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THE UNIFIED FORECAST/CLIMATE MODEL

by

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September 1991

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Summary: The reasons for adopting a unified forecast/climate model are discussed. The model is described and related to previous forecast and climate models in use in the Meteorological Office. The software system used to implement it is also briefly described. Examples of its performance are shown in global and limited area forecasts, long range forecasts, climate simulations, and upper atmosphere forecasts.

1. INTRODUCTION

The Meteorological Office has used a global numerical weather prediction model since 1982, Gadd(1985) and has used global climate simulation models since the late 1960s, Corby, Gilchrist and Rowntree (1977). The global weather prediction model was based on the design of the then current climate model. Experience with the two separate models suggested that it would be advantageous to combine them at the next major computer upgrade. The opportunity occurred with the installation of the CRAY YMP in January 1990. It was also decided that the resulting unified model should be used for upper atmosphere simulations taking advantage of the data supplied by the UARS satellite. This paper describes the justification for the move to a unified model, the model formulation and software system, and illustrates its performance in the main configurations.

2. JUSTIFICATION FOR THE UNIFIED MODEL

The global forecast and climate models implemented on the Meteorological Office CYBER 205 computer had many similarities. Both solved the equations of motion using finite difference methods on a grid regular in latitude and longitude. Both used a terrain-following vertical coordinate, with increased resolution near the ground and near the tropopause. Both included representations of the main physical processes such as boundary layer mixing, convection, large-scale precipitation, gravity wave drag, and radiation. The main differences were that lower horizontal and vertical resolution were used in the climate model, that a different arrangement of the variables on the grid and time integration scheme were used in the two models, and that the representation of physical processes in the climate model was considerably more advanced. The program structure required for both models was similar. However, the climate model contained a large amount of ancillary software to enable output to be processed automatically during the very long integrations required.

State-of-the-art atmospheric modelling requires a high degree of scientific expertise, and it had already been necessary to share this expertise by using or attempting to use similar physical formulations in the two models. However, it is much simpler to do this if the models use the same computer code. Use of a modular program design allows easy testing of alternative formulations, and means that different representations of some processes can still be used if necessary. Either model on its own, together with ancillary programs for processing input and output data, forms a large software system. The unified model system contains at present about 150,000 lines of code. Maintenance of two separate systems is no longer practicable or justifiable. Furthermore, it had already been decided that incorporating the output processing within the forecast model, as had already been done in the climate model, was a much more efficient method of generating the wide range of products required.

In order to achieve a unified model, however, several key steps had to be taken.

i) Successful use in the climate model of the very efficient split-explicit integration scheme, Gadd(1978), used in the forecast model. This required modifying it to ensure conservation of heat and moisture, and ensuring acceptable performance in climate mode.

ii) Modifying the boundary layer scheme to allow use of the longer timesteps permitted by the split-explicit integration scheme.

iii) Modifying the radiation and cloud scheme to allow use of the higher vertical resolution of the moisture field possible in the existing forecast model, and the planned unified model.

iv) Successful use in the forecast model of more elaborate representations of physical processes, particularly the use of explicit cloud variables and their interaction with radiation.

v) Design of a single maintainable software system to meet all the requirements, while achieving the same efficiency as a single purpose model.

3. DESCRIPTION OF THE UNIFIED MODEL

3.1 Equations of motion

The equations used are a more accurate approximation to the equations of motion than were used in the previous models. They are described in detail by White and Bromley (1988). They differ from those normally used in that the full three-dimensional representation of the effect of the Earth's rotation is included. This is necessary when planetary scale motions are considered, and the vertical component of the Coriolis force may also be important in regions of strong vertical motion.

In addition to the standard equations of motion, an arbitrary number of passive tracers can be advected by the model. This can be used to allow the model to study the evolution of chemical species, but could also be used to treat aerosols.

3.2 Grid and coordinate system

The equations are integrated in spherical polar coordinates, using a 'hybrid' vertical coordinate, Simmons and Burridge (1981). This is a function of pressure, equal to unity at the lower boundary, and equal to a multiple of pressure at the upper levels. It is chosen because terrain following coordinate surfaces are much more convenient in the lower layers of the atmosphere, while pressure coordinates are more likely to give accurate results in the upper layers.The unified model code is designed to allow any distribution of levels. However, it is found in practice that the performance of physical parametrization schemes is very sensitive to the distribution of levels. Most users of the model will therefore be using the standard 20 level configuration shown in Fig. 1. Upper atmosphere modelling will be using a 42 level configuration extending up

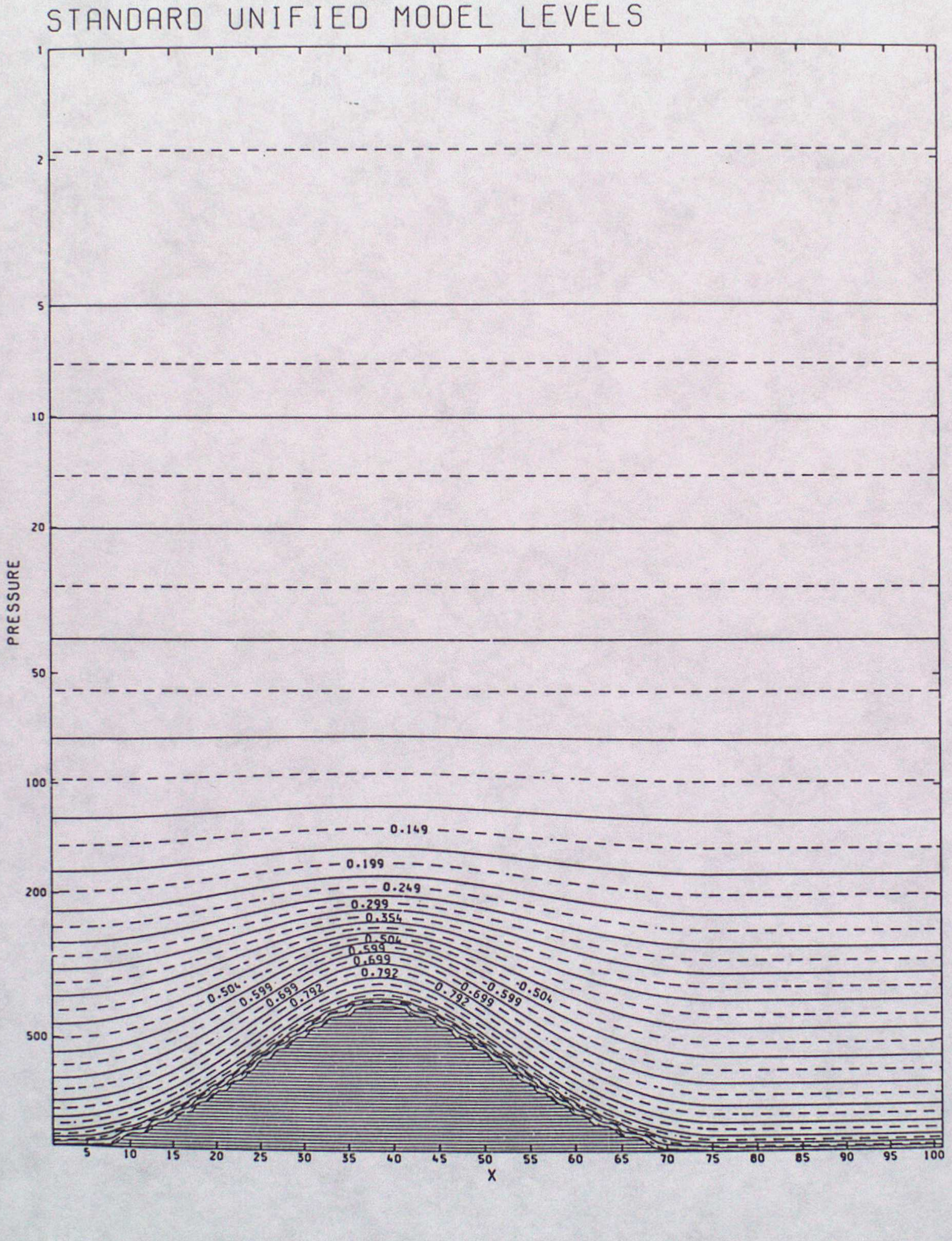

Fig.1 Standard levels for use in the unified model.

to 0.25 hpa.

A regular latitude-longitude grid is used in the horizontal, with the variables arranged according to the Arakawa 'B' grid as in the operational 15-level model, Gadd (1985). The arrangement of variables in the vertical is also the same as in the 15-level model. The code can be run at any desired resolution, subject to computer memory restrictions. The operational forecast grid has spacing in latitude $\Delta\phi=0.833^{o}$ and in longitude $\Delta\lambda=1.25^{o}$. The standard climate and upper atmosphere configurations will use $\Delta\phi=2.5^{o}$, $\Delta\lambda=3.75^{o}$.

The limited area model also uses spherical polar coordinates. However, to obtain uniform resolution over the area of interest, the coordinate pole is not placed at the geographical pole. This idea was first introduced in the Irish limited area model, Unden (1980). The unified model can be run with any choice of coordinate pole and area. the operational limited area model has the coordinate pole at 30^{o}N, 160^{o}E. The integration area is shown in Fig. 2.

3.3 Finite difference scheme

The split-explicit finite difference scheme used in the 15 level model is very efficient, and there was no need to chnage it for purely forecast applications. However, finite difference schemes for climate modelling have to satisfy additional requirements. total heat and moisture must be conserved under advection, and the conversions between kinetic and potential energy implied by the model dynamics must add up to zero when integrated over the domain. To meet these requirements, the Lax-Wendroff advection scheme was replaced by the Heun scheme, and the separation of calculations between the long advection step and the short adjustment step had to be altered. The new scheme is described in detail by Cullen and Davies (1991).

As with the previous model, Fourier filtering has to be used at high latitudes in the global model in order to prevent an undesirable restriction on the timestep that can be used. However, to ensure conservation, it is necessary to filter increments to the temperature and moisture fields rather than to filter the fields themselves. No filtering

Fig.2 Operational limited area model grid

is required in the limited area model.

3.4 Parametrizations

It is expected that a library of parametrizations will gradually become available for the unified model. those that are being used initially are desribed briefly below.

i)*Land surface model.* A multilayer soil temperature model and a soil moisture prediction scheme are included. Different soil types are specified, and used to determine the surface albedo. A model of the vegetation canopy is included. Moisture can be retained in the canopy or transferred to the soil or atmosphere. Different vegetation types can be specified. Snow depth is predicted and used in the calculation of albedo. The scheme is described in detail by Smith (1990) and Gregory and Smith (1990).

ii)*Boundary layer.* Vertical turbulent transport of primary variables and tracers in the boundary layer depends on the local Richardson number. The presence or absence of cloud is taken into account in calculating the transport coefficients. The scheme is described in Smith (1990).

iii)*Large-scale cloud and precipitation.* Large scale clouds are represented by their liquid water (or ice) content. The total optical thickness of the clouds is taken into account in the radiation calculations, Ingram (1990). Large-scale precipitation is calculated in terms of the water or ice content of the cloud; frozen cloud starts precipitating as soon as it forms. Cooling of the atmosphere due to evaporation of precipitation is included. The scheme is described by Smith and Gregory (1990).

iv)*Convection.* Sub-grid-scale convective processes are modelled using a simple cloud model; convection affects the large-scale atmosphere through compensating subsidence, detrainment, and the evaporation of falling precipitation. The scheme is described and illustrated by Gregory (1990) and Gregory and Rowntree (1991).

v)*Radiation.* The radiation calculation uses six bands in the long wave and four in the solar calculation. It allows for water vapour, ozone, carbon dioxide, and the large scale and convective cloud distributions. Cloud radiative properties depend on cloud water and ice content. The scheme is descibed by Ingram (1990).

vi)*Gravity wave drag.* The effects of the drag caused by sub-grid-scale gravity waves is estimated using the sub-grid variance of the orography and the known absorption properties of gravity waves in a given atmospheric profile. The scheme is described by Wilson and Swinbank (1990).

vii)*Horizontal eddy diffusion.* This is represented by simple grid scale filters The filters can be iterated to make them more scale selective for use at low resolution. The method is described by Cullen, Davies and Mawson (1991).

viii)*Vertical eddy diffusion.* This is sometimes required to remove oscillations caused by inadequately resolved quasi-inertia waves. Only the winds are smoothed. The method is descibed by Wilson (1990).

The calculations of surface exchanges require values of a number of surface parameters. Distributions of sea-ice and snow cover must be specified. Over the open sea, the surface contact temperature has to be analysed for forecast use. Over the land, sets of parameters defining the soil and vegetation characteristics must be specified.

3.5 <u>Coupling to other models</u>

Various types of coupling are available.

i)*Ocean model.* The atmosphere model can be coupled to both global and limited area ocean models. It can also be coupled to a highly simplifed ocean model known as a 'slab' model. The unified model system can be used to run ocean-only integrations.

ii)*Stratosphere only model.* The full atmosphere model can be used to generate the heights of an isobaric surface to drive a version of the unified model model covering only the stratosphere.

iii)*Limited area model.* The global atmosphere model drives the limited area version by generating values of the prognostic variables in a boundary zone. When the limited area model is integrated, the values on the boundary are constrained to be the same as those in the global model, with those close to the boundary replaced by a weighted mean of predicted values and prescribed values from the global model, Davies (1976).

iv)*Wave model.*This is driven by 10m winds output from the atmosphere model. It is likely that in future the wave model will be coupled to the atmosphere model and used to predict the surface roughness over the sea.

v)*Surge model.* This is deriven by model surface pressure and wind output.

vi)*Mesoscale model.* Complete model fields over the mesoscale area are supplied at hourly intervals.

3.6 Software implementation

An overview of the unified model software system is shown in Fig. 3. The main components are:

i)*User interface.* A panel driven system which allows a user to run any version of the model with any choice of diagnostic output. It holds a library of previous experiments conducted by the user, so that it is easy to make small changes to a previous experiment with the model.

ii)*Reconfiguration.* A system for converting an input unified model data set to a new resolution, importing new ancillary or analysed data, and expanding the data set to make room for extra diagnostics.

iii)*Model.* The atmosphere and/or ocean model is integrated with data assimilation if required.

iv)*Stash diagnostics.* Diagnostics generated in each section of the model are processed as required by the user, either being output to the front end computer or being retained for later time averaging.

v)*Output streams.* This includes the output for coupling to other models, dumps to allow integrations to be restarted, and chart output. Output can be time-meaned if required.

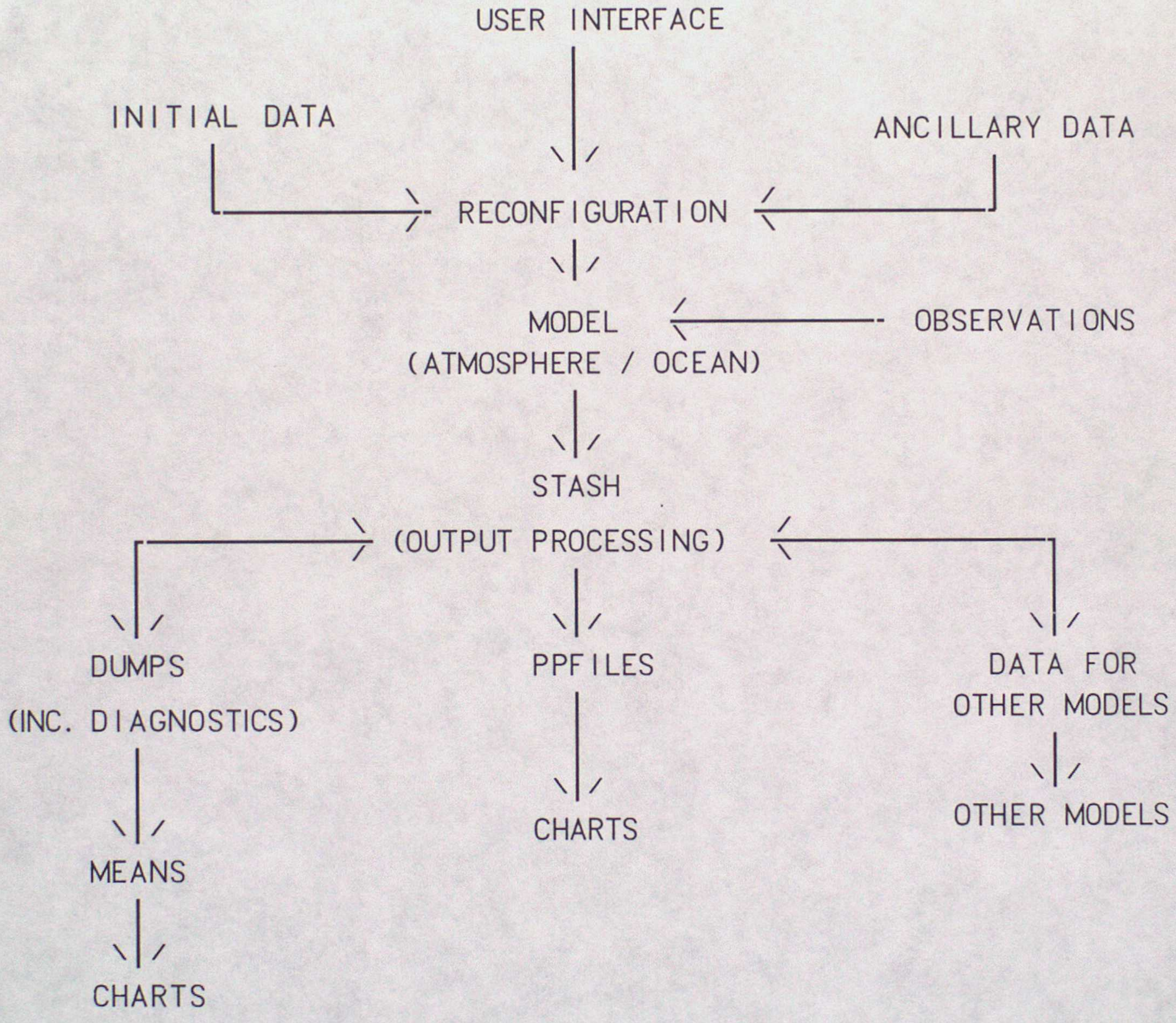

Fig.3 Unified model software system.

4. EXAMPLES OF THE USE OF THE UNIFIED MODEL.

4.1 Global forecasting

The enforcement of conservation properties in the integration scheme is the main dynamical difference between the unified model and the previous Meteorological office forecast model. This appears to be the reason why the unified model is much better at predicting upper ridges. An example is shown in Figs. 4-6. The ridge in the verification 500hpa chart (Fig. 4) developed over the previous 4 days. Though the unified model slightly underestimates the amplitude, it is still 12dm greater than that produced by the old forecast model. Other experiments showed that the resolution difference betweeen the two models had only small effects on this type of development.

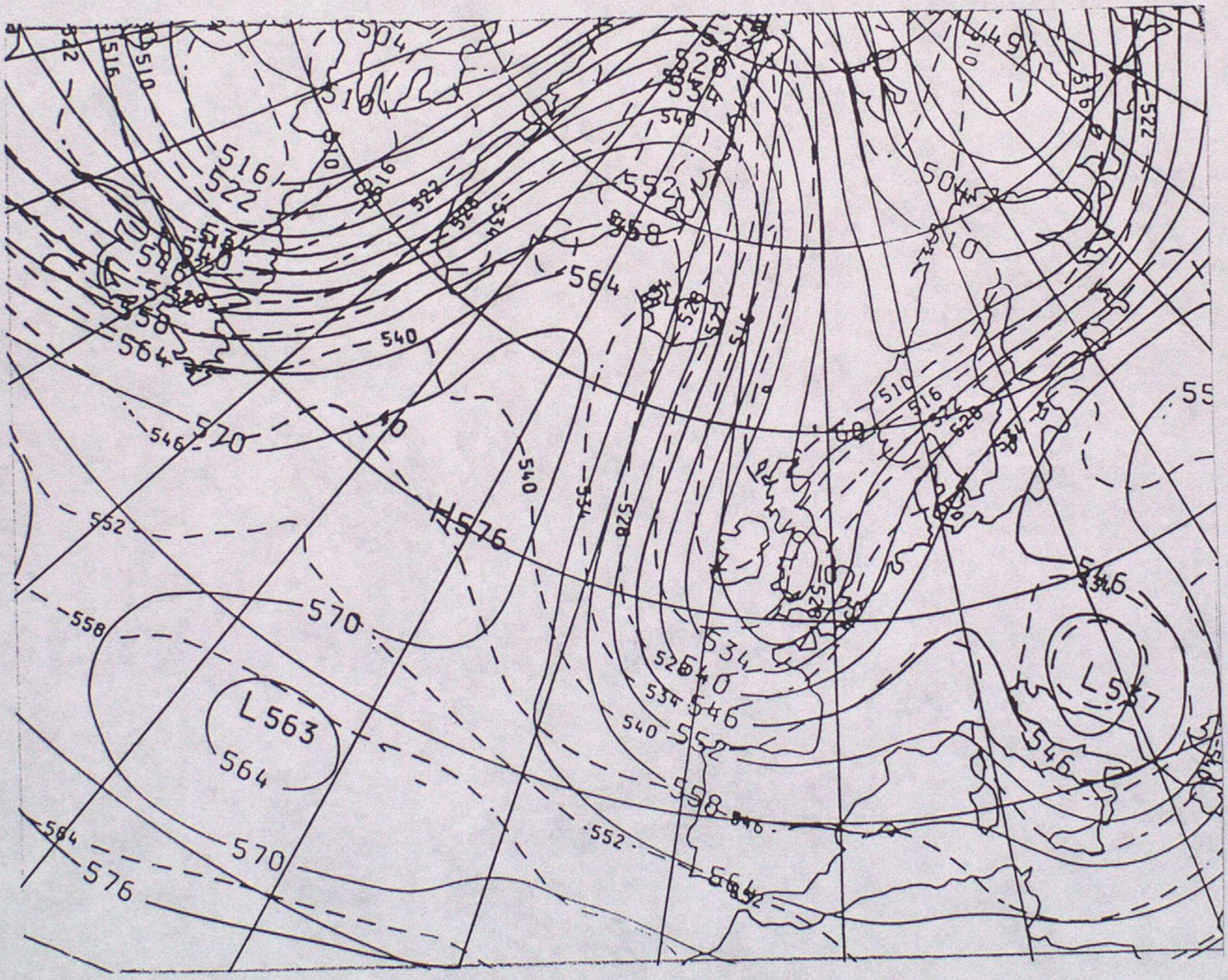

Fig. 4 500hpa analysis for 0 UTC 8 December 1990

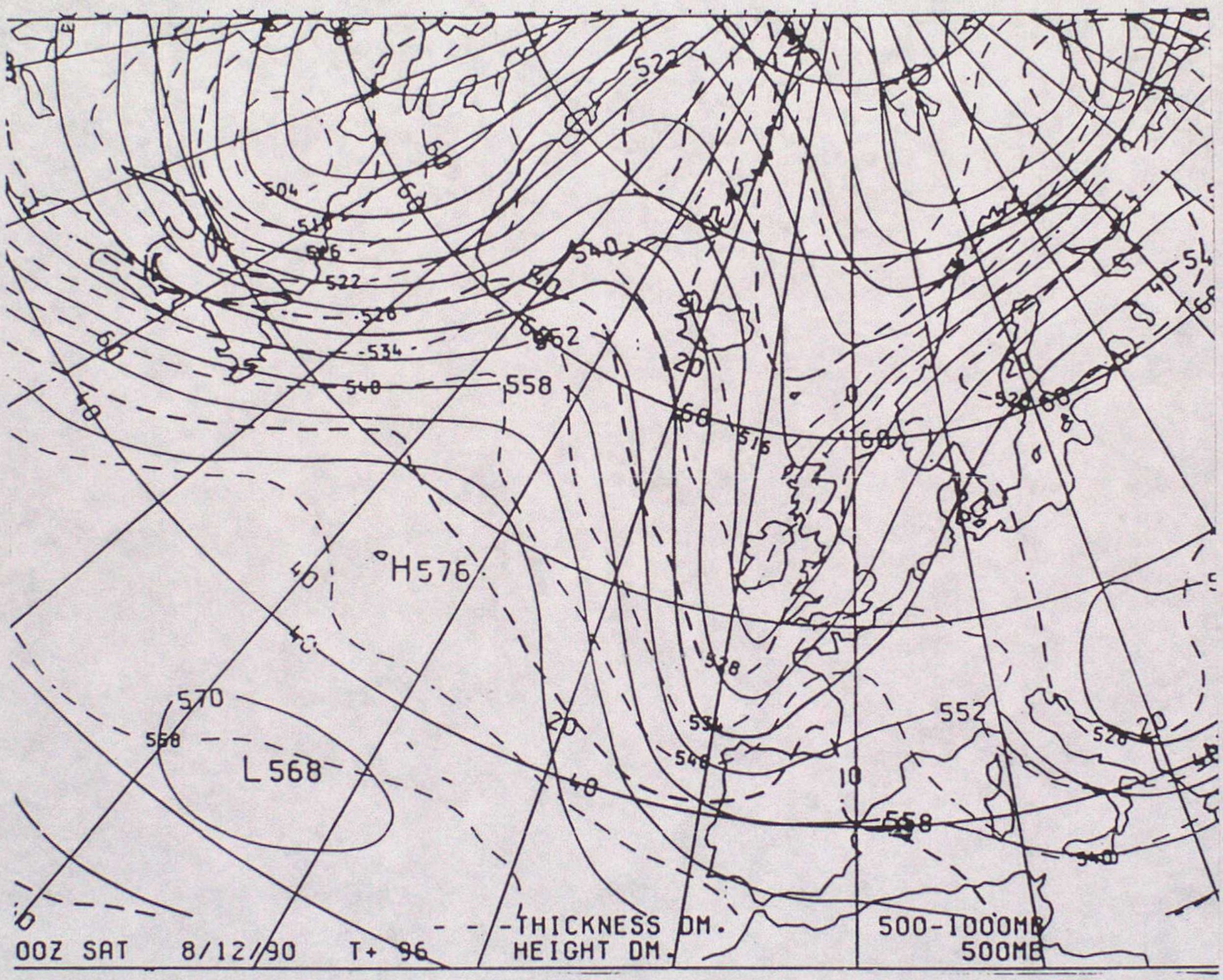

Fig. 5. 4 day 500 hpa forecast valid at 0 UTC using previous Met. Office forecast model.

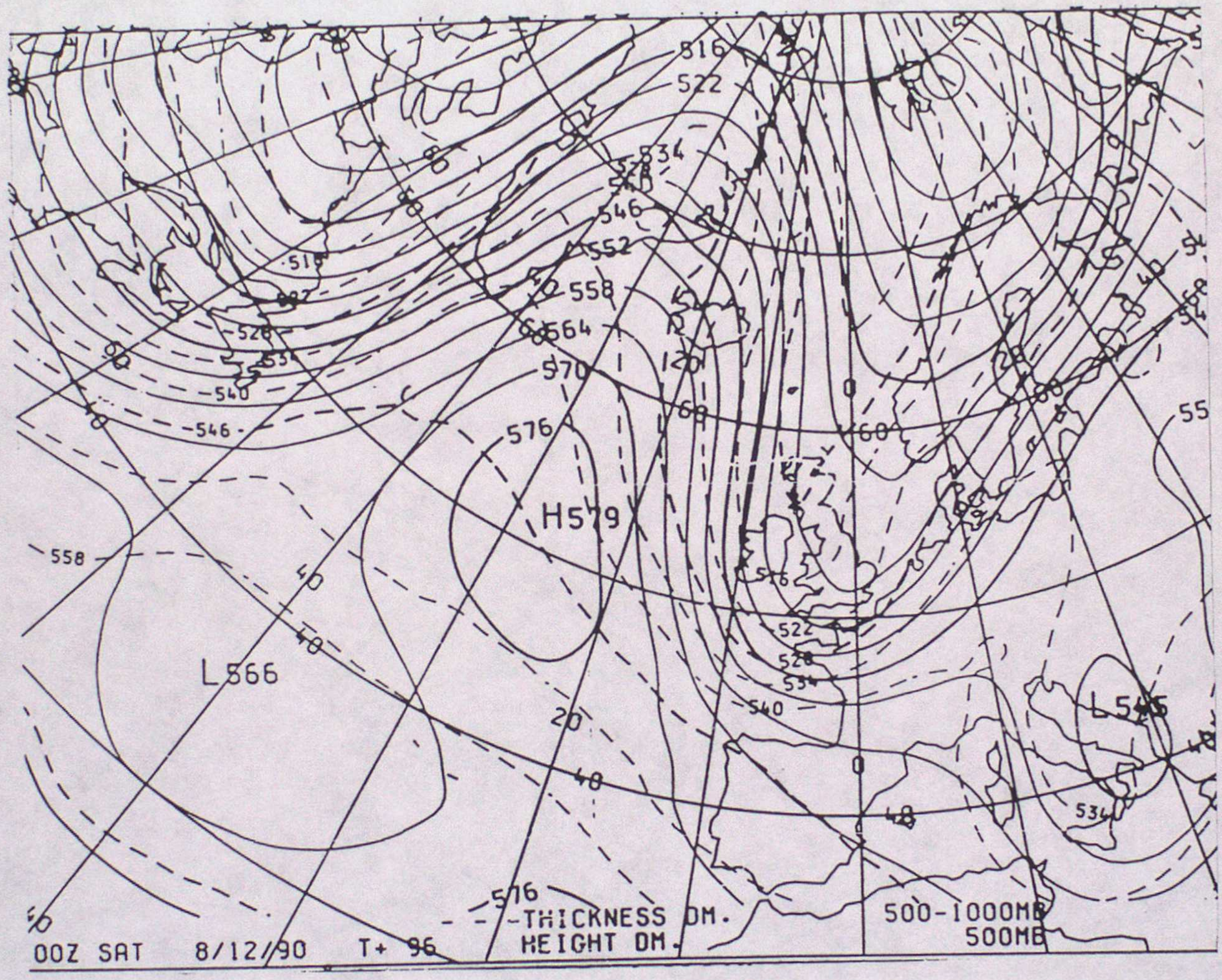

Fig. 6. 4 day 500 hpa frecast valid at 0 UTC 8 December 1990 using unified model.

4.2 Limited area forecast

The higher resolution and possibly the more advanced physical parametrizations of the operational limited area version of the unified model allow it to give a more organised representation of regions of precipitation than the previous limited area model. On occasions, the higher resolution also gives a better treatment of pressure systems. An example is shown in Figs. 7 to 9, where the depression to the east of Scotland is much better represented by the new model 24 hours ahead.

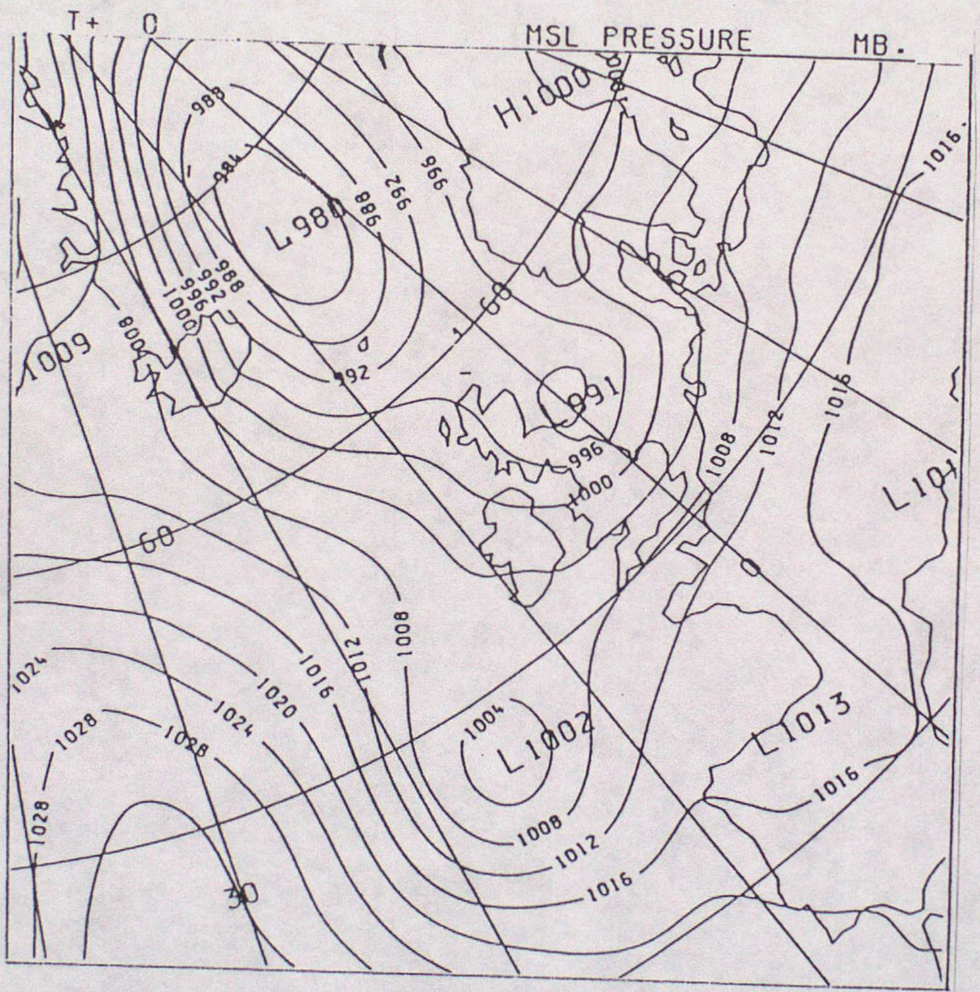

Fig. 7. Surface pressure analysis for 00 UTC on 21 March 1991.

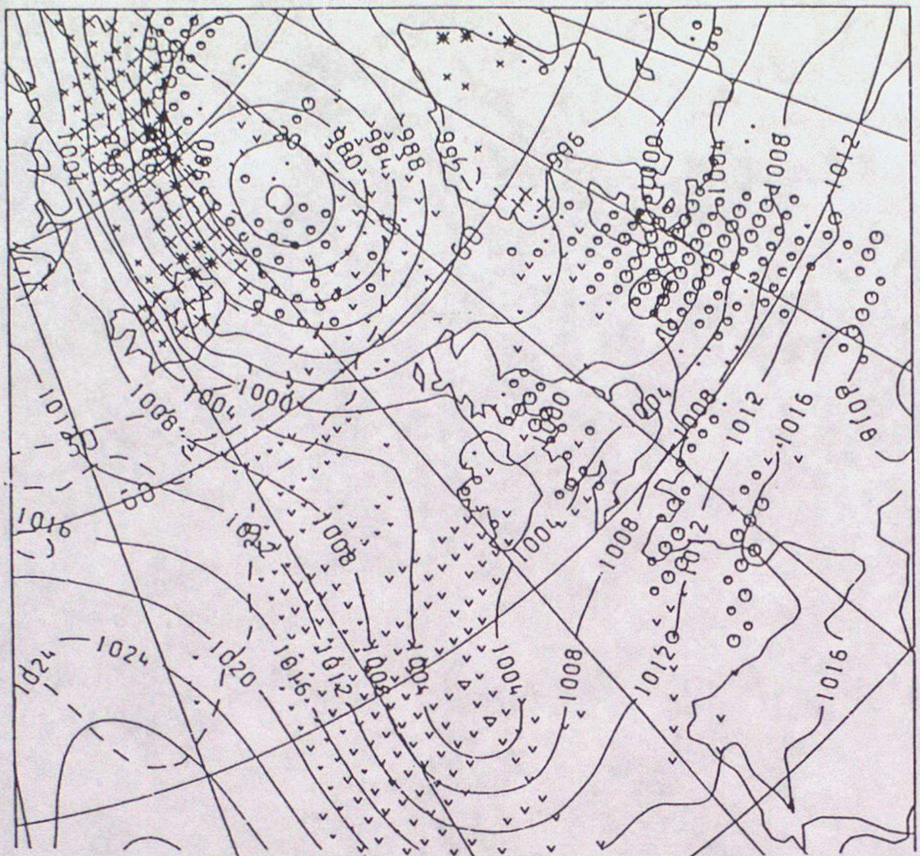

Fig.8. 24 hour PMSL forecast for 00 UTC 21/3/91, previous model.

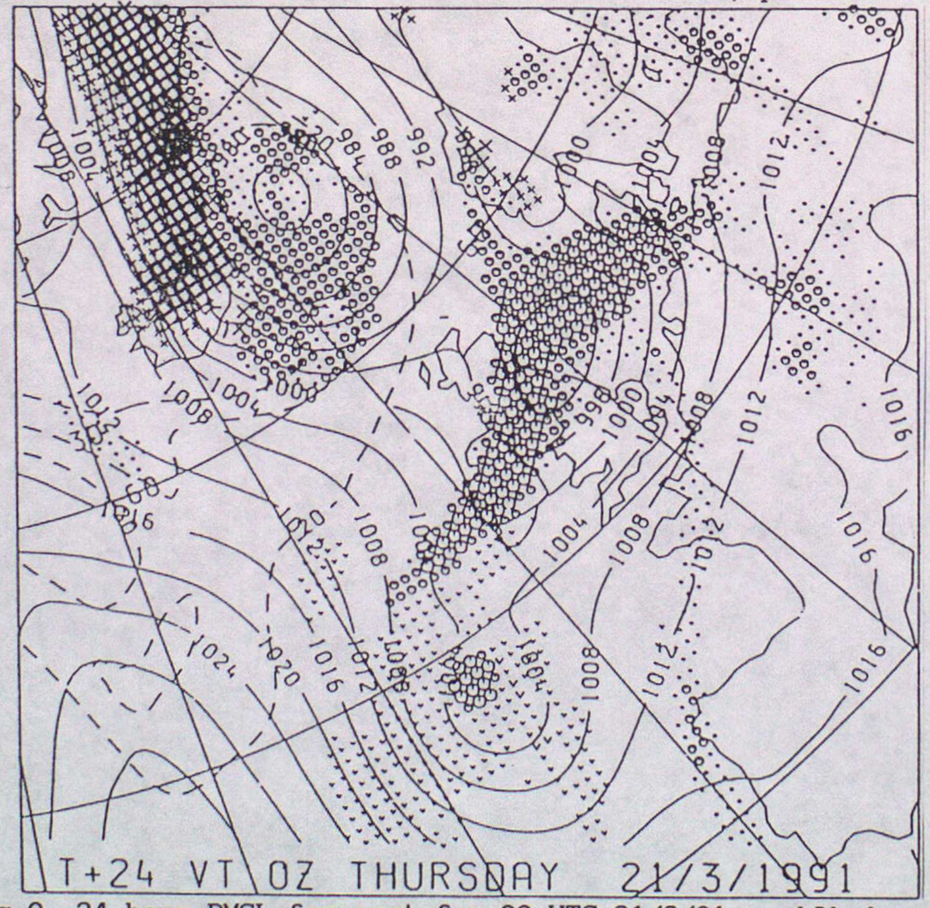

Fig.9. 24 hour PMSL forecast for 00 UTC 21/3/91, unified model.

4.3 Long range forecasting

The standard long-range forecast procedure is to run a set of nine forecasts from data times six hours apart, Milton(1990). The results are then averaged over a set of forecast periods, including days 6-15 and days 16-30. An example of an exceptionally good forecast made from the average of forecasts from data times between 18 and 20 May 1991, verifying for the period 26 May to 4 June, is shown in Figs. 10 and 11. The cool north-easterly flow over the United Kingdom is very well predicted. This forecast had an anomaly correlation coefficient of 0.79. The average value of this coefficient for unified model forecasts for this range to date is 0.17. The unified model was used with a 2.5×3.75^{0} grid for these simulations, a lower resolution than had been used previously. However, the performance relative to the previous model is similar to that of the short range forecasts, where higher resolution is used in the unified model than previously. This emphasises the importance of other aspects of the dynamical and physical formulation of the model.

4.4 Climate simulation

Figs. 12 and 13 show the typical winter simulation of the surface pressure and rainfall from the model. Figs. 14 and 15 show a typical summer simulation. All the diagrams are 90 day means. The main features of the observed circulation and rainfall distribution, particularly in the tropics, are clearly seen. However, the North Atlantic circulation is incorrect, with the centre of cyclonic activity too far south. It is found that the circulation is very dependent on the form of diffusion and gravity wave drag used in the model. In particular, the use of low order diffusion results in very poor high latitude simulations in the Southern hemisphere as well.

4.5 Upper atmosphere forecasting

A 5 day forecast of a stratospheric warming event using the 42 level version of the model is shown in Figs. 16 and 17. The 10hpa height is illustrated. At the initial data time, there was a single polar vortex at this level. The model has correctly forecast the splitting of the vortex into two, though it has produced two separate upper high centres rather than the cross-polar ridge shown in the observations.

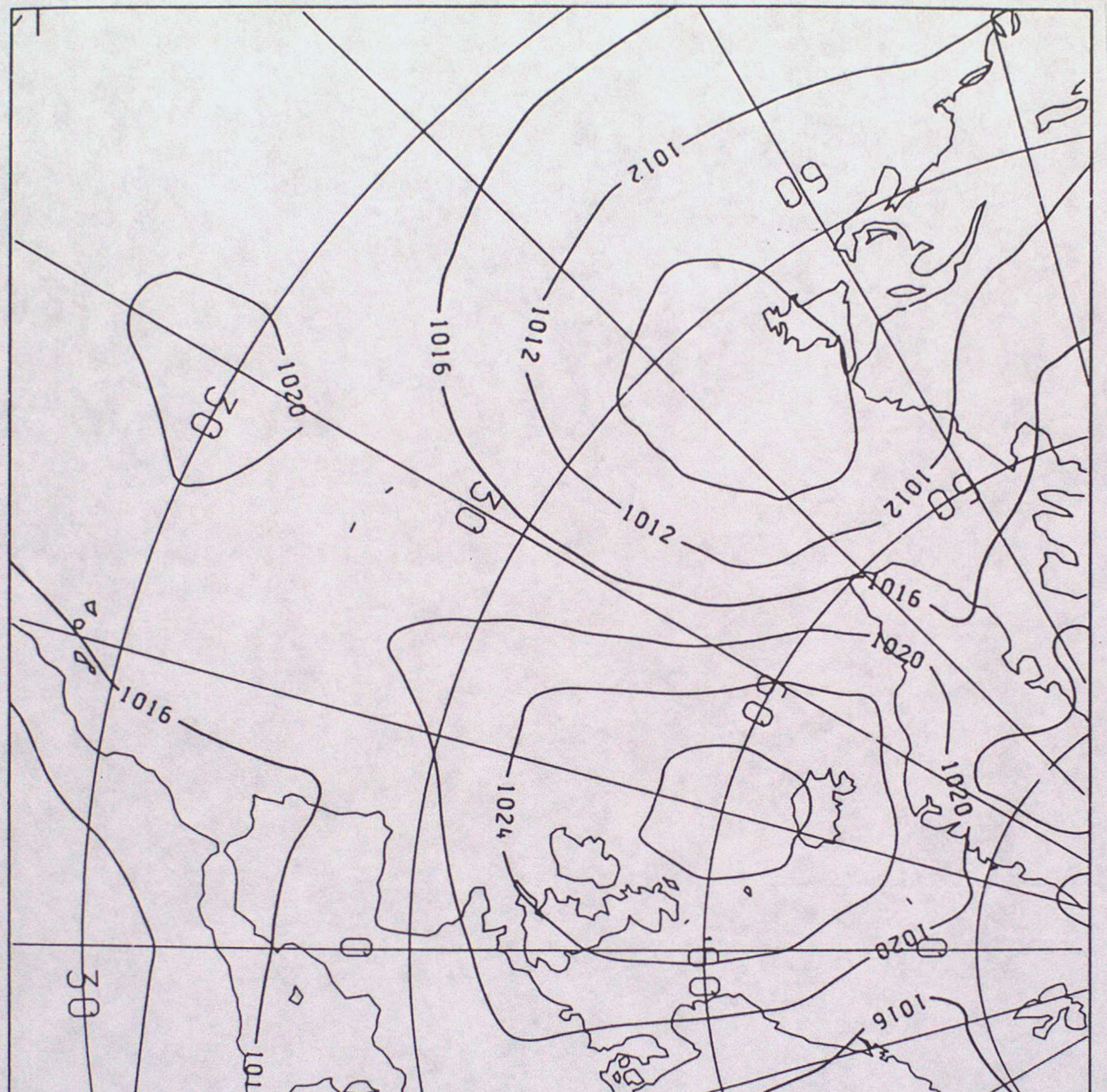

Fig. 10. Mean surface pressure analysis from 00 UTC 26 May to 00 UTC on 4 June 1991.

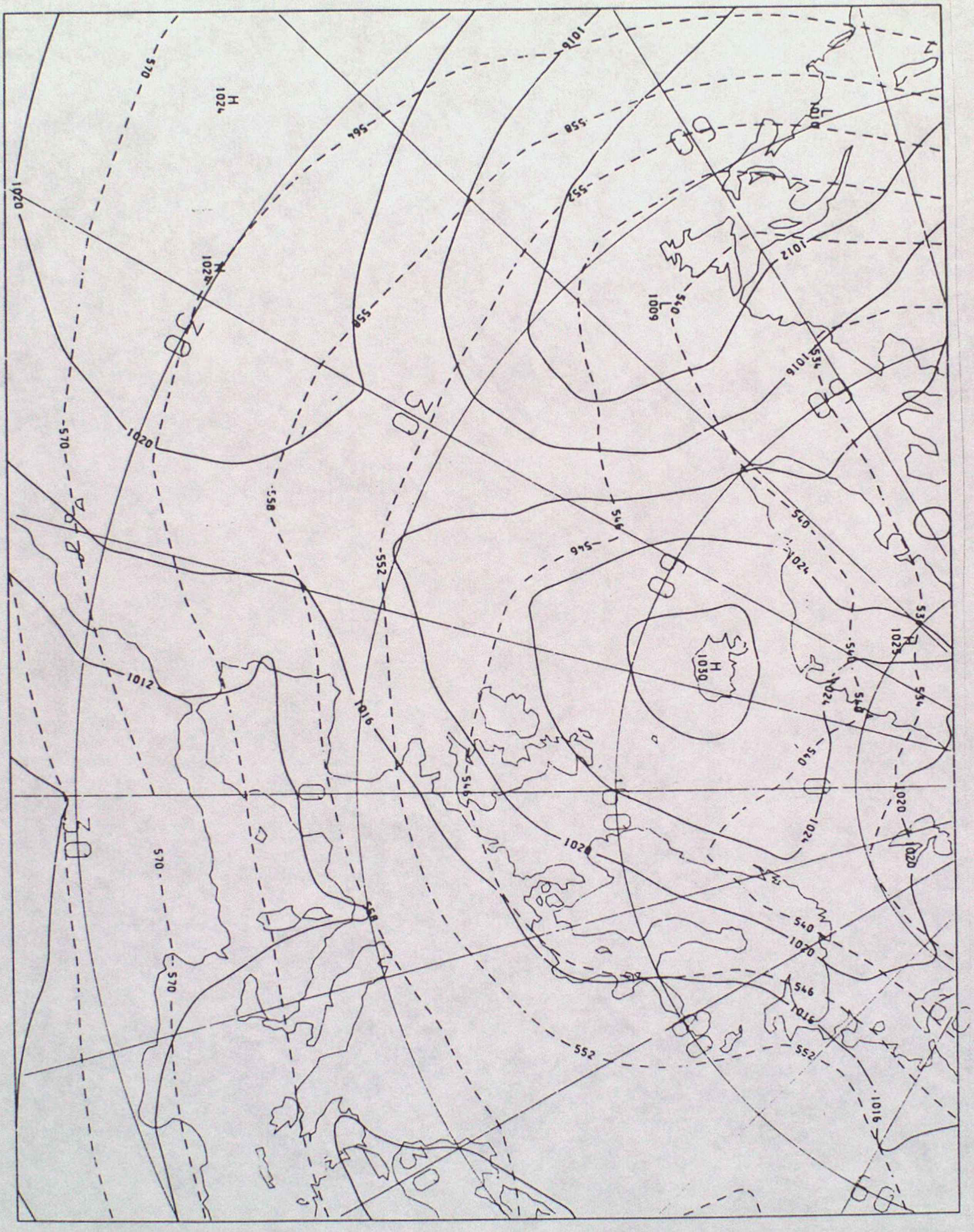

Fig. 11. Forecast mean surface pressure from 00 UTC 26 May to 00 UTC 4 June 1991, ensemble mean of nine forecasts from data times 00 UTC 18 May to 00 UTC 20 May, using unified model.

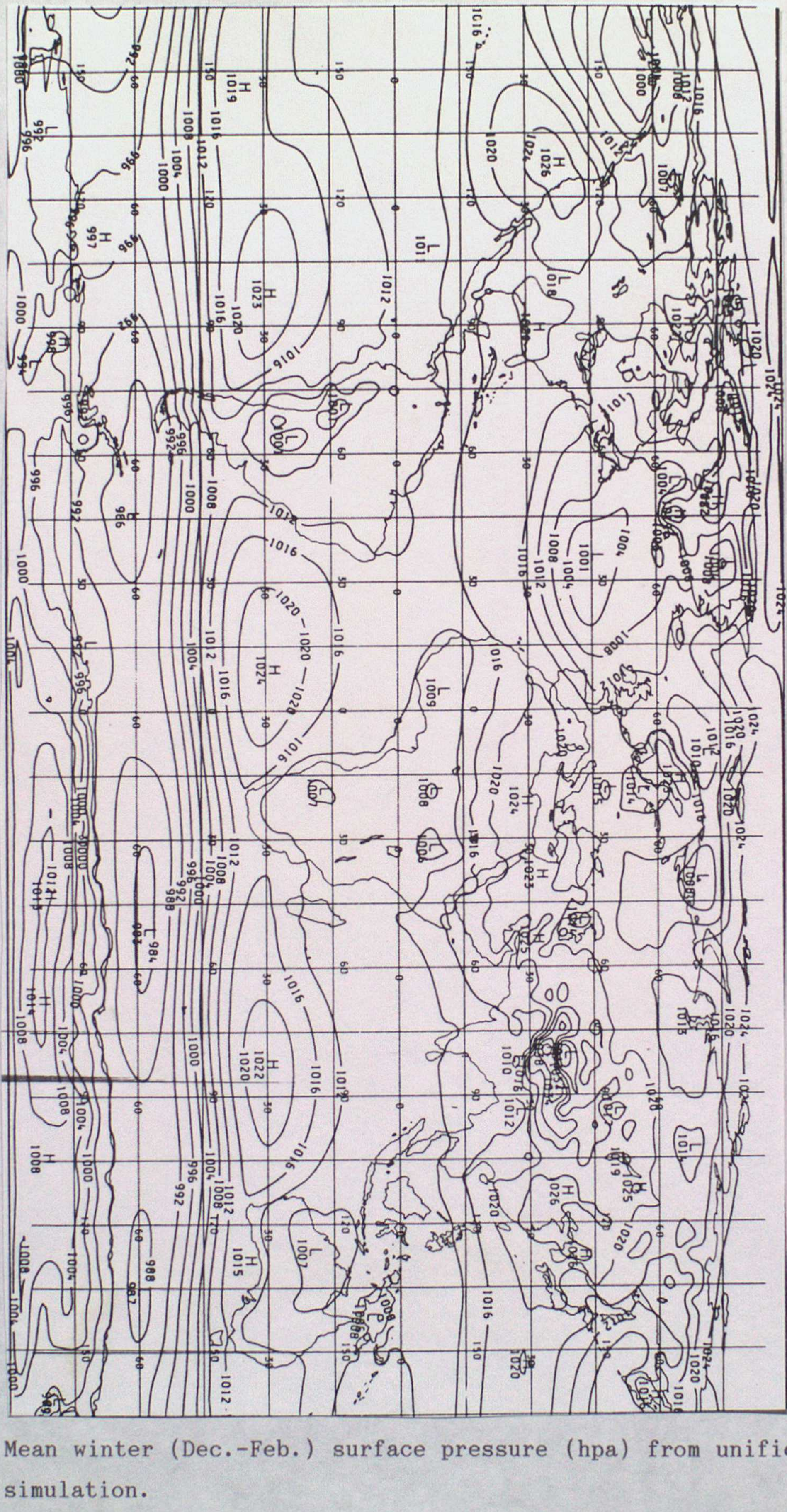

Fig.12. Mean winter (Dec.-Feb.) surface pressure (hpa) from unified model climate simulation.

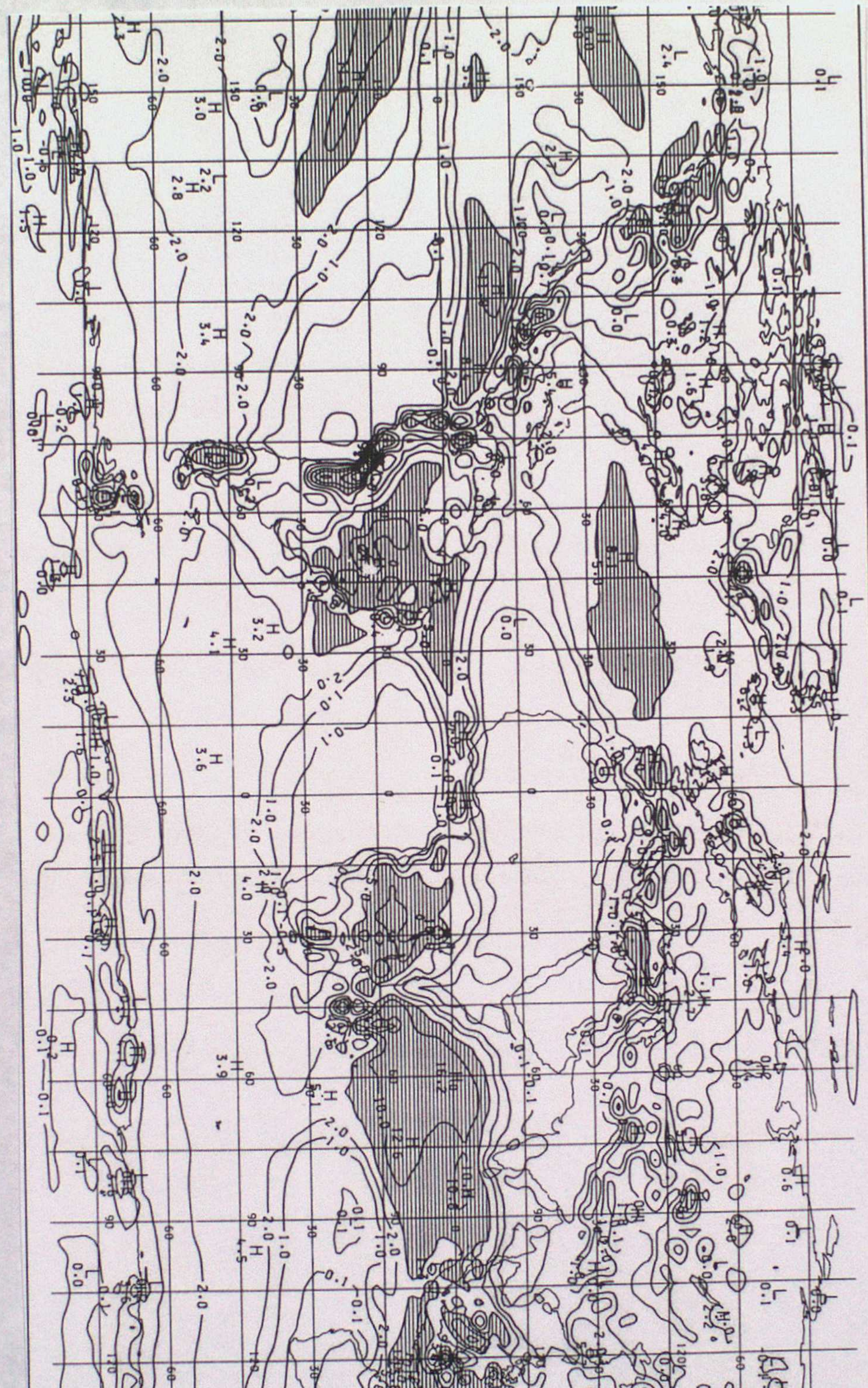

Fig.13. Mean winter (Dec.-Feb.) precipitation (mm/day) from unified model climate simulation. Isopleths at .1, 1, 2, 5, 10, 20 and every 20.

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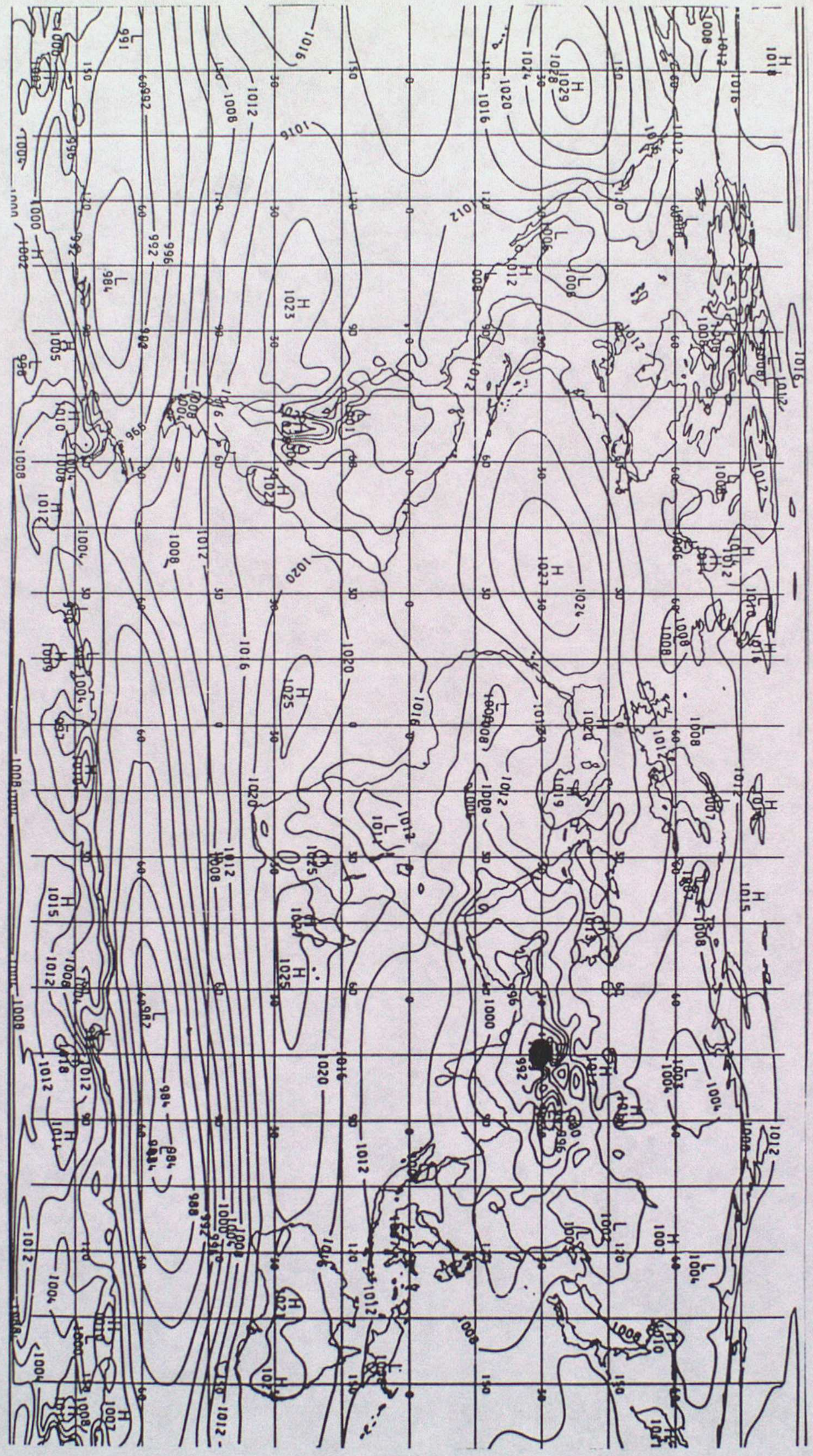

Fig.14. Mean summer (Jun.-Aug.) surface pressure (hpa)from unified model climate simulation.

Fig.15. Mean summer (Jun.-Aug.) precipitation (mm/day) from unified model climate simulation. Isopleths at .1, 1, 2, 5, 10, 20 and every 20.

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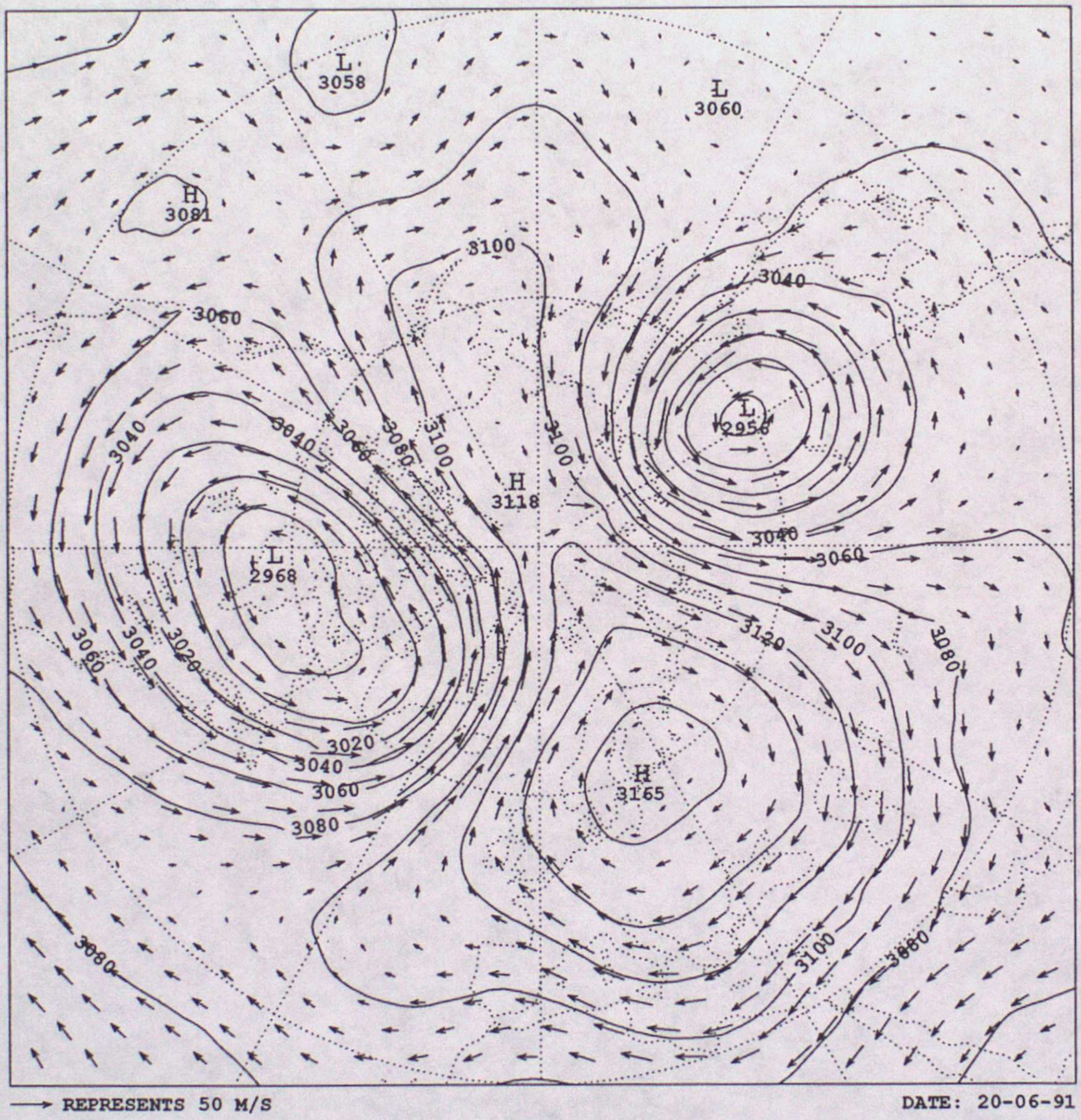

Fig. 16. SSU analysed 10 hpa height for 12 UTC 20 February 1989.

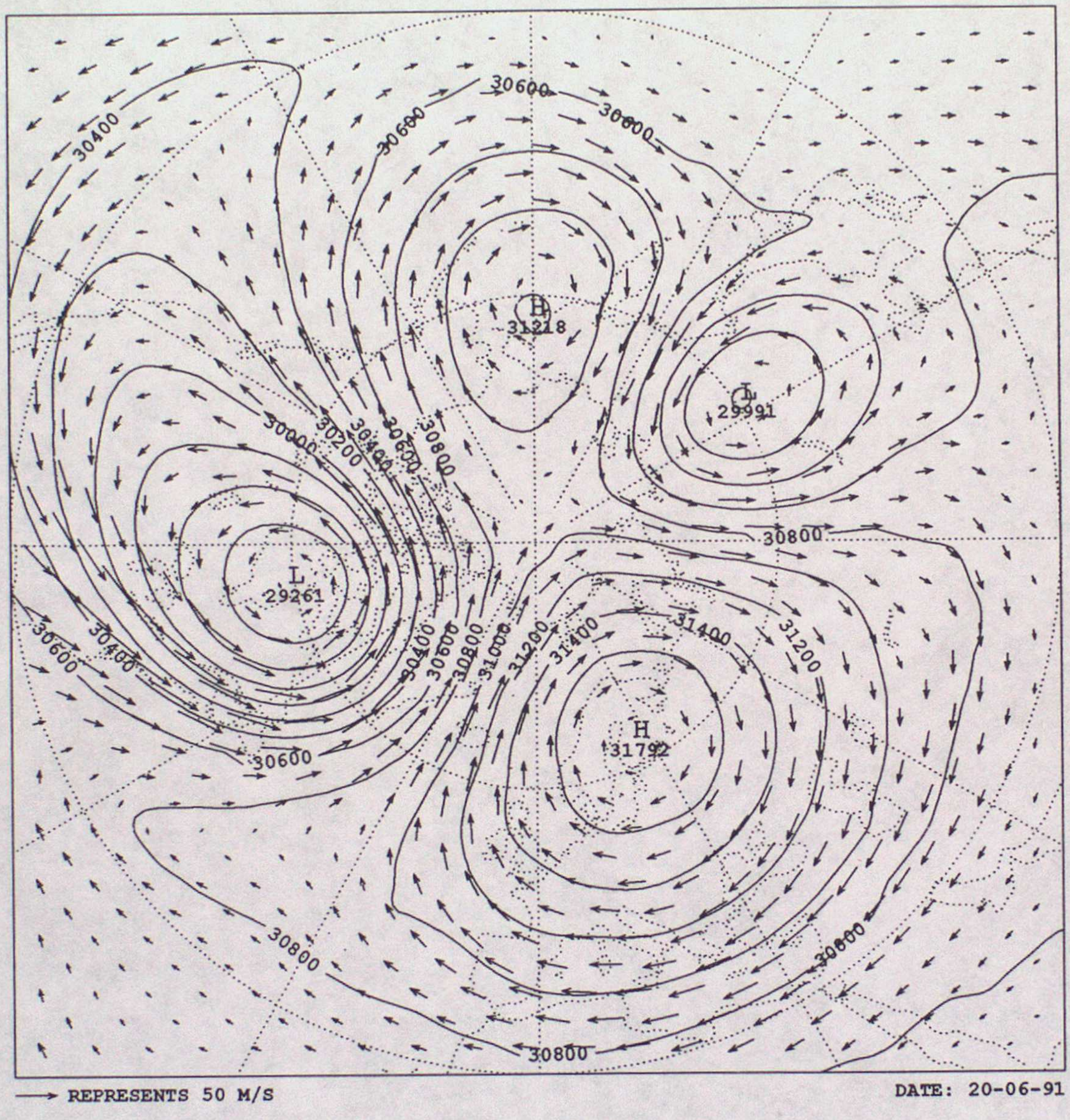

Fig. 17. 5 day forecast of 10 hpa height valid 12 UTC 20/2/1989 using upper atmosphere configuration of unified model.

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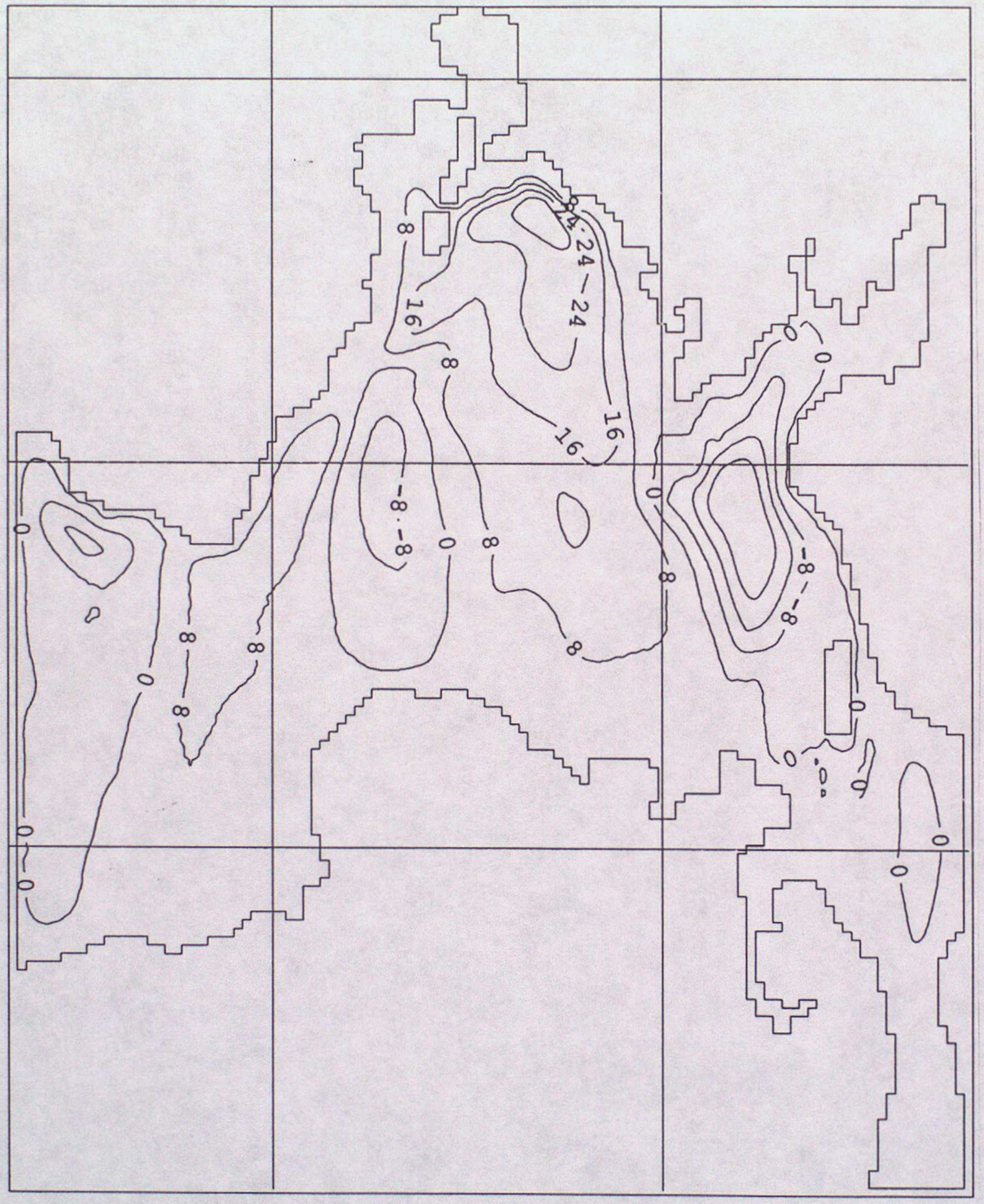

Fig. 18. Streamfunction (Sverdrups) for North Atlantic predicted by ocean model, valid on 1 October.

Fig.19 90 day mean (Dec-Feb) of surface temperature (^{o}K) from coupled ocean-atmosphere integration of unified model.

4.6 Ocean forecast

Fig. 18 illustrates the streamfunction for the North Atlantic forecast by the ocean component of the unified model running independently at 1° latitude/ longitude resolution. This is an instantaneous result after 1.5 years integration. The main coastal currents along the East Coast of the Americas are clearly seen.

Fig. 19 illustrates the surface temperature predicted by the unified model running in coupled ocean/atmosphere mode. This is a mean for the Northern hemisphere winter. The ice edge is claerly seen. The tropical sea temperatures are too high illustrating that techniques for coupling ocean/atmosphere simulations are still in a relatively early stage of development.

References

Corby,G.A.,Gilchrist,A.and Rowntree,P.R.,1977:United Kingdom Meteorological Office five-level general circulation model. Methods Comput Phys,17,67-110.

Cullen,M.J.P. and Davies,T.,1991:A conservative split-explicit integration scheme with fourth order horizontal advection. Q J R Meteorol Soc,117,July B.

Cullen,M.J.P.,Davies,T.and Mawson,M.H.,1991:Conservative finite difference schemes for a unified forecast/climate model. Meteorological Office, Unified Model Doc Paper no.10 (available from librarian)

Davies,H.C.,1976:A lateral boundary formulation for multi-level prediction models. Q J R Meteorol Soc,102,405-418.

Gadd,A.J.,1978:A split-explicit integration scheme fornumerical weather prediction. Q J R Meteorol Soc,104,569-582.

Gadd,A.J.,1985:The 15 level weather prediction model. Meteorol Mag,114,222-226.

Gregory,D.,1990:Convection scheme. Meteorological Office, Unified Model Doc Paper no.27 (available from librarian)

Gregory,D. and Rowntree,P.R.,1991:A mass flux convection scheme with representation of cloud ensemble characteristics and stability dependent closure. Mon Weather Rev,119, to appear.

Gregory,D. and Smith,R.N.B,1990:Canopy, surface, and soil hydrology.Meteorological Office, Unified Model Doc Paper no.25 (available from librarian)

Ingram,W.J.,1990:Radiation.Meteorological Office, Unified Model Doc Paper no.23 (available from librarian)

Milton,S.F.,1990:Practical extended range forecasting using dynamical models. Meteorol Mag,119,221-233.

Simmons,A.J. and Burridge,D.M.,1981:An energy and angular momentumconserving finite difference scheme and hybrid coordinates. Mon Weather Rev,109,758-766.

Smith,R.N.B.,1990:Subsurface, surface, and boundary layer processes. Meteorological Office, Unified Model Doc Paper no.24 (available from librarian)

Smith,R.N.B. and Gregory,D.,1990:Large-scale precipitation.Meteorological Office, Unified Model Doc Paper no.26 (available from librarian)

Unden,P.,1980:Changing the spherical grid for LFMs. LAM newsletter no.1, available from SMHI, Norrköping, Sweden.

White,A.A. and Bromley,R.A.,1988:A new set of dynamical equations for usein numerical weather prediction and global climate models. Meteorological Office, Met O 13 Branch Memo (available from National Meteorological Library, Bracknell)