluxes and hence the surface temperature, 12% is lost due to latent heat fluxes, and 79% is compensated by an increase in sensible heat flux. Only 0.3% of this energy input is compensated by an increase in energy for snowmelt.

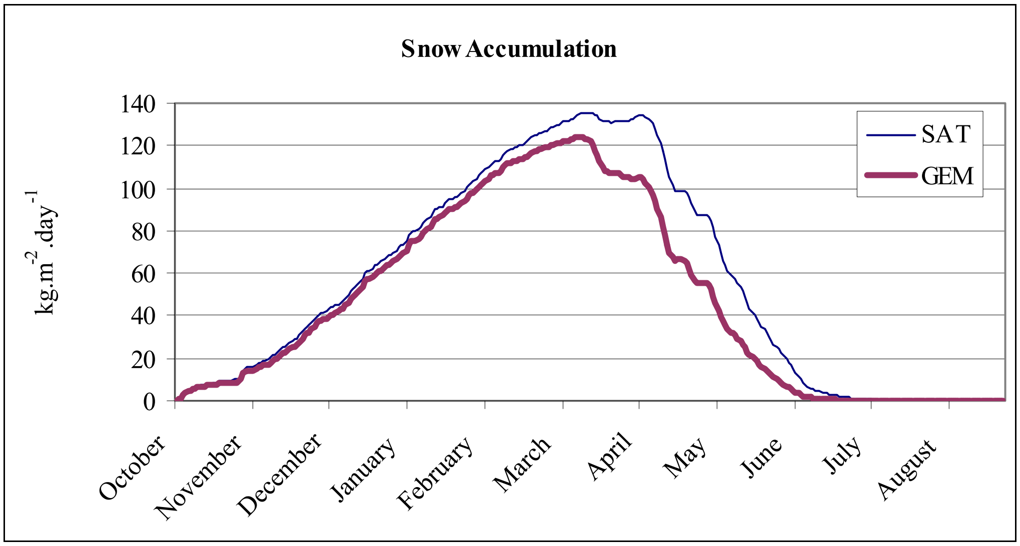

Figure 10. Basin daily average snow accumulation.

Water Balance

Variations in the energy budget lead to variations in the water balance. The precipitation is an atmospheric input and therefore is the same for both runs, i.e. 451 kg.m^{-2}.year^{-1} over the whole basin. The induced variations in evapotranspiration and sublimation rate (Figure 11) are equivalent to the latent heat fluxes changes. The annual GEM simulation overestimation is 40 kg.m^{-2}.year^{-1}, and there is a GEM simulation underestimation only in June.

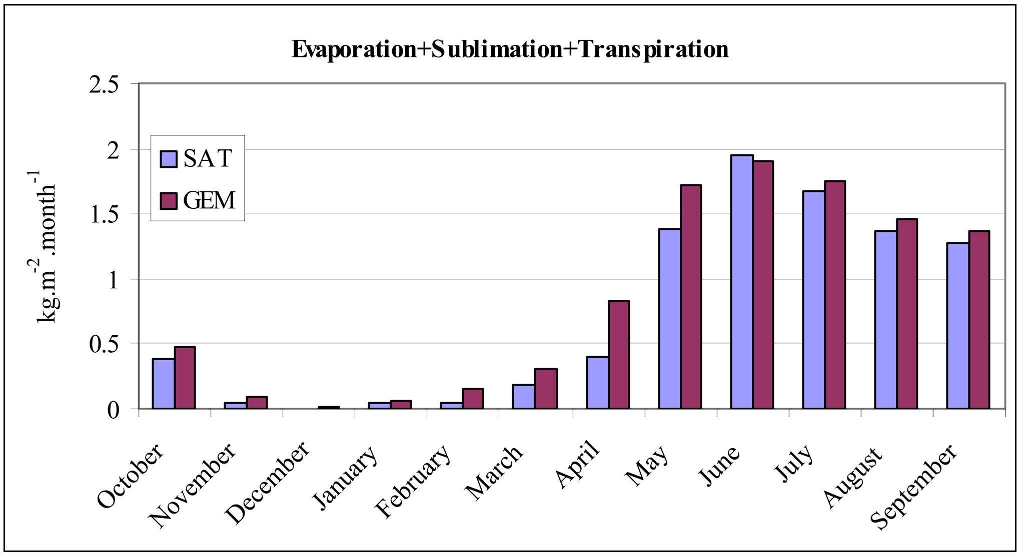

Figure 11. Basin daily average evapotranspiration and sublimation rate

As shown in figure 12, there is no delay in the first spring runoff peak, as might have been expected from the delay in the snowmelt. However there is a large amplitude difference in the first peak (greater than 10 kg.m^{-2}.day^{-1}). Overall there is also a 16% GEM simulation underestimation in runoff, i.e. 35 kg.m^{-2}.year^{-1} over the whole basin. This loss is mainly due to the greater evapotranspiration and sublimation in the GEM simulation.

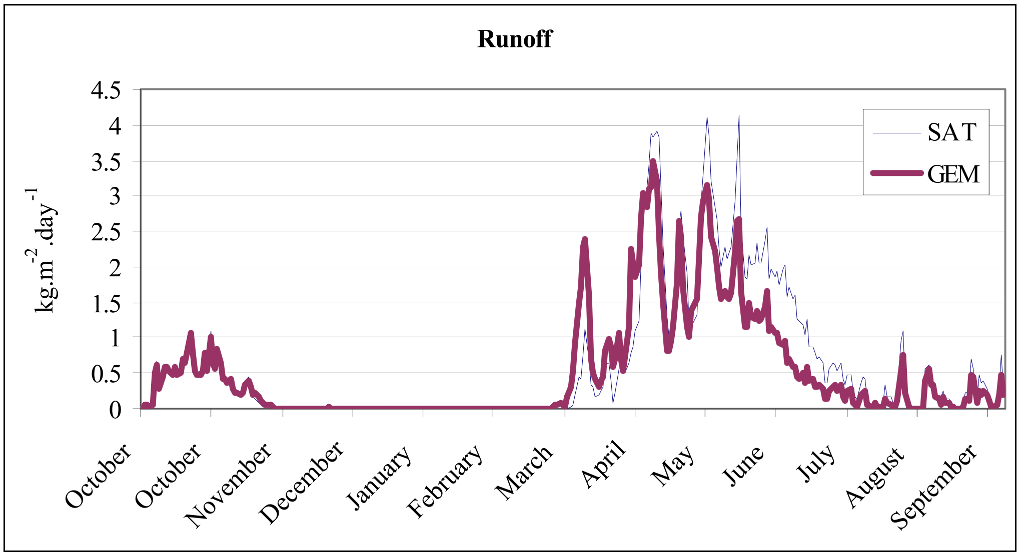

Figure 12. Basin daily average runoff.

CONCLUSIONS

Satellite retrievals suggest that the GEM model is overestimating the incoming solar flux in the basin by 36%. Our aim is to assess the sensitivity of the hydrology of the Mackenzie River basin, as simulated by WATCLASS, to this overestimation. We have, therefore, examined the induced changes in the energy budget and the water balance.

The energy budget distribution is sensitive, especially during the snowmelt season. The net longwave radiation fluxes showed the least sensitivity, with a 1°C temperature overestimation in spring. The latent heat flux is increased significantly, especially in spring and summer. The sensible heat fluxes show the highest increase: since the surface temperature increase is less than 1°C, we presume that the loss is from the canopy, which covers the entire surface in this simulation.

Concerning the water balance, the induced changes are a significant decrease in runoff, which is explained by a significant increase in loss of moisture through evapotranspiration and sublimation, and, to close the water balance, we assume also that there must be a change in the moisture storage in the different soil layers. There is also a significant increase in the magnitude of the first spring runoff peak. The linkage between the changes in snowmelt, water storage and runoff need to be investigated further.

The atmospheric model is for now linked but not coupled to the land surface – hydrological model. The lack of coupling is a limitation because of the absence of feedbacks. For instance, significant variations in evaporation rate could be expected to have a feedback on precipitation: a positive change in evaporation rate could increase the precipitation locally and increase runoff. In our result we can only see for now the loss of moisture through evaporation but no feedback on precipitation. This might have decreased the GEM simulation runoff underestimation compared to the simulation with smaller incident solar radiation.

A further limitation of this study is that only a single land class was used to describe the whole basin. WATCLASS is now available with seven land class types (wet forest, dry forest, urban, agriculture, bare ground, water and wetland). The response of the energy and water budget of the basin to solar radiation changes will undoubtedly be different in simulations in which the surface is modeled more realistically.

It will also be interesting to conduct the same studies on the different sub-watersheds of the basin, since there are large climatologic and hydrologic differences in, for example, their vegetation, precipitation and temperature.

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