THE SENSITIVITY OF THE SIMULATED LARGE-SCALE FLOW TO CONSERVATION PROPERTIES AND HORIZONTAL DIFFUSION SCHEMES IN THE ECMWF GRIDPOINT MODEL

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1. INTRODUCTION

This study is part of a series of investigations which were initiated at ECMWF in order to evaluate the results of a 30-day-integration from 1 January 1977 carried out by Miyakoda et al. (1980). In this series of experiments Miyakoda achieved a number of successful simulations of a severe outbreak of cold air and its subsequent persistence during a 30-day period over the eastern part of North America. Miyakoda's conclusion was that sufficient spatial resolution, as well as the specification of the parametrization scheme, were important for the simulation of this abnormal weather situation. Similar success was not achieved with the standard version for the 1980 ECMWF operational model.

In order to understand the reasons for the performance of the ECMWF model the effects of the various differences between ECMWF and GFDL model were evaluated; in particular the differences between the finite difference formulations, the schemes for horizontal diffusion and the conservation properties. The purpose of this report is to describe the sensitivity of the ECMWF gridpoint model to the differences in the conservation properties and horizontal diffusion.

In the first experiment the linear fourth order horizontal diffusion scheme of the ECMWF model was replaced by the nonlinear second order GFDL scheme. For a second experiment the conservation of enstrophy was replaced by a scheme conserving energy. Table 1. summarizes these three experiments.

Table 1

1.	Enstrophy conservation,	linear fourth order	(ES/L4)
2.	Energy conservation,	linear fourth order	(EN/L4)
3.	Enstrophy conservation,	nonlinear second order	(ES/NL2)

Each experiment comprised a 30 day integration with an N48 (1.875°*1.875° grid) model.

2. FINITE DIFFERENCE FORMULATIONS

Since the existing finite difference scheme of the ECMWF gridpoint model is already energy conserving in the vertical coordinate only the "horizontal" parts of momentum equations had to be modified. Therefore, in the following these equations are written in their barotropic form only. The enstrophy conserving finite difference scheme is given (Burridge and Haseler,1977):

$$\frac{\partial u}{\partial t} = \frac{1}{\cos\theta}\,(ZV\cos\theta) - \frac{1}{a\cos\theta}\,\delta_\lambda(\overline{\phi}^\sigma + E)$$

$$\frac{\partial v}{\partial t} = -ZU \quad - \frac{1}{a}\,\delta_\theta(\overline{\phi}^\sigma + E)$$

$$U = \overline{P}_S^\lambda\, u$$

$$V = \overline{P}_S^\theta\, v$$

$$Z = \frac{1}{\overline{p_S a\cos\theta}^{\lambda,\theta}}\,(a\, f\cos\theta + \delta_\lambda v - \delta_\theta u\cos\theta)$$

$$E = \frac{1}{2}\,(\overline{U^2}^\lambda + \frac{1}{\cos\theta}\,\overline{V^2\cos\theta}^\theta)$$

The energy conserving scheme is basically that of Lilly(1965) and takes the form:

$$\frac{\partial u}{\partial t} = - \frac{1}{a\cos\theta\bar{\phi}^{\lambda}} \left[\overline{\bar{U}^{\lambda}\delta_{\lambda}u}^{\lambda} + \overline{\overline{V\cos\theta\delta_{\theta}u}^{\lambda}}^{\theta} \right] + \text{Coriolis}_u - \frac{1}{a\cos\theta}\delta_{\lambda}\phi$$

$$\frac{\partial v}{\partial t} = - \frac{1}{a\cos\theta\overline{\phi}^{\theta}} \left[\overline{\bar{U}^{\theta}\delta_{\lambda}v}^{\lambda} + \overline{\overline{V\cos\theta}^{\theta}\delta_{\theta}v}^{\theta} \right] - \text{Coriolis}_v - \frac{1}{a}\delta_{\theta}\phi$$

where: $U = \bar{\phi}^{\lambda} u$ $\cos\theta V = \overline{\phi\cos\theta v}^{\theta}$

$$\text{Coriolis}_u \qquad \frac{1}{\bar{\phi}^{\lambda}\cos} \overline{\left[f\cos\theta + \frac{\bar{u}^{\theta}}{a}\sin\theta \right] \bar{V}^{\lambda}}^{\theta}$$

$$\text{Coriolis}_v \qquad \frac{1}{\overline{\phi\cos\theta}^{\theta}} \overline{\left[f\cos\theta + \frac{\bar{u}^{\theta}}{a}\sin\theta \right] \bar{U}^{\theta}}^{\lambda}$$

Energy conservation under advection processes is easily proved for this scheme and the symmetric formulation of the Coriolis terms guarantees, formally, conservation of energy.

3. TWO HORIZONTAL DIFFUSION SCHEMES

The linear fourth order horizontal diffusion scheme is documented in the Forecast Model Documentation Manual(1981).

$${}_{H}F_{x} = - \left[k_{\lambda}/a^4\cos^4\theta\delta_{\lambda}^4 + k_{\theta}/a^4\cos^4\theta\delta_{\theta}^4 \right] x$$

with

$$k_{\lambda} = 0.05 \ |u_o| \ (a\Delta\lambda)^3$$
$$k_{\theta} = 0.05 \ |u_o| \ (a\Delta\theta)^3$$

x represents u, v, T or q

The specification for the nonlinear second order horizontal diffusion is that of Smagorinsky (1963). The horizontal diffusion terms ${}_H F_u$, ${}_H F_v$, ${}_H F_T$ and ${}_H F_q$ for the two components of the momentum equation, the thermodynamic equation and the equation for conservation of moisture, are written as:

$$p_s\, {}_H F_u = 2(k_o a\Delta\theta)^2 \frac{1}{a\cos\theta}\left[\frac{\partial}{\partial\lambda}(p_s\, n\, |D| D_T) + \frac{1}{\cos\theta}\frac{\partial}{\partial\theta}(p_s n |D| D_s \cos^2\theta)\right]$$

$$p_s\, {}_H F_v = 2(k_o a\Delta\theta)^2 \frac{1}{a\cos\theta}\left[\frac{\partial}{\partial\lambda}(p_s\, n\, |D| D_s) - \frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(p_s n |D| D_T \cos^2\theta)\right]$$

$$p_s\, {}_H F_T = 2(k_o a\Delta\theta)^2 \frac{1}{a\cos\theta}\left[\frac{\partial}{\partial\lambda}(p_s\, n\, |D| \frac{\partial T}{\partial\lambda}) + \frac{\partial}{\partial\theta}(p_s n |D| \frac{\partial T}{\partial\theta})\right]$$

$$p_s\, {}_H F_q = 2(k_o a\Delta\theta)^2 \frac{1}{a\cos\theta}\left[\frac{\partial}{\partial\lambda}(p_s n |D| \frac{\partial q}{\partial\lambda}) + \frac{\partial}{\partial\theta}(p_s n |D| \frac{\partial q}{\partial\theta})\right]$$

D_s is the stress due to the shear in the flow, whereas D_T is the tensile stress.

$$D_s = \frac{1}{a\cos\theta}\frac{\partial v}{\partial\lambda} + \frac{\cos\theta}{a}\frac{\partial}{\partial\theta}\left(\frac{u}{\cos\theta}\right)$$

$$D_T = \frac{1}{a\cos\theta}\frac{\partial u}{\partial\lambda} - \frac{\cos\theta}{a}\frac{\partial}{\partial\theta}\left(\frac{v}{\cos\theta}\right)$$

with

$$D^2 = D_T^2 + D_s^2$$

and

$$n = \frac{2}{1+\left(\frac{\Delta\theta}{\cos\theta\Delta\lambda}\right)^2}$$

The notation used is that adopted in the ECMWF Forecast Model Documentation (1981).

4. EVALUATION

Fig.1 shows the geopotential height field for the northern hemisphere averaged over the forecast period of 30 days; differences between these 30 day means and the verifying analysis are given in Fig.2. The similarity of the flow pattern in all three ECMWF integrations suggests that for extended range forecasts this high resolution model is insensitive to the choice of type of horizontal diffusion or the conservation properties of the different schemes. These results have been confirmed by several medium range integrations which have been undertaken but are not shown here (R. Strüfing, 1982a and 1982b).

Whereas the GFDL simulation represents the anomaly over the USA together with the blocking high near the Northpole quite accurately, all three ECMWF forecasts fail to develop a ridge over the USA. The eastward shift of the deep low over eastern North America is very similar in all three ECMWF experiments. However, some differences occur in the simulation of the Aleutian low in position as well as in intensity. Furthermore the EN/L4 forecast shows an overdevelopment of the trough over East Asia, which is less pronounced in ES/NL2 and absent in the standard ES/L4 integration. The error maps for the 30 day mean, Fig. 2, clearly show that the ES/L4 model performs best in this particular case.

5. CONCLUSIONS

The implementation of (a) an energy conserving finite difference form of the momentum equations and (b) a nonlinear second order horizontal diffusion scheme into the N48 ECMWF gridpoint model results in only minor changes in performance. In the case of 1 January 1977 all ECMWF models failed to simulate a particularly significant cold 30 day period over North America, which was handled well in an integration carried out by Miyakoda with the GFDL model.

Miyakoda and Sirutis(1977) attributed their success to the use of a higher order closure parametrization scheme. It is intended to continue this series of experiments with the implementation of this scheme into the ECMWF model.

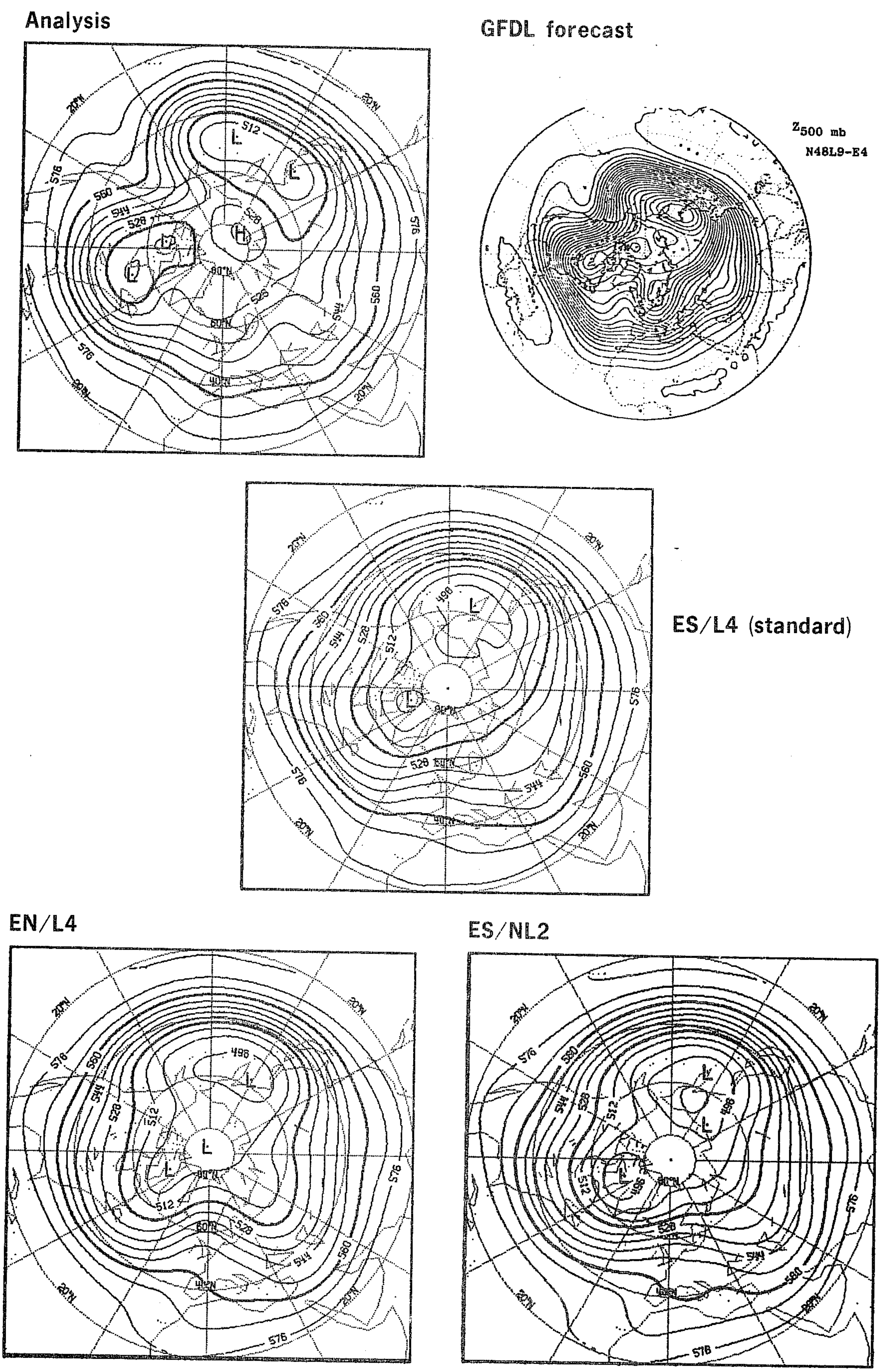

Fig. 1a 30 day mean northern hemisphere 500 mb height fields from 1 January 1977 for verifying analysis (top left); GFDL forecast (top right); ECMWF standard forecast (centre); energy conserving forecast (bottom left) and nonlinear second order diffusion forecast (bottom right).

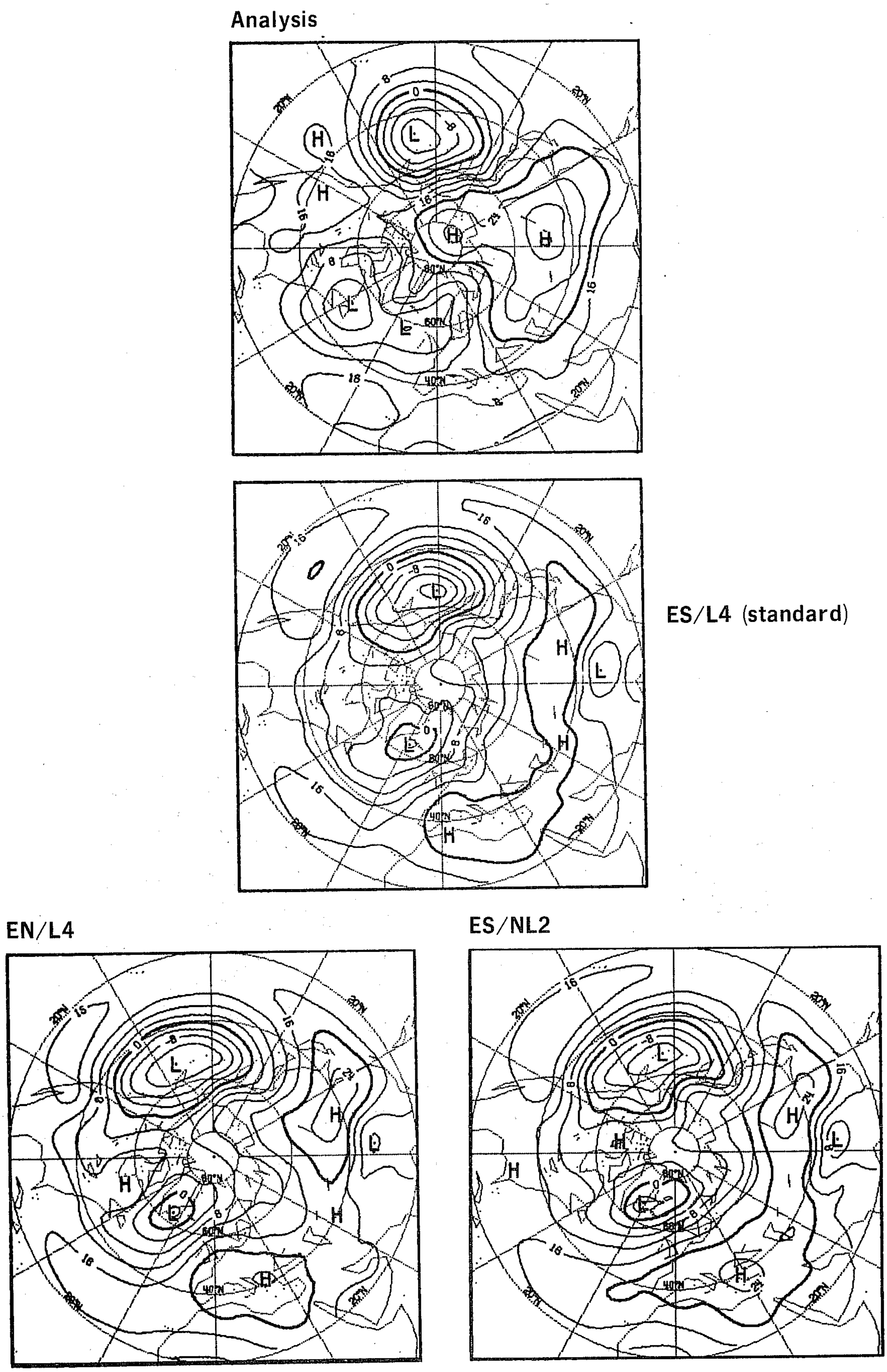

Fig. 1b As for Fig. 1a but for 1000 mb (except GFDL forecast which was not available).

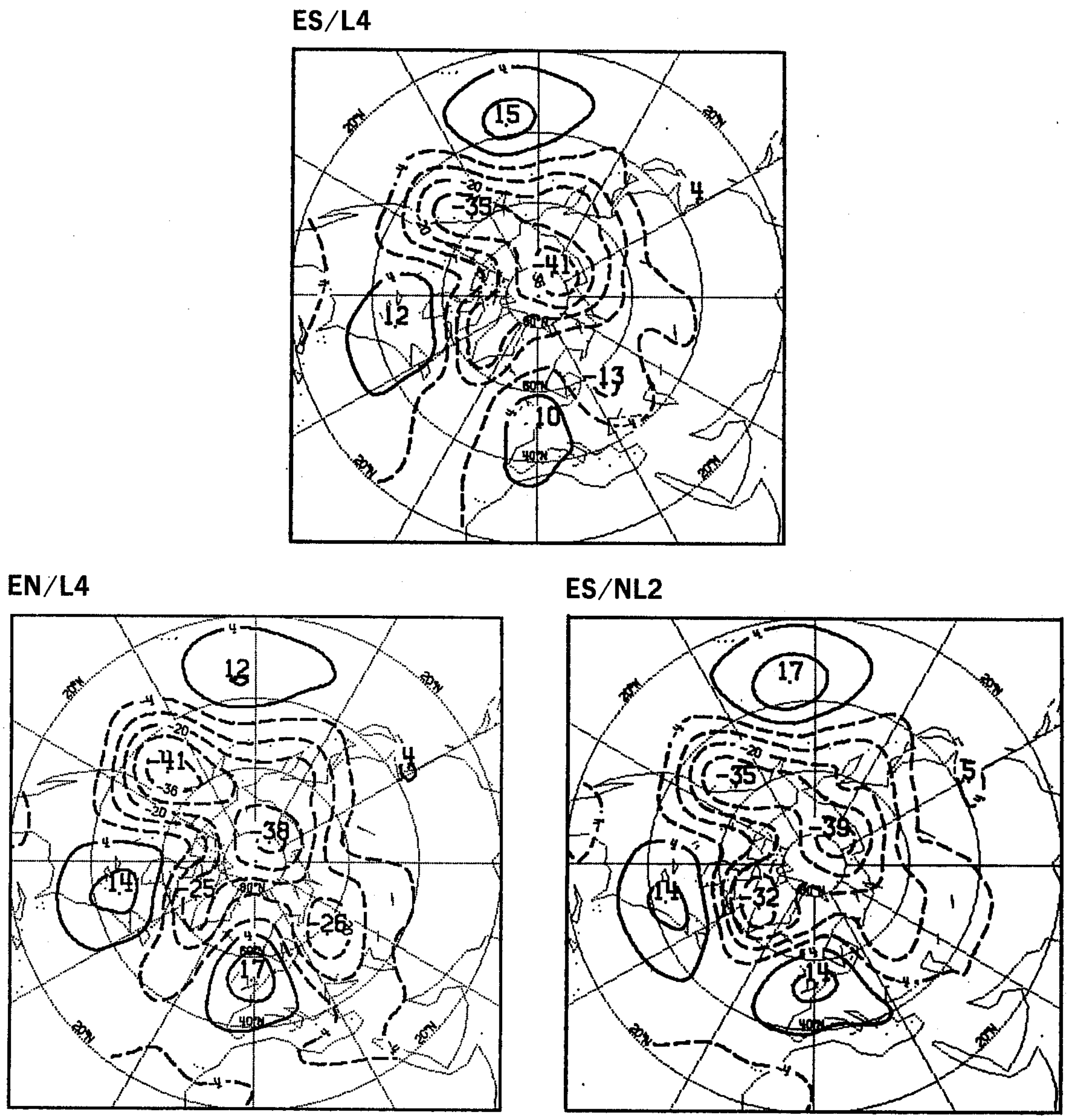

Fig. 2a Error maps for the 30 day mean northern hemisphere 500 mb height fields from 1 January 1977 for ECMWF standard forecast (top); energy conserving forecast (bottom left); and nonlinear second order diffusion forecast (bottom right).

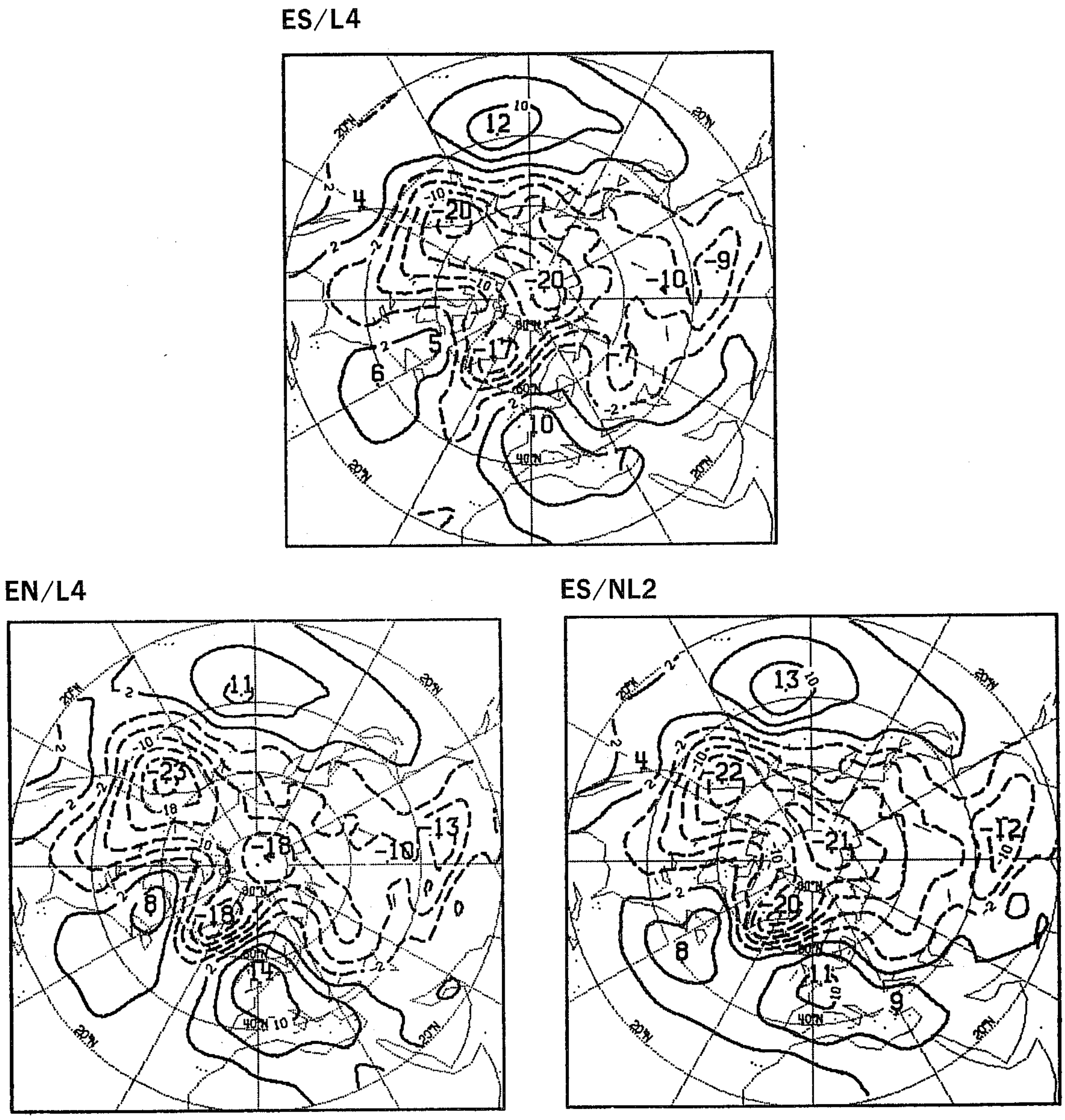

Fig. 2b As for Fig. 2a but for 1000 mb.

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