Towards a Mesoscale Global Forecast Model at the Canadian Meteorological Centre

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1. Introduction

The Global Environmental Multiscale (GEM) model (*Côté et al.*, 1998) is used to produce medium-range global forecasts at the Canadian Meteorological Centre (CMC). The model is currently integrated for 10 days, once daily, on a uniform resolution grid of 0.9° (~ 100 km). Apart from the change of dynamical/numerical core, which took place in October 1998 (i.e., Spectral Finite-Element model - SEF - replaced by GEM), very few changes were performed on the global modelling system in the last few years. The horizontal resolution has remained unchanged since summer 1995. To improve medium-range weather forecasting at CMC a significant increase in resolution is needed, among other things.

The rapid increase in computer power that is expected in the next few years, coupled with model optimisation, should allow us to increase the horizontal resolution of the medium-range model from 0.9° to about 0.33-0.45° (i.e., 35-50 km). The model would thus practically become a *mesoscale* model in which it would be possible to use more appropriate physical schemes for cloud processes. The vertical resolution also needs to be augmented. These days, 28 levels are used in the medium-range operational model. It is planned to expand this number to at least 35.

2. Hardware and Software

Until recently operations at CMC used a single shared-memory vector multiprocessor, currently a NEC SX-4/32. As it was anticipated that the increase in resolution of the forecast model and data assimilation system would require more than one such machine or "node" working together, a complete re-coding of the GEM model was undertaken.

The new code uses explicit message passing with the Message Passing Interface (MPI), together with multi- and micro- tasking, whereas the current code is only parallelized with multi- and micro- tasking on a single node. The resulting code can be run in a purely distributed memory mode or in a hybrid mode, taking advantage of the fact that some CPUs have a shared memory. Fig. 1 gives a schematic view of the current supercomputing cluster at CMC, note that the SX-4 and the SX-5 cannot be used together, since they are not linked by the IXS crossbar, which is the communication channel.

The limited-area version of GEM, called LEM, is also being coded and should be available for testing end of summer 2000. This version of the code will run all combinations of global/limited-area, uniform-/variable-resolution and hydrostatic/ non-hydrostatic.

3. Changes to the Model

The recoding was not a simple "port", and some model algorithms were revised, most notably the treatment of the Coriolis terms, and some options of the operational code were not carried over in the new version, such as the possibility of using cubic spline interpolation for the semi-Lagrangian advection.

In the meantime the operational model was improved, albeit at a fixed resolution. A special effort went into reducing the model diffusion. Both the implicit one inherent to the semi-Lagrangian interpolation by using cubic spline rather than cubic Lagrange interpolation and the horizontal diffusion, which as been set to zero except at the top levels of the model, were it acts as a sponge layer. These changes have been extensively evaluated, and are about to become operational along with the analysis on the model levels. This will allow the data assimilation system to begin ingesting non-conventional data.

The coupling of the dynamics to the physics has also been modified to correct the problem with splitting raised by *Caya et al.* 1998. It has a positive impact near the surface but there is a slight degradation in performance in the mid-troposphere. This is attributed to the need of revisiting the radiation scheme and its coupling with the model clouds. Pending this revision this change has not been implemented operationally.

4. GEM MODEL FORMULATION AND RESULTS

The GEM model can be succinctly described as a two-time-level implicit semi-Lagrangian grid-point model, with a latitude-longitude C-grid staggering in the horizontal and an unstaggered σ-type vertical grid. The non-hydrostatic terms are optionally activated with a switch. Schematically the adiabatic part of the model is,

$$\frac{dX}{dt}\mathcal{H}(X) = 0 \tag{1}$$

where X denotes the state vector (all the prognostic variables) and $\mathcal{H}$ the nonlinear model. The centered two-time-level implicit semi-Lagrangian discretization of (1) is,

$$\frac{X}{\tau} + \mathcal{H}(X) = R = \left(\frac{X}{\tau} - \mathcal{H}(X)\right)^{-}, \tag{2}$$

where $\tau = \Delta\tau/2$, and as usual - denotes evaluation at the upstream position at the previous time level $(t-\Delta t)$. The upstream positions are obtained from the auxiliary problem

$$\frac{d\mathrm{r}}{dt} = \tilde{\mathrm{V}}(\mathrm{r}),\ \tilde{\mathrm{V}}(\mathrm{r}) = \frac{\mathrm{V}(\mathrm{r},t-\Delta t) + \mathrm{V}(\mathrm{r},t)}{2}. \tag{3}$$

Note that the unknown wind at time t appears in the auxiliary problem, and (2)-(3) are solved sequentially starting with a first estimate of $\mathbf{V}(\mathbf{r},t)$. The nonlinear problem (2) is also solved iteratively, i.e.,

$$\begin{aligned} \frac{X^{(k)}}{\tau} + \mathrm{L}X^{(k)} &= R - N(X^{k-1}), \\ H(X^{(k-1)}) &= \mathrm{L}X^{(k-1)} + \mathcal{N}(X^{(k-1)}) \end{aligned} \tag{4}$$

The GEM model has an outer loop for the trajectory computation, and an inner loop for the nonlinearity of the equations, and the model is fully implicit or interpolatory. By comparison the ECMWF two-time-level model is explicit or extrapolatory for the trajectory and nonlinear terms (*Hortal*, 1998).

The time accuracy of the scheme is obviously second order, and performing the upstream interpolation in (2) with a cubic interpolator should provide adequate space accuracy. Cubic Lagrange interpolation or cubic spline interpolation should be equivalent, but the kinetic energy density spectrum has a better tail using cubic spline interpolation at a resolution of 0.9°.

The option of using cubic spline interpolation, which involves the solution of a global problem, has not been carried over to the distributed-memory code, and at the suggestion of Jim Purser, the more local quintic Lagrange interpolation was investigated as a substitute for cubic spline interpolation. Fig. 2 shows the kinetic energy density spectrum for various model configurations. The spectrum is the average of six 72-hour forecasts at 0.9o. resolution spread around the year. There are 5 curves: the dark green line is the -3 power law, the black line is the new operational model with cubic spline interpolation, the red dash line is the distributed memory model with quintic Lagrange interpolation, the thin dash and dash lines are the operational and distributed memory models respectively, both with cubic Lagrange interpolation. The last two curves sit on top of each other as expected. We see however that the quintic Lagrange curve while following more closely the cubic spline one falls off more rapidly near the end. This is being investigated further, as we are trying to develop an approximate cubic spline interpolation with the same data locality as the quintic Lagrange interpolation.

The stability of the scheme requires that the Coriolis terms be treated implicitly. The operational shared-memory version of the GEM model handles these terms by yet another iterative loop inside the inner loop (4) where they are part of the **L** operator, and it was felt that this should be removed in the distributed-memory version.

The most efficient way to do that in our scheme is to recast these terms in an advective form (*Temperton*, 1997), and they will appear as corrections to the metric terms. An initial attempt was made which, however did not perform satisfactorily with off-centering and long timesteps. After this was cured, data assimilation cycles have been run, and a greater sensitivity than had been expected for this change was measured by the verification scores. Held-Suares tests confirmed that we still had a problem. This prompted us to try the remaining option: to treat these terms as the nonlinear terms, i.e. to include them in N.

This lead to satisfactory results with the Held-Suares tests, and a reduced sensitivity in a deterministic 10-day forecast was observed. This is illustrated in Fig. 3 where the sensitivity of 500 hPa height forecasts to change in the formulation of the Coriolis terms is displayed. The operational model is the control; the dashed line is the advective treatment, the thin line is the non-linear treatment, and the thick line is the 3m/day criteria of acceptable difference.

This option was quickly incorporated to the distributed-memory version of the GEM model, and further testing is underway.

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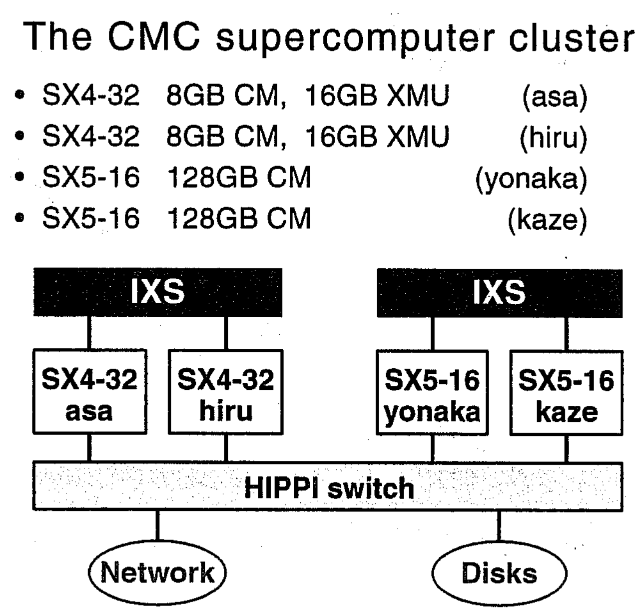

Fig. 1. The supercomputing cluster at CMC.

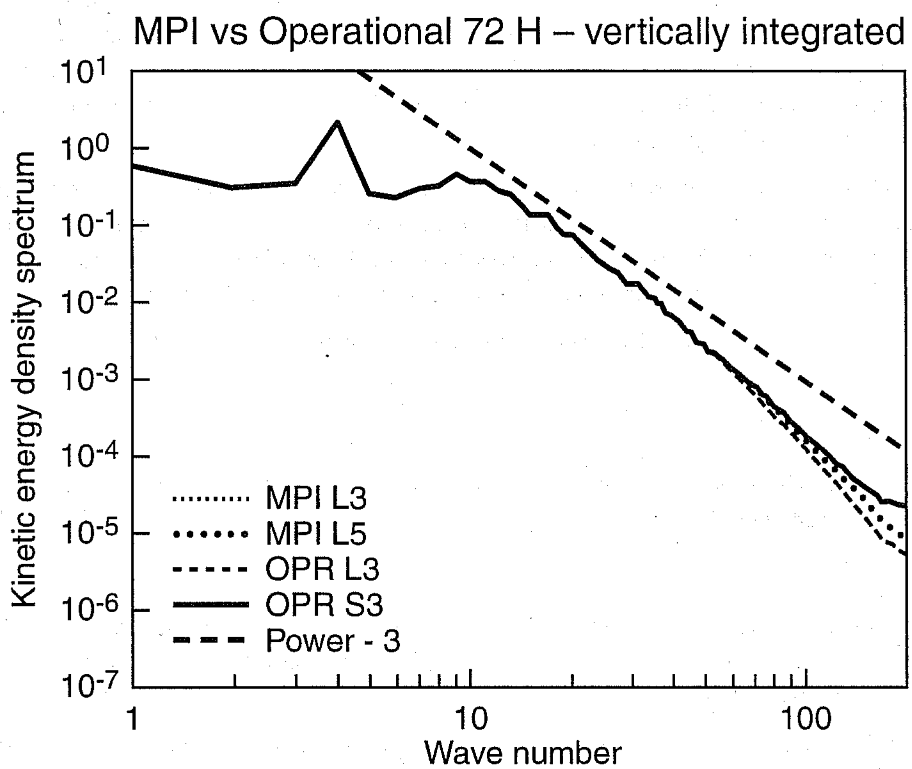

Fig. 2. Kinetic energy density spectrum for various model configurations.

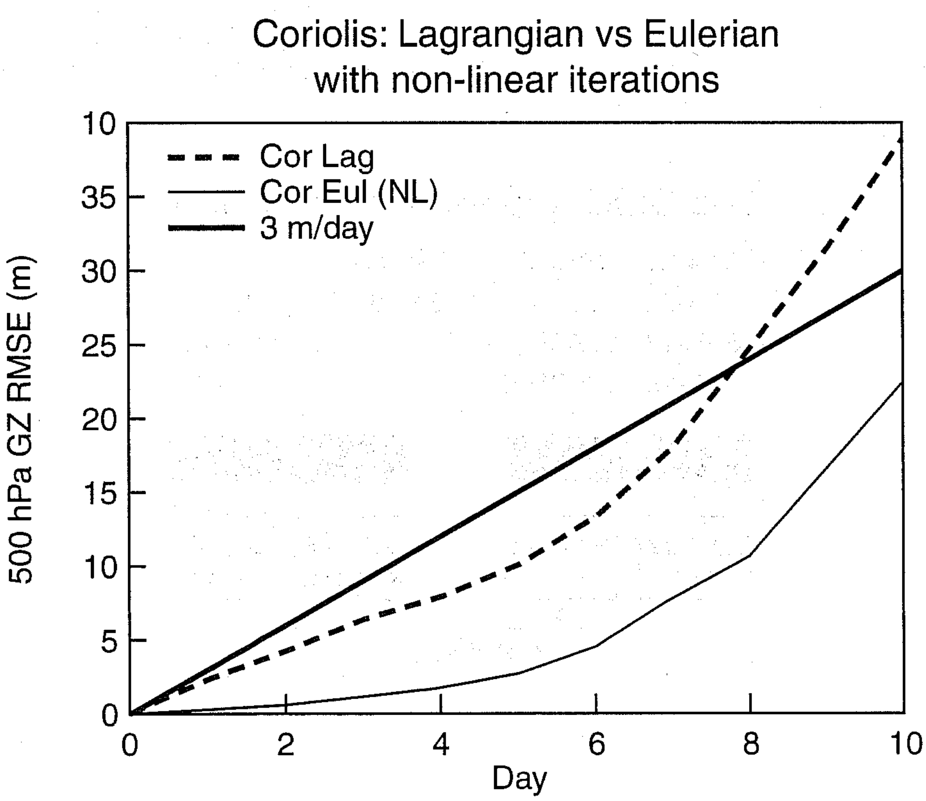

Fig. 3. Sensitivity to change in the formulation of the Coriolis terms, the operational model is the control.