4.7 Modeling heavy precipitation and flooding events using the coupled atmospheric-hydrological model

Zuohao Cao[1]*, Brian Murphy, Pierre Pellerin[2], Harold Ritchie[3], R. Paul Ford[1], and Paul J. Pilon[1]
[1]Meteorological Service of Canada, Ontario region, Burlington, Ontario, Canada
[2]Meteorological Service of Canada, Dorval, Quebec, Canada
[3]Meteorological Service of Canada, Dartmouth, Nova Scotia, Canada

1. Introduction

Quantitative precipitation forecasting (QPF) is one of the most important and significant challenges for weather forecasting. It substantially affects the economic activities of both the government and the private sectors who make their decisions under various weather scenarios. Based on QPF information, for example, utility companies decide if hydroelectric power generation is used rather than the more costly fossil fuel generation, and agricultural operators decide if they expend increasingly limited and expensive water resources for irrigating crops. More importantly, heavy precipitation is often associated with severe weather events such as damaging ice storms, snowstorms, and floods. These weather systems, especially ones associated with flash flooding, frequently result in property damages and casualties.

Despite the importance of QPF to commercial activities and public safety, skill in forecasting precipitation amount has historically been relatively low (Olson et al. 1995), indicating the extreme difficulty in making accurate forecasts of quantitative precipitation. Even with the advances in computational and observational technology together with theoretical advances during the past decades, the rate of improvement in skill had been very slow (Olson et al. 1995). As pointed out by Olson et al. (1995), most of the significant precipitation events occur during the warm season, and skill levels are the lowest at the time of year when the spatial extent of heavy precipitation is greatest. Furthermore, Heideman and Fritsch (1988) find that approximately half of the precipitation with 24-h amounts ≥ 12.7 mm is associated with extratropical cyclones (e.g., Cao and Cho 1995) and half is produced through mesoscale forcing mechanisms acting independently of traveling extratropical cyclones. They also find that over 80% of such precipitation is associated with thunderstorms. The warm season is dominated by these small-scale convective processes, which are poorly resolved by numerical models (Olson et al. 1995). It is clear that to improve 24-h QPF capability, we must improve our understanding of convective processes and numerical modeling of convective events.

Convectively-driven heavy precipitation during the warm season frequently results in flooding that have significant social and economic impacts. In this study, we will examine some heavy rainfall events that occurred in 2000 over southern Ontario. In an attempt to properly resolve these small-scale phenomena, we will perform very high resolution numerical simulations using a nesting technique. To better understand the physical processes that govern mesoscale extreme weather systems, particularly those associated with heavy precipitation and severe flooding events, the whole atmospheric-hydrological system must be taken into account. The coupling approach (e.g., Cao et al. 2001) is one of the most efficient ways to understand how the atmospheric and surface hydrological system operates. This approach is adopted in this study. In addition, the water balance approach (Cao et al. 2001) is used to diagnose the physical processes that govern the atmospheric-hydrological system.

The objectives of this study are, firstly to assess the accuracy of QPF through comparisons between observations (e.g., raingauge and Doppler radar data) and model predicted precipitation fields, secondly to assess the ability to simulate surface streamflow through coupling the mesoscale model with the hydrological model, and thirdly to identify key physical processes that are responsible for formation and maintenance of intensive precipitating systems.

This paper is organized as follows. In section 2, the models used for the coupling purposes will be described. In section 3, a case study will be presented. The conclusions will be made in section 4.

---

*Corresponding author address: Dr. Zuohao Cao, Meteorological Service of Canada - Ontario, 867 Lakeshore Road, P. O. Box 5050, Burlington, Ontario, Canada L7R 4A6, E-mail: zuohao.cao@ec.gc.ca.

2. Model description

(a) Atmospheric model

The limited-area mesoscale model MC2 (Robert et al. 1985; Benoit et al. 1997; Benoit et al. 2000) is used in this study. The MC2 model is based on the fully compressible nonhydrostatic Euler equations with a polar stereographic projection. The governing equations consist of prognostic variables of the three velocity components (u, v, w), logarithm of a dimensionless perturbation pressure p from the reference state $\ln(p/p_o)$ with $p_o = 1000$ hPa, temperature T, and the mixing ratios for water substances. The reference state used is an isothermal hydrostatic atmosphere at rest. The model is discretized using a fully three-dimensional semi-implicit and semi-Lagrangian time discretization scheme. The space derivatives are discretized by finite differences on a grid staggered in three dimensions, with an Arakawa C grid for the horizontal, and a Tokioka B grid for the vertical. The terrain-following Gal-Chen vertical coordinate is used. Lateral boundaries are specified as open with inflow-outflow determined by the normal components of velocity (Thomas et al. 1998).

The model uses a comprehensive physics package (Mailhot et al. 1998). It includes planetary boundary layer processes based on turbulent kinetic energy (Benoit et al. 1989), fully implicit vertical diffusion, and a stratified surface layer based on similarity theory. This package also includes a set of schemes for land surface processes. The solar (Fouquart and Bonnel 1980) and infrared (Garand and Mailhot 1990) schemes in the radiation package of the model are fully interactive with the clouds. A number of options are available for convective parameterization (e.g., Kuo 1974; Arakawa-Schubert 1974; Fritsch-Chappell 1980; Kain-Fritsch 1990, 1993) and stratiform precipitation (e.g., Sundqvist et al. 1989; Hsie et al. 1984; Kong and Yau 1997).

The MC2 model has capability for a one-way self-nesting with various horizontal domains. Three simulation domains with horizontal resolutions of 25, 8 and 2 km are set up, as shown in Fig. 1. The fields from a lower resolution run can be used to provide initial and boundary conditions for a higher resolution run. The initial and boundary conditions for the first simulation at a resolution of 25 km are obtained from CMC analyses generated by the 3D variational data assimilation system (Gauthier et al. 1996). For each model resolution, the model has been integrated for 3 days. The time step is calculated based on grid spacing for each simulation.

(b) Hydrological model

A distributed hydrological model WATFLOOD (Tao and Kouwen 1989; Kouwen et al. 1993) is used in this study. This model consists of two individual models, a land surface model and a channel flow routing model. The main feature of the land surface model is to use a gridded grouped response unit (GRU) technique, which models the land surface processes separately for each land cover within a computational grid element although all individual areas within that element are subjected to the same meteorological conditions. The channel flow routing model has a two-stage flow routing procedure. For overland flow, an explicit and noniterative method based on continuity and Manning's formula is used, which incorporates the average surface slope and roughness for each grid. Similarly, river flows are computed based on continuity and Manning's formula except that different parameters are used for channel and floodplain roughness and an iterative approach is employed. Interested readers may refer to Benoit et al. (2000) for more detail.

(c) Coupling

One-way coupling is implemented through the atmospheric model driving the hydrological model with a time step of one hour. Each model uses its own simplified land surface physical process module. The one-way coupling requires that the atmospheric forcing (e.g., precipitation and temperature) produced by the atmospheric model MC2 on a polar stereographic projection are interpolated to the universal transverse mercator (UTM) grid of the hydrological model WATFLOOD. In order to have a good initialization for variables such as soil moisture content, the hydrological simulations are run about 40 days before the period of interest and they are driven with hourly surface and/or radar observations.

3. Case study

The case presented here is a heavy rainfall and flooding event occurred from May 10 to 12, 2000. The MC2 simulated mean-sea-level pressure field showed that on 06 UTC May 10, 2000, there was a low-pressure system moving into the southern Ontario basin. The strong low-level south and southwesterly flows associated with the cyclone was dominant for moisture transport into southern Ontario, which contributed to the development of heavy precipitation. On the second day, however, a high pressure ridge was established over southern Ontario, providing a gap between two major precipitation periods. Presumably, evaporation played some role in enhancing the rainfall that occurred on the following day. On May

12, 2000, a low-pressure system is dominant again (Fig. 2), which resulted in large amount of rainfall over southern Ontario.

The impacts of this event over southern Ontario region were very significant. Strong wind felled trees, damaged houses, and downed power lines over a large area. The heavy rainfall and subsequent flooding caused public transportation disruptions in Toronto, and may have been a contributing factor in the increase of reported automobile collisions in the Greater Toronto area (457/day collisions on May 12 compared with the average of 330/day) This event also caused some disruptions through flooding basements and streets.

The detailed evolution of the rainfall event was examined. The hourly rainfall rate recorded by the Grand River Conservation Authority raingauge at Cambridge for May 2000 indicated that the hourly rainfall rate peak of this month appeared around May 10 and the magnitude was about 12 mm/h. The second peak occurred around May 12. Waterloo-Guelph area experienced a hourly rainfall rate peak of 31.4 mm/h between 2300 and 2400 UTC on May 12. It was observed that the first peak of streamflow for Grand River at Galt appeared around May 14.

The mesoscale model MC2 performance is evaluated through comparisons between the model predicted rainfall and observations. The spatial distributions of 24 h precipitation accumulation for May 10, 2000 are generated by interpolating the station data recorded by 81 raingauges onto gridded points using Kriging method. The precipitation recorded by King City Doppler radar is also interpolated onto the gridded points. As a result, the model predicted precipitation fields (Fig. 3) agree with the observations (not shown) very well in terms of pattern and magnitudes. The simulated precipitation field resolves well the banded structure of observed precipitation.

As one of the forcing fields, the precipitation simulated by the atmospheric model is incorporated into the hydrological model and then the hydrological simulations are made over the Grand River at Galt, a southern Ontario basin. The comparisons between the simulated streamflow with the observed one show that the streamflow simulated by the coupled atmospheric-hydrological model accurately represents the observed streamflow in terms of magnitudes and timing of peak flows (Fig. 4).

Physical processes leading to heavy precipitation were also examined. It has been observed from the atmospheric simulations that moisture from Gulf of Mexico is a very important source of water vapor in contributing to precipitation over southern Ontario basin. As a result of this moisture transport from the Gulf of Mexico, together with mesoscale convection, a very intensive precipitation band has been formed over the Ontario region. The formation mechanism of the rainband will be further investigated.

4. Concluding remarks

A heavy rainfall and severe flooding event over south Ontario is examined using the coupled atmospheric-hydrological model. The simulations are implemented with very high resolution self-nesting domains. Preliminary verifications of the model simulations against observations indicate that both precipitation and streamflow are well predicted by the atmospheric model and the coupled atmospheric-hydrological model. The results also show that precipitation patterns and magnitudes produced by the high resolution mesoscale model are better than those by low resolution simulations although simulations from 25 km resolution are not shown. Some key physical processes associated with this heavy precipitation and flooding event are examined. Detailed results will be presented at the conference.

References

Benoit, R., P. Pellerin, N. Kouwen, H. Ritchie, N. Donaldson, P. Joe, and E. D. Soulis, 2000: Toward the use of coupled atmospheric and hydrologic models at regional scale. *Mon. Wea. Rev.*, **128**, 1681-1706.

Cao, Z. and H.-R. Cho, 1995: Generation of moist potential vorticity in extratropical cyclones. *J. Atmos. Sci.*, **52**, 3263-3281.

Cao, Z., M. Wang, B. A. Proctor, G. S. Strong, R. E. Stewart, H. Ritchie, J. E. Burford, 2001: On the physical processes associated with the water budget and discharge of the Mackenzie Basin during the 1994/1995 water year. *Atmos.-Ocean*, in press.

Kouwen, N., 1993: Grouped response units for distributed hydrologic modeling. *J. Water Res. Planning Manage.*, **119**, 289-305.

Mailhot, J., and Coauthors, 1998: Scientific description of RPN physics library, Version 3.6, 188pp. [Available from Recherche en Prévision Numérique, Dorval, PQ H9P 1J3, Canada.]

Tao, T., and N. Kouwen, 1989: Remote sensing and fully distributed modeling for flood forecasting. *J. Water Res. Planning Manage.*, **115**, 809-823.

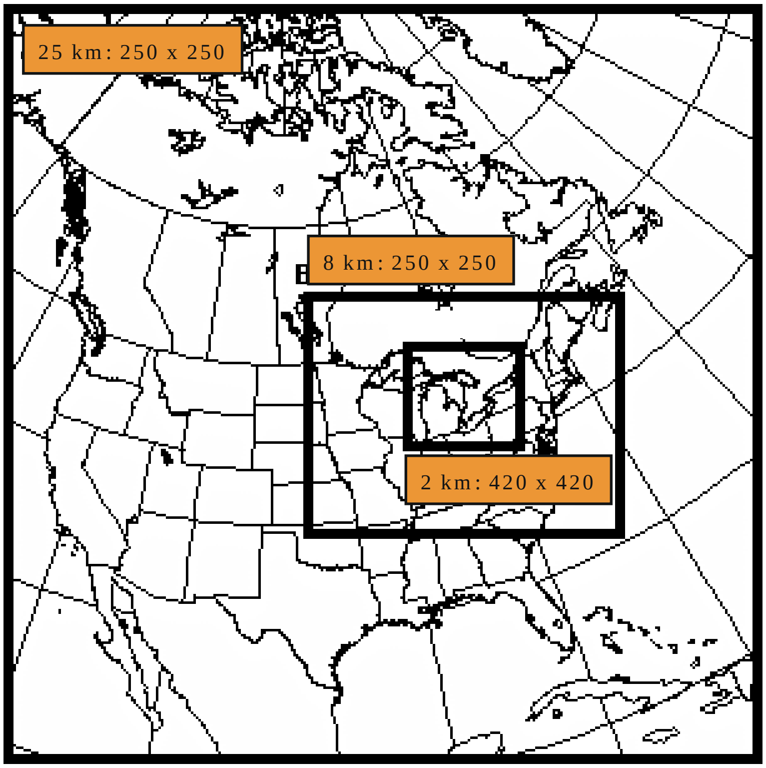

Fig. 1 Domains for atmospheric modeling

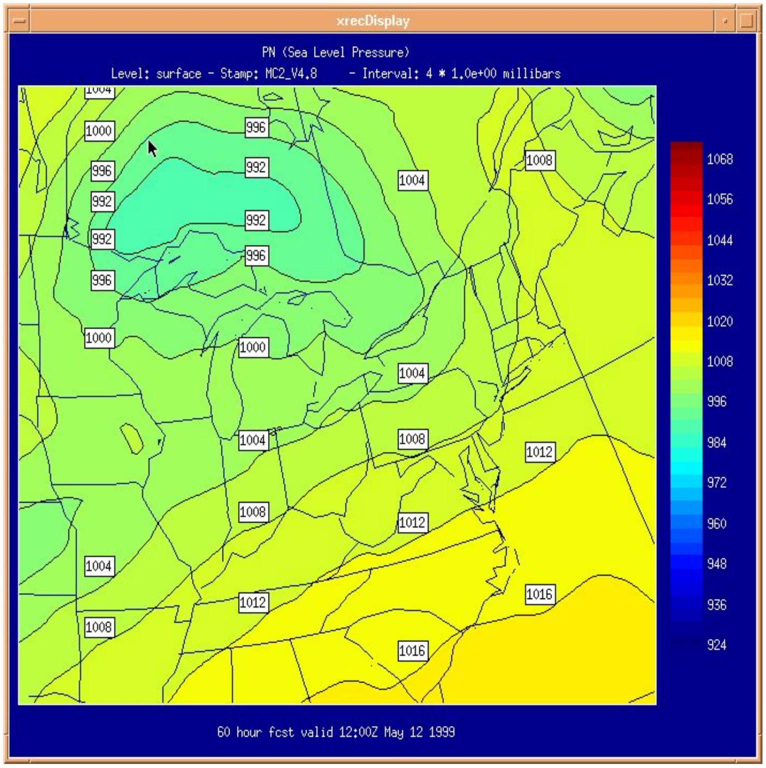

Fig. 2 The mesoscale model simulated mean-sea-level pressure on 12 UTC, May 12, 2000

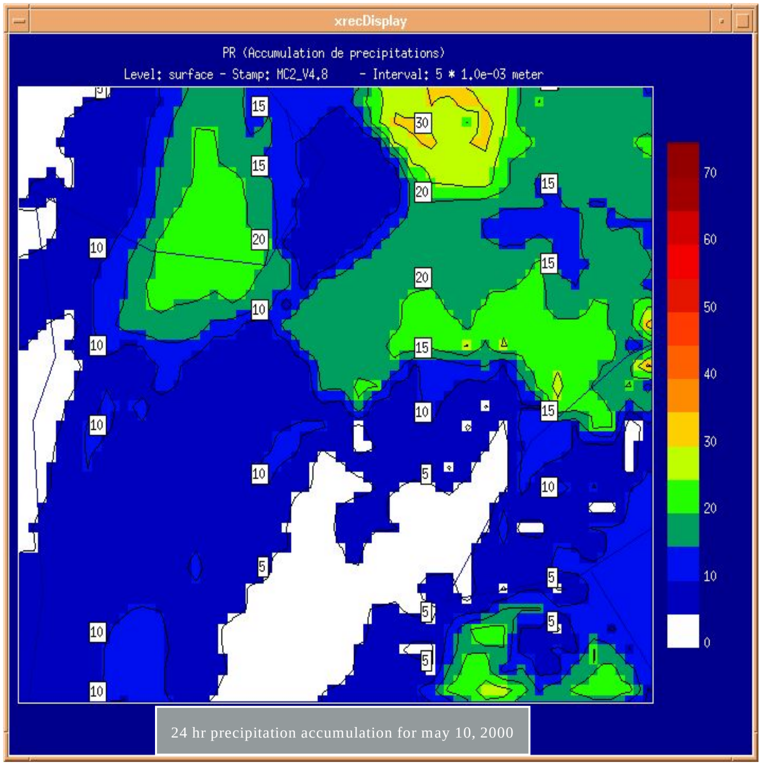

Fig. 3 The mesoscale model simulated 24 h accumulated precipitation for May 10, 2000

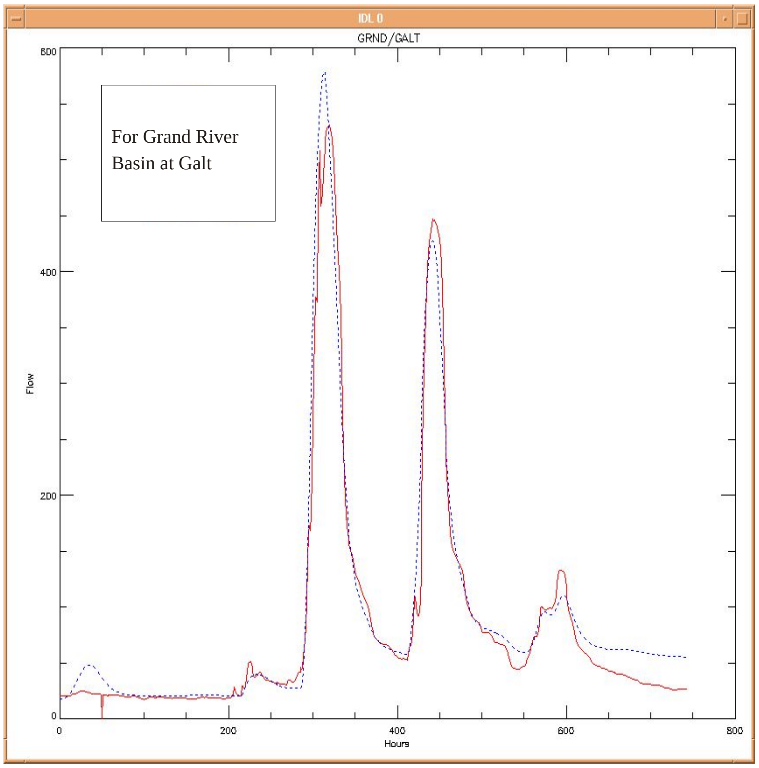

Fig. 4 The simulated streamflow (dashed lines) and observed streamflow (solid lines) for May 2000