TECHNICAL MEMORANDUM

99

A valley filled orographic representation in numerical weather forecast models

D. Radinovic

Research Department

March 1985

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Abstract

An attempt has been made to formulate an orography for numerical weather forecasting models which takes into account the orographic influences on synoptic-scale motion. The basic concept concerns the specification of a model orography over mountain complexes in which there is significant filling of the valleys with cold air. This occurs when a cold air mass penetrates into a mountain complex, or when a period of undisturbed weather leads to an accumulation of cold air in the valleys.

Bell and Thompson (1980) studied flow over a periodic saw-tooth topography in order to determine the circumstances under which flow in the valleys is "swept-out" or remains stagnant with the flow passing overhead. In the approach described here, their results are assumed to be valid for mountain complexes of moderate dimensions. This is supported by observations and synoptic analyses from the Alpine region.

Further, observations and investigations about the build-up of temperature inversions and the information about cold pools obtained in ASCOT (Atmospheric Studies in Complex Terrain) and ALPEX showed that valley temperature inversions are common throughout the year. This suggests that the local circulations in the valleys does not have much affect on the flow above the ridge tops - therefore the synoptic scale orographic forcing does not depend predominantly on the shape of the valleys.

On the basis of the two mechanisms of cold air accumulation and stagnation, the concept of a self-creating $\sigma=1$ surface has been formulated, and a new orography based on these ideas computed.

In order to compare different orographies, some geometric features of the real and four model prescribed orographies have been examined; the features studied are the meridional variation of land and sea, the terrain height frequency, the surface area occupied by land at different elevations, the deviation between the heights of the real and model orographies, and the slope and volume of the various orographies.

All the model orographies described here are for the ECMWF gridpoint model with a 1.875° lat-long resolution (192,97 grid points) and are derived from the United States Navy Dataset which has topographic heights on a 10' lat-long grid.

C O N T E N T S

1. INTRODUCTION

Long synoptic experience, as well as the latest assessment of numerical model outputs, shows that the most pronounced systematic errors in the short range weather forecasts appear in mountainous areas (Wallace, Tibaldi and Simmons, 1982; Akesson, Bolger and Pümpel, 1982; Johannessen, 1982). This is likely to be a consequence of a number of deficiencies in treating the effects of orography in the forecast models. On the other hand, these deficiencies may be due to an insufficient understanding of the various effects of the mountain complexes on the atmosphere, which then creates difficulties in treating orography both theoretically and numerically. Consequently the way in which the earth's topography is usually treated in numerical models is predominantly a matter of geometry. Thus the processes of smoothing, height rising or some other way of modelling orography is not directly based on the corresponding behaviour of the atmosphere over the mountain complexes.

There are several significant theoretical and numerical problems connected with the influence of orography on the atmosphere. But, from the point of view of improving weather forecasts, the synoptic-scale representation of orographic effects in numerical models is very important. It is the intention of this paper to describe an orographic representation which involves the self-creation of a σ=1-surface over the mountain complexes resulting from the accumulation of cold air and its stagnation in the valleys.

2. BASIC CONCEPT OF THE VALLEY-FILLING OROGRAPHY

2.1 Orographic effects relevant to synoptic-scale airflow

To explain the concept of a self-creating σ=1-surface over mountain complexes we shall make use of some numerical and laboratory experiments on stratified flow past obstacles, as well as the observations and investigations made in complex terrain. For that purpose the most relevant results are those obtained by Bell and Thompson (1980) with a periodic saw-tooth topography. Their primary object was to determine the circumstances under which flow in the valleys is "swept out" or remains stagnant with the flow passing overhead. They used a simple two-dimensional model with multiple obstacles and strongly stratified flows where the effects of turbulence are small. The key assumption was that the topography and the flow are periodic in the horizontal x-direction with wavelength L. The top of the model is assumed to be a free slip rigid lid where the vertical velocity and heat flux are both zero. Actually, it was taken as representing an inversion which acts as a barrier with the flow above. In numerical experiments, only one period of the topography was used and the equations were simplified by making the Boussinesq, incompressible and inviscid assumptions.

The results showed that sweeping occurs when the inertial forces dominate the buoyancy forces; when the buoyancy forces dominate there is stagnation. The Froude number, $F = u/\sqrt{gd}$, expresses the ratio of these forces (u is the horizontal velocity and d the depth of the fluid) and the critical case occurs when the forces balance - that is when the Froude number is of order of unity. In general it was found that stagnant fluid existed in the valleys for $F/(1-h/D) \leq 0.3$ and the valleys were swept out for $F/(1-h/D) > 1.3$ where h is the total depth of the valley and D is the total depth of the model.

In order to substantiate the numerical experiments, laboratory experiments were undertaken by the same authors. In these a symmetric saw-tooth shaped obstacle consisting of six ridges and five valleys was towed through a tank. The observed flow in all the valleys was similar, showing that a constant Froude number of about 1.3 can be used to separate stagnant from sweeping flows over the valleys. Also it was concluded that this result is independent of the slope of the valley sides and the total depth of the layer considered.

In their numerical experiments, Bell and Thompson used a total height D (the distance from the bottom of the valley to the top of the model) of 1250 m, a hill height h of 500 m and length L of 4 km. If we increase these values by a factor of 3 to 5 (less than one order of magnitude) we get typical values corresponding to a mountain complex like the Alps.

Following Bell and Thompson, this can be justified as follows; if two integrations are carried out with horizontal length scales L and X, with all other parameters the same except those that depend on L (such as the grid length), then at times t and tX/L and positions (x,z) and (xX/L,z) respectively, the solutions are found to be (u,w,T,p) and (u,wL/X,T,p). This scaling shows that the valley width does not alter the results; it is the vertical length scales that matter. This argument applies only to the hydrostatic model, so that the results are only independent of the horizontal length scale when the hydrostatic approximation is valid. On the other hand, if the atmosphere has a stable stratification the conditions $F<1$ and $(Fh/L)^2<0.1$ are satisfied, and thus the hydrostatic assumption is valid.

Now assume that the results obtained in Bell and Thompson's experiments are valid for large or at least moderate sized mountain complexes, and for synoptic-scale atmospheric processes. Then, instead of running similar experiments under different conditions, we shall try to find some supporting arguments for this assumption from the synoptic evidence. For this purpose the Alps are selected since they are the most important mountain complex in Europe, producing several well-known mountain-induced synoptic-scale phenomena (GARP, 1982). The intricate Alpine mountain range is shown in Fig. 1, but for synoptic scale phenomenon the Alps may be approximated by a simple range about 900 km long and 200 km wide, with a mean height of 2000 to 2500 m.

The idea of the self-creating σ=1-surface over the Alps can be illustrated by following a cold airmass penetration from the northwest towards the Alps. Let us suppose that the airmass is very deep, occupying the whole troposphere, with a high static stability in the lower layers.

As soon as cold air reaches the edge of the Alps, strong deformation of the cold front and all meteorological fields occurs. The cold air is retarded in the horizontal and partially blocked on the upwind side (Tibaldi, 1980). As a consequence an upwind ridge develops and most of cold air below the mountain tops starts to flow around the mountain (instead of over it) causing an acceleration of the frontal movement. The cold air which has accumulated in the windward side of the mountain slowly moves uphill as the large-scale upper trough moves towards the east or southeast. During the penetration through the mountain complex, which usually lasts 12 to 24 hours, the cold airmass fills the deep valleys in a relatively short time (less than an hour).

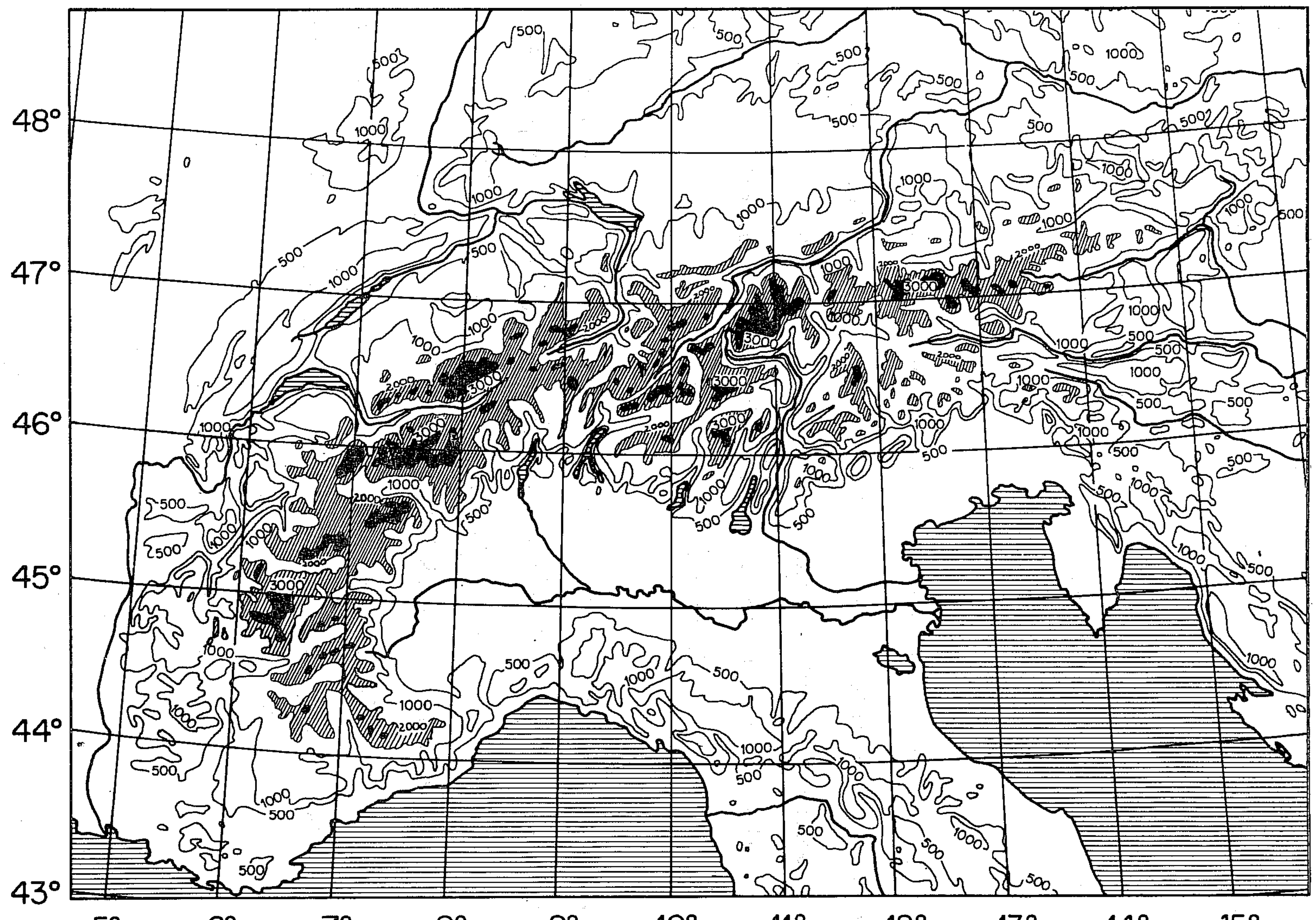


Fig. 1 Contour map of the Alpine massif (copied from GARP, 1982).

After that, air flows over the valleys following a smoother surface created by the atmosphere itself. Some aspects of this process have been analysed by Steinacker (1979) and are illustrated in Fig.2.

As is well known, the most pronounced orographic impact to the meteorological fields occurs during the cold airmass penetration. For that reason, in such situations it is very important to have a corresponding $\sigma=1$-surface in the numerical model which will be able to truly represent the effect of orography.

The $\sigma=1$-surface created by the atmosphere itself does not only occur when there is a cold air invasion. The same happens during the colder part of the year and, according to recent studies, throughout much of the rest of the year. We now consider some of the most relevant studies concerning the cold air accumulation and its stagnation in mountain valleys.

The observations and studies conducted during the last few years in valleys of the Rocky Mountains (ASCOT) and in the Alps (ALPEX) have confirmed the general belief that the cold air from the higher elevation flows by gravity into the lower parts of the landscape, somewhat as water fills the topography of canyons when dammed and flooded. On the other hand, this pooling of the cool air is a significant feature in the model solutions, since in Defant's (1951) descriptive model it is the filling of the valleys with cooled air which produces the along-valley mountain winds.

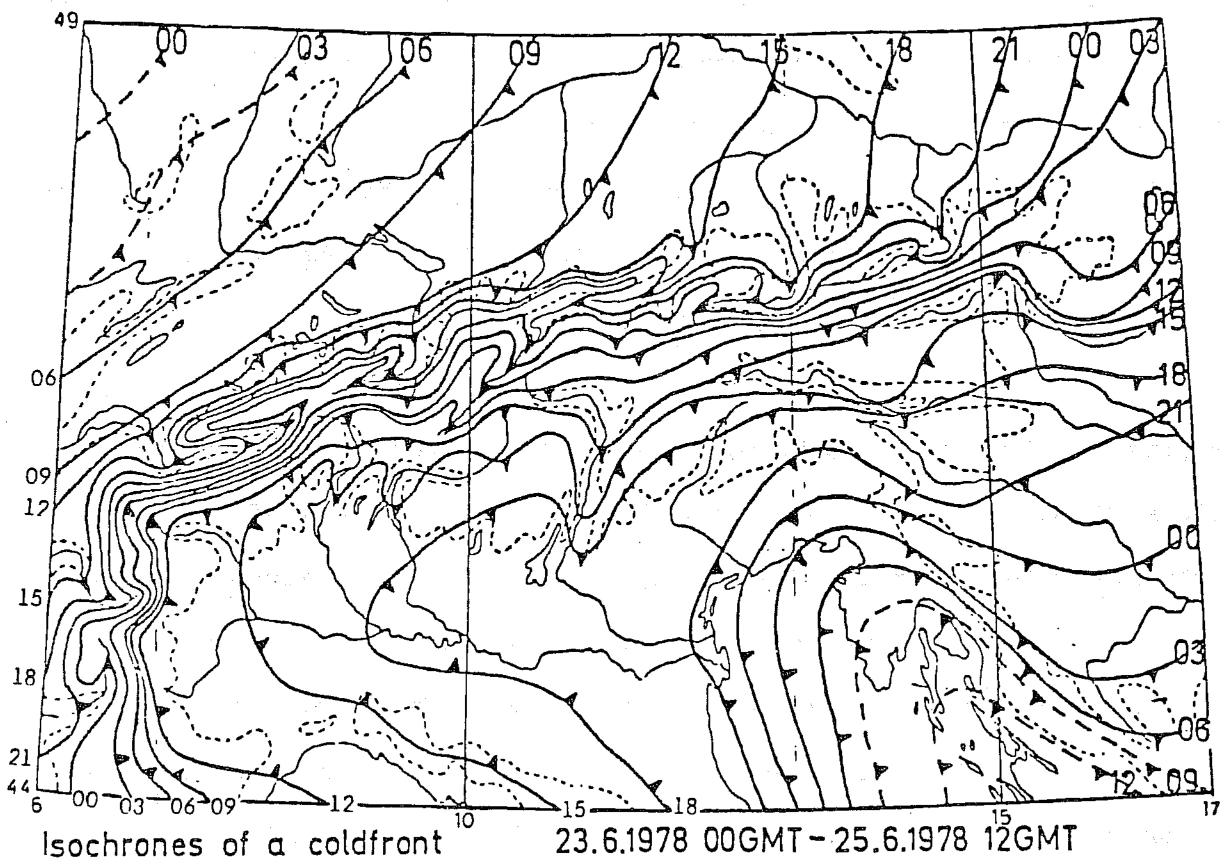


Fig. 2 Isochrones of a cold front crossing the Alps (Steinacker, 1979).

The assumption that the valleys in mountainous regions are filled by cooled air throughout most of the year is in accordance with the studies made by McNider and Pielke (1981). They represented the process of valley temperature inversion formation by numerical simulations of slope and mountain flows. As the sidewall slopes cool, the slope flows begin to fill they valley with cooler air. Initially there is only a slight stratification in the valley, while after six hours of slope flow an inversion has formed within the entire 2 km deep valley. That is represented in Fig. 3 by contours of potential temperature. From Fig. 4, which gives temperature profiles over the centre of the valley, it can be seen that the entire profile within the valley is cooled with time. This cooling pattern is consistent with that observed in deep valleys in the Rocky Mountains (Whiteman and McKee, 1977).

Studying the shape of air temperature inversion surfaces over mountain valleys, Marlatt et al. (1981) noted that there are a number of closed or nearly closed basins in the higher elevations of the Rocky Mountains region that have gained the reputation of being "ice boxes" due to cold air stagnation. He further noted that in the Gunnison Valley strong air temperature inversions are common throughout the year as the air near mountain tops drains to the valley floor. In winter, when the low angle of the sun combined with the shading effect of the high terrain and the high albedo of the snow cover limits the solar heating, the inversion becomes very strong. It persists for months, with only the occasional short breakdown caused by a storm system advecting the cold air from the basin.

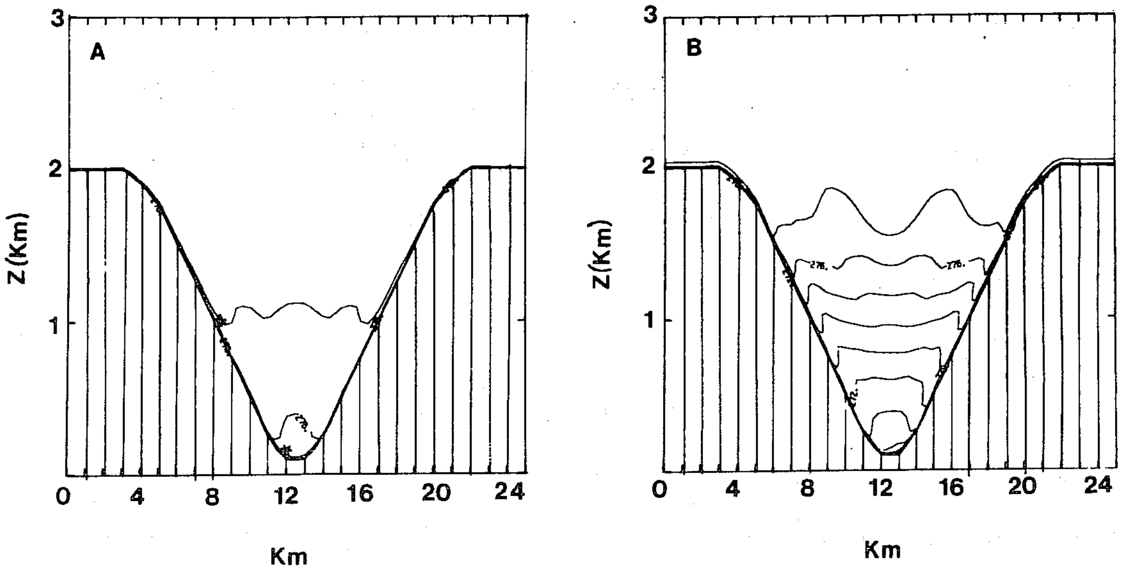


Fig. 3 Contours of potential temperature in the two-dimensional valley at (a) the initial time 2030LST and (b) after 6 hours. (After McNider and Pielke, 1981). Contour interval 1K.

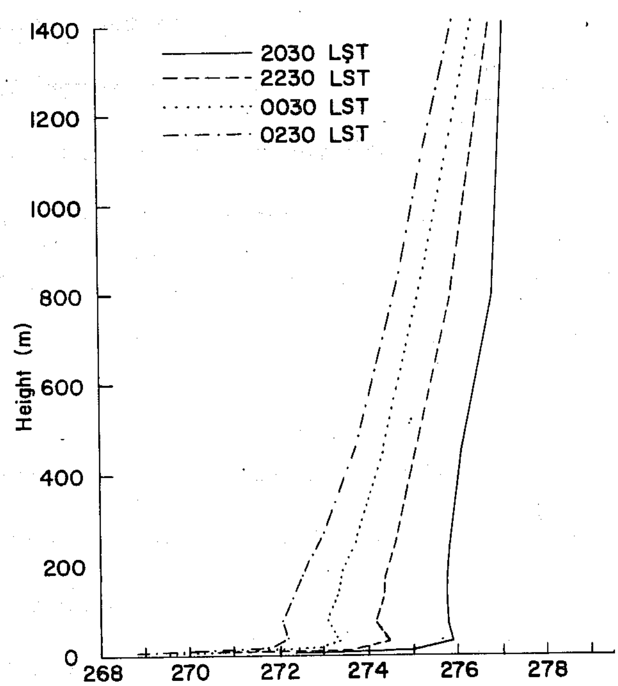


Fig. 4 Profiles of potential temperature over the centre of the two-dimensional valley for the indicated times (After McNider and Peilke, 1981).

Using the data acquired by a simple network of meteorological towers within the Anderson Creek valley, Gudiksen and Walton (1981) determined the frequency of occurrence of nocturnal drainage flows for a 10-month period. The results indicate that drainage flows are more frequent and intensive during the summer (over half of the time) than during the winter. That can be explained by the fact that the air in a valley during winter is more stably stratified and stagnant than during the summer.

Similar measurements were made by Thompson (1981) in a 9 km long and 500-1000 m deep canyon in the Wasatch Mountain Range. He found that during the investigation the same basic behaviour of inversion and circulation development occurred on about 90% of summer days.

Finally, it is worthwhile pointing out some of the interesting results obtained by Whiteman (1981). He was studying the temperature inversion build-up during the field experiments conducted in seven Colorado valleys in 1975, 1977 and 1978. The valleys studied are of various orientations on the western slope of the Colorado Rocky Mountains. They are 300-800 m deep with floor widths of 180-3100 m, ridge to ridge distances of 3-18 km and valley floor slopes of $0.5\text{-}19\times10^{-3}$.

Whiteman found that during periods of clear undisturbed weather, temperature inversions typically grow to the full depth of the valleys by sunrise. The mean potential temperature gradients are within the range of 22-33 K/km, but snow-covered valleys produce stronger inversion, whereas cloudy skies result in weaker ones. He further concluded that variations in synoptic wind speed and direction above ridge top level had no effect on the depth or strength of valley inversions. This suggests that one effect of the valley topography is to decouple the inversions and local flows from the upper air. Probably this can explain a phenomenon concerning the movement of warm fronts in the Alpine region; warm fronts sometimes appear to remain stationary for quite a long period of time at some distance from the Alps (GARP, 1982). This means that a wedge of stagnant cold air is not removed and is acting like a stationary frontal surface.

It may be concluded that an atmospheric self-created $\sigma=1$-surface in a mountain complex exists throughout most of the year provided the atmosphere is stably stratified. At other times when the atmosphere has a neutral or unstable stratification the Froude number becomes infinite and the mountain influence on the atmosphere is minimized. Therefore, there appears to be justification for using the concept of the atmospheric self-created $\sigma=1$-surface as a more realistic representation of the orography in numerical models.

2.2 Formulation of valley-filling orography

One way of representing the main orographic features in numerical models using the concept described above would be as follows. Consider a long, narrow valley between two parallel ridges. When the cold airmass penetrates into that region the cold air, in accordance with the thermal stratification, will either flow over the valley or fill it up in a very short time and then continue to flow as though the valley did not exist. The orographic forcing in this case corresponds to the height difference of the two crests, and any smoothing of the ridges and valleys in such a situation will give a wrong representation of the orographic forcing. We should, therefore, try to apply some valley-filling procedure in order to preserve such a feature in the model.

A procedure for producing the valley-filling orographic height (h_{ij}) at each grid point should consist of the following steps.

(a) First find the average height values of the grid sub-squares. This can be done by calculating the areas between two adjacent isohypses at a grid sub-square surface of the earth topography.

$$h_{ij} = \frac{1}{S} (s_1 h_1 + s_2 h_2 + \dots\dots\dots\dots + s_n h_n)_{ij}$$

or

$$h_{ij} = \frac{1}{S} \sum_{m=1}^{n} (s_m h_m)_{ij}.$$

Here, S denotes the surface of a grid subsquare, m is the number of segments, s is the surface of a segment between two adjacent isohypses and h is the average height of a segment surface.

(b) Make corrections in order to obtain the valley-filling height in the x-direction.

$$\text{if } h_{i+2} \geqslant h_i \text{ and } h_{i+1} < h_i \quad \text{then } (h_{i+1})_x = h_i$$

or

$$\text{if } h_{i+2} \leqslant h_i \text{ and } h_{i+1} < h_{i+2} \quad \text{then } (h_{i+1})_x = h_{i+2}.$$

(c) Carry out the same procedure as in (b), but in the y-direction.

$$\text{if } h_{j+2} \geqslant h_j \text{ and } h_{j+1} < h_j \quad \text{then } (h_{j+1})_y = h_j$$

or

$$\text{if } h_{j+2} \leqslant h_j \text{ and } h_{j+1} < h_{j+2} \quad \text{then } (h_{j+1})_y = h_{j+2}.$$

Notice that the valley-filling procedure eliminates valleys in the x- and y-directions separately. However, when from these two values a mean height has been calculated, new valleys with smaller amplitudes will appear. In order to eliminate them, the same correcting procedure should be repeated. Such a threefold iteration has been applied here and the results presented in Fig. 5.

The largest changes of heights and shapes were obtained after the first correction; further corrections, as might be expected, having less and less effect. Therefore, further radical changes of these elements can only be made by taking a larger horizontal grid.

When changing the grid scale from a smaller to a larger one, a smoothing technique is usually used. There are two well-known and commonly used methods of smoothing. One is the simple space smoothing technique (referred to as simple smoothing) by which an average value at a central point can be obtained as an arithmetic mean of the values at the central and surrounding points. This method is very efficient in reducing the height of ridges and enhancing the height of valleys - thus making the mountains almost flat.

The other method of smoothing consists of calculating an average value at a central point by a weighted mean of the central and surrounding grid points (referred to as weighted smoothing). The weighting coefficients are usually obtained by the binomial formula $(a + b)^n$, where n is taken to be 2 or 4. This method gives a smaller reduction in the mountain heights than the first one, but it radically changes the mountain shapes.

The method of scale changing which has been applied here consists of calculating the mean value in a central point by simply averaging the values of the points in the grid-square strictly belonging to that central grid point. In this way the value obtained at the central grid point is exactly the mean height of the corresponding grid square. In other words, by this method only the sub-grid scale shapes are smoothed, while the shapes and slopes exceeding that scale are preserved.

As an example we shall describe the various steps that lead from a 10' lat-long grid of mean heights to the 1.875° global model orography. There are 2,332,800 (1080x2160) 10' lat-long grid points over the globe. The first step is to apply the valley-filling procedure which should be repeated two or three times. Then, by averaging three by three consecutive 10' mean heights we obtain the 0.46875° lat-long gridded mean heights. In doing this a small correction is required in order to take sixteen instead of fifteen 10' gridded values to obtain five 0.46875° mean values. In such a way we get 294,912 (384x768) 0.46875° gridded mean height values. Now, the valley-filling procedure should be performed for this grid-scale. Afterwards, by averaging every four consecutive 0.56875° grid values, we obtain 73,728 (192x384) 0.9375° gridded mean height values. Again, the valley filling procedure should be applied for this grid-scale. Finally by averaging four 0.9375° gridded consecutive height values, we obtain 18,432 (96x192) 1.875° gridded mean height values. After two or three valley-filling iterations we get the valley-filled orography for the 1.875° lat-long global model.

If we consider that the mean grid square heights obtained by this method describe a mountain that contains scales that are still different from those that the model can represent, we can apply an additional correction by repeating this procedure.

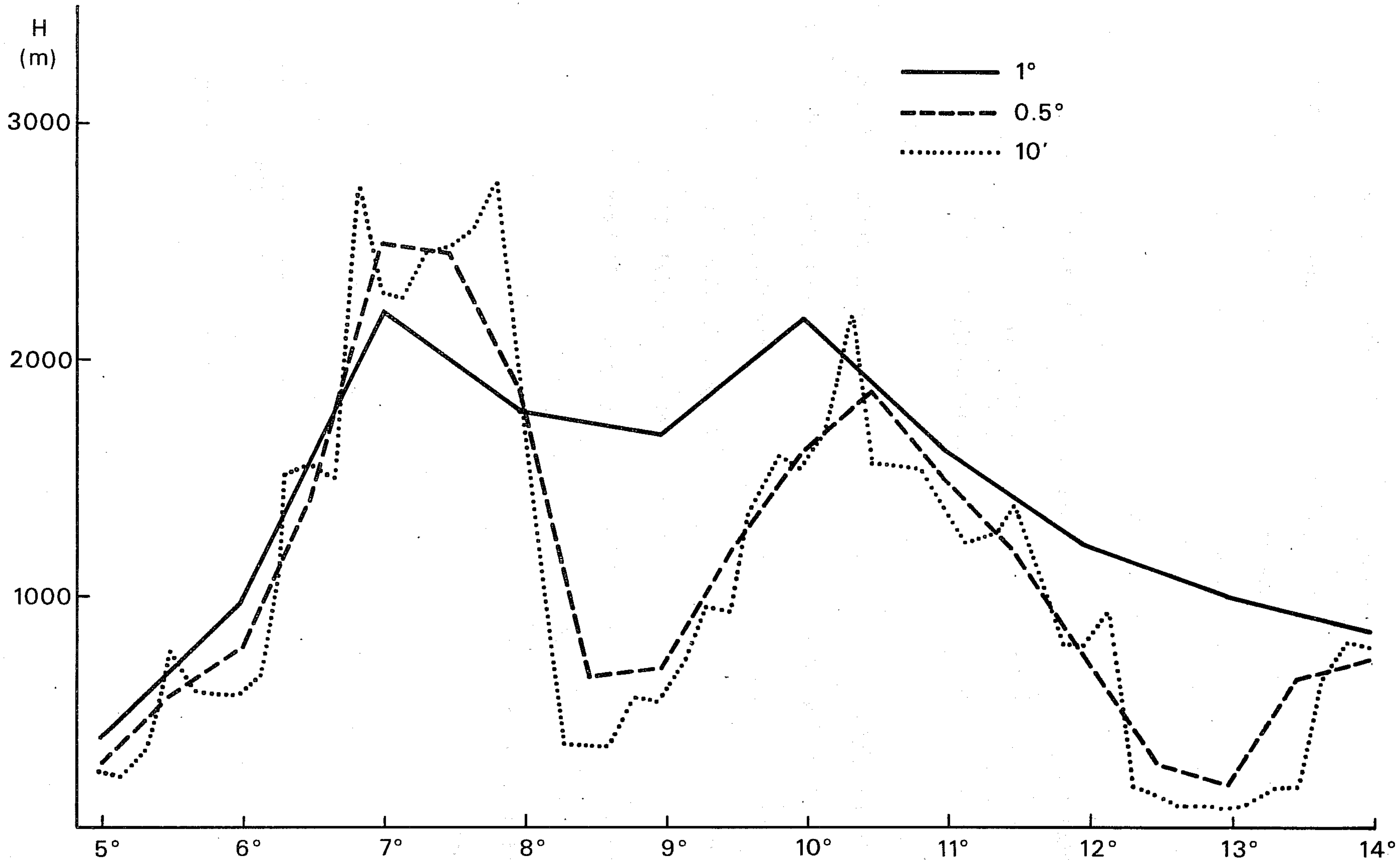


Fig. 5 Profile of the Alps along 46°N as represented by different scales of valley-filling orography.

2.3 Characteristics of valley-filled orography demonstrated on the Alps

In order to investigate the concept of the atmospheric self-creating σ-surface, we shall apply the method described in the preceding section to the Alps. For this purpose we selected an area between 5° and 14°E and 44° to 48°N.. That area, as shown in Fig. 1, encompasses the main massif of the Alps.

The initial heights were derived from the US Navy 10' lat-long regularly gridded orography provided by NCAR. These altitudes denote the mean values for corresponding subsquares covering approximately 240 km^2.

The simple analysis of these heights, as may be seen in Table 1, shows that the height averaging made on even such a fine grid mesh greatly reduced the height of the whole mountain range and particularly the tops of the Alps. From this table we can see that out of 1800 points, about 10% of grid points are situated at the sea level, 45% are under 500 m level, 70% below 1000 m, less than 10% above 2000 m, and only 0.3% (6 points) slightly exceed the height of 3000 m. This means that any further smoothing in a simple geometric manner will reduce the height of the mountain range so radically that it would become unrealistic.

Table 1. Distribution of the mean heights at 10' lat-long grid mesh covering the Alps.

Heights (m)	0	<500	500-1000	1000-1500	1500-2000	2000-3000	2500-3000	>3000
Number of points	194	634	418	198	187	128	36	6

Table 2 shows the distribution of height differences between adjacent grid points in the x- and y-directions. Considering the height differences in the x-direction, it is apparent that for 30% of grid points the height difference is zero, while in 60% of grid points height difference is below 500 m and only 2% (38 points) exceeds 1000 m. The mean height difference for the whole grid mesh in the x-direction is 199 m.

Table 2. Height differences between adjacent grid points in the x- and y-directions

Height difference (m)	0	<500	500-1000	>1000	Average height difference (m)
Number of points in the x-direction	516	1053	163	38	199
Number of points in the y-direction	408	1045	228	59	249

The height differences in the y-direction are somewhat larger and average about 249 m. This can be explained by the difference in distances between grid points in the x- and y-directions in the area considered.

When initial heights are corrected in the x- and y-directions, the height values were changed at 420 grid points (23% of total number). The average height of the whole area was raised about 3% (25 m) and the heights between adjacent points were decreased on average by about 15%.

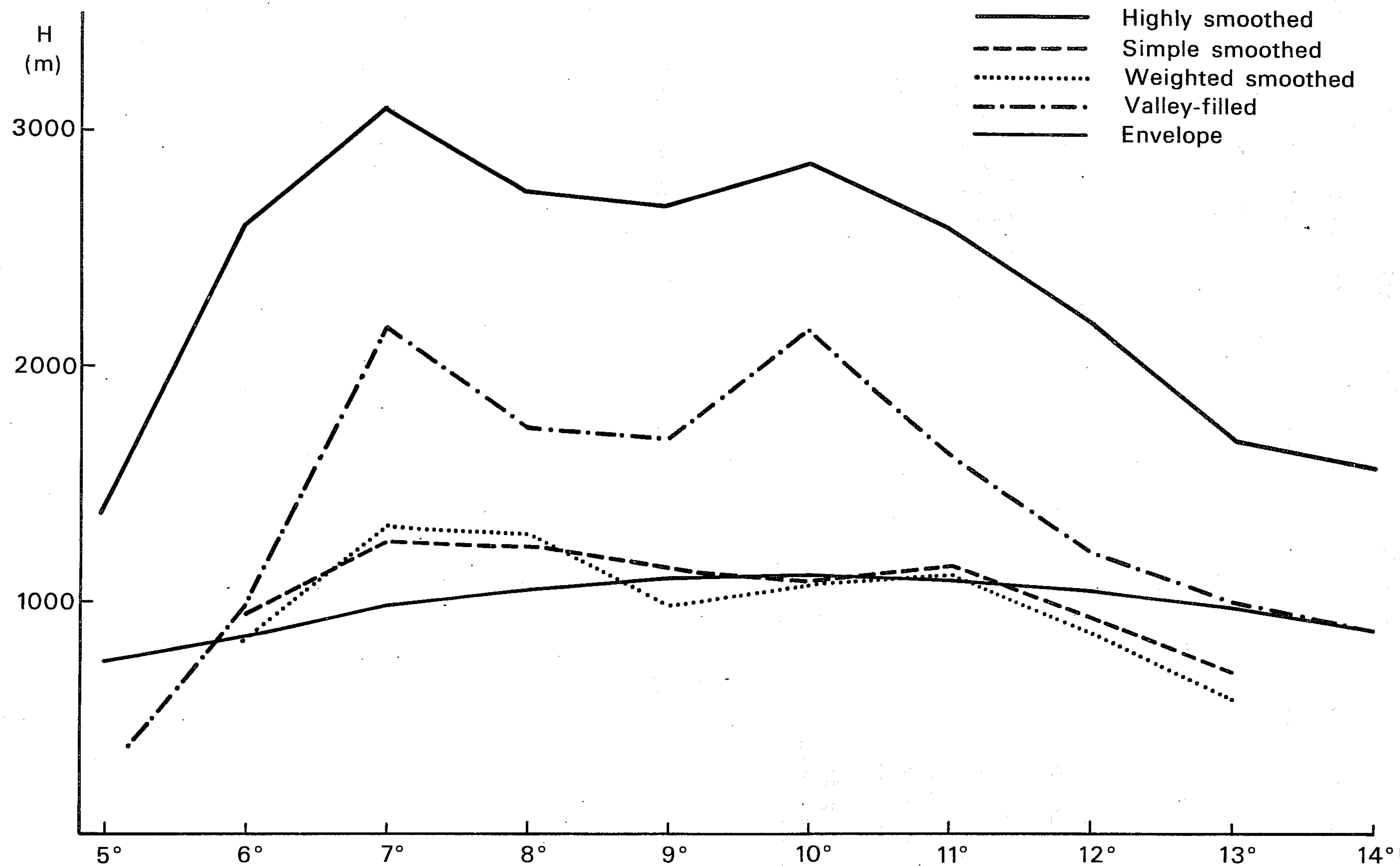


Fig. 6 Comparison of different types of orography representation - profile of the Alps along 46°N.

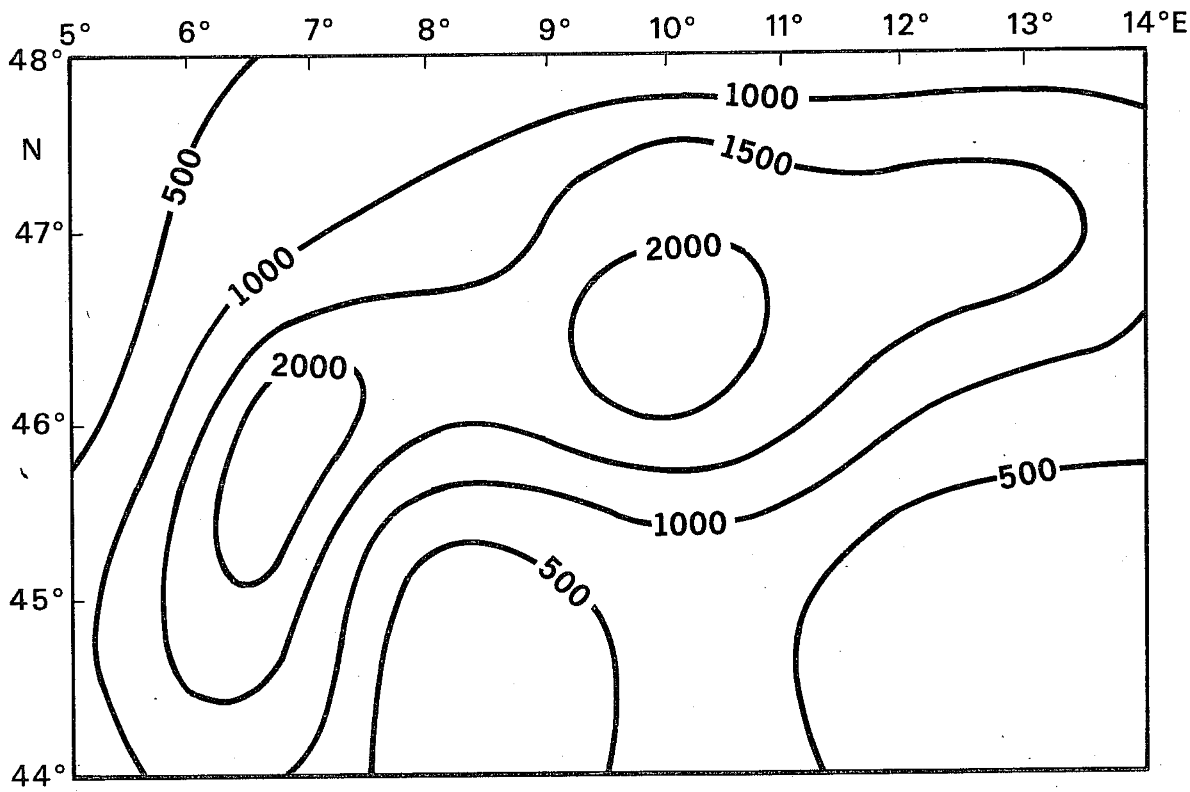


Fig. 7 The alps represented by the valley-filling 1° lat-long corrected heights. Contour interval 500m.

After the grid scale had been changed from 10' to 0.5° lat-long, and the averaging and correcting procedure carried out, the mean height of the whole area was raised by 63 m and the heights at several grid points were still above 2500 m. On the other hand, in spite of the rather marked change in heights, the average slope of the mountains was not changed very much. That can be explained by the fact that any correction performed using this procedure decreases the slope in one direction while at the same time increasing it in the other one.

The second change of the grid covering the Alpine area was the averaging of the heights at 0.5° lat-long in order to obtain 1° lat-long mean grid square heights. This change of grid scale decreased the mountain tops so that only a few grid points exceeded 2000 m. On the other hand, the average height of the whole area considered was raised to 878 m as a result of the valley-filling correction.

An analysis of the grid point values for the various scales of the valley-filled orography as illustrated in Fig. 5, shows that the change of the grid scale caused a rather large change in height distribution. A significant percentage of grid points with low heights were decreased, while the others, particularly with medium heights, were increased.

In view of the application of the results described here, it may be useful to compare them with the heights of the same mountain complex obtained by another method of orographic representation. Such a comparison is shown in Fig. 6, in which a profile of the Alps along 46°N (the central parallel of the area considered) has been represented by five different types of orographic representation.

Examination of Fig. 6 clearly shows that the highly smoothed orography, as well as simple and weighted smoothed orographies, do not give the general heights and shapes of the real one. Therefore, these three types of orographic representation are unrealistic. The envelope type of orography with two standard deviation increments reproduces the general shape. However the heights are too high - there are some points which are higher than 10' lat-long US Navy topography. This means that a mean 1° lat-long square height using the envelope orography is higher than the real mean 10' value - this certainly is not realistic.

The valley-filled type of orography, as revealed in Fig. 6, seems to be more similar to the real one, both in shape and in height. This is also confirmed by Fig. 7 which shows that the regularly gridded valley-filled 1° lat-long corrected heights reproduce the main features of the Alps.

3. COMPARISON WITH OTHER OROGRAPHIES

3.1 The earth's orography

Theoretical and numerical studies of the influence of orography on the atmosphere show a growing need for a quantitative treatment of the earth's orography. Several types of model prescribed orographies are in use for simulations and weather forecasting. These model orographies differ from the earth's orography and among themselves. These differences obviously produce varying effects and provide differing views of the influence of the orography on atmospheric processes. The knowledge of the simple geometry and other essential features of these orographies will help us understand some of the deficiencies in the orographies as well as providing an insight into the real mechanism by which the orography affects the atmosphere.

During the last few decades several topographic data sources have been used as a basis for global terrain height representation (Berkofsky and Bertoni, 1955; Smith, Menard and Sharman, 1966; Gates and Nelson, 1975). Although these data undoubtedly constitute a valuable source of large-scale continental elevations, the high resolution US Navy topography represents the best topographic data source available. The resolution of the original US Navy topography data set is one sixth of a degree in both latitude and longitude. One line of latitude contains, therefore, 2160 points and there are 1080 lines of latitude; in total there are 2,332,800 grid points for the entire globe.

The orography considered in this study was obtained by a simple averaging of the topographic heights over 1.875° latitude-longitude areas for the entire globe. In order to adjust the areas of the 10' lat-long to those represented by the global grid mesh, a slight correction was made to every fourteenth 10' lat-long area. Since the grid points in the first row around the poles cover a region of 0.9375° in latitude and longitude, the globe is covered by a mesh consisting of 18,624 grid points.

The first topographic feature we consider is the distribution of the number of grid points with zero height, representing the sea, and the remaining points representing the land surface. For the entire globe it was found that 10,821 grid points are at sea level and 7,803 grid points have non-zero orographic heights. However, it should be stressed that some of the grid points having zero height are located over land because the low-lying land has not been treated separately. Moreover, this method of calculation gives a somewhat unrealistic picture because the land surface becomes rather enlarged. This was caused by treating all coastal and island regions as though they were land because their surface elevations are above sea level. However, the results can be used in comparing different model orographies.

In Fig. 8 the meridional variation of land and sea is shown in terms of the number of grid points covering each type of area. There are five points of intersection of the two curves; these indicate where there is an equal portion of land and sea. Two of these points are located at about latitude 70° in the northern and southern hemispheres, whilst the other three points are situated between 30° and 40°.

The second feature which was considered is the terrain height frequency shown in the form of a histogram with 500 m intervals. Of the total number of grid points, 42% (i.e. 7803) have a height above sea level. Their frequency is shown in Fig. 9. Note in particular that more than half of the grid points representing the land surface have heights below 500 m and more than 2/3 are below 1000 m. Also there is a secondary maximum of terrain height frequency between 2500 and 3000 m. However, the histogram overemphasizes the terrain heights in higher latitudes since all grid points are treated equally. To avoid this discrepancy, the surface area of land in 500 m elevation intervals was computed and the results are shown in Table 3a. This shows that more than 2/3 of the land surface is below 500 m and only about 10% is above 1500 m.

The next feature which has been studied is the slope of the terrain. For this we only used the slope in the meridional direction; the results are presented in Table 3b. When we take all these height differences and divide by an appropriate distance we get an average slope of the unsmoothed earth topography of 0.53×10^{-3}. However, when zero differences are excluded, the slope is more than doubled to 1.17×10^{-3}.

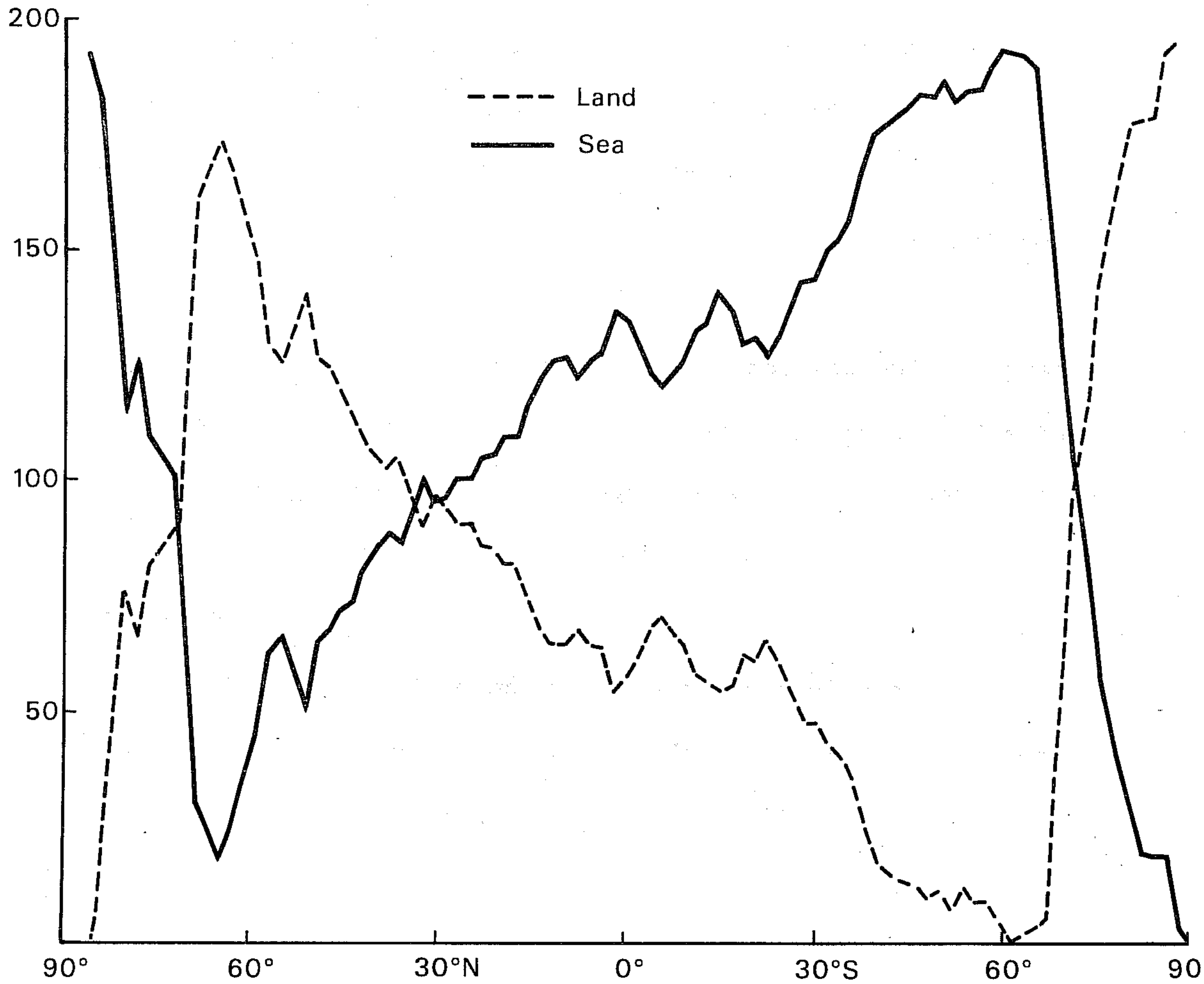


Fig. 8 Meridional variation of the number of gridpoints covering land and sea for the unsmoothed orography.

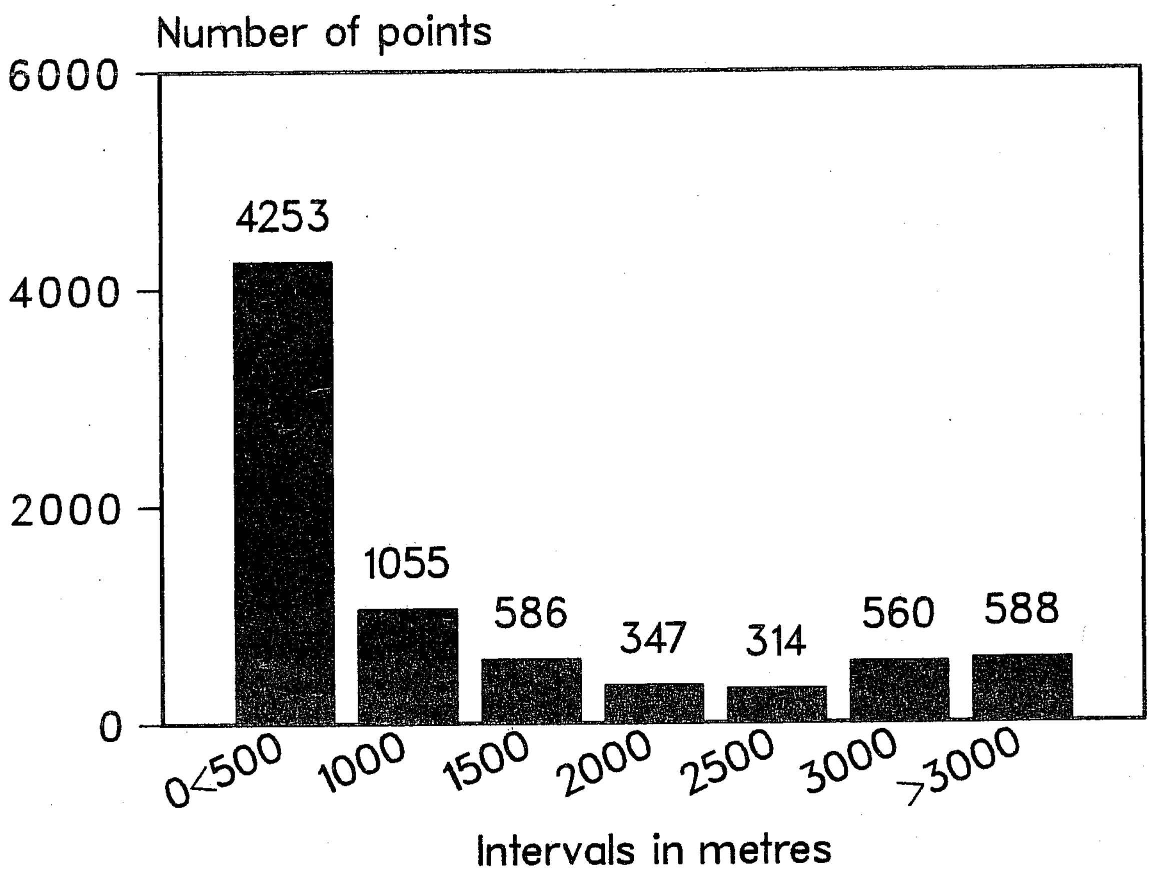


Fig. 9 Histogram of terrain heights at gridpoints for the unsmoothed orography.

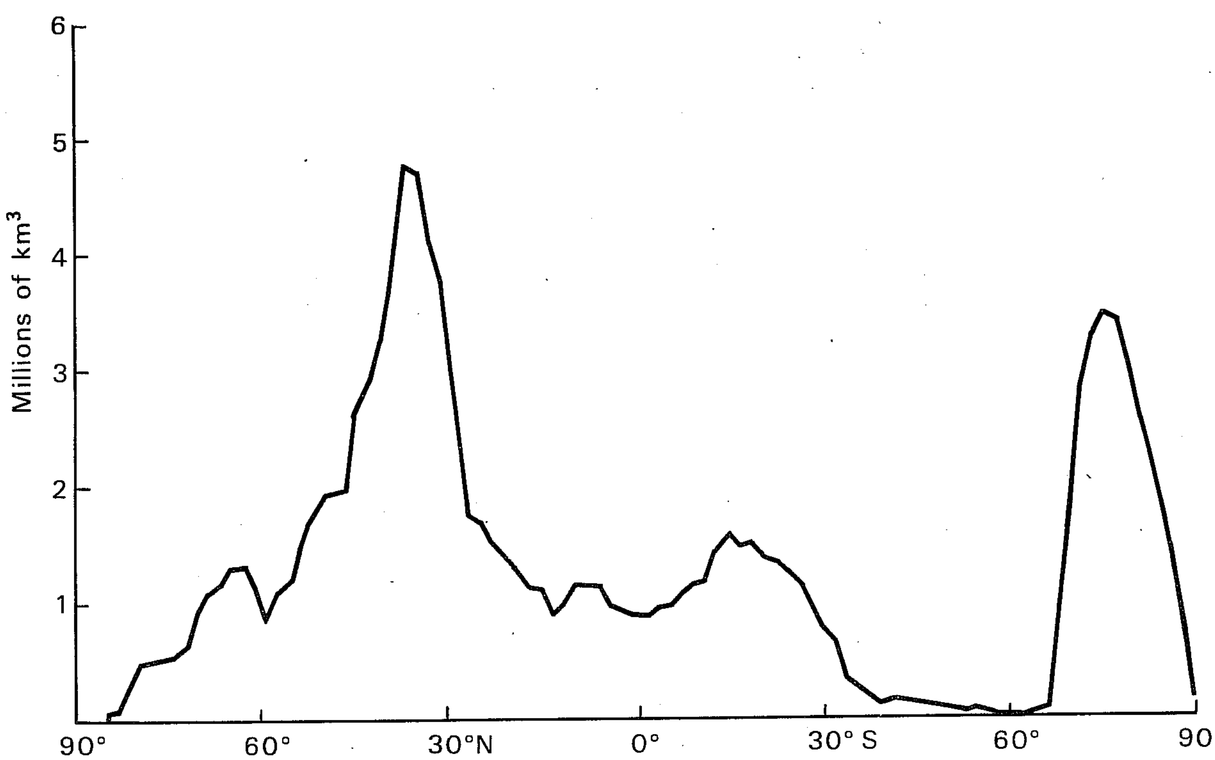


Fig. 10 Meridional variation of the **volume** of the unsmoothed orography.

Table 3a Unsmoothed surface area represented by land in 500 m height intervals

Height intervals (m)	<500	1000	1500	2000	2500	3000	>3000	Total
Surface area (10^6 km^2)	152.0	30.4	15.8	6.8	4.4	3.7	7.1	220.2
Part of total land (%)	69.0	13.8	7.2	3.1	2.0	1.7	3.2	100.0

Table 3b Frequency of height differences between adjacent grid points in the meridional direction for the unsmoothed orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	10043	3939	3291	771	264	73	34	5	12
Part of total number (%)	54.5	21.4	17.8	4.2	1.4	0.4	0.2	0.0	0.1

The last orographic feature which has been studied here is the orographic volume. The total volume of the earth's orography is found to be 120.868.000 km^3. In order to get an idea of the size of this volume, imagine a wall encircling the equator which is 1000 km wide and 3 km high. If the earth mass representing the orography is equally distributed over the globe, the sea surface would be at about 314 m higher than it is now. However, if the orographic mass is only distributed over the continents, the level of the land would rise about 800 m.

A comparison between the orographic volume and the volume of the atmosphere can be made by considering a homogeneous atmosphere in which the density is constant with height. The vertical extent of the homogeneous atmosphere is approximately 8000 m. This means that earth orography occupies a volume equivalent to about 4% of the homogeneous atmosphere.

Fig. 10 shows the meridional variation of the orographic volume in millions of cubic kilometres. It is obtained as a product of the surface area and height appropriate to each grid point. The maximum volume near 35° is produced by the Himalayas and Rockies. A secondary maximum appears in the Antarctic area near 75°S, while the minima are in the Arctic region and at about 60°S.

3.2 Highly smoothed orography

The orography which was originally used in the ECMWF operational model is a well-known orography taken from GFDL which was formulated by Berkofsky and Bertoni (1955). The main feature of this type of orography is its smoothness. So, for example, many synoptic and subsynoptic topographic features, such as the Alps, the Scandinavian mountains, the Atlas, etc., are almost absent.

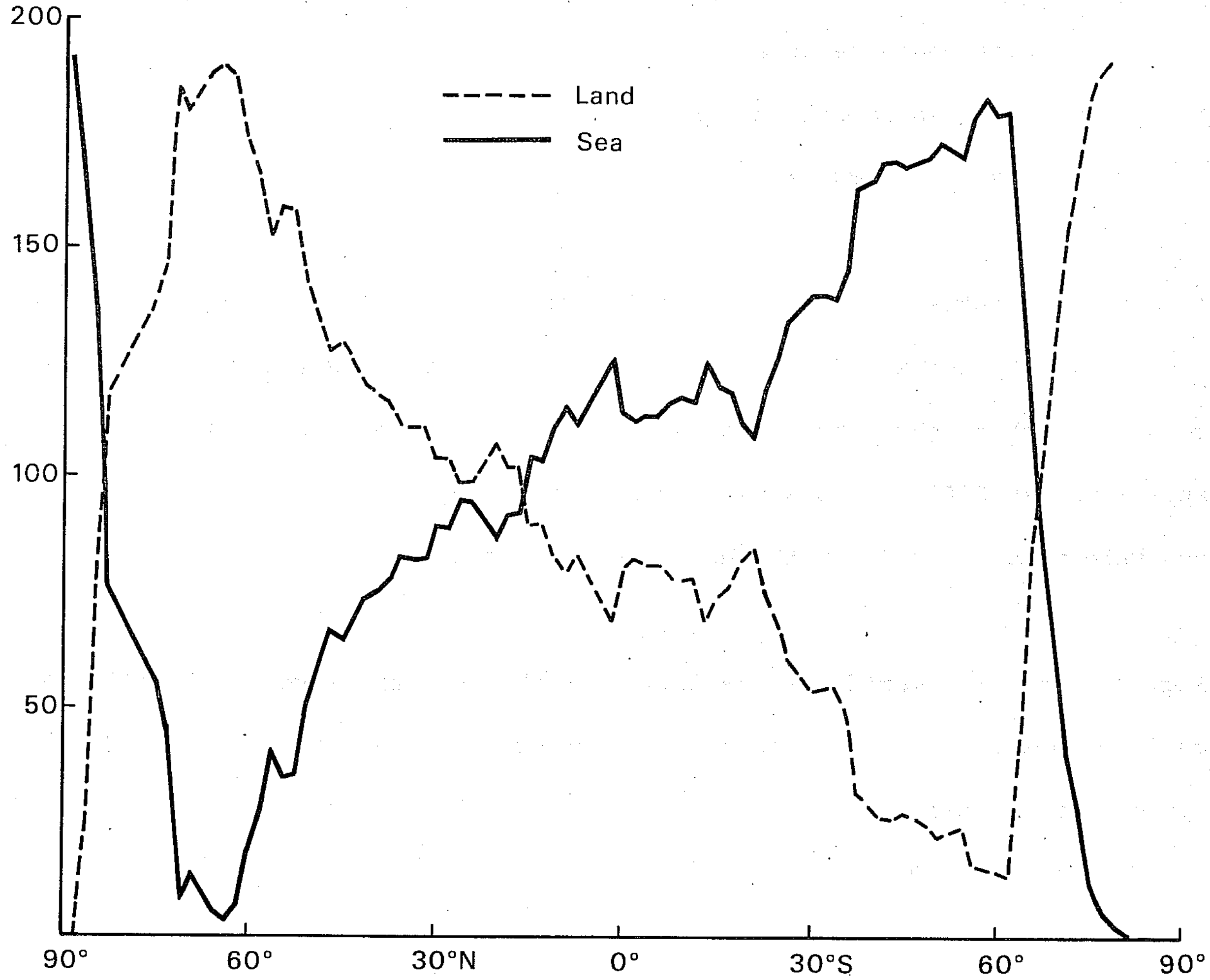


Fig. 11 Meridional variation of the number of gridpoints covering land and sea for the highly smoothed orography.

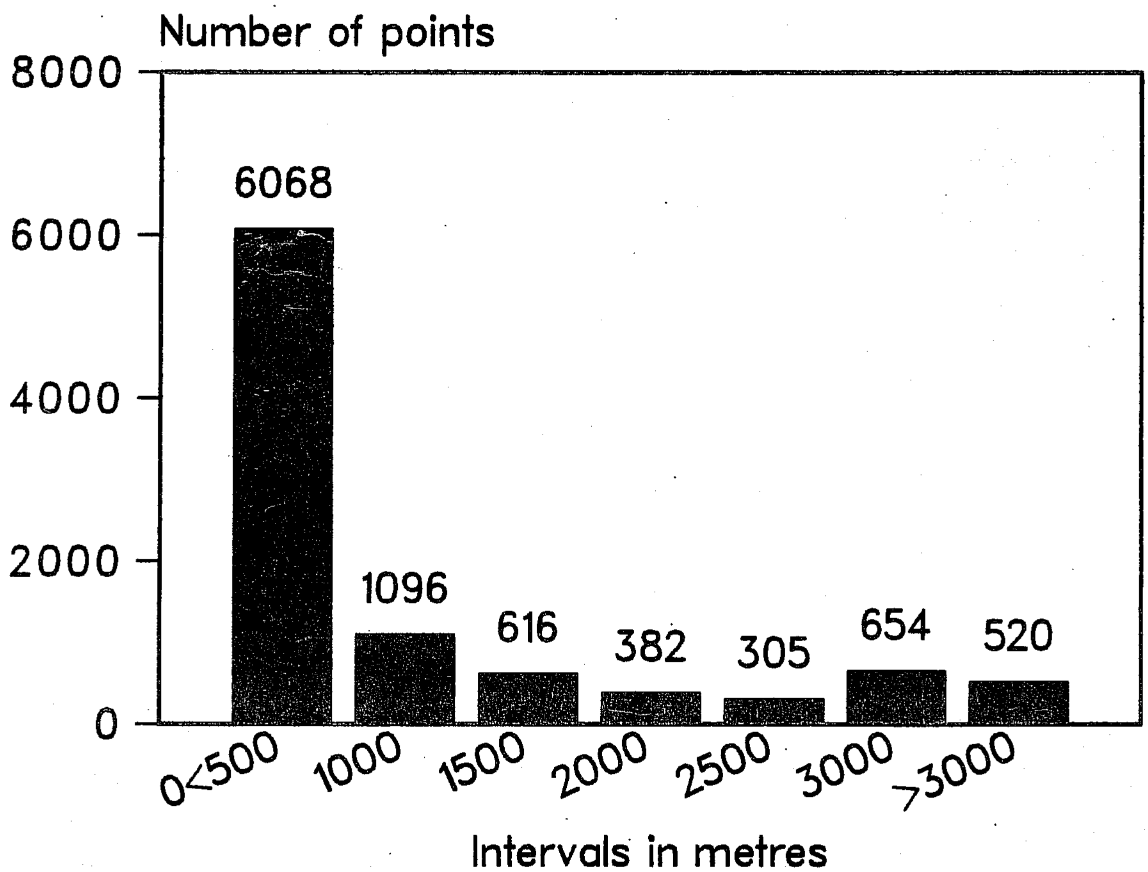


Fig. 12 Histogram of the terrain heights at gridpoints for the highly smoothed orography.

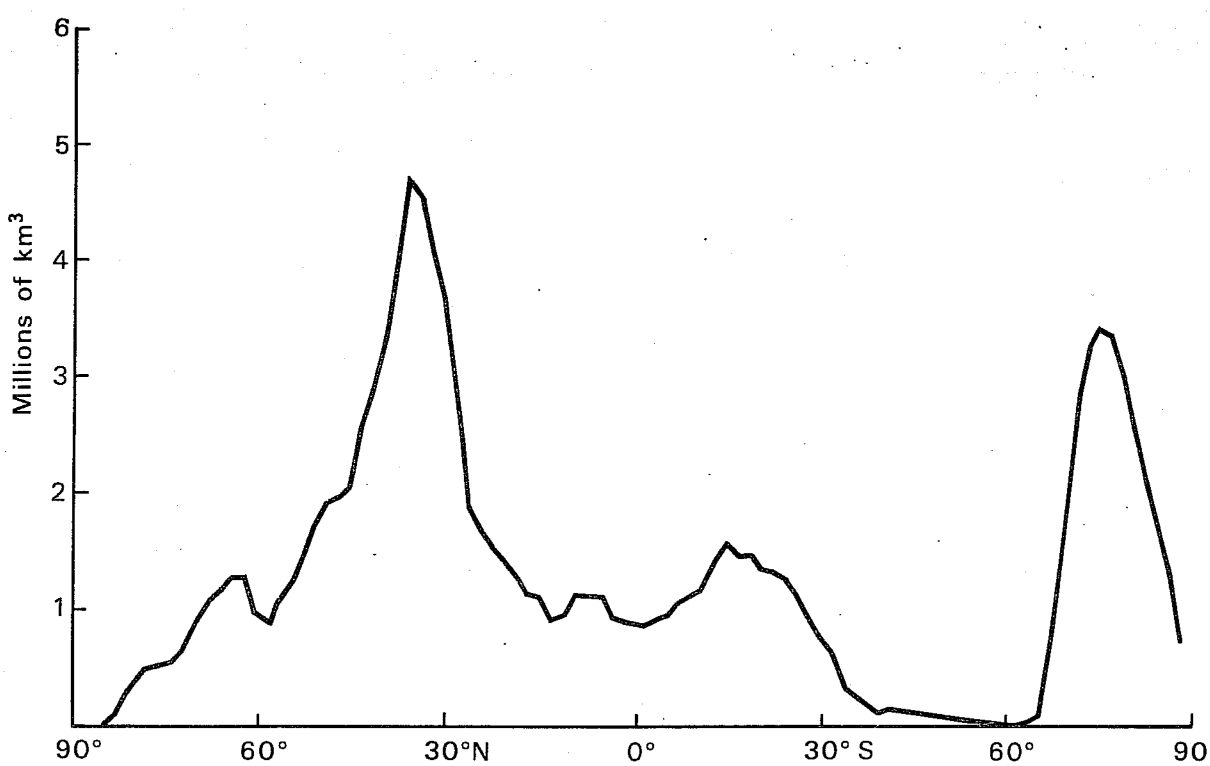


Fig. 13 Meridional variation of the volume of the highly smoothed orography.

Table 4a The highly smoothed surface area represented by land in 500 m height intervals

Height intervals (m)	<500	1000	1500	2000	2500	3000	>3000	Total
Surface area (10^6 km^2)	151.5	40.0	16.5	6.9	3.9	3.8	6.3	228.9
Part of total land (%)	66.2	17.5	7.2	3.0	1.7	1.6	2.8	100.0
Differ. to un-smoothed orog. (%)	-2.8	+3.7	0.0	-0.1	-0.3	-0.1	-0.4	+4.0

Table 4b Frequency of height differences between the highly smoothed and unsmoothed orographies

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	8927	6587	2691	319	60	28	7	5	0
Part of total number (%)	47.9	35.4	14.5	1.7	0.3	0.2	0.0	0.0	0.0

Table 4c The frequency of height difference between the grid points in meridional direction for the highly smoothed orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	8384	5759	3318	690	181	42	10	7	3
Part of total number (%)	45.5	31.5	18.0	3.7	1.0	0.2	0.1	0.0	0.0

Fig. 11 shows that the meridional variations of land and sea are much smoother than for the unsmoothed orography. As a result of heavy smoothing the land is enlarged, especially in the Northern Hemisphere. Further there are only three intersection points. The intersection point in high latitudes is pushed about 10° northwards while the one in the subtropics is moved about 10° southward. The third point which is situated in the Southern Hemisphere is located at approximately the same latitude as in the unsmoothed orography.

The heavy smoothing of the orography has drastically affected the frequency of terrain heights. So, in spite of the fact that sea covers about 70% of the earth's surface, the number of grid points having a height above sea level is more than half the total number. Fig. 12 illustrates the effect of smoothing the terrain; now about 63% of the grid points representing land surface have a height below 500 m, and only a quarter of the total number have a height over 1000 m.

Table 4a shows the surface area occupied by land in steps of 500 m elevation. The total land surface obtained in such a way is about 4% larger than the unsmoothed land surface shown in Table 3a. Also the land surface in the interval between 500 and 1000 m is enlarged by 3.7% while in other intervals it is decreased. As expected, the areas of the lowest and highest intervals are greatly reduced.

The height differences between corresponding grid points of two orographies is a measure of their similarity. Therefore, the frequency of the height differences between the unsmoothed and highly smoothed orographies were calculated and the results are presented in Table 4b. The average difference for the whole globe amounts to 62 m.

Table 4c shows the frequency of height differences between adjacent grid points in the meridional direction. The average difference for the whole globe is 95 m which corresponds to a slope of 0.4×10^{-3}. If we neglect the grid points with zero differences the corresponding figures are 175 m and 0.84×10^{-3}.

The total volume of the highly smoothed orography is slightly less than that of the unsmoothed orography. This difference is almost negligible, being below 0.2% of the total volume. A comparison of Figs. 10 and 13 shows that the meridional profiles of the volumes are almost identical. That means that the process of smoothing the orography did not affect its latitudinal distribution of the volume.

3. The 2σ-envelope orography

The envelope-type of orography was developed by passing a grid point filter with bi-dimensional normalised Gaussian weights and then adding two standard deviations to the N48 version of the orography (Tibaldi and Geleyn, 1981). The main characteristic of this orography is an enhancement of the heights which in some areas exceeds 50% of the unfiltered values.

A significant enhancement of the earth topography after smoothing led to an enormous enlargement of the continents in all directions. So, for example, if we compare Figs. 14 and 8 we see that the portion of land is bigger than that of the sea over the whole Northern Hemisphere, except in extreme polar and equatorial latitudes. Even in the Southern Hemisphere between 20°S and 25°S the land portion exceeds that of the sea surface, though in reality the sea surface is about twice as large as the land surface.

An analysis of the frequency of terrain heights shows that this type of orography has 44% of grid points at sea level. Further, Fig. 15 reveals that, as a result of the great enhancement of the heights, about 1/3 of grid points at the continents have an altitude above 1000 m and about 20% are above 2000 m.

The envelope orography height enhancement is well expressed in Table 5a; surface area below 500 m is somewhat less than in the unsmoothed case, but at all elevations above 1500 m it is about twice as large.

In Table 5b are shown the differences between heights of this type of orography and the unsmoothed version. The average difference over the whole globe is 160 m.

The frequency of height differences between adjacent grid points in the meridional direction is shown in Table 3c. The average difference taken over the globe amounts to 141 m which corresponds to a slope of 0.68×10^{-3}. If we neglect the cases with zero height difference then we obtain an average difference of 239 m, corresponding to a slope of 1.15×10^{-3}.

The total volume of the 2σ-envelope orography is 195,951 million km^3. It is about 62% bigger than the volume of the unsmoothed earth orography. As it may be seen in Fig. 16, the greatest difference between these type types of orographies is at about 35°N, where the highest and largest mountain complexes are situated.

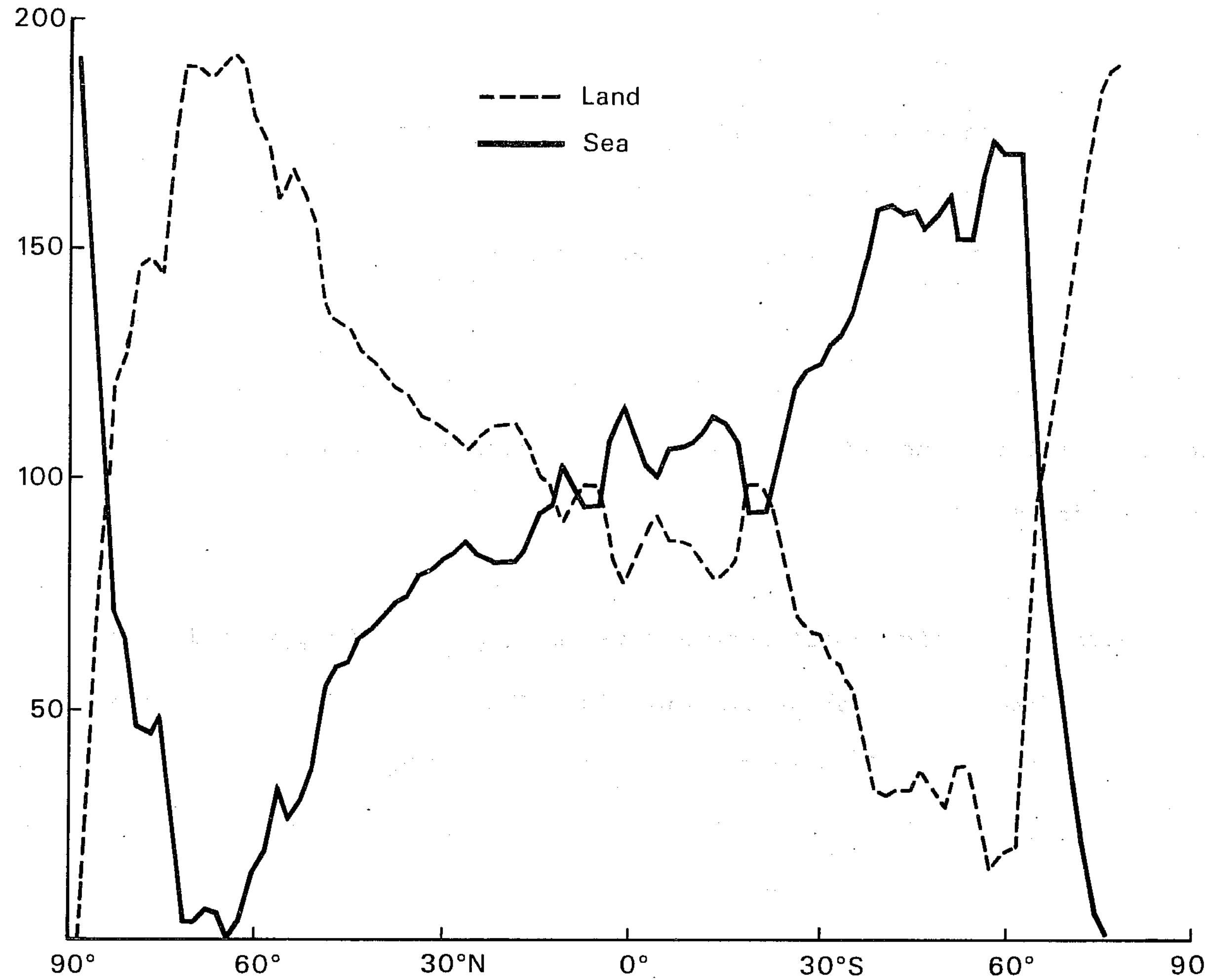


Fig. 14 Meridional variation of the number of gridpoints covering land and sea for the 2σ-envelope orography.

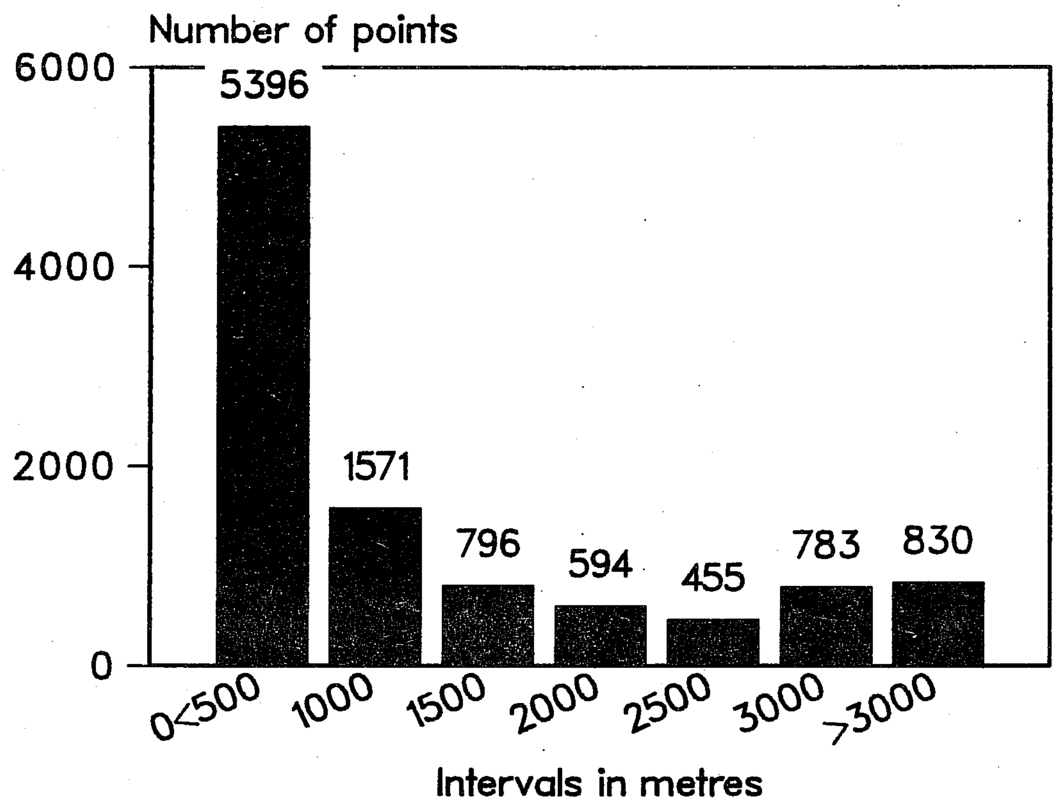


Fig. 15 Histogram of the terrain heights at gridpoints for the 2σ-envelope orography.

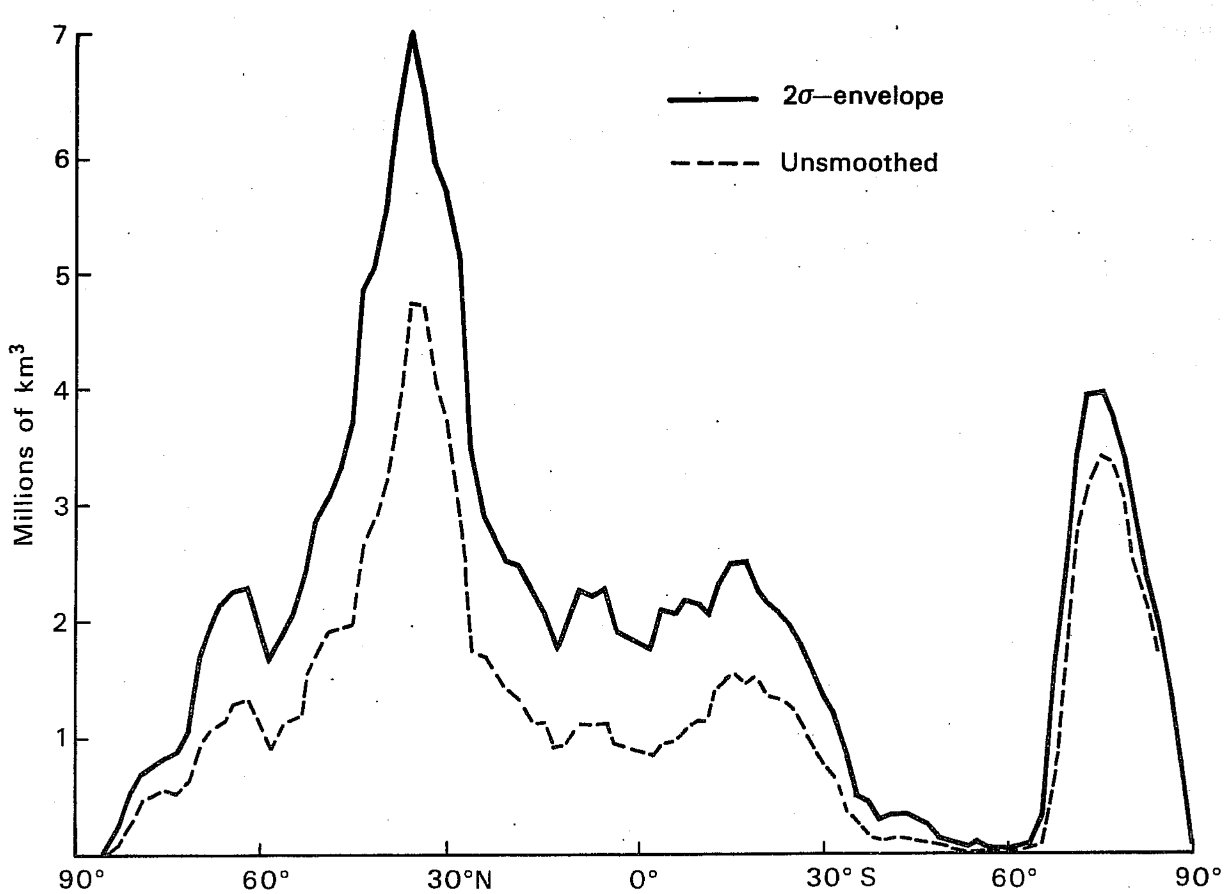


Fig. 16 Meridional variation of the volume of the 2σ-envelope and the unsmoothed orographies.

Table 5a Surface area represented by land in 500 m height intervals for the 2σ-envelope orography

Height intervals (m)	<500	1000	1500	2000	2500	3000	>3000	Total
Surface area (10^6 km^2)	149.1	46.1	22.0	14.0	8.6	7.9	11.6	259.3
Part of total land (%)	57.5	17.8	8.5	5.4	3.3	3.0	4.5	100.0
Differ. to unsmoothed orog. (%)	-11.5	+4.0	+1.3	+2.3	+1.3	+1.3	+1.3	+18.0

Table 5b Frequency of height differences between the 2σ-envelope orography and the unsmoothed orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of grid points	8199	4226	4336	1269	402	102	46	17	27
Part of total number (%)	44.0	22.7	23.3	6.8	2.2	0.6	0.2	0.1	0.1

Table 5c The frequency of height difference between the grid points in meridional direction for the 2σ envelope orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	7575	5267	4144	952s	302	115	49	10	18
Part of total number (%)	41.1	28.6	22.5	5.2	1.6	0.6	0.3	0.0	0.1

3.4 1σ-envelope orography

The envelope orography with one standard deviation increment is derived in a similar way to the 2σ-envelope orography except that one standard deviation is added to the N48 orography. Consequently the ratio of sea and land points at different latitudes is identical to that of the 2σ-envelope, and so this will not be discussed further.

In Fig. 17 is shown the frequency of the terrain heights; the characteristics are similar to those of the 2σ-envelope orography (Fig. 15). The number of grid points over the continents are slightly redistributed in such a way that frequency of the grid points with low elevations is increased at the expense of those with high elevations.

Table 6a shows that total land surface of this type of orography. Compared to the unsmoothed one (Table 3a) there is an increase of 9.8%. The surface area distribution by 500 m elevation intervals shows that the surface area below 500 m is decreased by 7%, while the areas in other intervals are increased.

The height differences between corresponding grid points for this type of orography and the unsmoothed earth orography are shown in Table 6b. These differences are bigger than those of the highly smoothed orography, but smaller than those of the 2σ-envelope orography. Over the globe the mean difference is 96 m.

The frequency of height differences between adjacent grid points in the meridional direction is given in Table 6c. The average value is 117 m which corresponds to a slope of 0.56×10^{-3}. After exclusion of the grid points which are at the same height level (zero difference) the average difference has risen to 198 m and the slope becomes 0.96×10^{-3}.

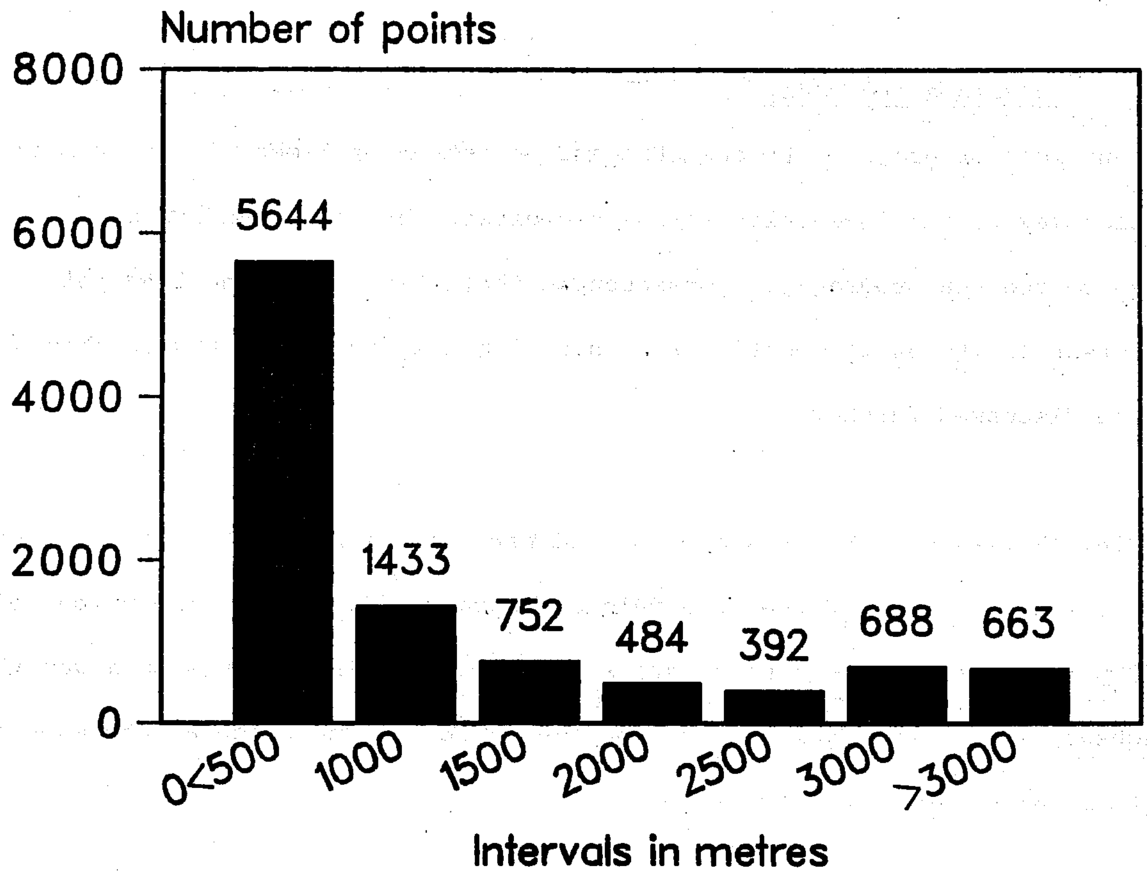


Fig. 17 Histogram of the terrain heights at gridpoints for the 1σ-envelope orography.

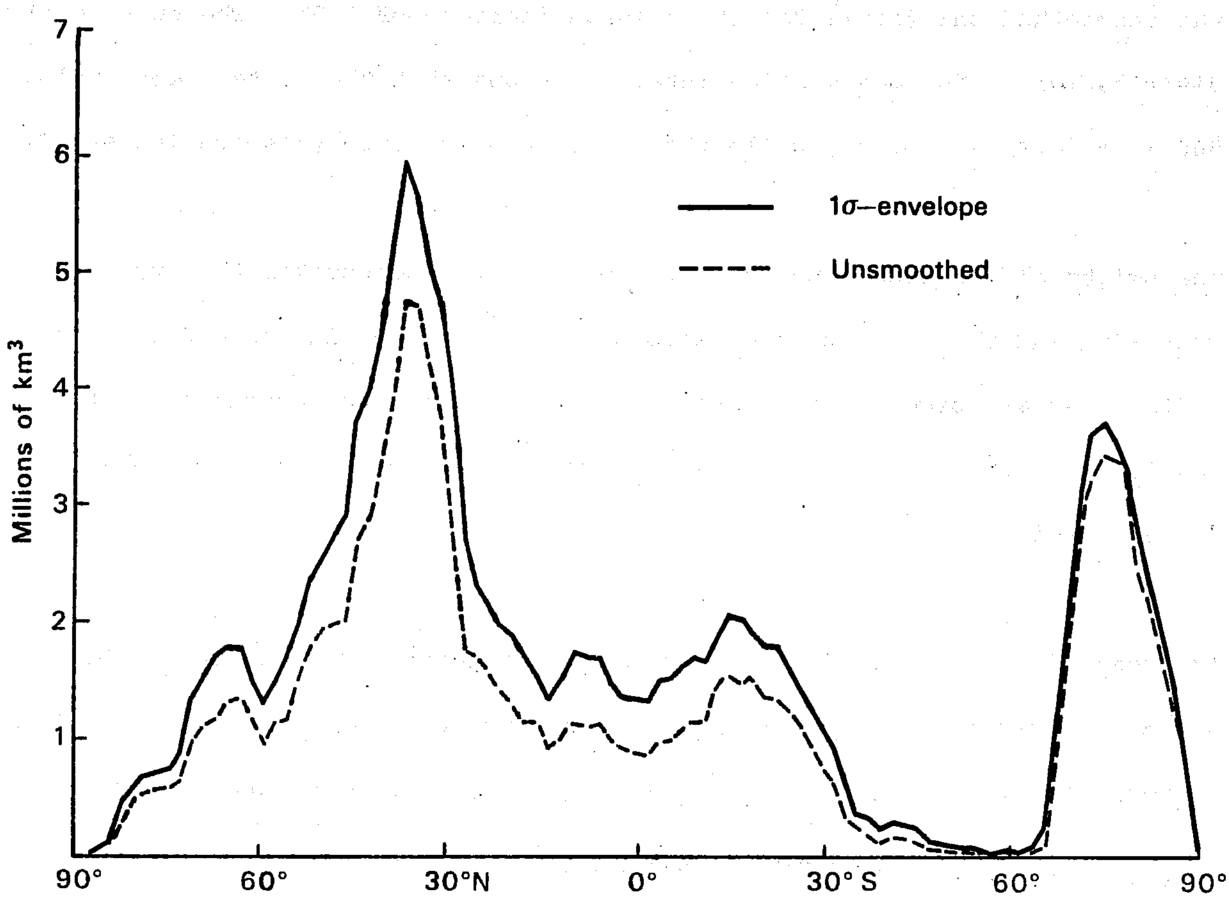


Fig. 18 Meridional variation of the volume of the 1σ-envelope and the unsmoothed orography.

Table 6a Surface area represented by land in 500 m height intervals for the 1σ-envelope orography

Height intervals (m)	<500	1000	1500	2000	2500	3000	>3000	Total
Surface area (10^6 km^2)	150.1	40.9	20.2	10.6	6.9	4.6	8.6	241.9
Part of total land (%)	62.0	16.9	8.4	4.4	2.8	1.9	3.6	100.0
Differ.to un-smoothed orog.(%)	-7.0	+3.1	+1.2	+1.3	+0.8	+0.2	+0.4	+9.8

Table 6b Frequency of height differences between the 1σ-envelope orography and the unsmoothed orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of grid points	8199	5912	3639	692	110	40	20	8	4
Part of total number (%)	44.0	31.8	19.6	3.7	0.6	0.2	0.1	0.0	0.0

Table 6c The frequency of height difference between the grid points in meridional direction for the 1σ-envelope orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	7560	5788	3938	815	228	71	17	8	7
Part of total number (%)	41.0	31.4	21.4	4.4	1.2	0.4	0.1	0.1	0.0

The total volume of the 1σ-envelope orography is 158,298 million km^{-3} which is 31% larger than the volume of the unsmoothed earth orography. The meridional variation of the volume is shown in Fig. 18. Its shape is the same as for the 2σ-envelope orography. However, the difference between its volume and that of the unsmoothed orography is halved.

3.5 Valley-filled orography

The concept of the valley-filled orography discussed earlier was based on evidence that throughout most of the year the valleys in mountain complexes are filled by cold air. This type of orography was formulated by a procedure which increases the heights of valleys, while the ridge heights remain practically unchanged. As a result of that, the essential features of mountain complexes (heights, slopes, ridge orientation, etc) are preserved and mountain ranges become more compact.

According to the procedure applied here, the valleys in the fine resolution, 10' lat-long US Navy topography were filled up. After that, the mean heights over a 0.5° lat-long grid were calculated. At this stage of the calculation a slight correction was made to adjust to the grid of the ECMWF forecasting model. Then, the same procedure of valley-filling and mean height calculation, without any further correction or smoothing, was repeated to obtain the orographic heights for 0.9375° and 1.875° lat-long resolutions.

The valley-filled orography obtained did not substantially change any synoptic-scale features of the real orography. This is confirmed by a comparison of Figs. 19 and 11, which shows that the ratio between sea and land points is almost identical to the valley-filled and unsmoothed orographies.

Fig. 20 shows the frequency of valley-filled orography terrain heights. The frequency deviation of this type of orography from the unsmoothed orography is very small. Comparison of these two orographies reveals that the terrain height frequency of the valley-filled orography is less at low intervals and larger at higher ones. In addition, the secondary maximum of terrain height frequency between 2500 and 3000 m is well expressed. These facts are fully in accordance with the basic concept of the valley-filled orography.

In Table 7a we can see the surface areas occupied by land in 500 m intervals. The total land surface is 2% larger than for the unsmoothed orography. However, as a result of valley-filling, the surface area in the lowest interval is decreased, while in the higher intervals it is correspondingly increased.

The frequency of height deviation between the valley-filled orography and unsmoothed earth topography is shown in Table 7b. It should be noted that valley-filled orography is very similar to the unsmoothed one, and as a result of valley-filling procedures an average height difference taken for the whole globe is only 13 m. Table 7b further shows that nearly 97% of all grid points have height differences below 100 m and not one grid point with a height difference exceeding 1500 m.

The frequency of height differences between adjacent grid points in the valley-filled orography is presented in Table 7c. An average difference for the globe was 104 m, with a slope of 0.5×10^{-3}. On the other hand, when zero differences are omitted, the average difference amounts to 227 m and the corresponding slope is 1.09×10^{-3}.

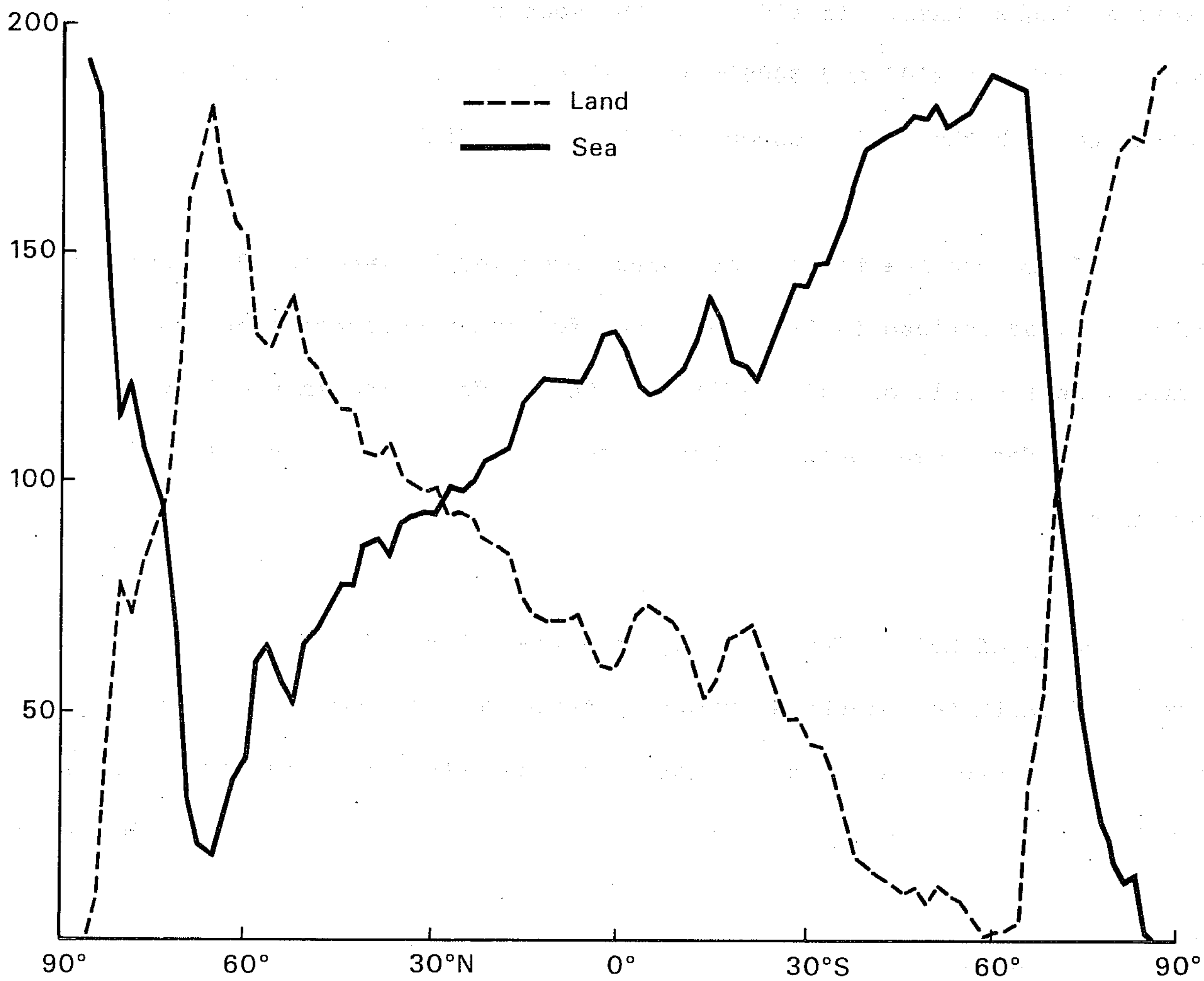


Fig. 19 Meridional variation of the number of gridpoints covering land and sea for the valley-filled orography.

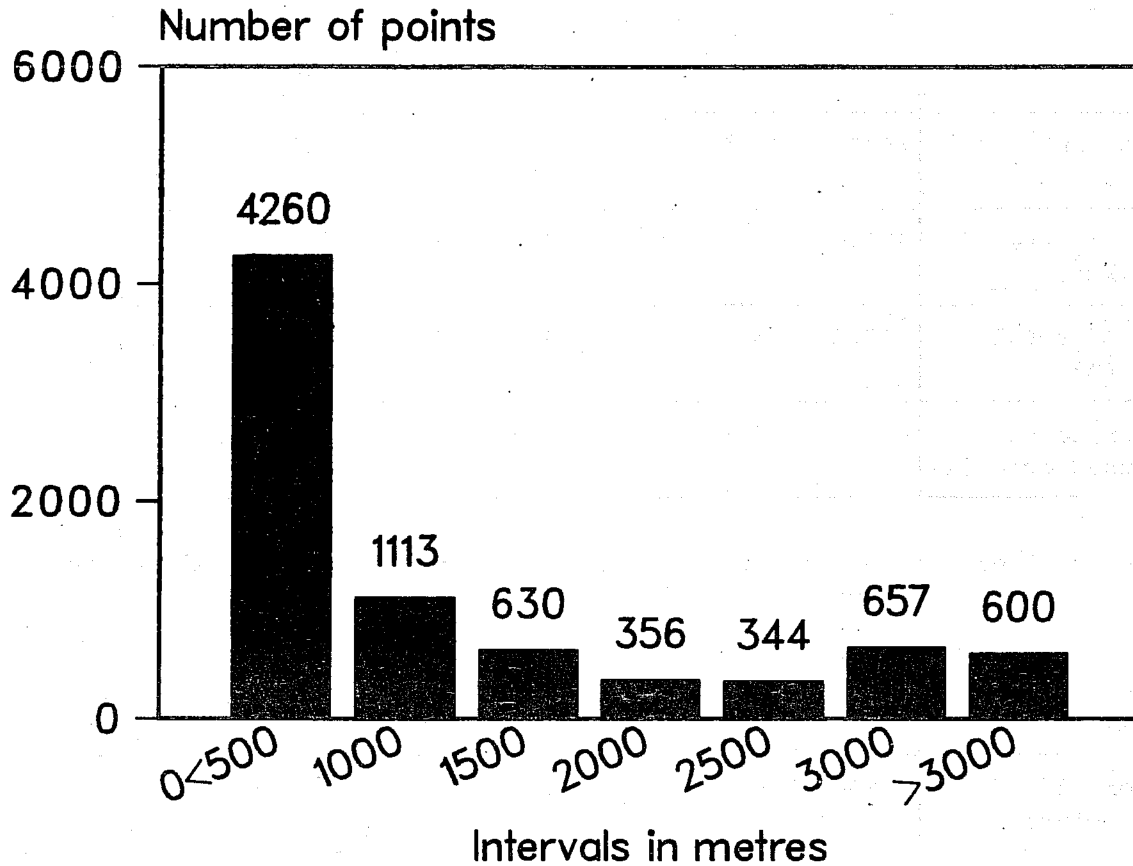


Fig. 20 Histogram of the terrain heights at gridpoints for the valley-filled orography.

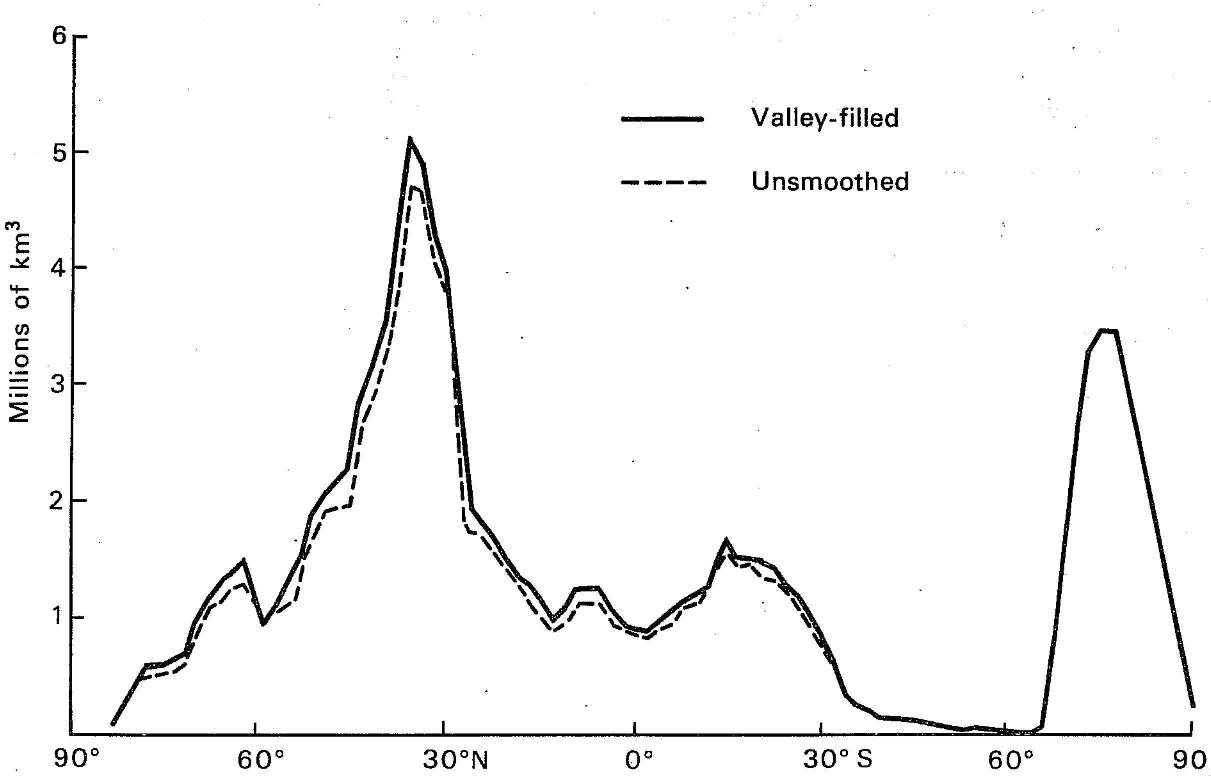


Fig. 21 Meridional variation of the volume of the valley-filled and unsmoothed orographies.

Table 7a Surface area represented by land in 500 m height intervals for the valley-filled orography

Height intervals (m)	<500	1000	1500	2000	2500	3000	>3000	Total
Surface area (10^6 km^2)	151.9	32.1	17.2	7.0	5.3	3.8	7.3	224.6
Part of total land (%)	67.61	14.3	7.7	3.1	2.4	1.7	3.2	100.0
Differ.to unsmoothed orog.(%)	-1.4	+0.5	+0.5	0.0	+0.4	0.0	0.0	+2.0

Table 7b Frequency of height differences between the valley-filled orography and the unsmoothed earth orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of grid points	11988	5864	547	30	3	0	0	0	0
Part of total number (%)	65.0	31.8	3.0	0.2	0.0	0.0	0.0	0.0	0.0

Table 7c The frequency of height difference between adjacent grid points in the meridional direction for the valley-filled orography

Height intervals (m)	0	<100	500	1000	1500	2000	2500	3000	>3000
Number of cases	9988	4322	3013	727	260	72	34	4	12
Part of total number (%)	54.0	23.5	16.4	4.0	1.4	0.4	0.2	0.0	0.1

The total volume of the valley-filled orography is 127.926 million km^3 - 5.8% bigger than the volume of the unsmoothed orography. That difference corresponds to the volume of the valleys which were filled up.

In Fig. 21 may be seen that the difference between the volumes of the unsmoothed orographies represents a slight correction to the shape of the valley-filled mountains. This correction is more marked at the latitudes where the mountain complexes are irregularly shaped than in the Antarctic where the mountain shapes are simple and more uniform.

3.6 Differences between the model prescribed orographies

The main purpose of this analysis was to find out the differences between the earth's unsmoothed orography and the other model prescribed orographies, as well as examining the differences between the model prescribed orographies. In summarising the differences obtained we shall use the common abbreviations which are well-known to the most of the research and operational staff in the ECMWF. The abbreviations are:

The unsmoothed earth topography - U.S. Navy
The highly smoothed orography - OPOR2
The envelope orography with two standard deviation increments - ENVOR
The envelope orography with one standard deviation increment - ENVORH
The global valley-filled orography data - GVFOD.

In order to compare the main quantitative features of the various orographies, a review of some relevant quantities is presented in Table 8.

Table 8 A review of main quantitative features of different types of orographies

Type of orography	US NAVY	OPOR2	ENVOR	ENVORH	GVFOD
Earth surface covered by land (10^6)	220.2	228.9	259.3	241.9	224.6
Earth surface covered by sea (10^6 km^2)	290.0	281.3	250.9	268.3	285.6
Surface area above 1000m elevation (10^6 km^2)	37.8	37.4	64.1	50.9	40.8
Average height deviation from unsmoothed orog.(m)	0	95	141	117	13
Average slope of the terrain ($x10^{-3}$)	1.17	0.84	1.15	0.96	1.09
Total orographic volume (10^6 km^3)	120.9	120.6	196.0	158.3	127.9

Considering the unsmoothed orography as a reference, we can see from Table 8 the extent of the variation of some of the quantities. The land surface of the earth in all cases is enlarged between 2 and 18%. The surface area above 1000 m elevation varies from -0.4 to 26.3 million km^2 or from -1.1 to 69.6% of the total amount of this area for the unsmoothed orography. The average height deviation varies from 13 to 141 m or for 2.9 to 44.9% of the total thickness of a layer which would be formed if the earth's orography was equally distributed over the globe. The average slope of the terrain is less than in the unsmoothed orography in all model prescribed orographies; it varies from 0.8 x 10^{-3} to 1.15 x 10^{-3}, or from 71.8 to 98.3% of the reference one. Finally, the volume of the orography varies from -0.3 to 75.1 million km^3 or from 99.8 to 162.1% of the volume of the unsmoothed orography.

4. RESULTS FROM EXPERIMENTAL FORECASTS

4.1 Experiments with the global model

Experiments have been carried out with the ECMWF global gridpoint model (N48, 15 levels) to compare the results of using the valley-filling orography with those already obtained for the 2σ-envelope and mean orographies. Eight forecasts were run using initial data from January 1981. The procedure used was to use the operational analyses and to insert the valley-filling orography during the first 12 hours of a 10-day forecast by adding the difference between the valley-filling and mean orographies to the mean orography itself.

Fig. 22 shows the variation in time of the anomaly correlation of height (1000-200 mb, 20°-82.5°N) for various wavenumber groups for the forecasts starting from 8 January 1981. Clearly there is little difference between the results using the valley-filled and mean orographies, though they do differ from the results from the envelope orography experiment. Naturally there are variations between the results from the 8 experiments, but overall they show that the forecasts with the valley-filling orography do not differ substantially from those with the mean orography, and that in many cases the anomaly correlation of the 2σ-envelope forecasts are very different from the other two. These findings are illustrated by Figs. 23 and 24 which show the anomaly correlation of height and temperture for the ensemble of the 8 cases.

The zonal mean of the zonal and deviations from the observed (Fig. 25) shows that below 500 mb the valley-filled orography gives slightly better results than the mean orography, though it is certainly worse than those from the

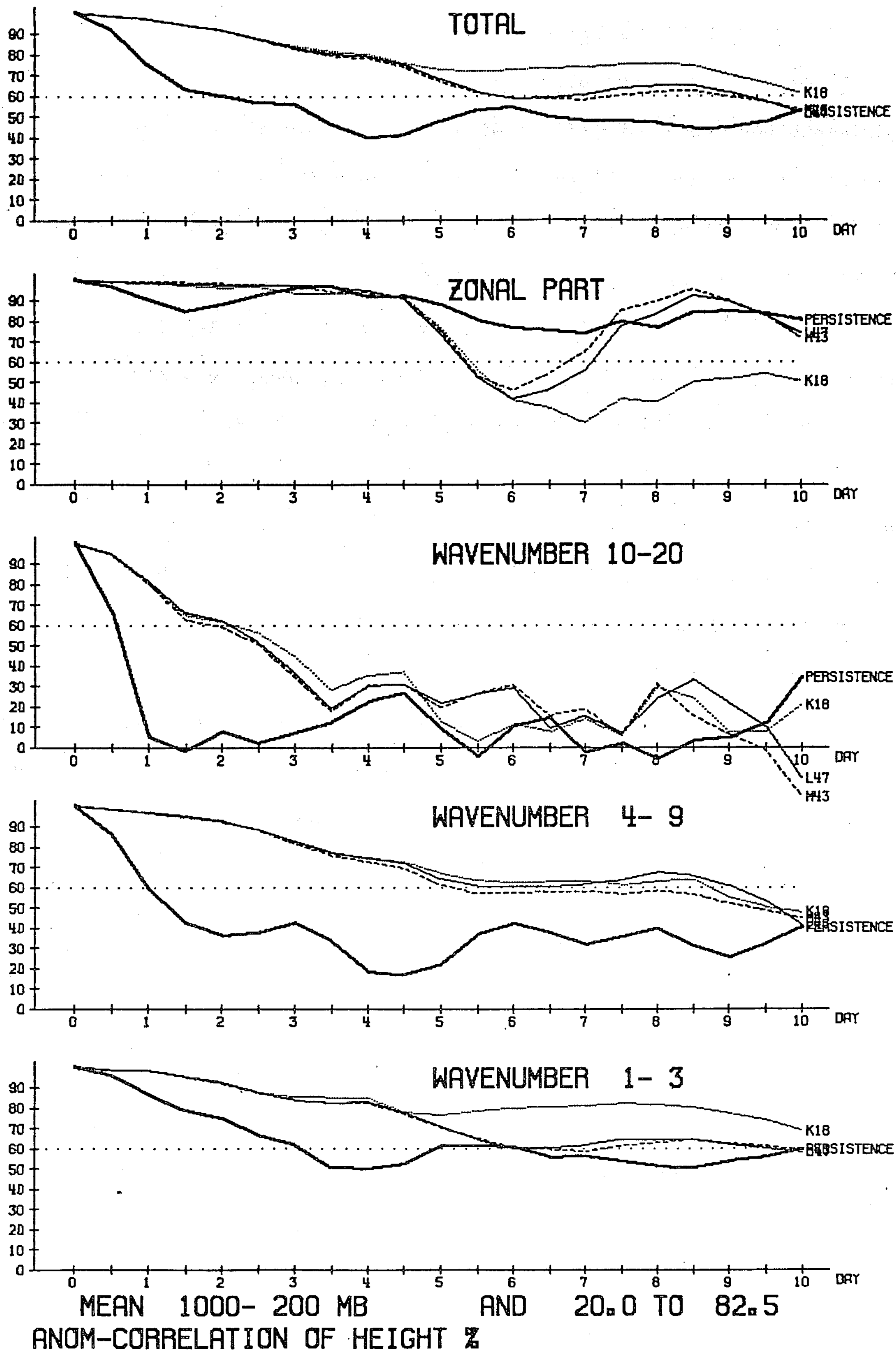


Fig. 22 Anomaly correlation of height for the forecasts starting 8 January 1981 for the valley-filled (M43), 2σ-envelope (K18) and mean (L47) orographies.

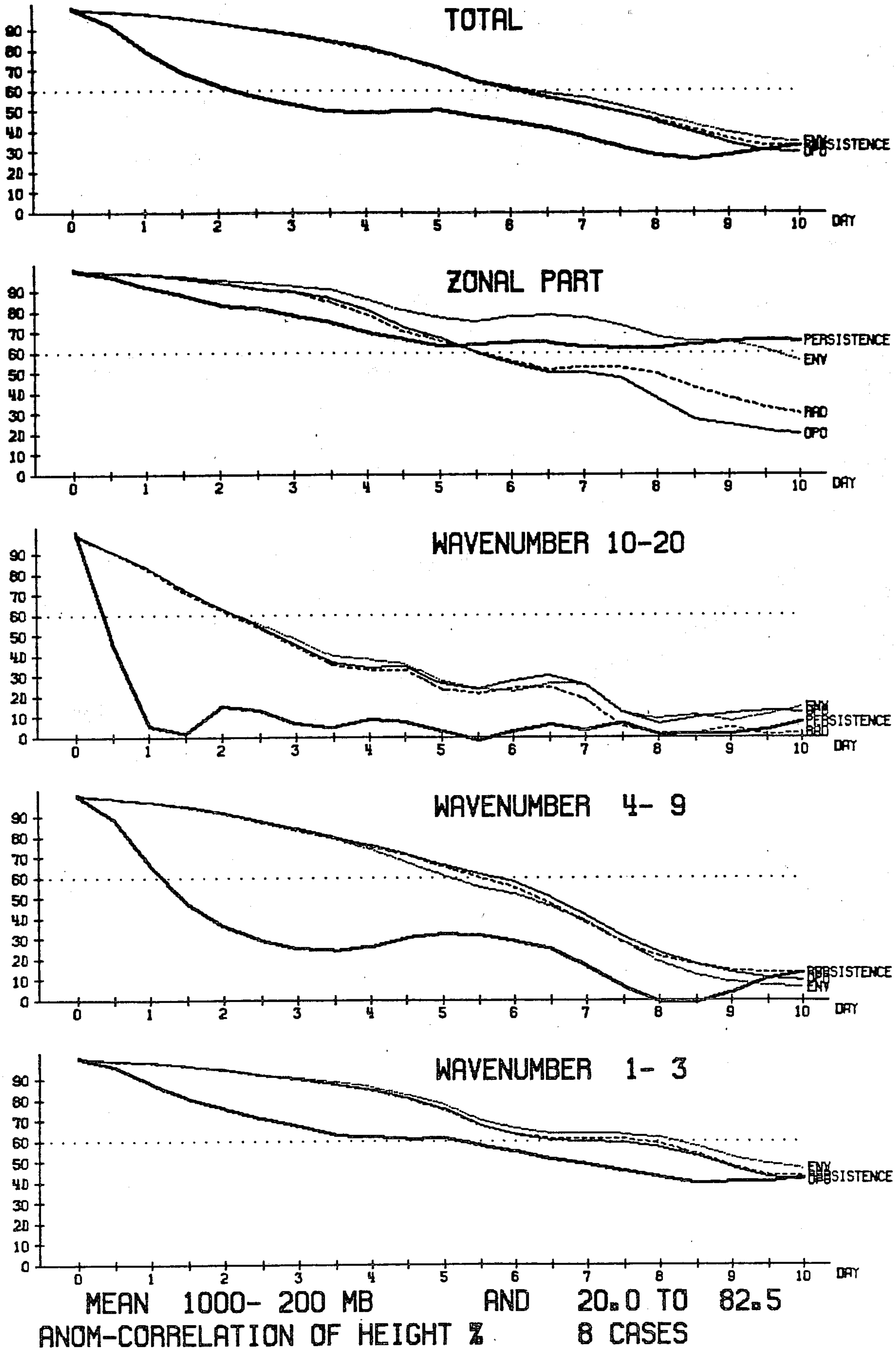


Fig. 23 Anomaly correlations of heights for the ensemble of 8 cases for the valley filled (RAD), 2σ-envelope (ENV) and mean (OPO) orographies.

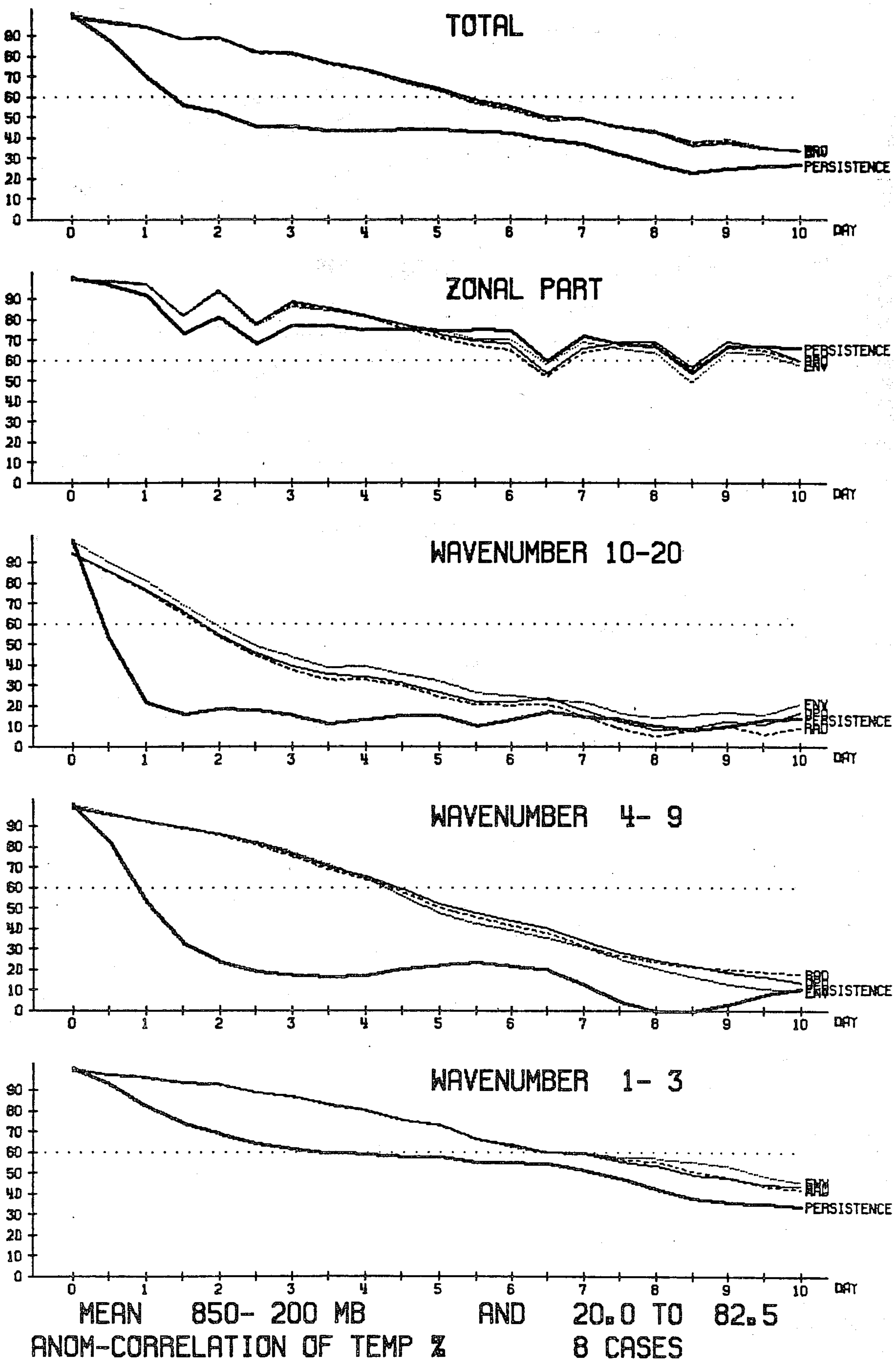


Fig. 24 As Fig. 23 but for temperature.

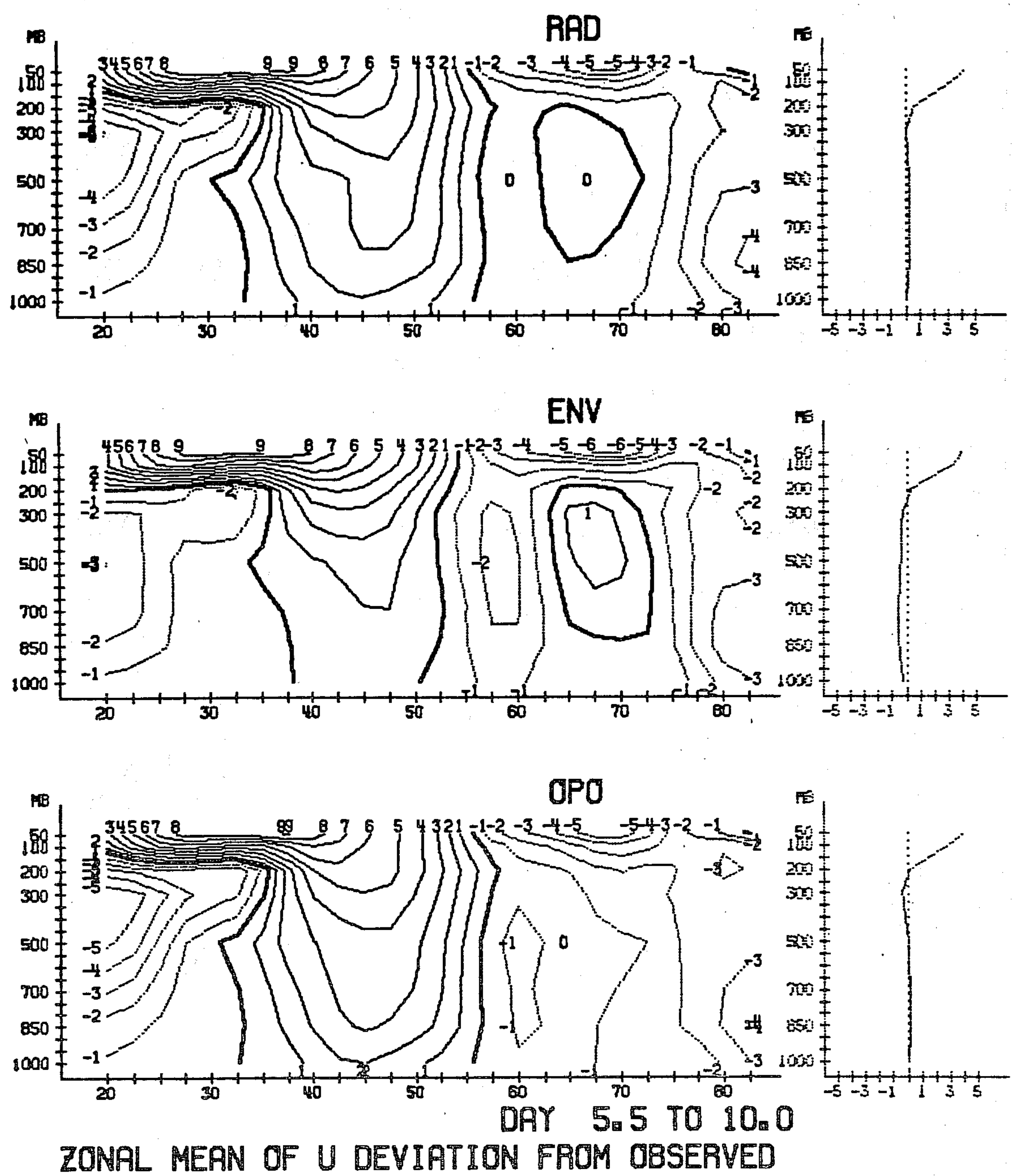


Fig. 25 Zonal mean of the zonal wind deviations from the observed for the valley-filled (RAD), 2σ-envelope (ENV) and mean (OPO) orographies.

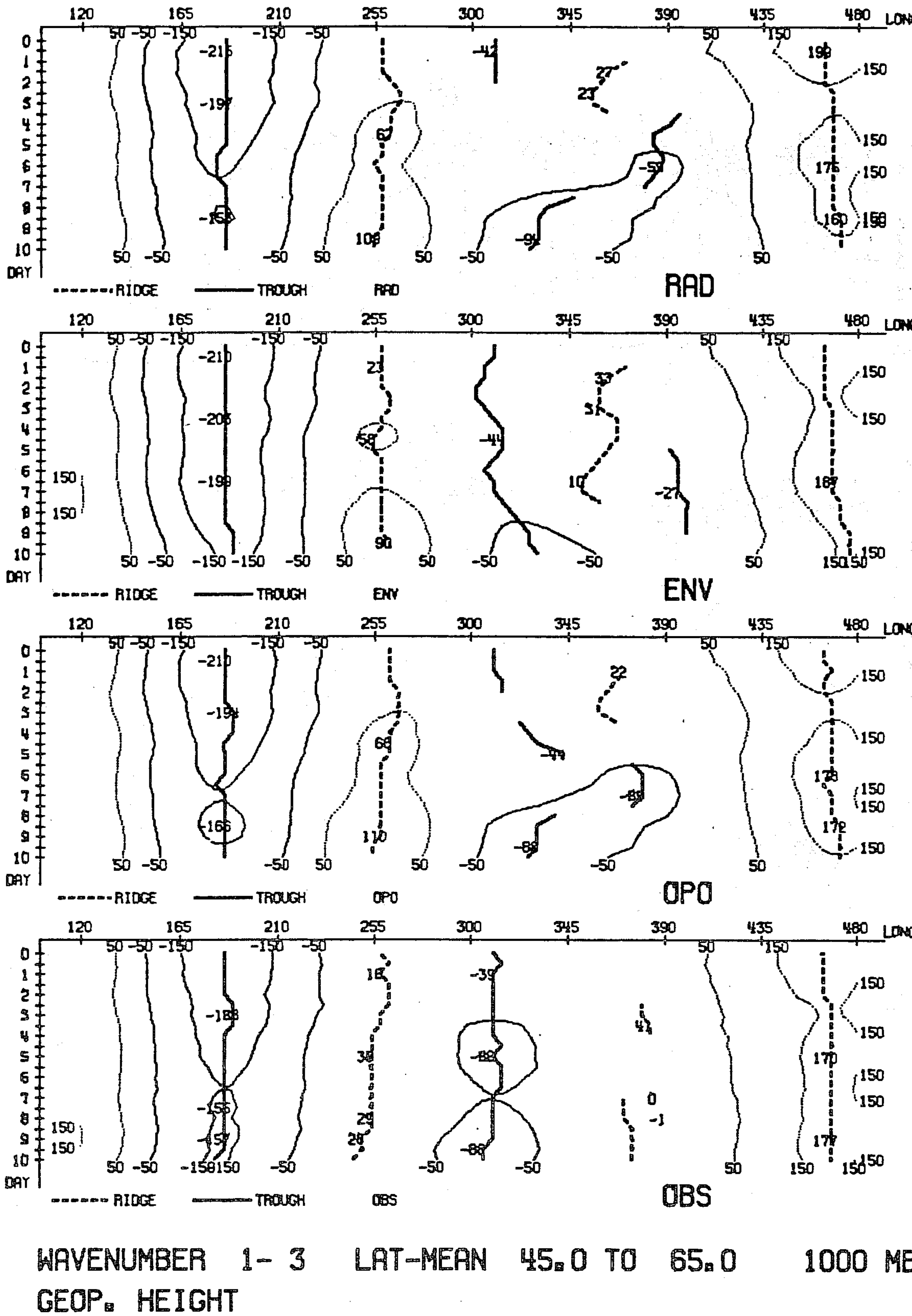
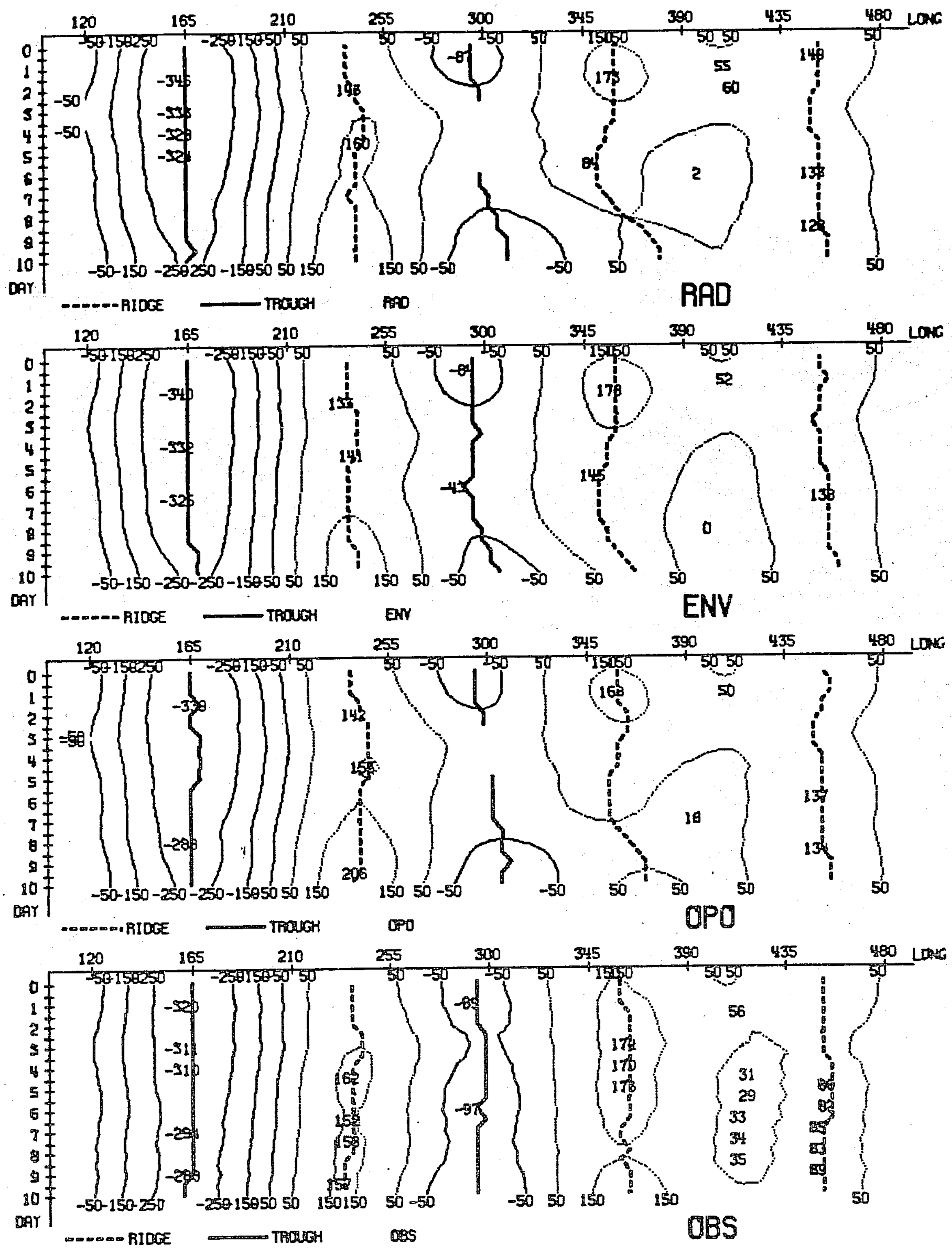


Fig. 26 Hovmöller diagrams at 1000 mb for the valley-filled (RAD), 2σ-envelope (ENV) and mean (OPO) orographies, and for the observed flow (OBS).



WAVENUMBER 1- 3 LAT-MEAN 45.0 TO 65.0 500 MB
GEOP. HEIGHT

Fig. 27 As Fig. 25 but for 500 mb.

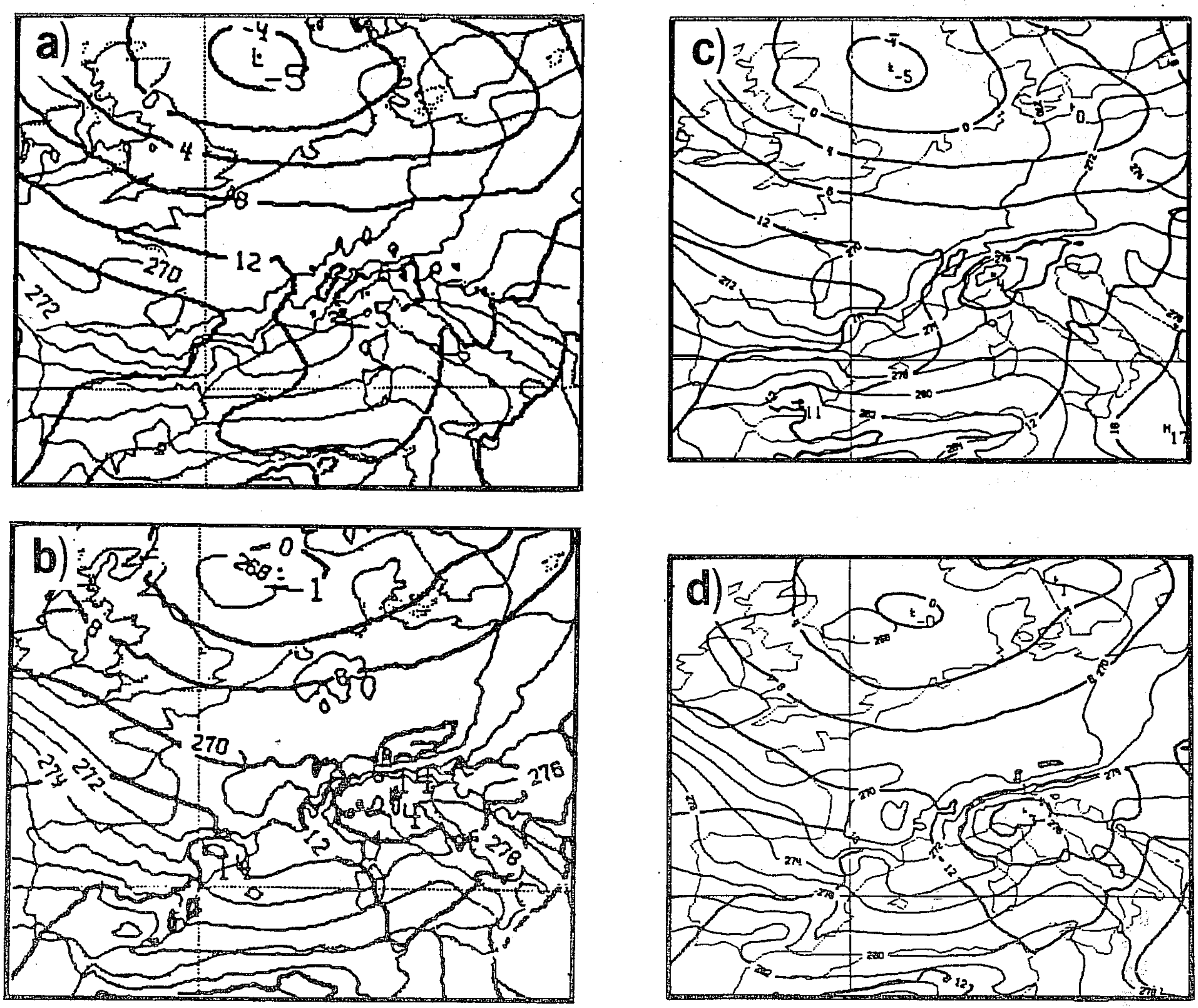


Fig. 28 Forecasts of the 1000 mb height and temperature using the limited area model. (a) and (c) are 36-hour forecasts using the valley-filled and mean orographies and (b) and (d) are the corresponding 48-hour forecasts.

2σ-envelope orography. Finally we consider the Hovmöller diagrams for height at both 1000 mb and 500 mb (Figs. 26 and 27). Once again there is no indication of any substantial difference between the valley-filled and mean orographies. Overall, all of the parameters examined indicate that the errors from the use of the valley-filled and mean orographies are similar, and tend to be larger than in the experiments with the 2σ-envelope orography.

4.2 Experiments with a high resolution model

An experiment was carried out with the N192 limited area model; the case chosen was the Alpine cyclogenesis of 18 March 1982. This case has already been investigated by Dell'Osso and Radinovic (1984) using a mean orography.

The valley-filled orography used in the experiments did not undergo any filtering, consequently a certain amount of noise in the forecasts is to be expected. The 36 hour forecast of the 1000 mb height (verifying at 00GMT 18 March) is given in Figs. 28a and c for the valley-filled and mean orographies. In both cases the cyclone is created in the same place, and the central values are similar - 5 dam for the valley-filled orography and 4 dam for the mean one. The ridge upward of the Appenines is slightly further east in the valley-filled case, but in general there are only small differences. The forecasts from 12 hours later (Figs. 28b and 28d) are also similar.

5. CONCLUSIONS

From the numerical and laboratory saw-tooth topography experiments, as well as the atmospheric studies over complex terrains, there appears to be a proper physical foundation for the use of a valley-filling technique for representing synoptic-scale orography in numerical models.

The valley-filling height correction procedure increases the heights of valleys, while the ridge heights remain the same. As a result the basic height of mountains are preserved and mountain ranges become more compact. The second important contribution of the valley-filling technique relates to the slope of mountains. With this technique the slope becomes more uniform and less steep.

The analysis of the quantitative features of the earth's orography and four model prescribed orographies has shown that they differ in many aspects. There is no doubt that these differences are reflected in the synoptic-scale atmospheric processes which are simulated in numerical models. However, more details about this can only be obtained by further studies of the influence of changes to the orography on the atmosphere followed by a series of specially designed numerical experiments.

The results from experimental forecasts with the valley-filled orography, in comparison with the envelope and mean orographies, did not reveal a noticeable improvement. However, it is hardly possible to believe that the effects of the valley-filling technique and its physical consequences are negligible in comparison with the mean orography. In order to find out a satisfactory explanation for this, it is necessary to make a more detailed study of the experiments.

Acknowledgements

The author expresses warm thanks to Dr. L. Bengtsson, Director of ECMWF, for his kind invitation to make these studies and Dr. D. Burridge for providing the facilities and support. Further thanks are due to Dr. A. Simmons for reviewing the manuscripts, Dr. Dell'Osso for conducting the experiments and Dr. R. Riddaway who helped to edit the paper.

References

Akesson, H., H. Bottger and H. Pumpel, 1982: First results of direct model output verification of near-surface weather parameters at 17 locations in Europe. ECMWF Tech.Memo.No.47, 46pp.

Bell, R.C. and R.O.R.Y. Thompson, 1980: Valley ventilation by cross wind. J.Fluid Mech., Vol.96, part 4, 757-767.

Berkofsky, L. and E.A. Bertoni, 1955: Mean topographic charts for the entire earth. Bull.Amer.Meteor.Soc., 36, 350-353.

Defant, F., 1951: Local winds, Compendium of Meteorology, Boston, Amer.Met.Soc., 655-675.

Dell'Osso, L. and D. Radinovic, 1984: A case of study of cyclone development in the lee of the Alps on 18 March 1982. Beitr.Phys.Atmosp. Vol.57 No.3, 369-379.

Drazin, P.G., 1961: On the steady flow of a fluid of variable density past an obstacle. Tellus, 13, 239-251.

Faukner, D.A., 1981: A winter-time low-level jet in a Yukon valley. Second conference on mountain Meteorology, Amer.Meteor.Soc., 36-39.

GARP, 1982: Alpex experiment design. Alpex No.1, 99 pp.

Gates, W.L. and A.B. Nelson, 1975: A new (revised) tabulation of the scripps topography on a 1° global grid. Part I: Terrain heights. The RAnd Corporation, 132pp.

Gudiksen, P.H. and J.J. Walton, 1981: Categorization of nocturnal drainage flows in the Andersen Creek valley. Second conference on mountain meteorology. Amer.Met.Soc., 218-221.

Hunt, J.C.R. and W.H. Snyder, 1980: Experiments on stably and neutrally stratified flow over a model three-dimensional hill. J.Fluid Mech., 96, 671-704.

Johannessen, K.R., 1982: Verification of ECWMF quantitative precipitation forecasts over Europe. ECMWF Tech.Memo.No.51, 71pp.

Lee, J.T. et al., 1981: Wind tunnel studies of flow channeling in valleys. Second conference on mountain meteorology. Amer.Meteor.Soc., 331-338.

Marlatt, W.E., J.D. Beach and D.C. Fox, 1981: The shape of air temperature inversion surfaces of mountain valleys. Second conference on mountain meteorology, Amer.Meteor.Soc., 173-178.

Marrs, R.W. and J.D. Marwitz, 1977: Location areas of high wind energy potential by remote observation of eolian geomorphology and topography. Proc. Third Conference and Workshop on Wind Energy Conversion Systems. JBF Scientific Corp., Washington, D.C., 307-320.

Martner, B.E. and J.D. Marwitz, 1981: Airflow through the "wind corridor" in Southern Wyoming. Second conference on mountain meteorology, Amer.Meteor.Soc., 309-315.

McNider, R.T. and R.A Pielke, 1981: Numerical simulation of slope and mountain flows. Second conference on mountain meteorology, Amer.Meteor.Soc., 95-100.

Pettre, P., 1981: An integrated system of meteorological measurement in a large valley in France. Second conference on mountain meteorology, Amer.Meteor.Soc., 321-324.

Reed, T.R., 1931: Gap winds of the Strait of Juan de Fuca. Mon.Wea.Rev., 59, 373-376.

Reed, J.W., 1974: Wind power climatology. Weatherwise, 27, 236-242.

Smith, S.M., H.W. Menard and G. Sharman, 1966: World-wide ocean depths and continental elevations averaged for areas approximating one deree square of latitude and longitude. Scripps Institution of Oceanography, S10.

Sommers, W.T., 1981: Variation of flow in a mountain canyon during initiation and dimunition of strong synoptic scale forcing. Second conference on mountain meteorology. Amer.Meteor.Soc., 339-345.

Steinacker, R., 1979: Moglichkeiten synoptischer Analysen mit dem derzeitigen Beobachtungesnetz. Inst.Meteor.Insbruck.

Thompson, A.H., 1981: On the physical processes of inversion development in a canyon. Second conference on mountain meteorology. Amer.Meteor.Soc., 257-258.

Tibaldi, S., 1980: Cyclogenesis in the lee of orography and its numerical modeling, with special reference to the Alps. GARP Publ.Ser., No.23, 208-231.

Tibaldi, S. and J.F. Geleyn, 1981: The production of a new orography, land-sea mask and associated climatological surface fields for operational purposes. ECMWF Tech.Memo No.4, 43pp.

Wallace, J.M., S. Tibaldi and A.J. Simmons, 1982: Reduction of systematic forecast errors in the ECMWF model through the introduction of an envelope orography. ECMWF manuscript, 48pp.

Walter, B.A. and J.E. Overland, 1981: The role of orography in determining mesoscale wind fields in the Strait of Juan de Fuca. Second conference on mountain meteorology. Amer.Meteor.Soc., 28-35.

Whiteman, C.D. and T.B. McKee, 1977: Observations of vertical atmospheric structure in a deep mountain valley. Arch.Met.Geoph.Biokl., 26, 39-50.

Whiteman, C.D., 1981: Temperature inversion buildup in valleys of the Rocky Mountains. Second conference on mountain meteorology, Amer.Met.Soc., 276-282.