RECENT FORECAST AND CLIMATE SIMULATION EXPERIMENTS WITH A GLOBAL FINITE DIFFERENCE SEMI-LAGRANGIAN MODEL

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1. INTRODUCTION

The merits of the semi-Lagrangian method of integration have by now become widely recognized and, as witnessed by the articles in this workshop proceedings, the tendency to adopt the method for both forecast and climate models seems set to continue. The advantages of the semi-Lagrangian approach have been discussed by a number of authors (Staniforth and Cote,1991; Bates et al.,1993; Williamson and Olson,1994; Ritchie et al.,1995) and can be summarized as follows:

1. The method allows the linear stability criteria associated with both advection and gravity-inertia waves to be overcome and thus permits the use of long timesteps, which can be chosen on the basis of accuracy alone. It also results in nonlinear computational instabiliy being overcome without additional work.
2. Semi-Lagrangian advection with tricubic interpolation has minimal phase error, minimizes computational dispersion and can handle sharp discontinuities. High accuracy of vertical advection is maintained even when the levels are unequally spaced.
3. Monotonic constraints in advection are easily allowed for.
4. Difficulties associated with the polar singularity in finite difference global models are overcome.

The above advantages have been bought at the price of abandoning the exact global conservation properties that are characteristic of Eulerian models (though it should be noted that Eulerian spectral models which use the logarithm of surface pressure as a prognostic variable are also not mass conserving), and of incurring problems with orographic resonance at high resolution. The effect of restoring mass in an extended range integration with a semi-Lagrangian model has been investigated by Moorthi et al. (1995). From a comparison of two parallel 17-month integrations, one with and one without mass restoration, it was concluded that mass restoration has no significant impact on the seasonally averaged climate statistics. Mass restoration has also been used in climate integrations by Williamson and Olson (1994) (see also the article by D Williamson in this volume). From the point of view of medium range forecasting, the global mass change in semi-Lagrangian models is insignificant. The orographic resonance problem has been the subject of much recent research, and now appears to be well under control (see the article by H Ritchie in this volume).

Current developments in the area of spectral semi-Lagrangian modelling include a move from three-time-level towards two-time-level schemes (see the paper by C Temperton in this volume) and the adoption of a linear grid (Cote and Staniforth 1988). Both of the above have been shown to be capable of giving large gains in efficiency.

The present author and his collaborators have over a number of years been involved in the development of a two-time-level finite difference semi-Lagrangian model (McDonald and Bates,1989; Bates et al.,1990; Bates et al.,1993; Moorthi et al.,1995) .The model has been tested in the context of medium range forecasting and of climate simulation (Chen and Bates, 1996a,1996b; Moorthi, 1996) and has been found to give very encouraging results. It has also been shown to be suitable for data assimilation using 4DVAR (Li et al., 1993; 1994). A selection of the results obtained in the recent forecast and climate simulation experiments are presented below. Details can be found in Chen and Bates (1996a; 1996b).

2. FORECAST EXPERIMENTS

A series of 10-day forecasts was carried out to test the sensitivity of the above finite difference semi-Lagrangian model (henceforth referred to as the SLM) to the size of the dynamics timestep Δt, the value of the uncentering parameter ϵ and the numerical treatment of the physical parameterizations (semi-Lagrangian versus Eulerian). The SLM forecasts were also compared with those produced by the GEOS-1 model, an Eulerian finite difference global model developed at NASA/GLA (Takacs et al., 1994; Suarez and Takacs, 1995). Both models were run at the same spatial resolution (2x2.5 degrees in latitude/longitude, with 20 vertical levels) and used the same physical parameterizations. Each experiment consisted of fourteen forecasts, seven for January and seven for July 1985.

Fig. 1 shows the SLM skill scores for the 500mb height field for the January case with dynamics timesteps of Δt= 15, 30, 45 and 60 min. A split Eulerian treatment of the physics was used, with the timesteps for the physics components held constant, and an uncentering parameter ϵ=0.2 was chosen. It can be seen that the value of Δt has a significant impact on the forecast

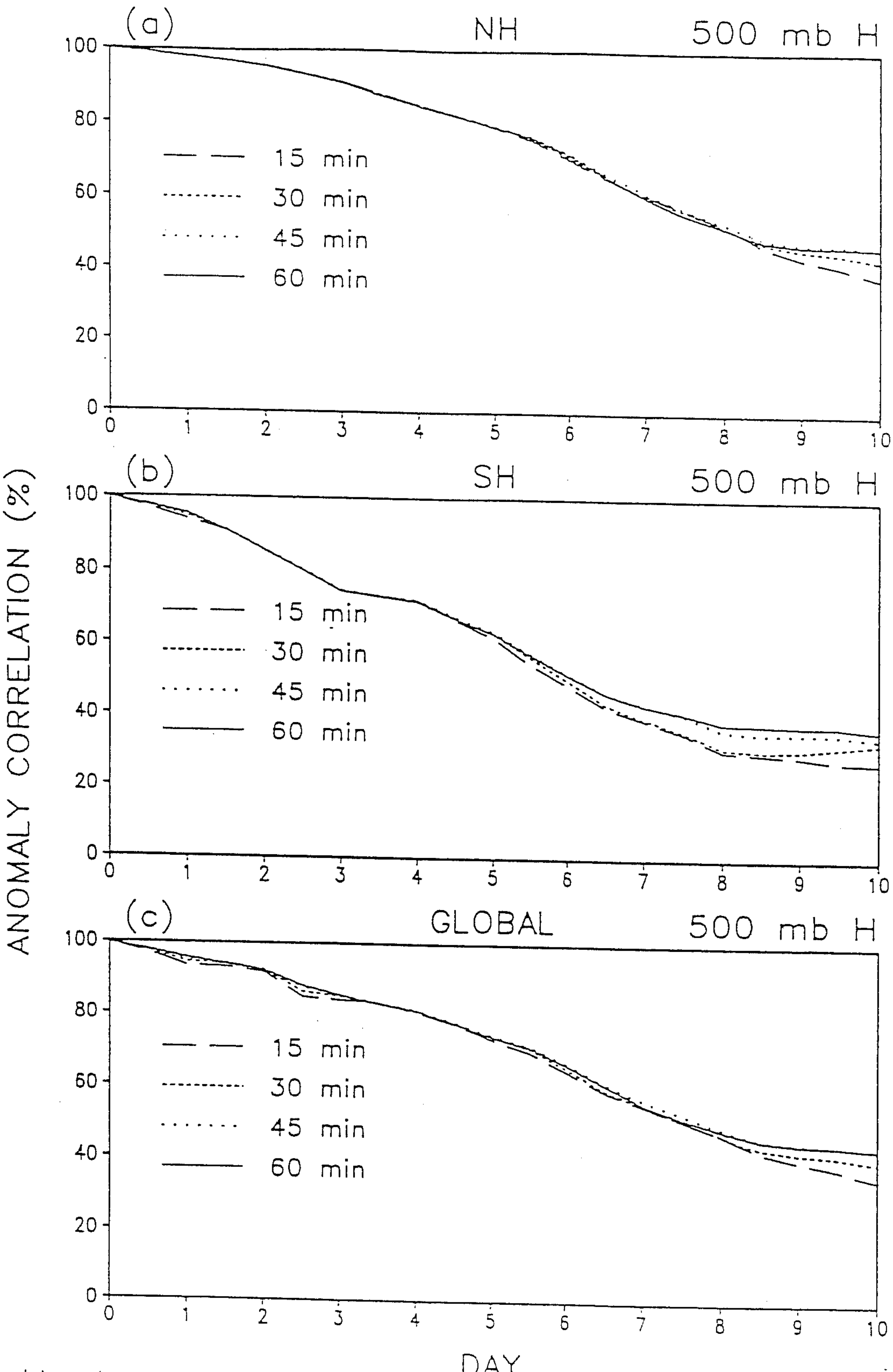

Fig. 1 Anomaly correlation of 500mb height (average of seven forecasts for January 1985) with different values of the dynamics timestep: (a) NH extratropics (30-90°N), (b) SH extratropics (30-90°S), (c) the globe. The corresponding RMS errors are shown in (d), (e) and (f).

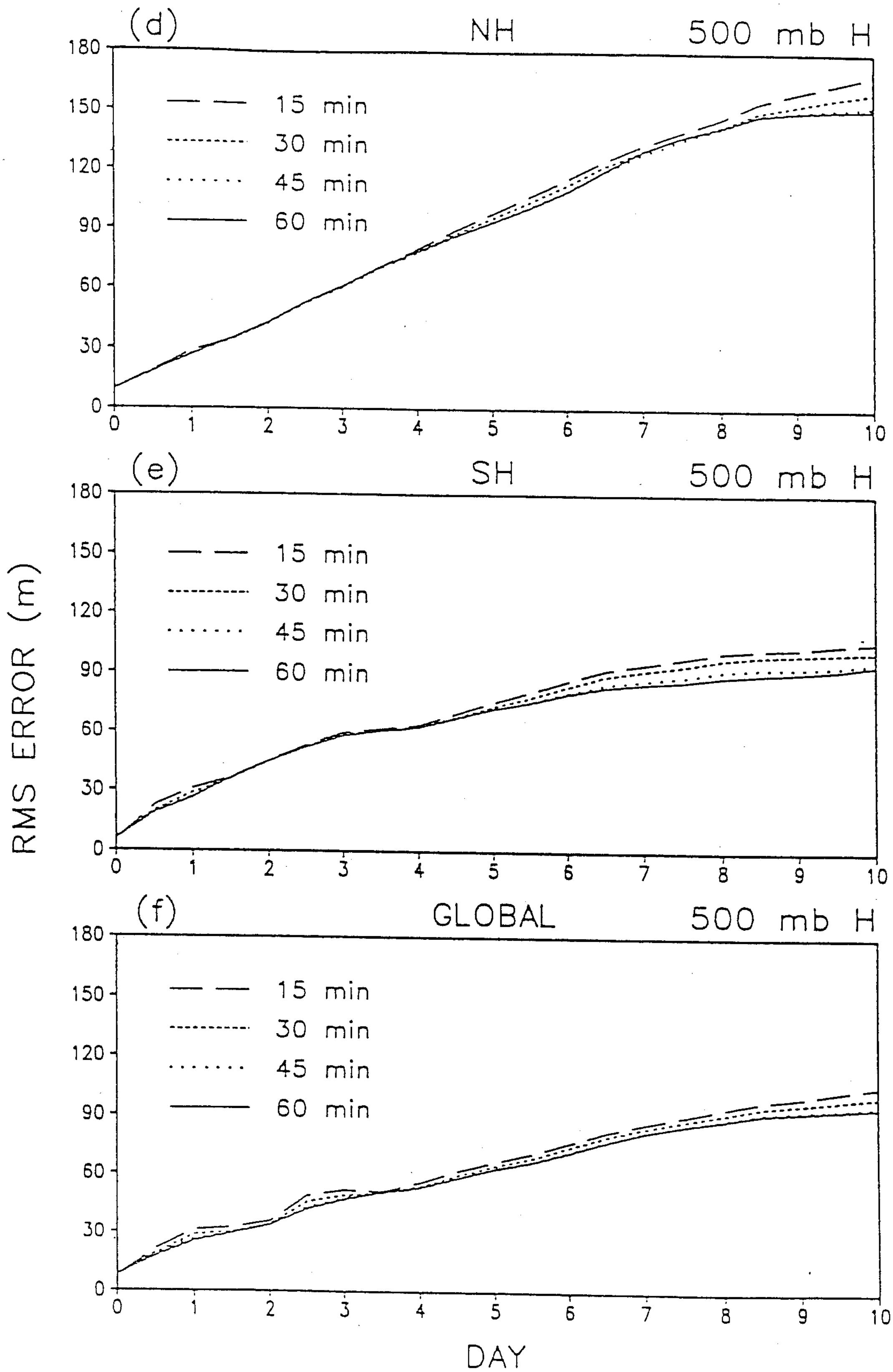

Fig. 1 (Continued.)

scores in the latter part of the range. Generally, an increase of Δt from 15 to 60 min results in better forecast scores. The difference between the scores for Δt=45 min and 60 min is negligible. The results for the July case (not shown) show a mixed signal, with the large values of Δt giving better anomaly correlations at some days and the small values at others. As in the January case, however, increasing Δt from 15 to 60 min was always found to reduce the rms errors.

A corresponding set of forecasts was carried out with ϵ varying from 0.0 to 0.4, holding Δt=60 min and treating the physics as above. A notable improvement in forecast scores was found as ϵ was increased from 0.0 to 0.3. Little difference was found between the results for ϵ=0.3 and ϵ=0.4. The best anomaly correlation for the 850mb winds was found for ϵ=0.2.

A further set of forecasts was carried out to test the effect of changing from a split Eulerian to an unsplit semi-Lagrangian treatment of the physical parameterizations. Values of Δt=30 min and ϵ=0.2 were used. For the January forecasts the scores were virtually identical for the first seven days, but the Eulerian treatment of the physics gave marginally better scores at the later days. For the July case, no perceptible difference between the two cases was evident.

Finally, a set of forecasts was carried out to test the difference between the SLM and the GEOS-1 model. For these forecasts the GEOS-1 model used the fourth order Sadourny (1975) scheme for horizontal differencing and a dynamics timestep of 3.75 min. The SLM used the Eulerian treatment of the physics, a dynamics timestep Δt=60 min and ϵ=0.2. The timesteps of the physical parameterizations were the same for both models. Fig. 2 shows the 500mb scores for the two models for the case of the January forecasts. The main difference in the anomaly correlations is found in the NH extratropics in the latter part of the range, where the SLM shows the better skill. In terms of rms errors, the SLM forecasts are consistently better than those of the GEOS-1. For the July case (not shown) , the anomaly correlations are more mixed, but the rms errors are almost everywhere smaller for the SLM forecasts. These results show that the SLM performs well even though it uses a dynamics timestep 16 times longer than that of the GEOS-1 model and the physical parameterizations were developed and tuned for the latter model.

3. CLIMATE INTEGRATIONS

Two parallel five-year climate simulations have been carried out using the SLM and the GEOS-1 models, with the same spatial resolution and physical parameterizations as in the forecast experiments above. The SLM used a dynamics timestep Δt=60 min, ϵ=0.2 and the split Eulerian treatment of the physics. The GEOS-1 model used a dynamics timestep of 2.5 min. In

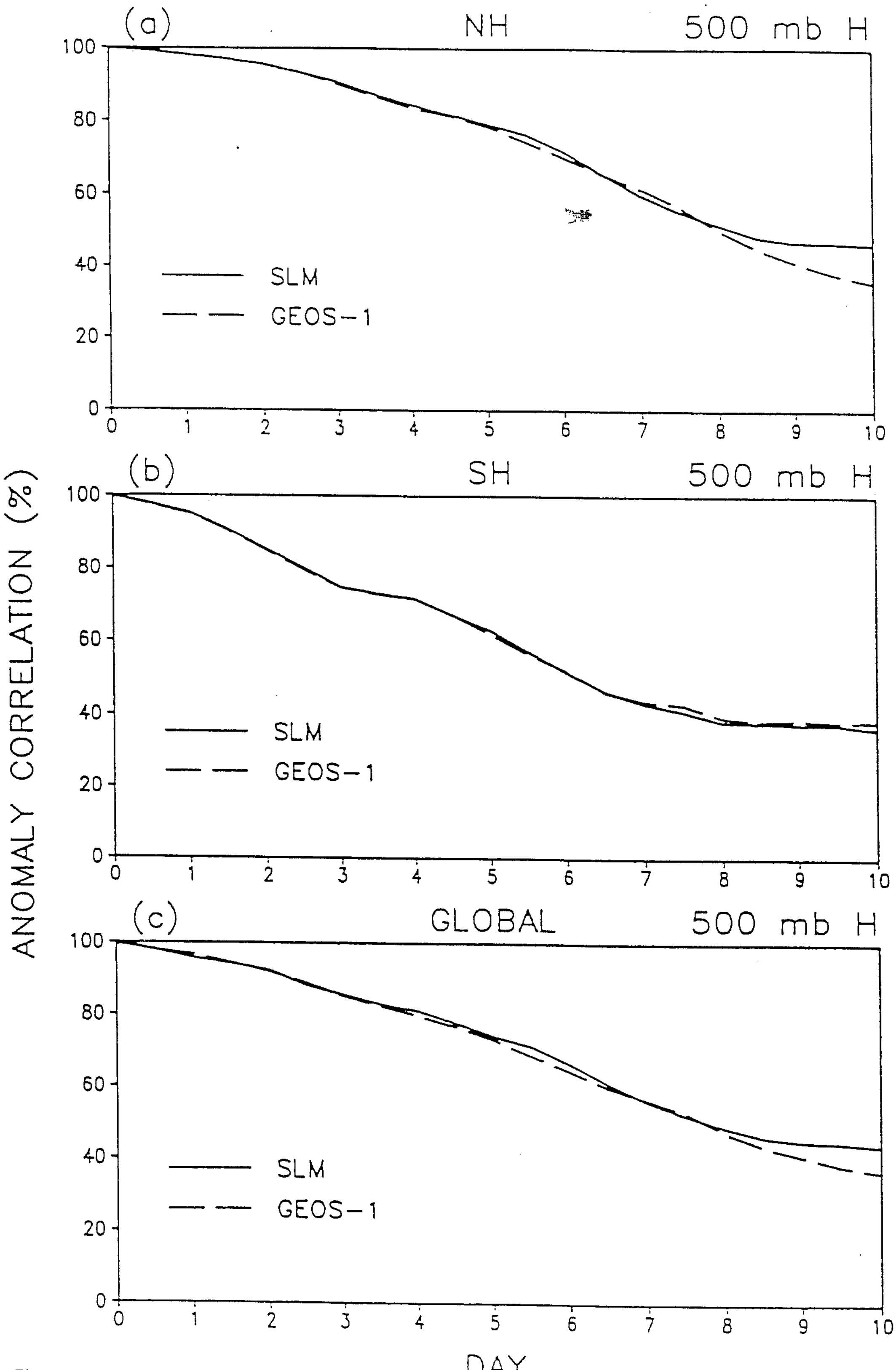

Fig. 2 Anomaly correlation of 500mb height (average of seven forecasts for January 1985) from the semi-Lagrangian and Eulerian models, for (a) NH extratropics (30-90°N), (b) SH extratropics (30-90°S), (c) the globe. The corresponding RMS errors are shown in (d), (e) and (f).

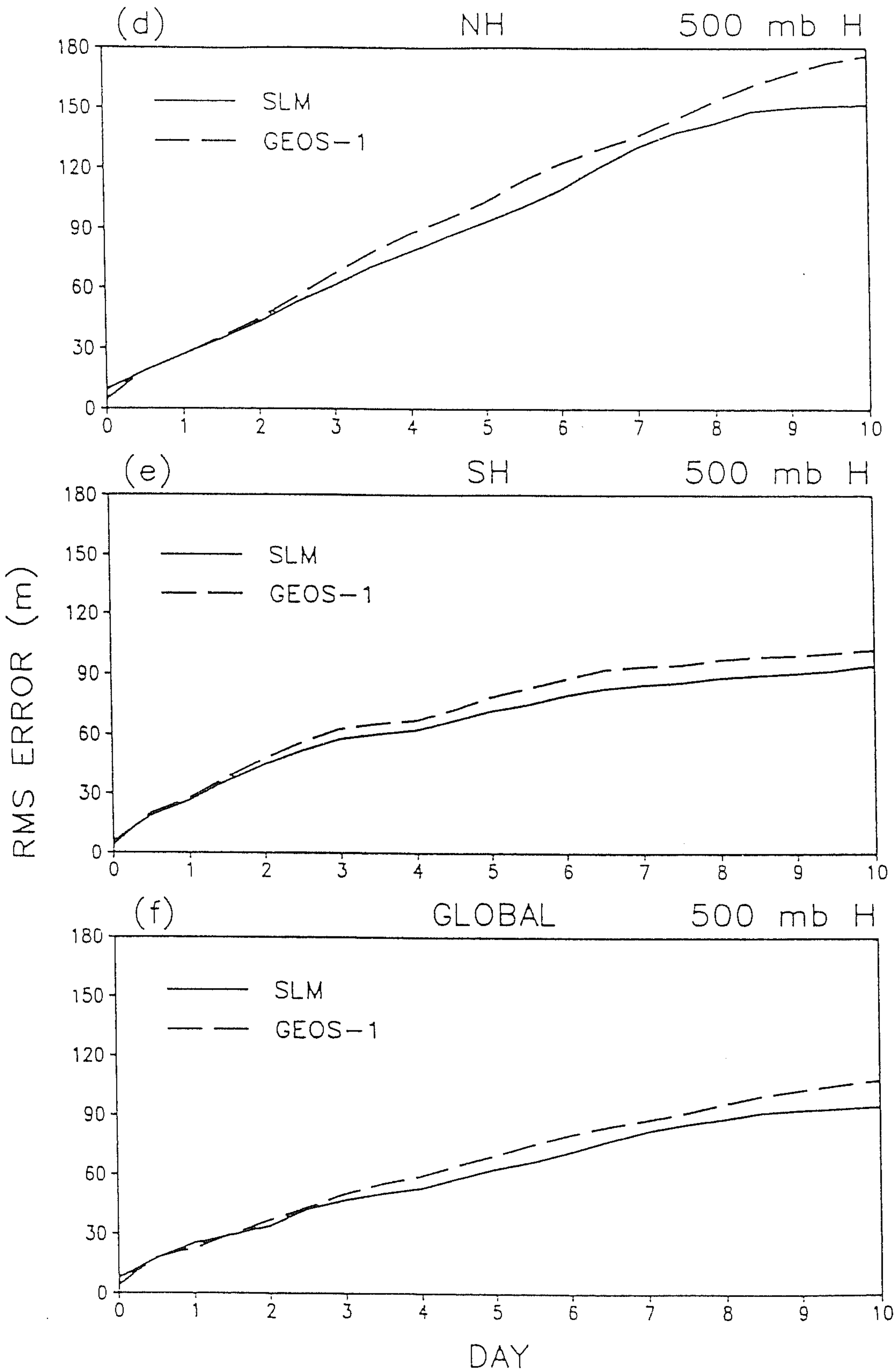

Fig. 2 (Continued.)

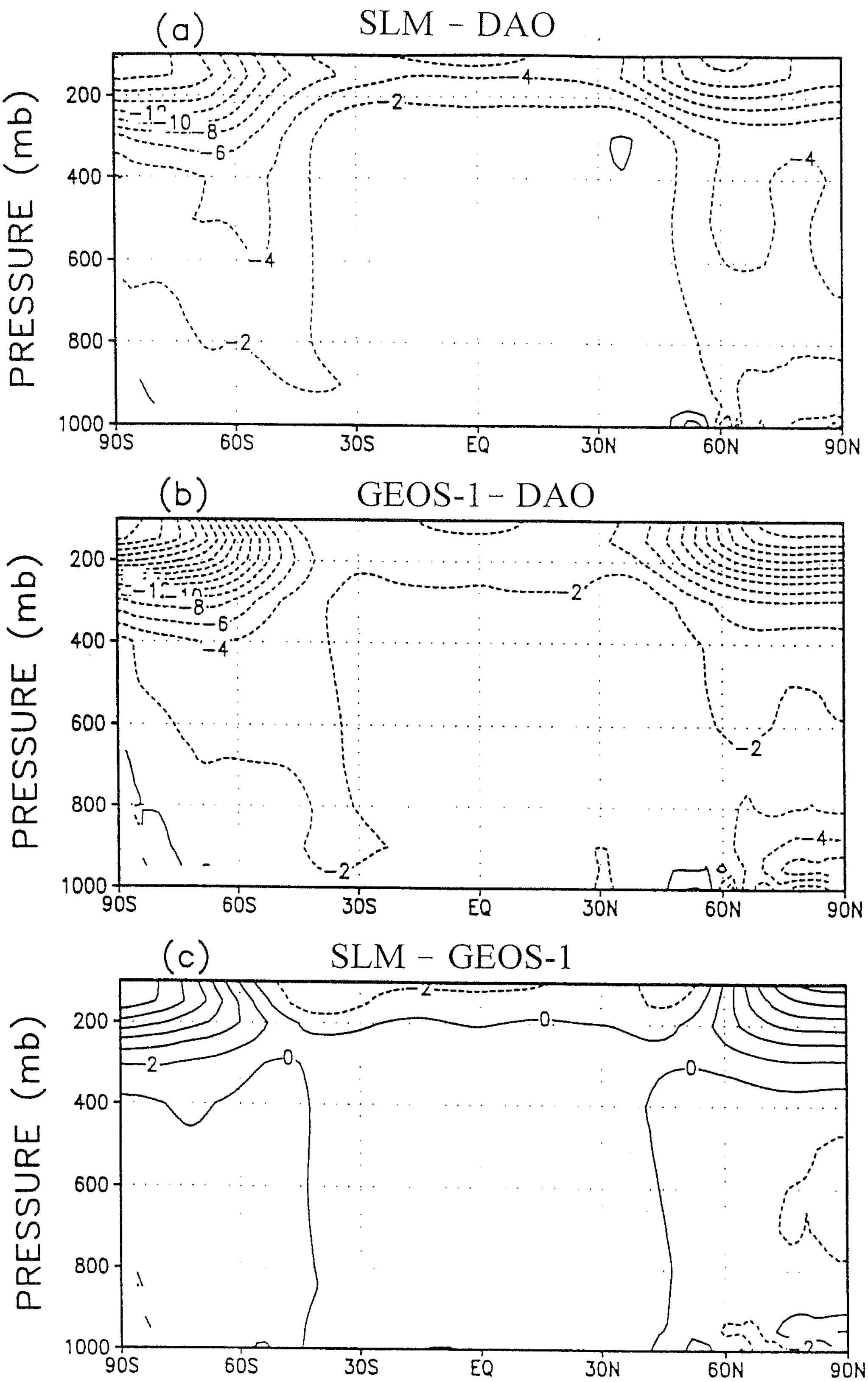

Fig. 3 Differences in the 5-year-mean zonal mean temperatures for Dec-Jan-Feb: (a) SLM simulation minus DAO assimilation, (b) GEOS-1 simulation minus DAO assimilation, (c) SLM simulation minus GEOS-1 simulation. Contour interval: 2K.

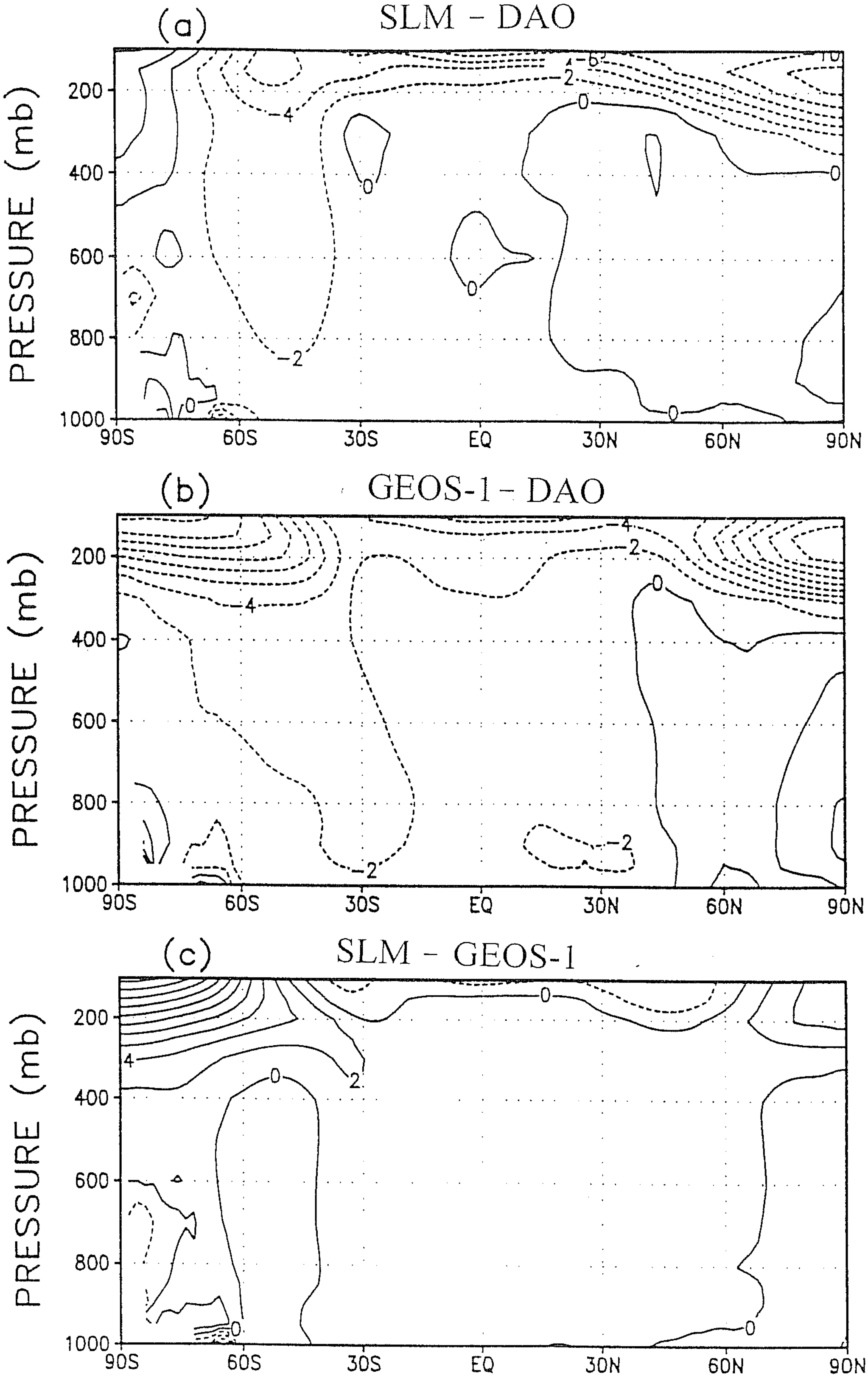

Fig. 4 As in Fig 3, but for Jun-Jul-Aug

contrast to the forecast experiments, a second order Sadourny (1975) scheme was used for horizontal differencing in the GEOS-1 in the case of the climate simulation. The timesteps for the physics components were the same for both models. Prescribed seasonally varying climatological lower boundary conditions for the period 1985-90 and a prescribed time-varying zonally symmetric ozone distribution were used. A mass adjustment scheme, as in Moorthi (1995), was used to conserve global mass in the SLM. For verification of the simulated climates, the assimilation of the Data Assimilation Office (DAO) at NASA/GLA for the period 1985-90 was used. This assimilation was carried out using the GEOS-1 model.

Both models gave simulated climates that fall within the range of those from current GCMs. Neither could be said to be in all respects closer to observation than the other. However, a number of features were notably better simulated by the SLM. In particular, the zonal mean temperature field of the SLM simulation was considerably more realistic , as seen in Figs. 3 and 4. It can be seen that the large cold biases in the polar upper troposphere and lower stratosphere which are a feature of the GEOS-1 simulations in both hemispheres and in both seasons have been very much reduced, or even eliminated, in the SLM simulation.The maximum difference in the seasonal means, amounting to 20K, occurs in the stratosphere at the south pole in Jun-Jul-Aug. The polar cold bias in the region of the tropopause is a feature that is common to almost all GCMs and seems independent of many differences in numerics, resolution and physical parameterizations (Boer et al.,1992). The present comparison shows that a replacement of Eulerian by semi-Lagrangian dynamics can have a large beneficial impact in this area. Williamson (this volume) also reports a reduction of the polar cold bias , though of a smaller magnitude, on changing from an Eulerian to a semi-Lagrangian formulation of the NCAR Community Climate Model.

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