

A coupled atmospheric-hydrological modeling study of the 1996 Ha! Ha! River basin flash flood in Québec, Canada

Charles A. Lin¹

Department of Atmospheric and Oceanic Sciences, and Centre for Climate and Global Change Research, McGill University, Montréal, Canada

Lei Wen, Michel Béland,² and Diane Chaumont

Centre de recherche en calcul appliqué, Montréal, Canada

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[1] We use a high-resolution regional atmospheric model coupled to a hydrological model, and an off-line routing module to simulate a hydrograph during the 1996 July flash flood that occurred in the Saguenay region of eastern Québec. The hydrograph is at the outlet of the Ha! Ha! Lake in the Ha! Ha! River basin. The former has a drainage area of 250 km² and is covered by 6 model grid squares; the precipitation at these grid squares compare well with observations at the nearest available rain gauge located 20 km south of the basin. The hydrological model is a modified version of a land surface scheme which consists of three soil layers, and the routing module is based on the geomorphological unit hydrograph. The simulated hydrograph is compared with another reconstructed hydrograph in the published literature. *INDEX TERMS*: 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions, 1860 Hydrology: Runoff and streamflow, 1821 Hydrology: Floods

1. Introduction

[2] In the summer of 1996, a record-breaking flash flood resulting from unprecedented heavy rainfall occurred in the Saguenay region of eastern Québec, Canada. The accumulated average precipitation over a 48-hour period from July 19 to 21, 1996 was about 200 mm over an area of 5000 km². This heavy rainfall caused the most devastating flood disaster in modern Canadian history. Two reservoir dikes at lakes Ha! Ha! and Kénogami collapsed as a result of the flood. Life and property loss from eight communities in the Saguenay region included ten deaths, and 1,718 houses and 900 cottages were destroyed or damaged. 16,000 people were forced to evacuate their homes. The financial loss due to the flood is estimated at \$CAN 700 million.

[3] An accurate and timely flood warning system can help to minimize flood damage. A coupled high-resolution atmospheric and hydrological model has the potential to be part of such a system, as the atmospheric model could provide precipitation to the hydrological model with a significant lead time. In this study, we use a coupled atmospheric-hydrological modeling system to reconstruct the 1996 flash flood hydrograph at the outlet of Ha! Ha! Lake in the southern Ha! Ha! River basin, which is a sub-basin of the Saguenay basin. The present work builds on two recent modeling studies. *Wen et al.* [2000a] used an earlier version of the coupled model to examine the sensitivity of short-range precipitation simulation to land surface treatment. *Wen et al.*

[2001] tested the routing module of the modeling system using flood data from 252 flood events in 25 catchments in the Zhejiang province of China.

[4] The paper is organized as follows. Section 2 presents an overview of the flood case, section 3 describes the modeling system and initialization, sections 4 and 5 present respectively the results and discussion, and the conclusions.

2. Overview of the July 1996 Saguenay Storm

[5] Rainfall had been light in the Saguenay region of eastern Québec in the three successive years prior to 1996, leaving the Ha! Ha! reservoir level low for summer usage. Precipitation during the spring of 1996 was above normal. Heavy rains and early snowmelt culminated in high spring runoff and near saturated soil moisture, and the reservoir management authority allowed the reservoir to fill to the brim. On July 18, 1996, a small low pressure system which had originated over southern Manitoba with a central sea level pressure of 1002 mb formed and slowly deepened as it moved eastward toward Lake Ontario (*Yu et al.*, 1997). The system then began to deepen rapidly, and reached the Saguenay region of eastern Québec 24 hours later, with a pressure drop of 20 mb. Over the next 48 hours (July 19–21), the low stalled over the Gaspé Peninsula of Québec, resulting in intense precipitation. The observed maximum value of the 48-hour accumulated precipitation was over 270 mm in the Saguenay region, several times larger than the maximum record of the past 120 years.

3. Coupled Atmospheric-Hydrological Modeling System

[6] The atmospheric-hydrological modeling system consists of a high-resolution regional atmospheric model coupled interactively to a hydrological model, and a routing module which is run off-line. The atmospheric model used is MC2 (Mesoscale Compressible Community Model), a 3-dimensional compressible regional model developed by *Benoit et al.* [1997]. MC2 uses the force-restore method (*Deardorff*, 1978) as the default treatment of land surface processes. The hydrological model is a modified version of the 1-dimensional column land surface model CLASS (Canadian Land Surface Scheme) with three soil layers and a “mosaic” approach for vegetation treatment, first developed by *Verseghy* [1991] and *Verseghy et al.* [1993] for atmospheric general circulation models. A higher effective resolution of land surface characteristics is obtained through the mosaic approach. The advantages of this approach are further discussed by *Avissar and Pielke* [1989], *Koster and Suarez* [1992], *Wood et al.* [1992], and *Ducoudré et al.* [1993]. In an earlier study (*Wen et al.*, 2000a), we have coupled the original unmodified version of CLASS interactively to MC2 to study the effects of CLASS and force-restore method on the simulation of the intense precipitation of the

¹Also at Centre de recherche en calcul appliqué, Montréal, Canada.

²Also at Réseau québécois de calcul de haute performance, Montréal, Canada.

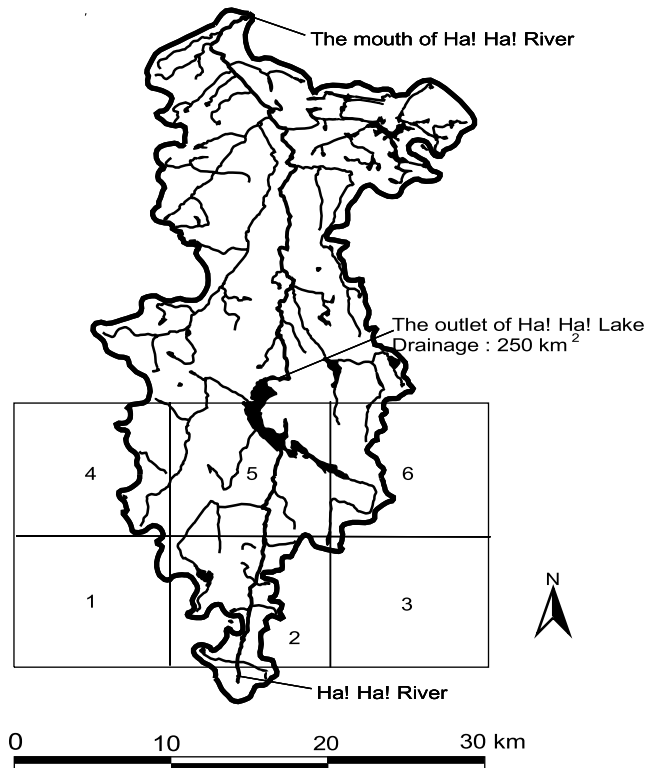


Figure 1. The geography of the Ha! Ha! River basin. The grid indicates the 6 model grid squares covering the upper basin. The nearest rain gauge is located 20 km to the south of the upper basin (Gauge number 7043713).

Saguenay storm, at a spatial resolution of 5 and 10 km. Our study showed that the higher effective resolution of land surface characteristics achieved by CLASS means that MC2-CLASS at 10 km resolution can give better results than MC2-force restore at 5 km. The impact of land surface treatment on short-range precipitation simulation can thus be significant, especially in regions with complex vegetation characteristics.

[7] For this study, we have modified CLASS to allow for interflow and baseflow (Wen *et al.*, 2000b). We will refer to the modified version as CLASS*. The original version of CLASS has no interflow, and a baseflow which is not appropriate for hydrological purpose. Our modification consists of the use of a field capacity threshold to allow for interflow generation, and the introduction of a reservoir at the bottom of the third CLASS soil layer. The latter is similar to the parameterization of drainage introduced by Dümenil and Todini [1992].

[8] The details of the initialization procedure of the coupled atmospheric-hydrological model (MC2-CLASS) is described in Wen *et al.* [2000a]. Initialization of MC2-CLASS* follows the same procedure. Soil moisture content is initialized using CMC (Canadian Meteorological Centre) analyses. With no modification to CLASS, the coupled model MC2-CLASS gives an effective precipitation that can be several times larger than the precipitation for certain grid squares. Effective precipitation is the component of rainfall that contributes to storm runoff, and is calculated by the coupled model. The large effective precipitation of MC2-CLASS is due to incorrect initialization of soil moisture based on CMC analyses. The initial soil moisture exceeds the field capacity, thus resulting in large amounts of free water in the soil column. This is especially true for sandy soil, leading to large drainage at the bottom of the column. With our modification to CLASS, the effective

precipitation of MC2-CLASS* of these grid squares become more realistic, as the newly introduced reservoir at the bottom of the third CLASS soil layer moderates the baseflow, thus circumventing the initialization problem. Soil moisture initialization remains an important unsolved problem in weather prediction models. At this stage, we have no objective method for obtaining alternative values of initial soil moisture other than using CMC analyses, which may not be adequate for hydrological applications.

[9] The catchment scale routing module is based on the GUH (geomorphological unit hydrograph). The GUH was first introduced by Rodriguez-Iturbe and Valdés [1979] to link the catchment hydrologic response, given by the instantaneous unit hydrograph (IUH), with geomorphologic parameters of the catchment. The latter is assumed to be drained by a perfect Horton network. We have extended the GUH to a Horton network of order 4 and higher (Wen *et al.*, 2001). All but one parameter of the GUH can be obtained from the basin geomorphology using GIS (Geographic Information System) methods. These parameters are Horton's bifurcation ratio, stream length ratio, stream area ratio, and the length of the highest order channel. The remaining parameter is a flow velocity, which can be obtained from calibration with historical data or methods appropriate for ungauged catchments. Wen *et al.* [2001] describe the GUH extension and discuss six methods to obtain the flow velocity. They have also tested the GUH using 252 flood events over 25 catchments in the Zhejiang province of China with encouraging results. In the present study, the geomorphologic parameters of the Ha! Ha! River basin were obtained using standard GIS methods, and the flow velocity obtained using the method reviewed by Wen *et al.* [2001] for ungauged catchments.

4. Results and Discussion

[10] We apply the coupled modeling system MC2-CLASS* together with the GUH router to the Ha! Ha! River basin. This is a sub-basin of the Saguenay basin; serious flood damage occurred near the industrial town and port terminal of La Baie located at the mouth of the Ha! Ha! River. A detailed description of the study site and flood erosion in the stream valley can

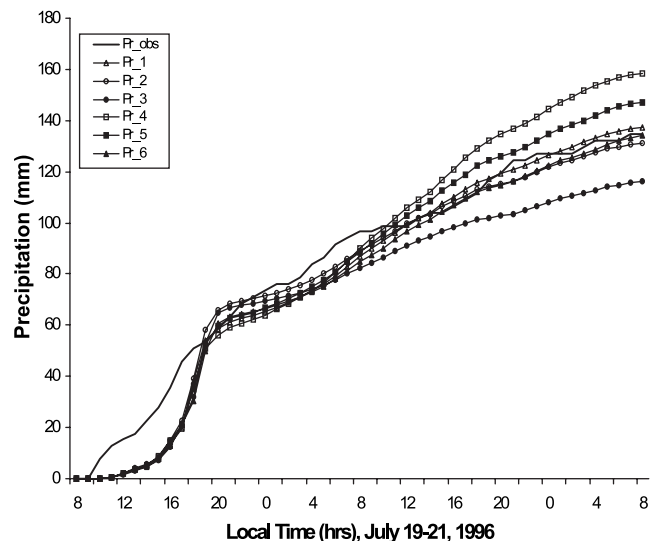


Figure 2. The model precipitation (Pr₁, ..., Pr₆) over 48 hours at the 6 grid squares of the upper Ha! Ha! River basin, compared with the observations (Pr_{obs}) of rain gauge number 7043713.

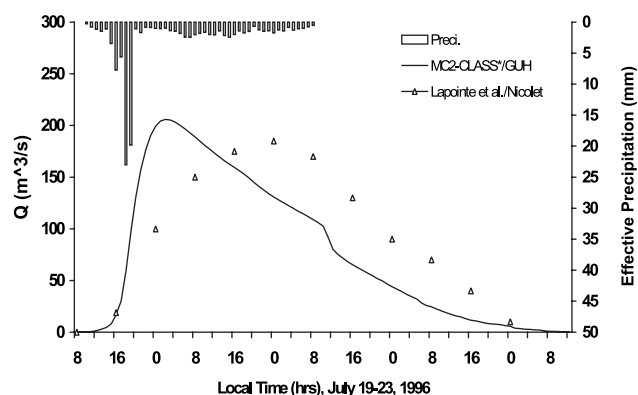


Figure 3. A comparison of two reconstructed hydrographs at the outlet of the Ha! Ha! Lake. The solid line represents the results of our coupled atmospheric-hydrological modeling system, and the triangles are taken from the Lapointe et al./Nicolet results. The precipitation from our coupled model is also shown.

be found in Lapointe et al. [1998]. Figure 1 shows the geography of the Ha! Ha! River basin. It has a drainage area of 610 km² and is located in the mountainous and forested area of the Saguenay basin in eastern Québec. The basin extends about 45 km in the south-north direction, and about 14 km in the east-west direction. The Ha! Ha! River flows from south to north. We use our modeling system to reconstruct the hydrograph at the outlet of the Ha! Ha! Lake in the southern Ha! Ha! River basin; the results will be compared to the published work of Lapointe et al. [1998] and a Government of Québec report (Nicolet, 1997).

[11] The Ha! Ha! River basin is covered by 15 grid squares of the MC2-CLASS* model at a resolution of 10 km. The southern basin is covered by 6 such squares (Figure 1). We have examined the time variation of the precipitation at these 6 locations throughout the duration of the storm, and compared it to the observations available at the nearest gauge (Station No. 7043713) located 20 km to the south of the upper basin. The agreement between the simulated and observed precipitation over 48 hours is very good (Figure 2). We have examined the effective precipitation of MC2-CLASS* for the 15 grid squares of the Ha! Ha! River basin, and found it to be much more consistent with the simulated and observed precipitation compared to MC2-CLASS. Figure 3 shows the hydrograph at the outlet of the Ha! Ha! Lake in the southern Ha! Ha! River basin produced by our modeling system. The effective precipitation from MC2-CLASS* (area-weighted average of the six grid squares) is used to drive the GUH routing module. The total runoff at the outlet of the Ha! Ha! Lake from our study is 312 million cubic meters, which compares very well with the runoff of 322 million cubic meters of another reconstructed hydrograph published in the scientific literature (Lapointe et al., 1998) and in a Government of Québec report (Nicolet, 1997). Our hydrograph shows a peak flow of 204 cubic meters per second that occurs about 9 hours after the maximum precipitation. The Lapointe et al./Nicolet hydrograph shows a peak flow of about 185 cubic meters per second, occurring more than 30 hours after the maximum precipitation. Although the precipitation sources used in the present study and in the Lapointe et al./Nicolet studies are different, the peak precipitation and timing of the peak precipitation of both studies are approximately the same. It is thus unclear why the time lag between peak precipitation and peak flow in the Lapointe et al./Nicolet studies is much longer than in our work. We were not able to get any measured flow data to further verify the

model results as most of the stream gauges were flushed away during the flood. However, an indication of the occurrence of the peak flow is the time when the dyke at the Ha! Ha! Lake broke as a result of the flood. It was reported by a Montréal newspaper (The Gazette, November 2, 1996) as occurring at 5 am on July 20, 1996. This corresponds well to the peak flow in the hydrograph of our study, which occurred at 4 am.

5. Conclusions

[12] We have used a coupled atmospheric-hydrological modeling system to simulate the July 1996 flash flood which occurred in the Ha! Ha! River basin of the Saguenay region of eastern Québec. The system consists of a high-resolution regional atmospheric model (MC2), a modified version of the land surface scheme CLASS, and an off-line GUH routing module. The modification to CLASS allows for interflow and baseflow in the soil column. The original unmodified version of CLASS has already been coupled to MC2 and tested for the Saguenay precipitation case (Wen et al., 2000a). The GUH routing module has also been tested using 252 flood events in 25 catchments in the Zhejiang province of China (Wen et al., 2001). Our reconstructed hydrograph at the outlet of the Ha! Ha! Lake is compared to another reconstructed hydrograph published in the scientific literature (Lapointe et al., 1998) and a Government of Québec report (Nicolet, 1997). The total runoff compares well in both studies, but there is a significantly longer time delay between peak precipitation and peak flow in the Lapointe et al./Nicolet studies compared to our results.

[13] Our results demonstrate the feasibility of using a coupled atmospheric-hydrological modeling system for flash flood forecasts. This approach could give a longer lead time compared to the use of conventional precipitation data from radars or rain gauges. This modeling system is now fully functional, and additional cases will be examined.

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M. Béland, D. Chaumont, and L. Wen, Centre de recherche en calcul appliqué (CERCA), 5160, boul. Décarie, bureau 400, Montréal, Québec, H3X 2H9, Canada. (beland@CERCA.UMontreal.CA; chaumont@CERCA.UMontreal.CA; leiwen@CERCA.UMontreal.CA.)

C. A. Lin, Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montréal, Québec, H3A 2K6, Canada. (lin@zephyr.meteo.mcgill.ca.)