Numerical simulation of Genoa cyclogenesis

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1. Introduction

Synoptic experience and statistical investigations show that in the region of the Gulf of Genoa there is a pronounced maximum in the frequency of cyclogenesis (e.g. Petterssen, 1956; Radinović and Lalic, 1959; Radinović, 1965a). Cyclogenesis in this region, within an area of, say, 3 x 3 deg longitude x latitude, occurs on the average more than twice per month. This frequency is about an order of magnitude greater than the frequency of cyclogenesis within the same area in most other neighbouring regions. A fair proportion of these cyclones, perhaps about half, are deep tropospheric phenomena; but even the weak and short-lived Genoa depressions frequently have a very important effect on the weather (Radinović, 1965a).

Numerical experiments (Egger, 1972; Bleck, 1977) have given convincing evidence that mountains are the prime cause for the outstanding frequency of cyclogenesis in this region. The details of the dynamical mechanisms involved, however, are not well understood; and neither is the role played by a number of physical factors likely to be of importance. Prevailing opinion is that the barrier-induced intensification of baroclinic instability is the essential dynamical ingredient of a typical deep Genoa cyclone (Radinović, 1965b; see also the recent review by Tibaldi, 1979). However, the cyclones that remain shallow would then seem to require a different explanation, perhaps a mechanism that could be a component of the deep developments. For example, in a very careful study of a single deep Genoa cyclogenesis, Buzzi and Tibaldi (1978) came to a feeling that there was a distinction between "trigger" phase during which a low level small-scale perturbation was produced, and a baroclinic upper-tropospheric development during which the perturbation acquired a vertical coherence and grew into a larger-scale mid-latitude cyclone.

As pointed out by Tibaldi (1979), this viewpoint is not inconsistent with results of the numerical experiments by Bleck (1977). In forecasts done by Bleck, for three real data cases, a reasonable height of the mountain barriers (Alps higher than 2000 m) turned out to be necessary to obtain surface developments. However, in neither of the three cases has the model used by Bleck predicted the accompanying cut-off low aloft. The forecasts were done for a 24-hour period each, with an adiabatic model, and the mesh size (over the Mediterranean, and in the interior of a nested grid) of about 85 km.

Therefore, both in attempting to further the physical understanding of the phenomenon, and in testing the performance of a numerical model, there are strong reasons to perform further numerical case studies of the Genoa cyclogenesis. A brief preliminary report on an investigation under way at the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, will be presented here. Compared to the experiments done by Bleck, the scope of this study is extended in a number of ways. The integration period (in control experiments) is increased to 48 hours, in order to include always the complete pre-incipient stage of the process, before the frontal surface of the oncoming cold air has reached the Alpine obstacle. Experiments are being done in each case using a number of versions of the numerical model, including a version with a complete "physics" package, so that the role and/or the sensitivity to the physical processes, as parameterized in the model, can be estimated. Finally, in addition to the three cases studied by Bleck, one more case has been selected, that of 22 - 24 August 1975. Results for this last case will be discussed here in some more detail; preliminary results on two of the remaining three cases will also be shown.

First a brief outline of the properties of the model used for the present study shall be given.

2. The model

The model used here has been developed at GFDL as an outgrowth of the model originally formulated at the Federal Hydrometeorological Institute and Belgrade University (HIBU), Yugoslavia (Janjić, 1977; Mesinger, 1977). This "HIBU 1977 version" model is a limited area model on the E (Arakawa notation) grid, using longitude-latitude horizontal coordinates and the sigma vertical coordinate. Its horizontal momentum advection scheme conserves enstrophy and energy for the rotational component of the wind. The analogue of the hydrostatic equation is chosen so as to minimize the vertical discretization error. The two terms of the pressure gradient force are calculated in a hydrostatically consistent way, and, in addition, so as to avoid a spurious height staggering of the pressure gradient and the Coriolis force in the presence of mountains. Finally, the analogue of the $\omega\alpha$ term in the thermodynamic equation is chosen in such a way as to conserve total energy in transformation between the kinetic and the potential energy. The two-grid-interval noise is prevented by calculating the divergence term of the continuity equation so as to have gravity waves generated at single grid points propagate along all other points of the grid.

Numerical schemes of this model have been further developed at GFDL in a number of directions. The formulation of the horizontal momentum advection terms has been generalized so as to conserve energy in the case of divergent flow as well as nondivergent flow, and the accuracy of these terms was increased from second to the fourth (or approximately fourth) order. A temperature (and moisture if present) horizontal advection scheme of approximately fourth order has been developed which conserves total energy (and moisture) inside a closed integration domain. A conserving ∇^4 type lateral diffusion was incorporated, including a careful treatment of the diffusive fluxes in case of sloping sigma layers. The model has also been extended to a full weather prediction model by provision of one of the available GFDL "physics" packages, in which detailed calculation of the radiation, hydrologic cycle and boundary layer processes are incorporated.

A special effort was made to construct grid point terrain heights which would be enhanced, compared to grid point averages, so as to better simulate the barrier effect (Mesinger, 1979). Experiments to be shown in the next section were performed with a horizontal grid of 51x19 grid points (carrying the same variable), formed by a 1.5x1 deg longitude x latitude mesh. This results in the grid distance of about 162 km. There were 9 (GFDL) vertical levels.

3. Results

The August 1975 case is the same as that chosen for the example of the HIBU 1977 version paper (Mesinger, 1977); a deep cyclogenesis that occurred over the region of the Gulf of Genoa during the time of approximately 00 GMT 23-24 August 1975. The referred previous example was started with the initial data of 00 GMT 23 August. However, by that time the cold front, which presumably plays a crucial role in the process of Genoa lee cyclogenesis (e.g. Buzzi and Tibaldi, 1978), has apparently passed the Alpine obstacle, and the process of cyclogenesis was already under way. For example, analysis of the German Weather Service (Taglicher Wetterbericht, 1975, No. 235) shows on the surface map of 00 GMT 23 August a frontal line and a closed 1010 mb isobar in the region of the Gulf of Genoa. Therefore, for the present experiment the situation 24 hours earlier, at 00 GMT 22 August 1975, was chosen to start the integration. At that time the cold front was clearly in front of the Alpine obstacle, on both the German and the U.S. National Meteorological Center (NMC) operational analyses.

The data for the initial situation were now obtained from the NMC Data Systems Test 5 (DST-5) analyses, as the considered 2-day period, it was found, is included in the DST-5 set period. Fig. 1 shows the initial fields of the sea level pressure (above) and of the 500 mb geopotential heights (below). Contour intervals on these maps are 2.5 mb for surface pressure, and 40 gpm for geopotential; and the region shown is, for reasons of convenience, one grid line on each side smaller than the actual integration region.

As the cold front deformed in passing the Alpine obstacle, intensive cyclogenesis occurred in the region of the Gulf of Genoa, with closed contours appearing throughout the troposphere up to and including the 300 mb level (Taglicher Wetterbericht, 1975, No. 236). Fig. 2 shows the situation (below), at 00 GMT 24 August 1975, 48 hours after the initial situation in Fig. 1. The maps shown are extracted, for the present integration region, from the referred analyses of the German Weather Service. On the surface map (above), note the characteristic increase in sea level pressure to the northwest and to the southwest of the Genoa low, associated with the advance of cold air and its interaction with the Alpine obstacle and the developing cyclonic circulation. Examination of surface reports, on this and on other maps published in the referred bulletins, shows that the sea level pressure at the centre of the low has a value of about 1003 mb. On the

500 mb map (below), the minimum reported height in the region of the Gulf of Genoa is 5610 gpm (station Cagliari, on Sardinia); however, values below 5600 gpm appear likely, and were presumed by the analyst.

Fig. 3 shows the 48-hour forecast/simulated maps of the sea level pressure (above) and of the 500 mb geopotential heights (below). The experiment shown here was performed using the adiabatic version of the model, and with "observed" boundary conditions: analyses at 00 GMT 23 and 24 August were used, and the boundary data were linearly interpolated in time.

The general pattern of the sea level pressure map appears to be very well predicted, including the location and intensity of the Genoa low, position of the associated cold front, and the increase in sea level pressure to the northwest and to the southwest of the Genoa low. The sea level pressure in the centre of the low is several millibars higher than on the verification map. However, one can note that this is true for a wide region covering most of the integration area, and therefore, appears to be a consequence of an erroneous net inflow of mass through the boundaries; a well known difficulty of limited area models with prescribed time dependent boundary conditions.

The cut-off in 500 mb heights is also quite well predicted. It lags to some extent, both in time and space, compared to the observed cut-off process. Examination of individual reports on the verification map shows that the 5660 gpm contour should have also been cut-off at the considered time; thus, both the depth of the cut-off low and the intensity of the associated "ridging" in central Europe are slightly insufficient.

A question arises as to whether the simulated cyclogenesis is to some extent, if any, a consequence of the observed boundary conditions, rather than a result of the abilities of the forecasting model to simulate the dynamical processes involved in the phenomenon. For that reason it is of interest to compare the results shown in Fig. 3 with those shown in Fig. 4, obtained in an experiment with constant boundary conditions. It is seen that the cyclogenesis with constant boundary conditions is even slightly more intensive, both at the surface and aloft. An encouraging by-product of this experiment is the finding that the forecasts/simulations done with observed boundary conditions were clearly less noisy, both visually and according to diagnostic integrals (e.g. average enstrophy), than the forecasts with constant boundary conditions. In other words, the model is seen to prefer the observed boundary data, taken from the atmosphere, to constant initial boundary values.

Fig. 5 shows the results obtained in the same way as those in Fig. 4, except that there were no mountains. Both the surface low and the 500 mb cut-off are seen to be deeper than with the mountains present! Thus, in this particular case, mountains are not needed for cyclogenesis. However, without mountains, the location of the surface low is different, there is no ridging at the surface to the northwest and to the southwest of the low, and only a rather reduced ridging at 500 mb north of the cut-off.

With respect to this last point, it is perhaps revealing to look at the 850 mb temperature maps shown in Fig. 6. The 850 mb temperatures obtained in the forecast with mountains (above) in central Europe north and west of the Alps are much lower than those obtained in the same region without mountains (below). For example, the point marking 10E longitude and 50N altitude is seen to have a temperature more than 5 K lower with mountains than without mountains. Note that this is the area in which the ridging at 500 mb in a way executes the cut-off process, and that this ridging is with mountains visibly more intensive than without mountains. It would appear that the accumulation of cold air north of the Alpine barrier is responsible for the increase in surface pressure, and, relative to the trough pattern, also of geopotential heights; and that this is the mechanism which then remarkably accelerates (in this case) the cut-off. In some other cases, such accumulation of cold air possibly makes the cut-off occur, even though it would fail to occur, in this region, without mountains. In agreement with this view, in the run with "observed" boundary conditions in which the accumulation of cold air north of the Alps happened to be slower, the cut-off (Fig. 3) was also slower.

In the experiment with "physics" (not shown) the intensity of the surface development was not much different. The 500 mb low was only slightly deeper; at the same time, however, this low was less cut off than the low without "physics", seen in Fig. 3. Pichler and Steinacker (1978) on the basis of scale analysis arguments, apparently expect latent heat in this particular case to be of more importance for cyclogenesis. The reason for this relatively minor effect of latent heat on cyclogenesis in present experiments seems to be the space distribution of the simulated precipitation: rather than in the region of the surface low, precipitation was located more along the trough within the region of the Alps and north of Alps. In this way the effect of latent heat, in the experiment, has actually reduced the speed of the cut-off process.

Contrary to this August 1975 case, in the three cases studied by Bleck (1977) mountains appear to have had a decisive influence on cyclogenesis, since, as mentioned earlier, Bleck has obtained cyclogenesis only after raising the height of the mountains in his model. Verification maps for the first of these three cases are shown in Fig. 7, and the results obtained presently in a 48-hour simulation with "observed" boundary conditions are shown in Fig. 8. While there is some modest success in simulating the surface cyclogenesis, the cut-off aloft is not simulated. In an experiment with a high resolution version of the present model (81 km grid distance at 45 deg latitude), the amplitude of the 500 mb trough did increase to some extent, but not nearly as much as needed for the cut-off pattern seen on the verification map. Other experiments will be made in search for the cause of the difficulty.

Verification maps for the second of the cases studied by Bleck are shown in Fig. 9; unfortunately, no verification 500 mb analysis for this time is available at present, and the 300 K isentropic analysis by Buzzi and Rizzi (1975) is shown instead. The result of a 48-hour simulation, again with "observed"boundary conditions, is shown in Fig. 10. The surface low is not nearly as deep as it should be; however, the experiment done so far for this case and shown here was made using rather low mountains (Alps with the highest peak less than 2000 m) and a deeper low could be expected with higher mountains (and resolution). The mountains used for this experiment had some erroneous (excessively high) values over Greece, and this is believed to be the cause of the noise seen in the surface map east of the low. At higher levels, there were closed cut-off contours both at the 850 and at the 700 mb map; the 500 mb cut-off seems to be well on its way, and is possibly only slightly behind.

4. Conclusions

In two out of three cases of Genoa cyclogenesis simulated here, encouraging results were obtained in simulating the 500 mb cut-off process; apparently (Bleck, 1977) a major difficulty in attempting to accomplish a satisfactory numerical simulation of Genoa cyclogenesis. Experiments (with participation of R. F. Strickler, J. Sirutis and J. Chludzinski) are being continued with one more case, with inclusion of a "physics" package, and with the high resolution version of the present model.

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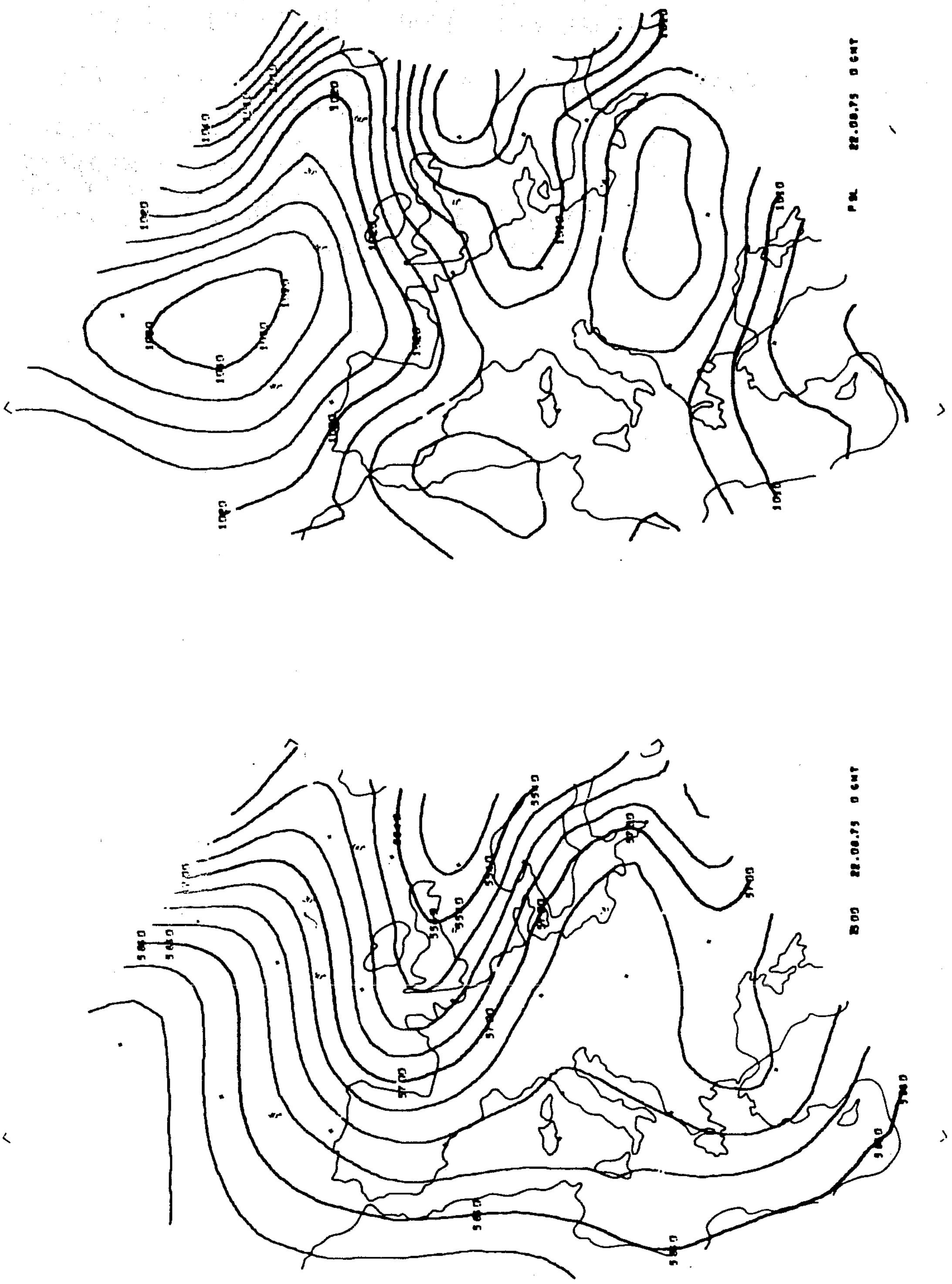

Fig. 1 Initial fields of the sea level pressure (above) and of the 500 mb geopotential height (below), 00 GMT 22 August 1975. Data obtained using the National Meteorological Center's Data Systems Test 5 (DST-5) analyses.

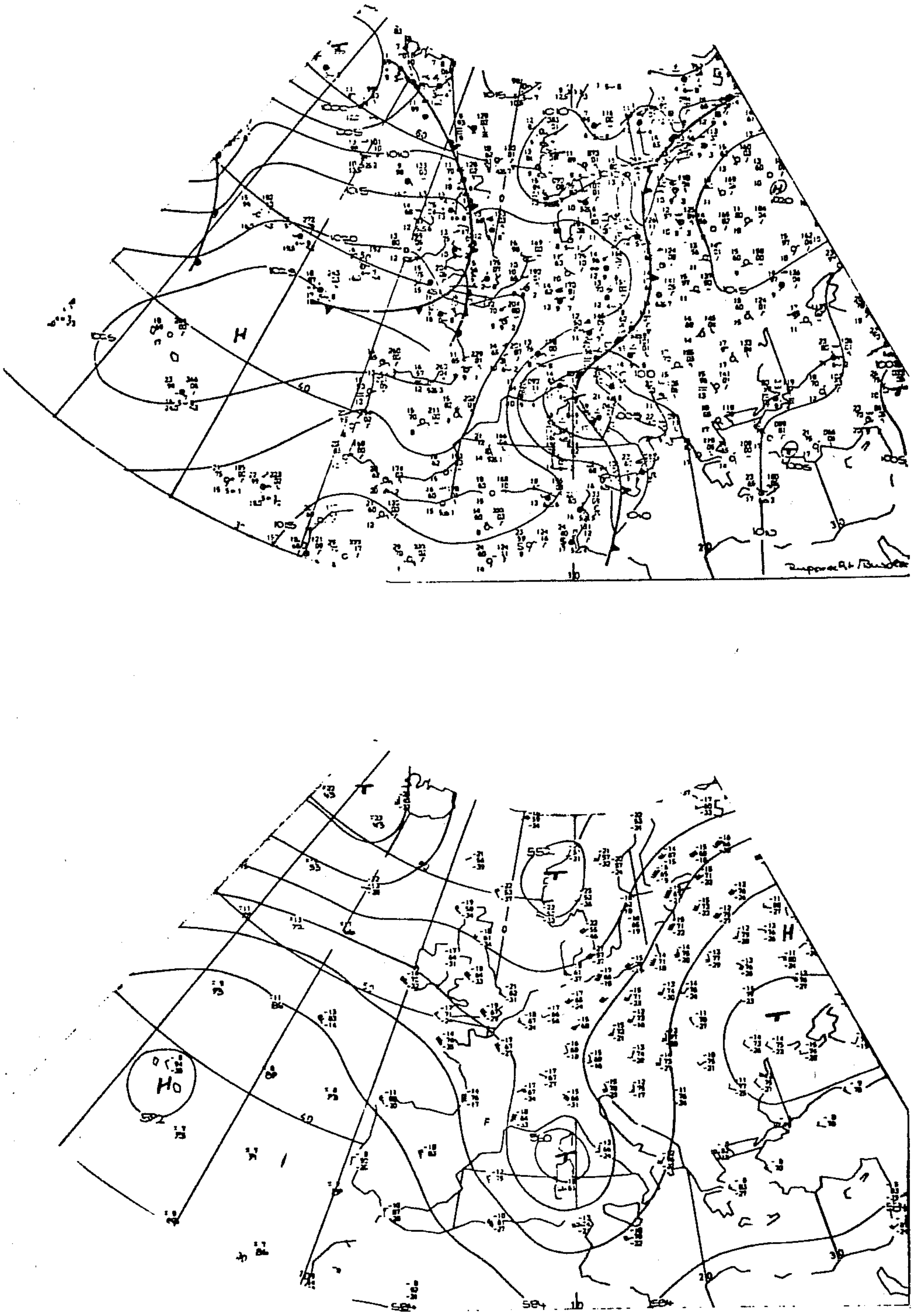

Fig. 2 00 GMT 24 August 1975 sea level pressure (above) and 500 mb geopotential height (below) maps. Analyses of the German Weather Service.

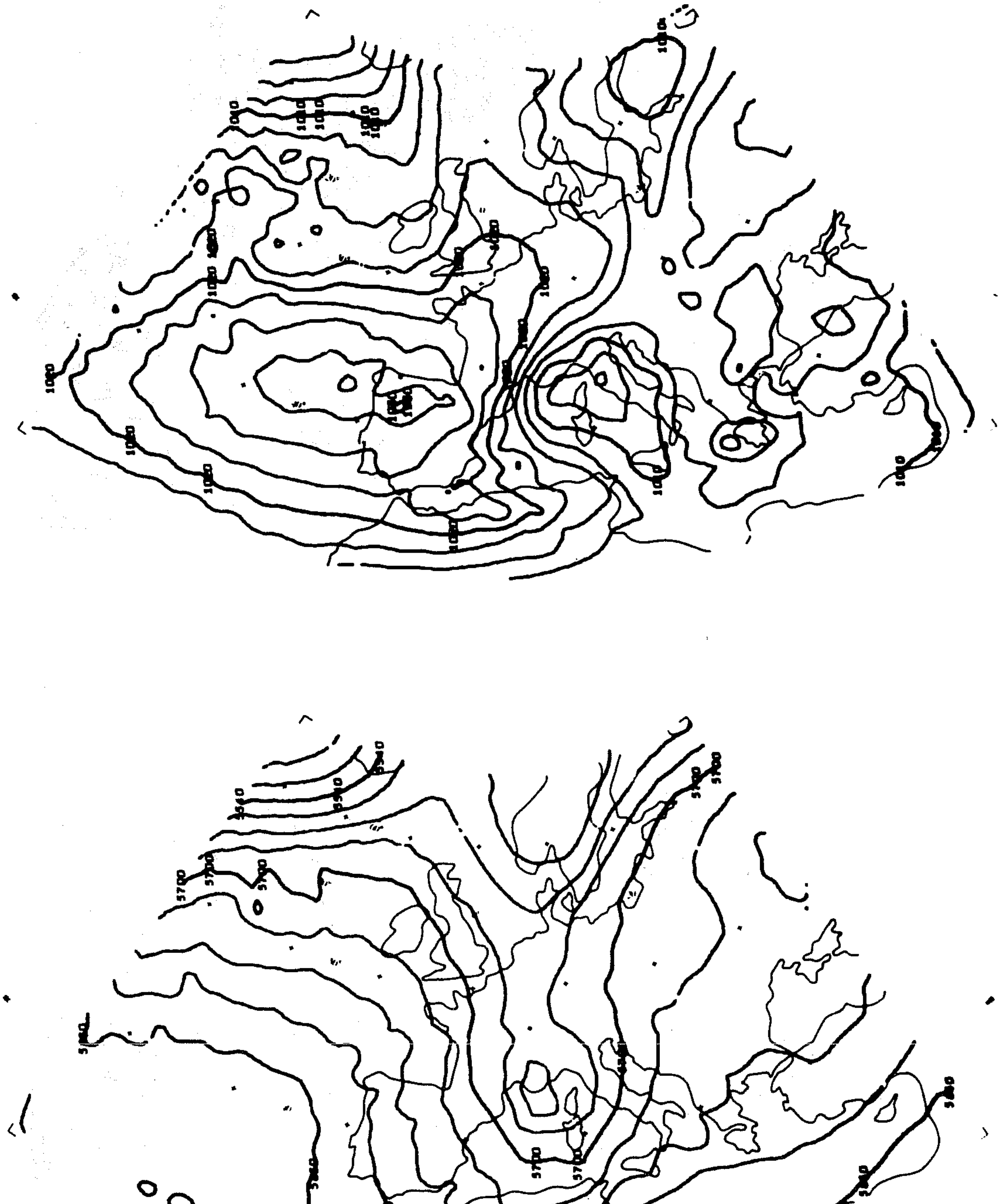

Fig. 3 00 GMT 24 August 1975 sea level pressure (above) and 500 mb geopotential height (below) maps. 48-hour forecast simulation obtained using the present model, initial situation shown in Fig. 1, and time-dependent (analyzed) boundary conditions.

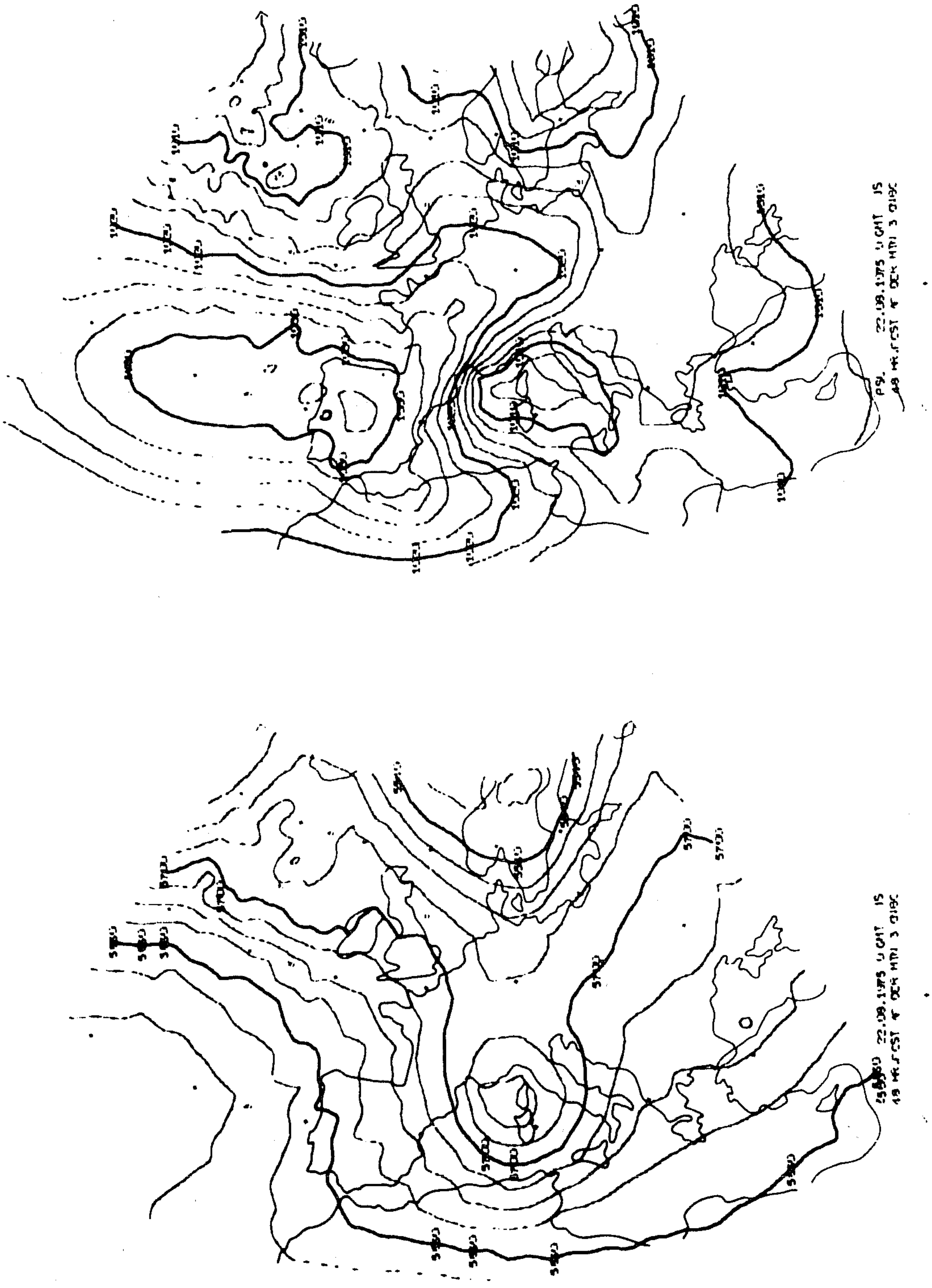

Fig. 4 As in Fig. 3, except that integration was done with constant boundary conditions.

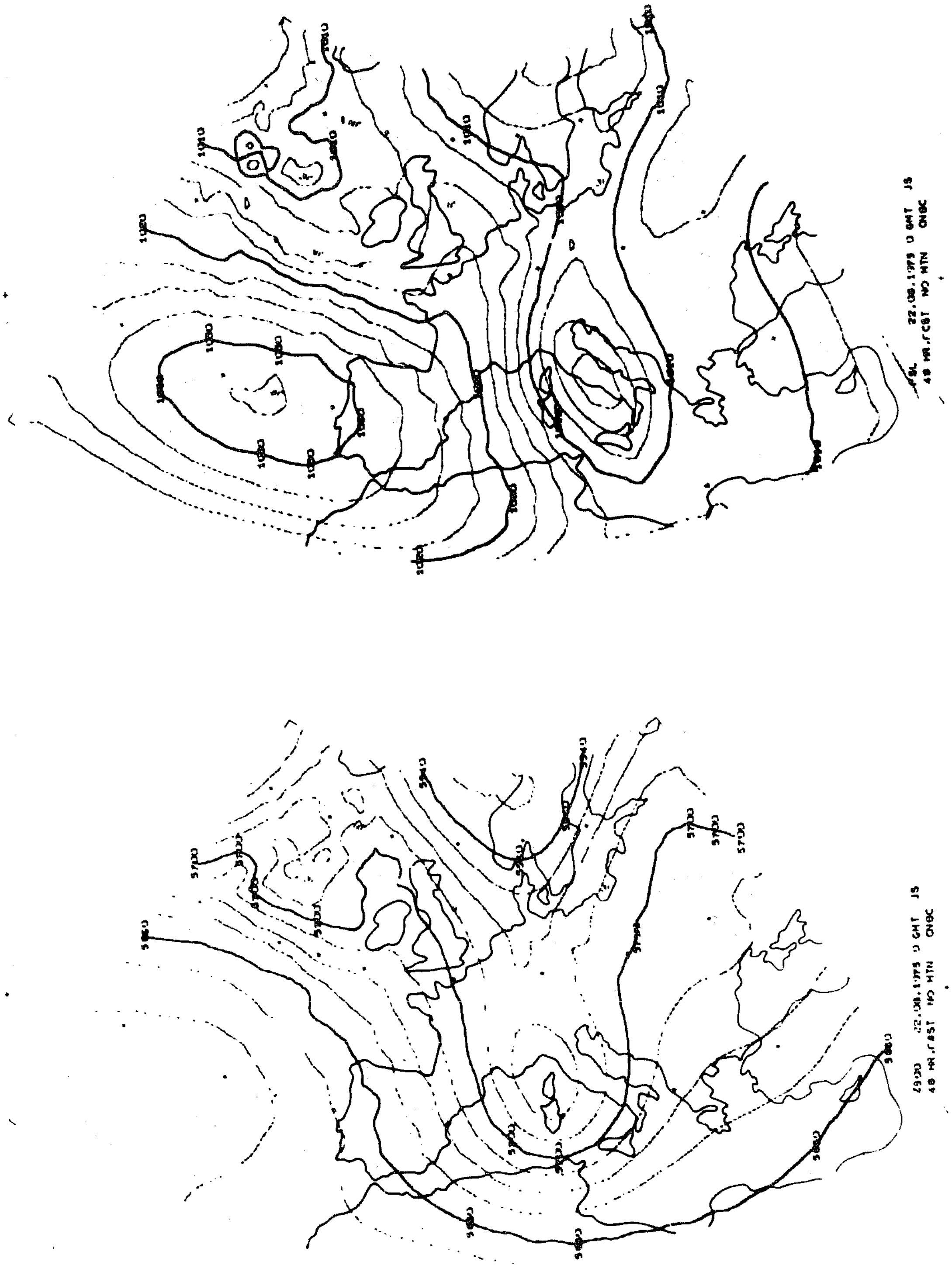

Fig. 5 As in Fig. 4, except that integration was done with no mountains.

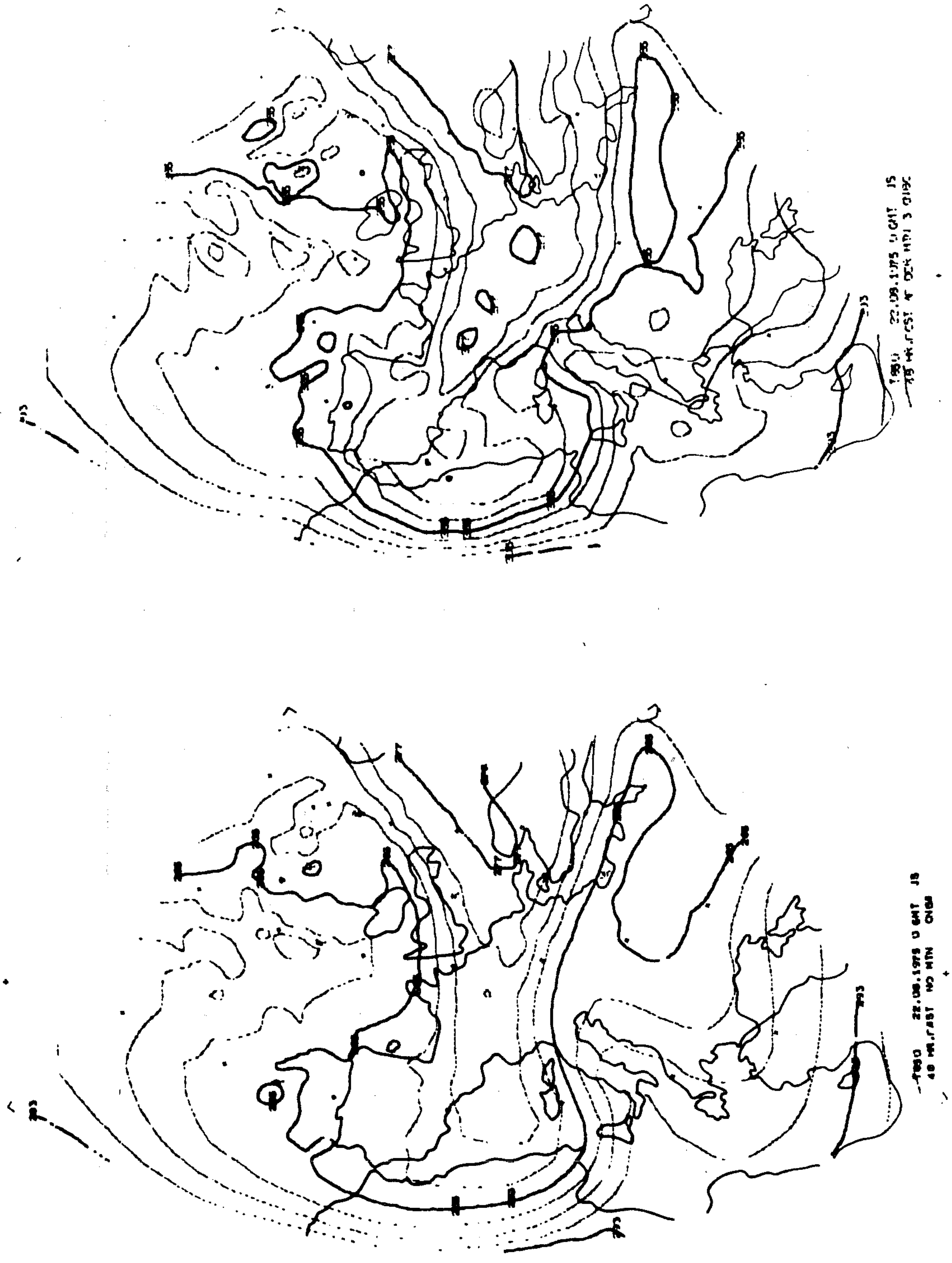

Fig. 6 00 GMT 24 August 1975 850 mb temperature maps, obtained in forecasts with constant boundary conditions shown in the preceding two figures, with mountains (above) and with no mountains (below).

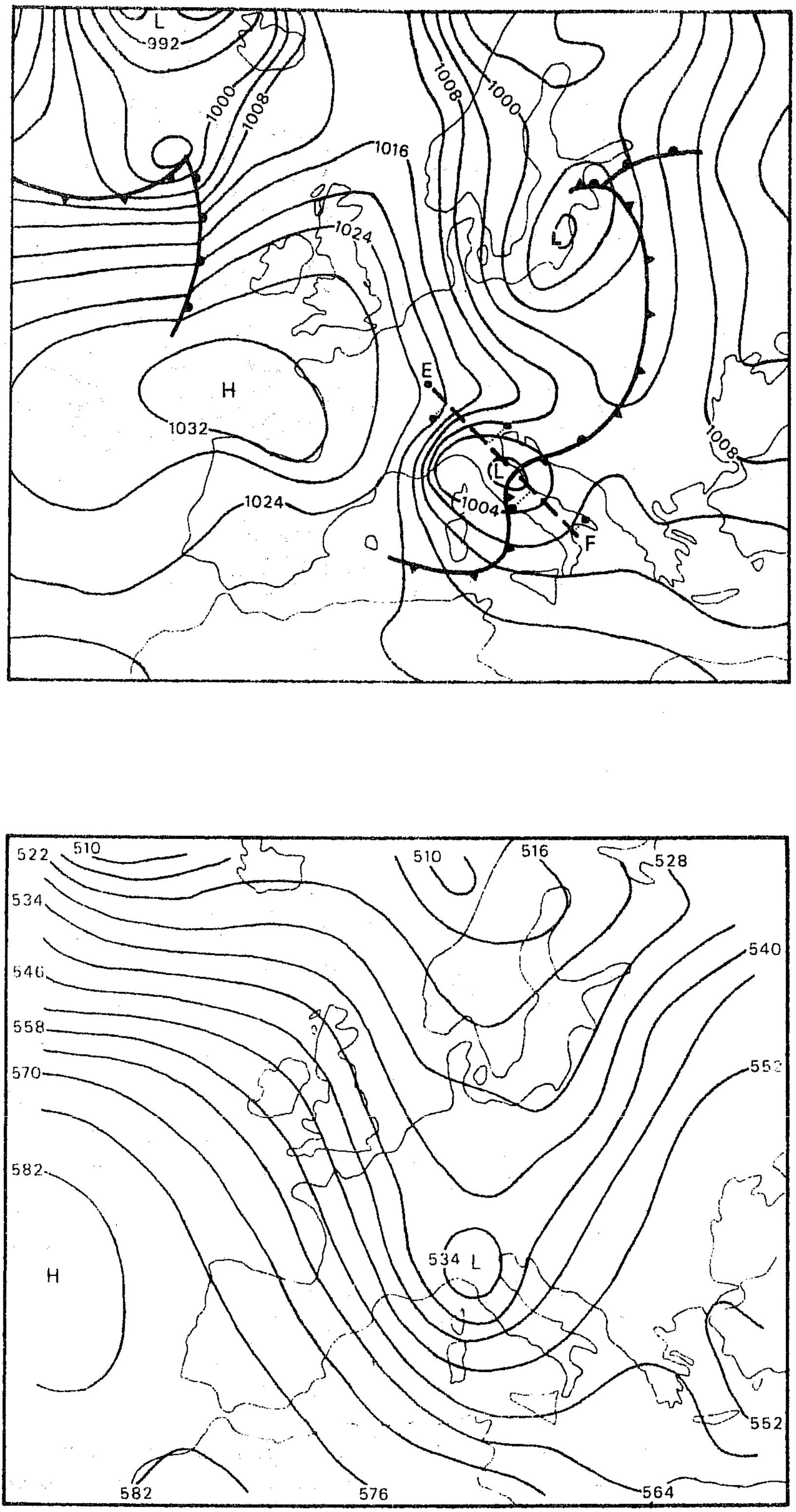

Fig. 7 12 GMT 3 April 1973 sea level pressure (above) and 500 mb geopotential height (below) maps. Analyses by Buzzi and Tibaldi (1978).

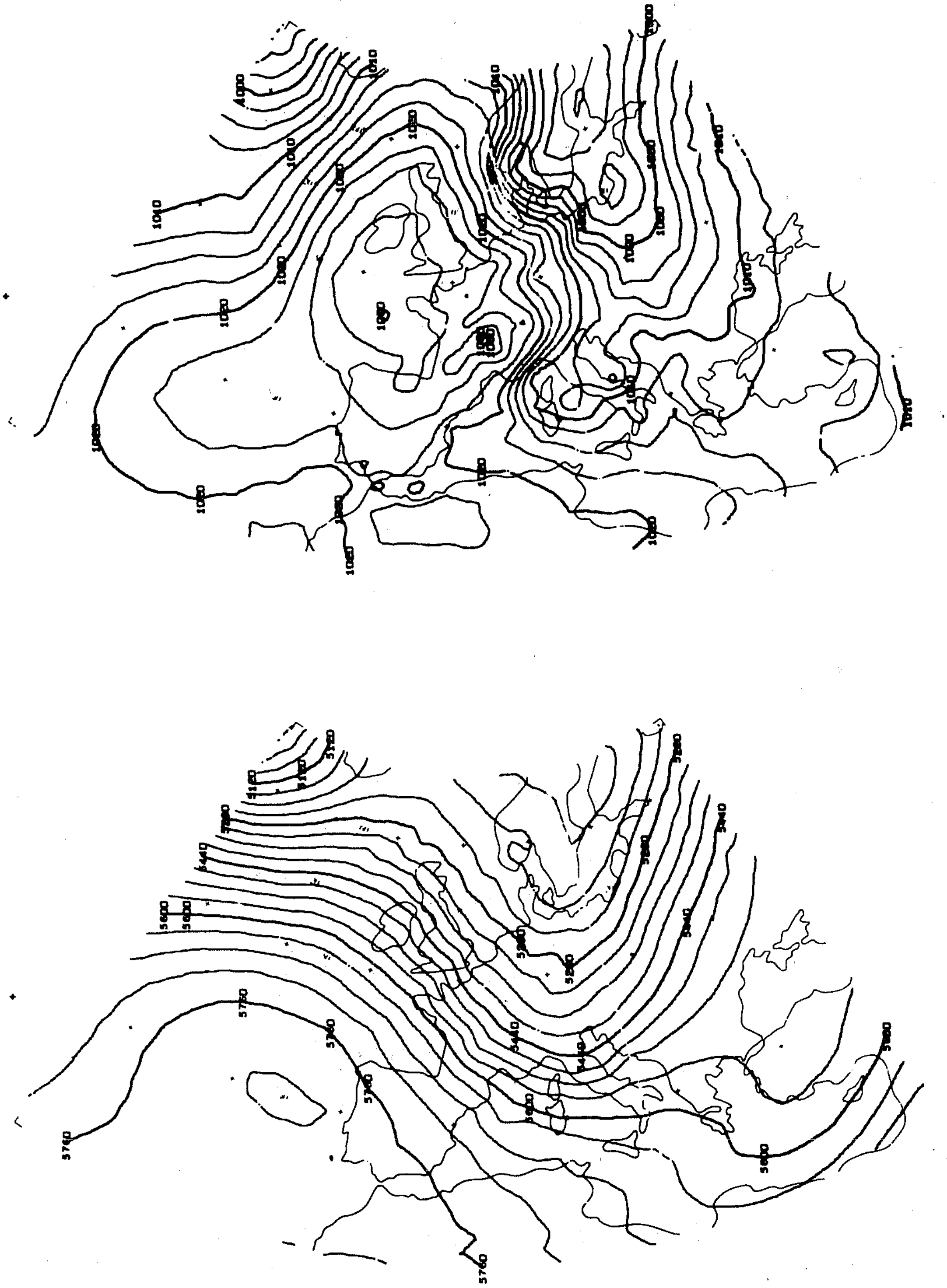

Fig. 8 12 GMT 3 April 1973 sea level pressure (above) and 500 mb geopotential height (below) maps. 48-hour forecast simulation obtained using observed (analyzed) boundary conditions.

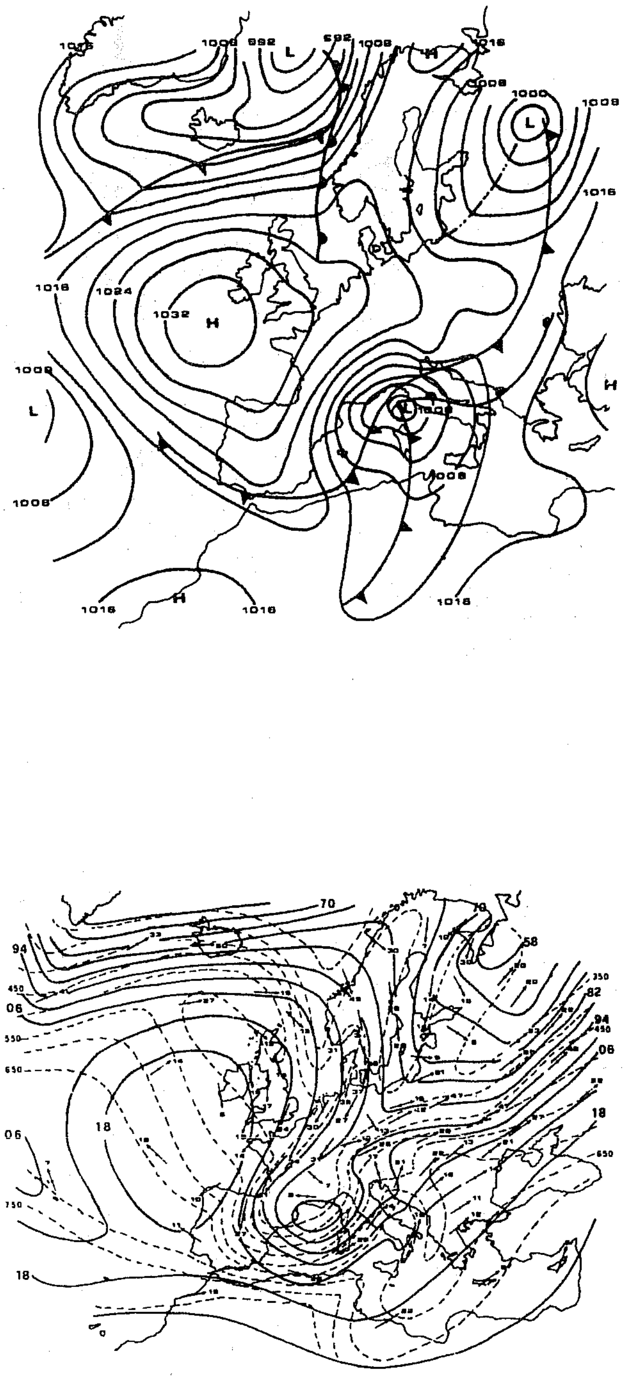

Fig. 9 12 GMT 4 February 1969 sea level pressure (above) and 300 K isentropic surface (below) maps. On the isentropic map full lines are isolines of Montgomery streamfunction, drawn at 6×10^2 m^2 s^{-2} intervals, and dashed lines are isobars, with values of pressure in mb. Analyses by Buzzi and Rizzi (1975).

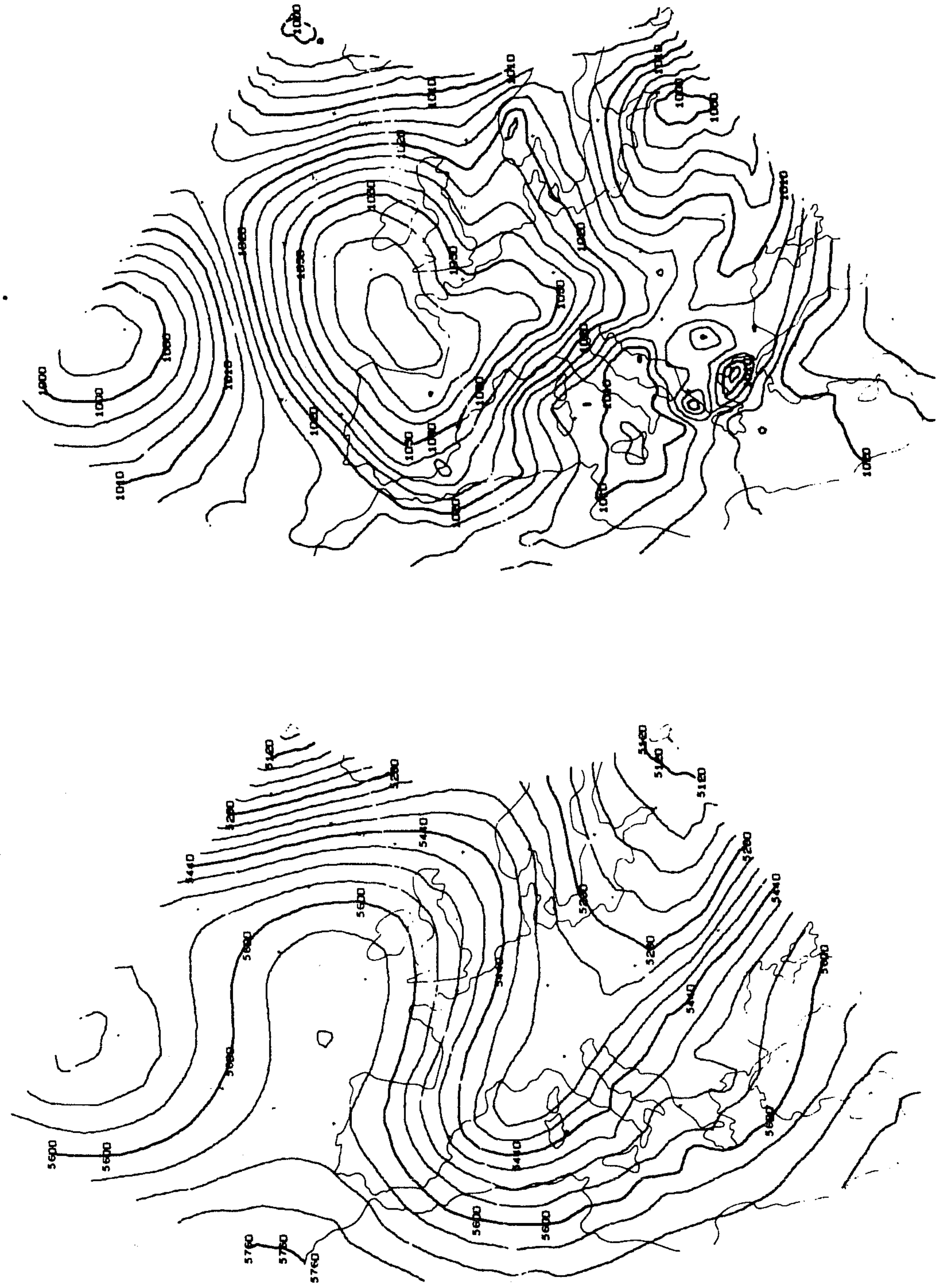

Fig.10 12 GMT 4 February 1969 sea level pressure (above) and 500 mb geopotential height (below) maps. 48-hour forecast/simulation obtained using observed (analyzed) boundary conditions.