A PRACTICAL APPROACH TO THE PROBLEMS OF LIMITED AREA MODELLING

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1. INTRODUCTION

Most operational meteorological centres use a limited area model (hereafter referred to as LAM) both as an operational model and as a research tool. At the ECMWF, the LAM was implemented as a research vehicle to study the nature of particular phenomena, and to investigate and test a variety of new techniques before introducing them into the global operational model. For this reason the Centre's LAM was built as a derivative of the global grid point model and so it has essentially the same characteristics.

The solution of the mathematical problems and the fulfilment of technical requirements in using a LAM can be very difficult. The boundary values and a 'boundary scheme' for the treatment of the lateral boundary are the first requirement of a LAM. Then, the possibility of changing the resolution of the model gives rise to the problem of the fine mesh analysis of initial and boundary data, and the use of different kinds of orographic representation requires an initialization procedure. These problems are difficult to solve because both the fine mesh analysis schemes (ECMWF, 1983; Durend, 1983) and the initialization procedures for limited area models (Bratseth, 1982; Briere, 1982; Creplet, 1983) are still in the research stage.

In the rest of this paper I will give some examples of the pragmatic approach that has been adopted at the ECMWF for solving the problems involved in using a LAM.

2. BOUNDARY CONDITIONS

The effect of an inadequate treatment of the lateral boundaries is the creation of instabilities that can destroy the forecast in quite a short period of time. Practical solutions to the problem involve using 'sponge', 'radiative' or 'relaxation' schemes. While the first two methods can be shown to be inappropriate (Davies, 1984), the relaxation method has been found to be effective without any major drawbacks.

In the Centre's LAM, a practical approach was taken by using a simplified version (Kallberg and Gibson, 1977) of Davies' (1976) relaxation method. To illustrate this scheme consider the equation

$$\frac{\partial X}{\partial t} + F(X) = 0$$

The time stepping algorithm is the following

$$\frac{X^{n+1} - X^{n-1}}{2\Delta t} + F(X^n) = -k(X^{n+1} - \tilde{X}^{n+1}) \qquad (1)$$

The term on the right hand side determines the degree to which the solution relaxes towards the prescribed value $\tilde{X}$. Therefore near the boundaries k is chosen to have a large value, whereas away from the boundaries k is small. Solving the associated homogeneous equation gives the explicit solution

$$\hat{X}^{n+1} = X^{n-1} - 2\Delta t\ F(X^n)$$

Substitution in (1), gives

$$X^{n+1} = \frac{\hat{X}^{n+1}}{1 + 2\Delta t\ k} + \frac{2\Delta t\ k\ \tilde{X}^{n+1}}{1 + 2\Delta t\ k}$$

that is

$$X^{n+1} = (1-\alpha)\ \hat{X}^{n+1} + \alpha\ \tilde{X}^{n+1}$$

with

$$\alpha = \frac{2\Delta t\ k}{1 + 2\Delta t\ k} \qquad (2)$$

The profile chosen for α is specified by

$$\alpha = 1 - \tanh (j/2)$$

where j is the number of grid lengths to the nearer boundary. The values of α are given in Table 1.

Table 1 Relaxation factors

j	$\alpha = 1 - \tanh (j/2)$
0	1.0
1	0.538
2	0.238
3	0.095
4	0.036
5	0.013
6	0.005
7	0.002

Thus, while the outermost value of X is replaced completely, the others are a combination of internal and external values; the importance of the latter decreasing rapidly, so that after four points its influence is already less than 10%. To update the boundary every step we use a linear interpolation in time between data taken at 12 hour intervals, either from the analysis or from a global forecast.

It is evident from (2) that no errors can be attributed to the boundary scheme if the boundary values for the LAM are obtained from the forecast of an identical unbounded model (global) with the same resolution, every time step. Baumhefner and Perkey (1982) claim that this is not the case with a relaxation scheme proposed by Perkey and Kreitzberg (1976). However in their method some diffusion is applied near the boundaries and the boundary data is interpolated to a grid which is staggered in both space and time; thus there is no reason to expect identical results from bounded and unbounded models.

The most important differences between forecasts from bounded and unbounded models with the same resolution are due to three factors: the size of the domain of integration, the size of the relaxation zone and the frequency of the updating of boundary values. Depending on the size and time scale of the phenomenon that we want to forecast we must allow the larger scale atmospheric system, relevant to the evolution of that particular phenomenon, to enter the area of integration. Thus, if the chosen area is small, the frequency of the boundary updating must be increased as well as the number of points of the boundary zone.

Figs.1a, b and c show respectively the results of the 24, 36 and 48 hour global forecasts starting on 12GMT 3 March, 1982, for the 1000 mb geopotential height and temperature. Let us consider the fast moving trough that is in the region around 40°N, 50°W in the global forecast. It is not yet in the LAM area after 24 hours (Fig.1a), but it is already out of the eight point boundary relaxation zone after 48 hours (Fig.1c). Thus, that trough can be totally missed in the LAM forecast if the boundary data is obtained by interpolating the results of the 48 and 24 hour global integration. However, that feature can also be missed by reducing the number of boundary relaxation points, even when interpolating the values of 48 and 36 hour global forecasts. The 48 hour LAM integration, with frequency of boundary updating every 12 hours and boundary relaxation zone eight points wide, was capable of giving a smooth representation of that trough, Fig.1d. However that feature predicted by the global model was not present in the objective analysis of the 12GMT 5 March 1982 verifying the 48 hour forecast (Fig.2a), and the LAM did not reproduce it in its inner area. But note the values in the east boundary relaxation zone are clearly adjusted to the external values and only very slight differences between results of bounded and unbounded models can be noticed in that region. The results from the 48 hour forecast with boundary values obtained from the analysis (Fig.2b) can be compared with the analysis itself in the boundary relaxation region to show the accuracy of the boundary scheme.

Some other considerations must be taken into account when the horizontal resolution and the orographic representation is different in the bounded and unbounded model, as will be described in Sect.4.

3. FILTER-DIFFUSION

A single algorithm is used to filter the short waves due to the convergence of the meridians towards the poles and to diffuse horizontally the u, v, T and q fields. It is a fourth order implicit formula written as

$$\frac{\partial}{\partial t} = - K \left(\frac{\partial^4}{(a\cos\theta)^4 \, \partial\lambda^4} + \frac{\partial^4}{a^4 \, \partial^4\theta} \right)$$

with a the radius of the earth, and θ, λ the latitude and longitude. The diffusion coefficient is given by

$$K = K_o |U_o| (a\ \Delta\lambda)^3\ m^4\ s^{-1} \qquad (2)$$

where $U_o = 10\ m\ s^{-1}$ and $K_o = 0.5$ in the N48 resolution model. The meridional term is treated explicitly, while the zonal term is treated implicitly and it depends on the wavenumber and latitude. If X is a Fourier mode of the model, the finite difference form of the filter-diffusion is given by

$$\frac{X^{n+1} - X^{n-1}}{2\ \Delta t} = - \frac{K}{a^4\ \cos^4\ \theta} (k')^4\ X^{n+1}$$

where

$$k' = \frac{\sin\ (k\ \Delta\lambda/2)}{(k\ \Delta\lambda/2)}$$

Rearranging to give an expression for X^{n+1} yields

$$X^{n+1} = \frac{X^{n-1}}{1 + \frac{2\ \Delta t\ K}{a^4\ \cos^4\ \theta} (k')^4}$$

Having considered a single Fourier mode now consider an arbitary variable f which can be expressed as the sum of a linear trend and a sine series

$$f(x_j) = \alpha\ x_j + \beta + \sum_{k=1}^{N-1} b_k \sin \left(\frac{k\pi(j-1)\Delta\lambda}{L}\right)$$

where the interval of integration is $0 \leqslant x_j \leqslant L$.

After subtracting the linear trend, diffusing and adding the linear trend again, we get

$$f(x_j) = \alpha x_j + \beta + \sum_{k=1}^{N-1} \frac{b_k}{1 + \frac{2\ \Delta t\ K(k')^4}{(a\ \cos\ \theta)^4}} \sin \left(\frac{k\pi\ (j-1)\Delta\lambda}{L}\right)$$

with $N = L/\Delta\lambda$. Therefore we have a system with N+1 degrees of freedom.

4. RESOLUTION PROBLEMS

The problems that arise when the horizontal resolution of the LAM is increased are mainly associated with the analysis of data and initialization.

4.1 Initial and boundary data

It is well known that an objective analysis of data on a scale of the order of 100-50 km is particularly difficult over topographically irregular surfaces. An analysis of data at the model resolution is needed as initial field and to update the boundaries of the LAM. An obvious pragmatic solution of this problem is the interpolation of the coarse mesh data to the fine mesh, which is the solution adopted in the Centre's LAM. The interpolation of the data from a global analysis or forecast is done using bilinear interpolation for the physical parameters and by fitting the dynamical fields with spherical harmonics.

Results have shown that this interpolation procedure is sufficient to produce an accurate high resolution forecast if the forcing is mainly due to the topography, but for an accurate forecast of baroclinic development a more detailed analysis is needed. However, it can be shown that, in this case, a detailed analysis becomes less necessary as the length of the forecast is increased: the model is in fact capable of developing the new systems if it has the time.

An analysis of the observations at the model resolution would be very useful for verifying all the details obtained with a fine mesh model. At present, verification with satellite pictures or with data from special observation periods is the best way to assess the results of the high resolution experiments.

4.2 Initialization

When the horizontal resolution is increased a new balance of the initial fields is needed. Also the state of the art of the initialization for the limited area model is not very advanced, even if some progress has been made recently.

A practical approach to this problem was to let the orography grow from the coarse to the fine resolution values and allow the model to balance the fields itself. At the same time the surface pressure, as well as the deep and surface soil moisture and temperature, must be adjusted in accordance with the increased height of the orography. However special attention is needed at the boundaries. The simple approach of letting the mountain grow only in the inner area and not at the boundary should be avoided to prevent the creation of walls in mountainous regions of the boundaries. A relaxation function of the same kind as that described in Sect.2 can be used for the growing orography at the boundaries. But problems still arise because the external values are on different σ surfaces from those of the LAM because the orographies of the coarse and fine mesh model are different. Thus, a reduction of the external values to the new σ surfaces must be performed before updating the boundaries.

5. EXAMPLES OF FORECASTS

Experiments were performed with N48, N96 and N192 resolutions for the case of lee cyclogenesis in early March 1982. When definining the orography for the respective resolutions, the choice was between an average and an envelope orography. The 'average' orography is derived by taking the grid box mean of a high resolution orography. The envelope orography is a representation that tries to simulate the sub-grid scale orographic effects by adding to the average orographic height in each grid box a quantity proportional to its sub-grid scale standard deviation.

It was found that at the N48 resolution, the envelope orography, with only one standard deviation added, was able to create the right kind of obstacle for the flow to produce the Genoa cyclone in the correct position. When the resolution was increased to N96, the envelope orography with one variance still gave a better forecast than the average orography. Further refinement of the mesh to N192 caused the forecast to become noisy and the centre of the cyclone was displaced to the west - the envelope orography with one standard deviation was clearly too steep. However, at this resolution, the average orography provides an accurate description of the steepness and height of the Alps and was able to give a good description of the Genoa cyclone.

Comparison of an N48 resolution analysis (Fig.2a) with the corresponding subjective analysis (Fig.3a) gives an indication of the detail that a coarse mesh analysis can miss. The (D+2) high resolution forecast shown in Fig.3b verifies with these analyses; clearly the fine mesh model is capable of generating features due to topographic forcing which are absent in the corresponding coarse mesh model forecast (Fig.2b).

In particular a comparison of the wind fields from the fine and coarse resolution models (Figs.4a and 4b) gives an indication of the degree of accuracy that can be achieved in a 48 hour fine mesh forecast. Note also that the forecast of heavy rainfall over the Catalonian region in Spain is an example of the ability of the model to reproduce this kind of phenomena. Fig.5a shows the detailed analysis of the accumulated precipitation between 6-7 November 1982. The region of precipitation near the Pyrenees can be recognised in the pseudo-satellite picture of Fig.5b, which was derived from a 24 hour forecast with the LAM (resolution N192 and average orographic representation). A comparison between pseudo (Fig.5b) and actual satellite pictures (Fig.5c) shows the success of the LAM in simulating many other atmospheric features but, at the same time, it stresses the limitations of the model forecast in reproducing the detail of the atmosphere flow.

6. SUMMARY

We have seen that the boundary relaxation scheme, if carefully applied, works correctly. The major differences that can be noticed between bounded and unbounded forecasts at the same resolution, derive from the frequency of the boundary updating. An indirect but significant indication of the efficiency of the boundary scheme is given by the successful long integrations of the LAM at high resolution, in which the boundary procedure, applied hundreds of times, would have the opportunity of deteriorating the forecast.

The practical solution of replacing a high resolution analysis with data interpolated from a coarse to a fine mesh produced detailed and accurate forecasts specially when the forcing was imposed by the lower boundary. However, a fine mesh analysis is still needed so that meteorologically important small features can be included in the initial data and the details of the forecast can be verified.

The practise of allowing the difference between old and new orography to grow in the first 12 hours of the forecast can successfully replace the initialization procedure if carefully applied. Thus it is possible to test different orographic representation and their success in reproducing the effect of the mountains on the atmosphere.

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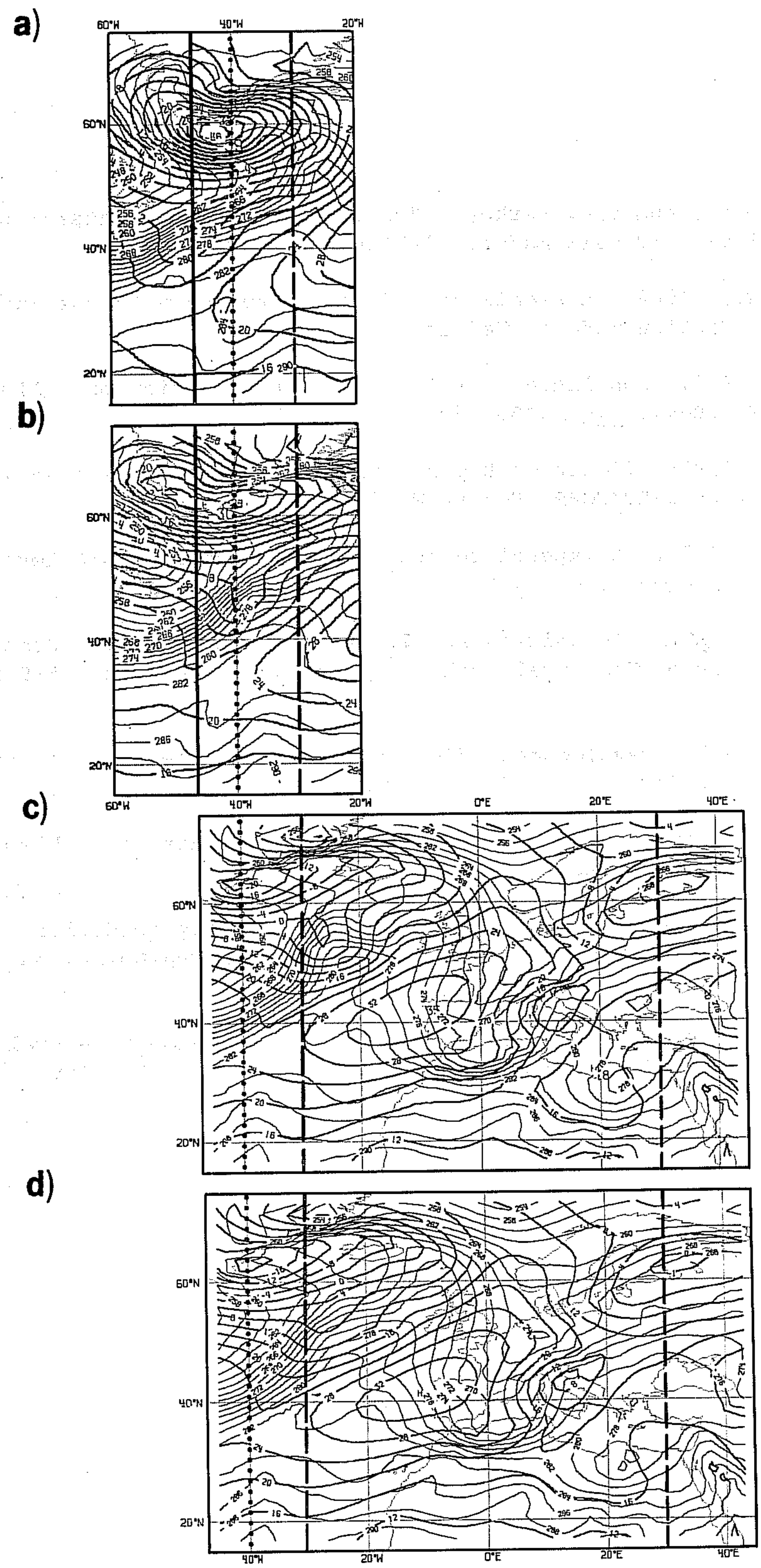


Fig. 1 Maps of the geopotential height and temperature at 1000 mb from the a) 24 hour, b) 36 hour, and c) 48 hour global forecast starting at 12GMT, 3 March, 1982 , d) the 48 hour limited area model forecast using boundary data interpolated from the 48 hour and 36 hour global forecast values. Vertical solid line indicates the western boundary of the limited area model, dashed line the eight point lateral boundary relaxation zone and the dotted line the four point lateral boundary relaxation zone.

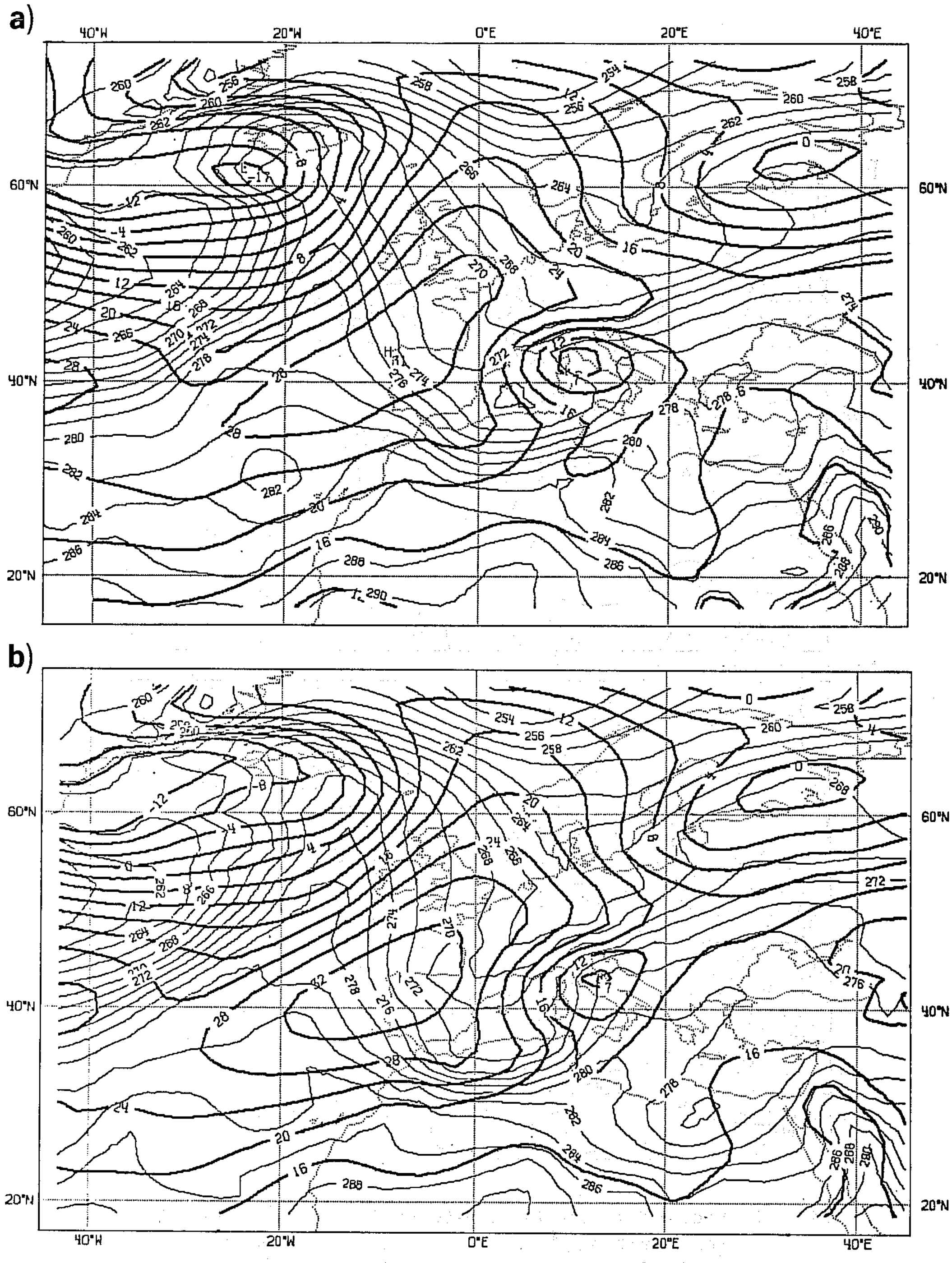


Fig. 2 Maps of the geopotential height and temperature at 1000 mb from a) the analysis at 12GMT, 5 March, 1982 and b) the 48 hour limited area model forecast (using 12 hourly analysed boundary updating) verifying at the same time.

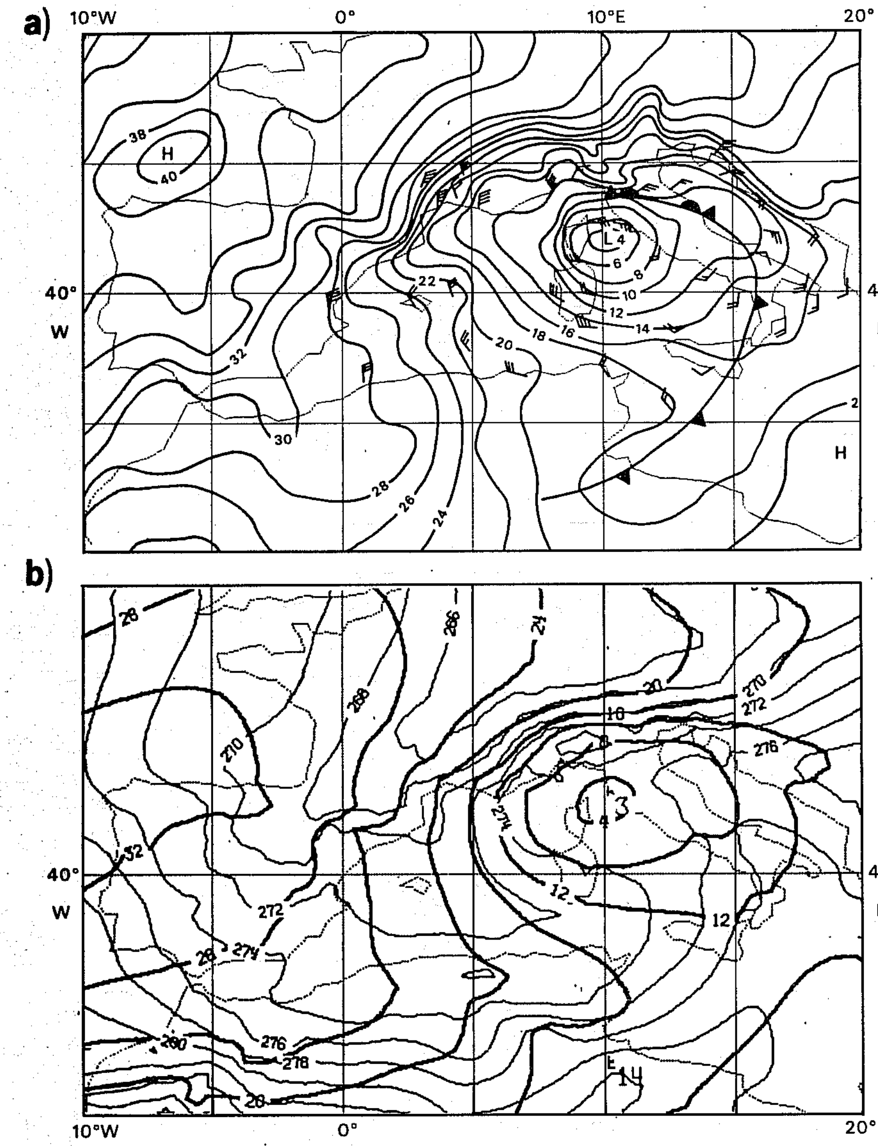


Fig. 3 Maps of a) Subjectively analysed MSLP and wind (one barb is 10 knots) at 12GMT, 5 March, 1982, b) 1000 mb geopotential height (thick line) and temperature from the 48 hour of the N192 resolution limited area model forecast.

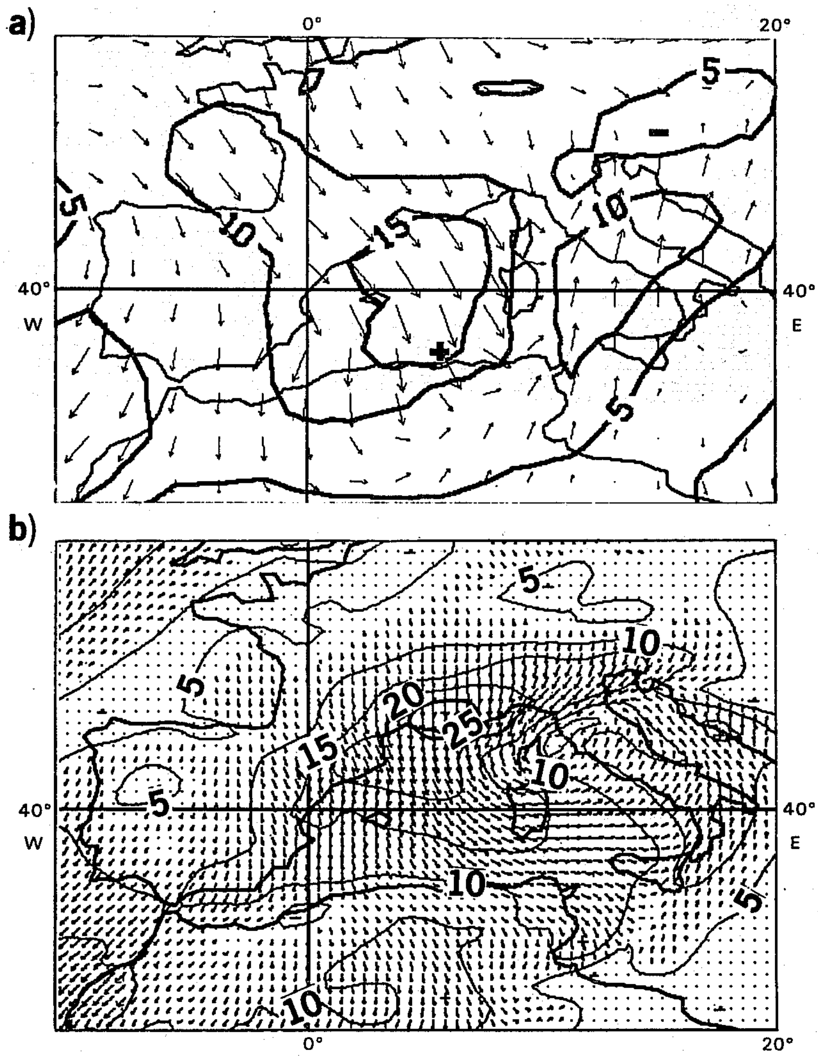


Fig. 4 Maps of the wind field at 1000 mb from the 48 hour limited area model forecast at resolution a) N48 and b) N192 verifying at 12GMT, 5 March, 1982. (Isotachs every 5 ms^{-1}).

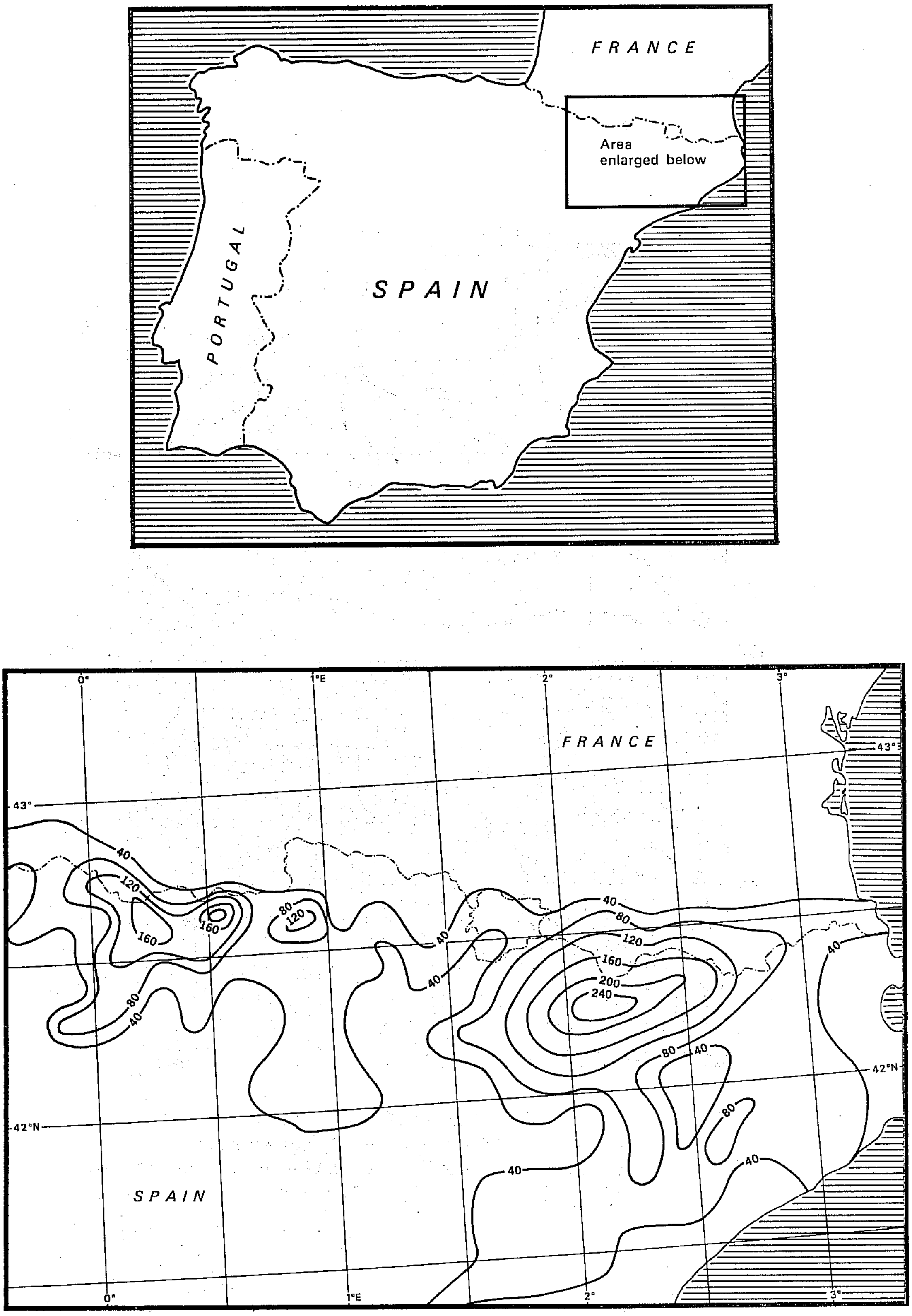
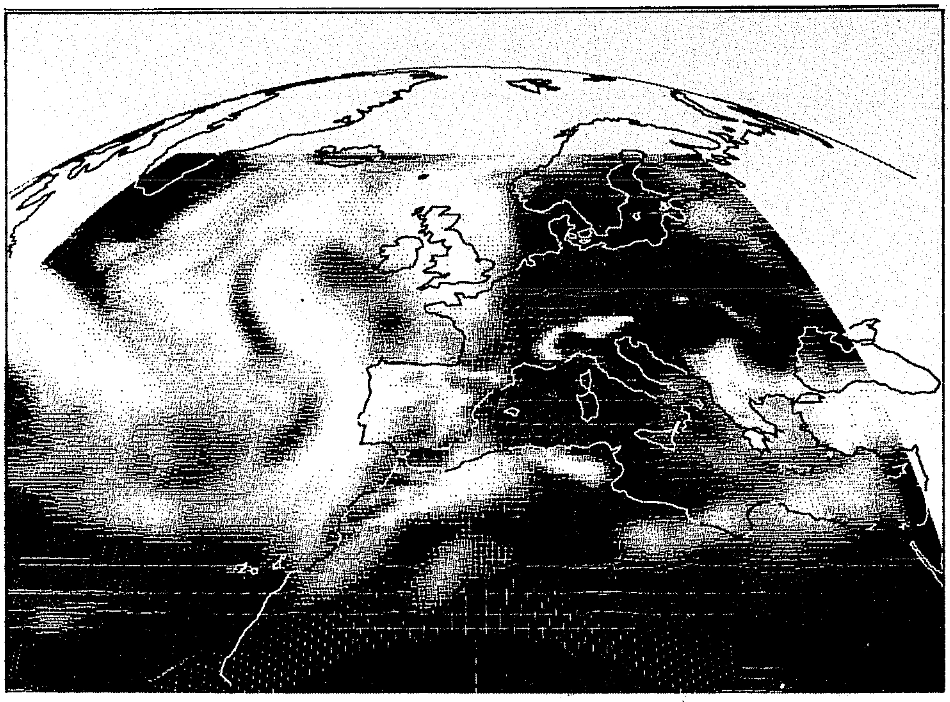


Fig. 5 a) Map of the 24 hour accumulated precipitation (between 06GMT, 6 and 7 November, 1982) over the Catalonian region.

b)



c)

Fig. 5 b) Pseudo-satellite picture from the 24 hours limited area forecast with resolution 5^{o}.
c) Composite satellite picture (NOAA 7, visible) between 12 and 16 GMT, 7 November, 1982 to be compared with b).