SENSITIVITY OF NUMERICAL MODELS TO MOUNTAIN REPRESENTATION

BY

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Introduction

The U.K. Meteorological Office 5-level general circulation model (GCM) with its standard orography appeared to underestimate the barrier effects of mountains. A series of sensitivity integrations was therefore performed in which mountain heights were increased.

The 5-level GCM will be described briefly here, with particular reference to the treatment of orography, and then descriptions will be given of the experiments with increased mountain heights. Some earlier model experiments will also be mentioned in this context.

The Model

[For more complete details see Corby et al. (1972) and Corby et al (1978)]

The UK Meteorological Office 5-level GCM is a finite difference grid point model on the whole globe, employing spherical polar coordinates. The points are placed in rows on lines of latitude 3^{o} apart in such a way that the east-west grid length is approximately equal to the north-south grid length of 330 km. This results in the number of points on a row decreasing towards the poles from 120 at the equator. So that truncation errors in polar regions are not excessive, a minimum of 16 points per row is maintained. Fig. 1 shows the grid superimposed on a polar stereographic projection of the northern hemisphere.

Using pressure as the vertical coordinate with height as a dependent variable, as is conventional in meteorology, leads to problems with the lower boundary condition on the motion. Furthermore, some of the grid points on the lower levels would be underground leading to difficulties in assigning values to the variables here. Accordingly, most GCMs adopt a vertical coordinate s which has the lower boundary at s = constant. The UKMO 5-level GCM uses

$$s \equiv \sigma = {}^{p}/{}_{p_*}$$

where p denotes pressure and the suffix $_*$ indicates a value at the ground.

The ground is now defined as the surface $\sigma = 1$ and the top of the atmosphere is at $\sigma = 0$.

The upper and lower boundary conditions are now

$$\frac{D\sigma}{Dt} = \dot{\sigma} = 0 \quad \text{at} \quad \sigma = 0 \text{ and } \sigma = 1$$

i.e. all motion is in sigma-surfaces at $\sigma = 0$ and $\sigma = 1$, so that there are no fluxes into the ground or out of the top of the atmosphere.

A complication now arises in the pressure gradient term:

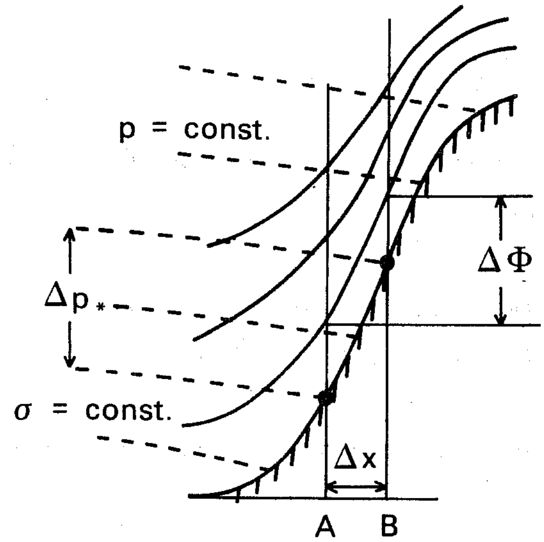
$$\frac{1}{\rho} \underset{\sim}{\nabla}_z p \quad \text{becomes} \quad \underset{\sim}{\nabla}_\sigma \Phi + \frac{RT}{p_*} \underset{\sim}{\nabla}_\sigma p_* \qquad (1)$$

where $\underset{\sim}{\nabla}_z$ denotes the horizontal gradient operator in z-coordinates and Φ is the geopotential $= \int_0^z g dz'$

[= gz in the model]

The method of evaluating (1) must be chosen with some care. The two terms in (1) are often similar in magnitude but opposite in sign and so the terms should be evaluated consistently.

Corby et al. (1972) shows how this is done.



The vertical sum used to approximate the integrated continuity equation when evaluating thicknesses gives exact answers in an atmosphere of the form $T = A \ln \sigma + B$, for any constants A and B. We therefore arrange for exact cancellation of the two pressure gradient terms in such an atmosphere. [The thickness $\Delta\Phi$ in the diagram above appears in the first term and is exactly evaluated with this temperature structure].

The first term is simply evaluated by approximating

$$\left(\frac{\partial \Phi}{\partial x}\right)_\sigma \simeq \delta_x \overline{\Phi}^x$$

where the notation means $\delta_x(\cdot) = \frac{1}{\Delta x}\left[(\cdot)_{x+\frac{1}{2}\Delta x} - (\cdot)_{x-\frac{1}{2}\Delta x}\right]$

$$\overline{(\cdot)}^x = \tfrac{1}{2}\left[(\cdot)_{x+\frac{1}{2}\Delta x} + (\cdot)_{x-\frac{1}{2}\Delta x}\right]$$

The approximation for $\frac{RT}{p_*}\left(\frac{\partial p_*}{\partial x}\right)_\sigma$ then turns out to be

$$\overline{R\overline{T}^x \; \delta_x \ln p_*}^x \; .$$

A similar problem is encountered in evaluating the flux divergence term in the thermodynamic equation, where terms like $\frac{\partial}{\partial x}(p_* uT)$ occur.

If we have a horizontally homogeneous atmosphere with a dry adiabatic lapse rate, air moving along sigma surfaces and rising over topography gives rise to no change in temperature higher up because the advection of warmer air from upstream on the sigma-surface cancels an adiabatic cooling of the air. In practice, therefore, we have large terms of opposite sign, almost cancelling.

By assuming sigma-surfaces are stream surfaces and arranging such terms to cancel we obtain the finite difference approximation of

$$\frac{\partial}{\partial x}(p_* u.T) \text{ as } \widetilde{\delta_x(p_* u).T}^x$$

where $\widetilde{AB}^x = \frac{1}{2}(A_{x+\frac{1}{2}\Delta x}B_{x-\frac{1}{2}\Delta x} + A_{x-\frac{1}{2}\Delta x}B_{x+\frac{1}{2}\Delta x})$.

The Experiments

Four control integrations of 50 days each were performed from northern hemisphere data for 1st, 12th, 13th and 14th December 1976. They were then repeated using increased orographic heights. These were intended as a sensitivity test to assess the value of a more realistic representation of the barrier effects of mountains. The changes were accordingly kept simple. They were as follows:

All smaller-scale mountains; doubled in height.
Larger massifs [Rockies, Himalayas, Greenland]; increases limited
to { 1 km north of 63°N
1.5 km elsewhere.

The results presented here are divided into sections as follows:

(a) Effect on 30-day means of 500mb height and sea-level pressure.

(b) Effect on standing and transient eddy kinetic energy.

(c) Response in the first few days.

(d) Comparison of Summer Integrations.

(a) Effect on 30-day means

(i) 500mb height

Comparing the mean of all four experiments with the mean of the controls (see Fig. 2), we find that enhanced orography induces higher 500mb surfaces to the north of mountains and lower surfaces downstream. North of the Rockies we have a maximum difference of 18 dam and to the north of the Himalayas about 13 dam. Over Japan, downstream of the Himalayas, we find a drop of 17 dam in the 500mb height and over the Eastern Seaboard of North America a drop of 7 dam.

These results are consistent with results from earlier experiments in which the mountains were eliminated, but are rather larger and the more northerly latitude of the rises was not evident previously. The 30 day means of differences between the individual experiments were also consistent in showing this pattern.

The mean 500mb height field in the enhanced orography experiments agreed rather better with observation for the years 1974-77 than did the control mean (see Fig. 3). For example, the ridge over western North

America is stronger, as is the trough over Japan. The jet to the east of Japan is increased in strength, an improvement also.

(ii) Sea level pressure

[Note that caution should be exercised when considering these results, because of the difficulty of reducing surface pressure over high ground to sea level].

Comparing once again the four-experiment means (Fig. 2) for standard and enhanced orography, we see that there are increases in sea-level pressure over and to the north of the increased orography. These have magnitudes of about 10mb over the Rockies and 6mb north of the Himalayas. There is an area of large increases (up to 20mb) in North Eastern Siberia.

Downstream of increased orographic heights, there are falls of pressure of about 5mb over the Western North Atlantic Ocean and about 14mb over the North Pacific Ocean. An improvement when compared with climatology is the southward movement of the Pacific subtropical ridge from 35-40^{o}N to 25-30^{o}N.

If we combine these changes with the changes in 500mb height we see the changes in 1000-500mb thickness shown in Fig. 4. There are increases (representing a warming in the lower half of the atmosphere) over and to the north of the Rockies with a maximum change of about 12 dam and increases of up to 9 dam to the north of the Himalayas. Falls of 7 dam and 13 dam occurred downstream of the Rockies and Himalayas respectively.

As a test of the reliability of these results, charts of student's t-statistic for sea-level pressure and 500 mb height are shown in Fig. 5. They are charts showing isopleths of t calculated for the difference between two small-sample means. Values of magnitude about two represent differences in the means which would, on average, be exceeded due to the natural variability of the model on about 10% of occasions. Values of magnitude greater than three represent differences which would be expected to occur very infrequently (about 2%).

It can be seen that highly significant changes occur in the expected areas, with significant falls of sea level pressure to the south of the massifs.

In previous work (Rowntree, 1975) an earlier version of the model was run with standard orography and with no mountains at all. A cross-section of 500mb height differences along 49½^{O}N is shown in Fig. 6. The three lower curves represent the effect of the mountains on the flow in these earlier experiments. A further experiment produced results (not shown) which were very similar to (C4-NM3). The top curve shows the results obtained by Manabe and Terpstra (1974).

(C7-NM7) is not very like the other two, probably because the model was different and because both experiments of the pair are different from those in the other experiment pairs. It is broadly similar to (C6-NM3), however, in having no trough near 60^{O}E. It may be noted that the response to the orography in (C4-NM3) is to have ridges over all the mountains and in (C6-NM3) over the Rockies. In (C7-NM7), however, the ridges were well upstream of the mountains and the trough just downstream.

From considerations of potential vorticity we see that the absolute vorticity of a column of air decreases as it passes up the slope of or around to the north of a range of mountains, and increases as it passes down the other side or around the south.

A mechanism suggested by Rowntree (1975) distinguishes between progressive and retrogressive travelling waves. Shorter waves (say wavenumber > 4) would be progressive and long waves retrogressive, the exact wavenumber for stationarity depending on the north-south structure. The retrogressive waves would contribute to a fall in mean heights over mountains as they traverse the cyclogenetic eastern slope of the orography. The converse would occur as progressive waves pass over the western slope towards the mountain tops. Thus one would expect a fall of heights over mountains when long waves predominate and a rise where short waves predominate.

Referring again to Fig. 6, we may therefore explain the difference in behaviour between (C7-NM7) and (C4-NM3). The following table gives 500mb height amplitudes in metres at $49\frac{1}{2}^{o}$N in each wavenumber for each experiment pair difference.

Wavenumber	1	2	3	4	5	6	7	8
C3-NM3	10	19	29	51	17	7	9	5
C4-NM3	32	19	30	49	17	7	11	5
C6-NM3	55	86	32	41	17	7	8	3
C7-NM7	37	98	47	16	17	12	9	5

It may be seen that (C7-NM7) had mainly long waves while (C3-NM3) and (C4-NM3) had a predominance of shorter waves, supporting Rowntree's hypothesis.

The corresponding table (at 300mb) for the more recent experiments with standard and enhanced orography shows mainly long wave response, together with a rise of heights in phase with the mountains:

Table showing, for each experiment pair, at each wave-number, the amplitude of the differences (in metres) together with the difference in phase between the response and the orography (in wavelength

Wavenumber	1	2	3	4	5	6	7	8
experiment A	94 -0.30	110 -0.15	51 -0.14	31 -0.21	26 -0.06	8 -0.25	10 0.39	5 -0.29
experiment B	50 -0.34	100 -0.03	110 -0.10	78 -0.32	43 0.14	3 -0.15	12 -0.40	6 -0.24
experiment C	62 -0.07	130 -0.18	25 0.49	14 -0.49	49 -0.04	32 -0.43	21 -0.34	3 -0.18
experiment D	110 -0.24	178 -0.07	81 -0.18	59 -0.38	30 -0.04	22 -0.43	10 -0.40	2 0.04

The outlined wavenumbers have a large amplitude and are mainly associated with a response in phase with the orography. This behaviour, different from that reported by Rowntree, may indicate that the now very large mountains are having a different effect on the flow; that is, the greater barriers are causing more flow around to the north and to the south. The effect of this is noticeable on the charts as a raising of heights to the north and a depression of heights to the south.

(b) Effect on eddy kinetic energy

An examination of the latitudinal distribution of transient and standing eddy kinetic energy shows:

(i) The hemispheric mean total eddy kinetic energy is a little increased in the enhanced orography experiments compared with the controls.

(ii) The splitting between the transient and standing energy is different in the two cases; the control experiments have more transient energy, whereas the enhanced orography experiments have more standing energy.

It appears that the increased amplitude in the orographically induced standing waves is largely at the expense of transient waves.

Hemispheric mean eddy kinetic energy (m^2s^{-2})

Experiment pair		transient	standing
A	Standard orography	31	20
	Enhanced "	28	39
B	Standard "	40	29
	Enhanced "	26	48
C	Standard "	30	30
	Enhanced "	29	40
D	Standard "	36	31
	Enhanced "	27	40

This is a poor result of the increased mountain heights, since the transient eddy kinetic energy values are already much too low in the standard model. Observed values are typically 87 m^2s^{-2} (transient EKE) and 17 m^2s^{-2}(standing EKE).

(c) Response in first few days

The building of 500mb height to the north of mountains occurs quickly and reaches typically 10 dam higher than the control by 2 days and 20 dam by 4 days. Typical rises of sea-level pressure are 14mb by day two and 20mb by day four with falls downstream of 6mb by day two and 10mb by day four.

Even with these differences, the experiments in each pair are more similar to one another than to reality. This results from the errors being mainly due to misplacing of depressions and other centres rather than poor representation of standing features.

(d) Comparison of summer integrations

Three experiments were run from May 1977 data with standard orography and three with enhanced orography. Days 21 to 50 of each experiment were meaned and a grand mean formed from the three runs of each sort.

The 500mb height differences are shown in Fig. 7. Here the changes are predominantly increased with a regular zonal pattern. The chart of t-statistics, however, shows that the significant increases occur mainly in two widespread regions north of the mountains (see Fig. 8).

The following table displaying the eddy kinetic energy values for these experiments shows a rise in standing energy in the enhanced orography experiments but a rather smaller fall in transient energy.

Hemispheric mean eddy kinetic energy (m^2s^{-2})

Experiment pair		transient	standing
A	Standard orography	12	14
	Enhanced	10	19
B	Standard	12	15
	Enhanced	10	20
C	Standard	12	16
	Enhanced	9	20
	Estimated Observed values	47	9

Conclusions

Experiments with the UKMO 5-level GCM were performed to assess the effects of including mountains with more realistic barrier characteristics than in the standard model. Some aspects of the mean flow were seen to be improved, although the reduced transient behaviour is an undesirable feature of the experiments.

References

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Corby, G.A., Gilchrist, A. and Rowntree, P.R.	1977	"United Kingdom Meteorological Office Five-level General Circulation Model". Methods in Computational Physics, 17, pp.67-110.
Manabe and Terpstra	1974	"Effects of mountains on the General Circulation of the Atmosphere as Identified by Numerical Experiments". J. Atmos. Sci., 31, No.1, p.3.
Rowntree, P.R.	1975	"Thermal and Orographic forcing of the northern hemisphere winter circulation in a numerical model". Met O 20 Tech.Note II/43, May 1975.

Figures

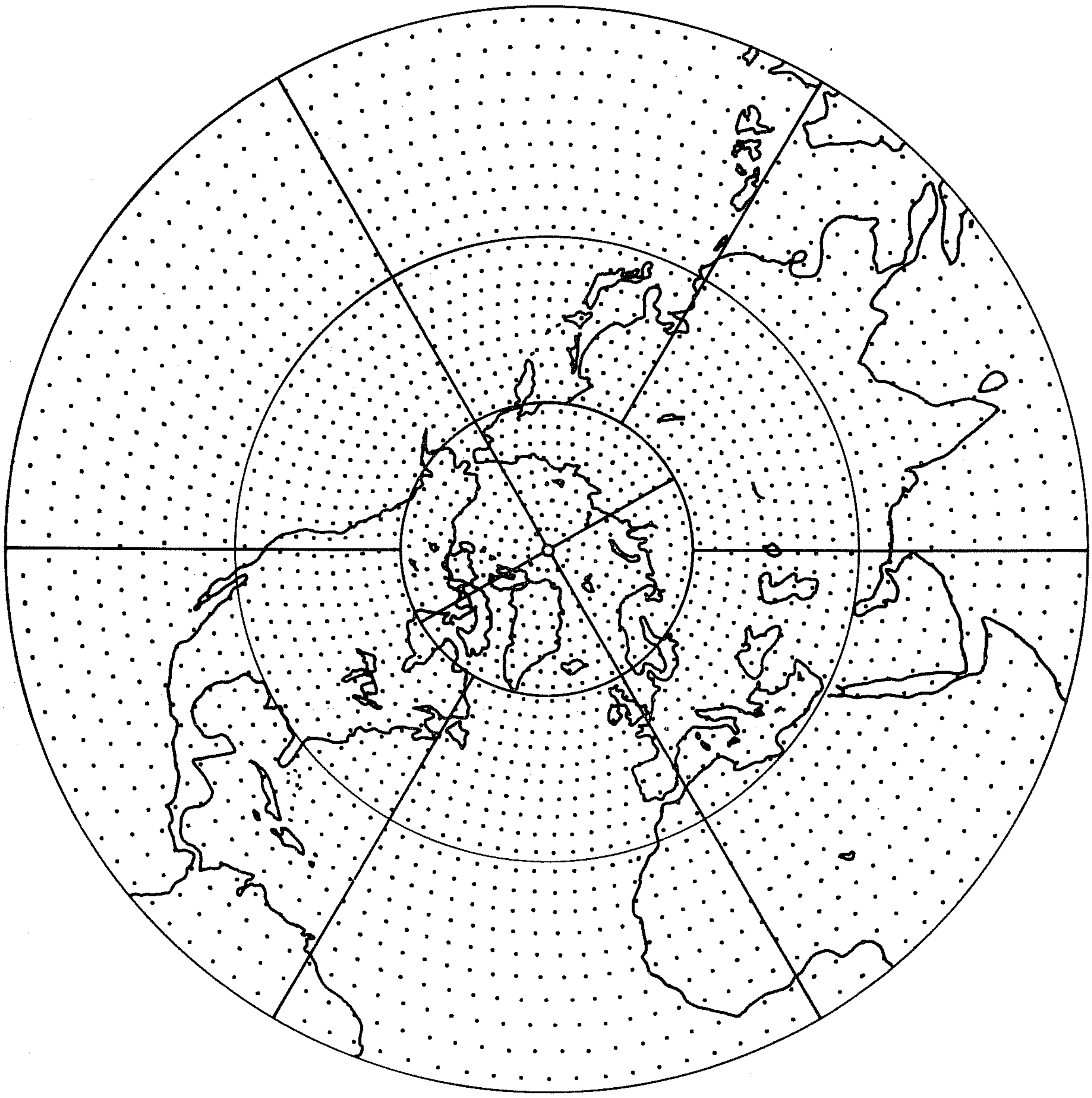
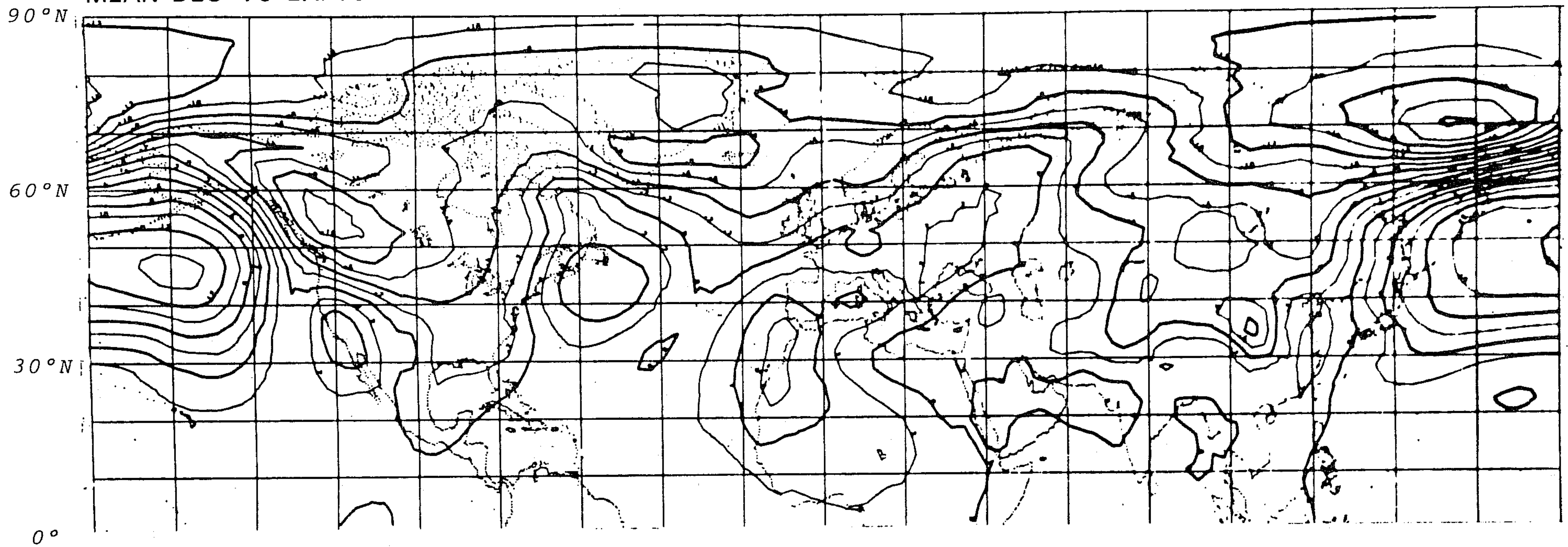


Fig. 1 Medium resolution model grid.



MEAN DEC '76 EXPTS. MINUS MEAN WITH DOUBLED TOPOGRAPHY H500.

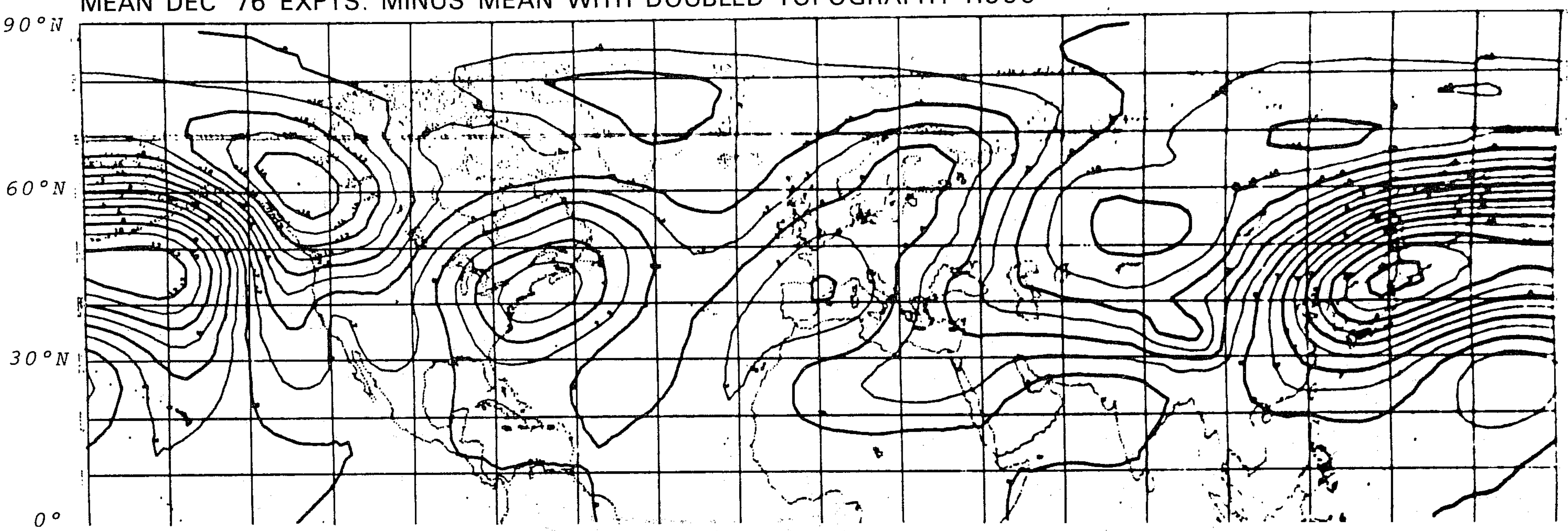


Fig. 2

MEAN OF 4 DEC '76 CONTROL EXPTS. (STANDARD TOPOGRAPHY) H500

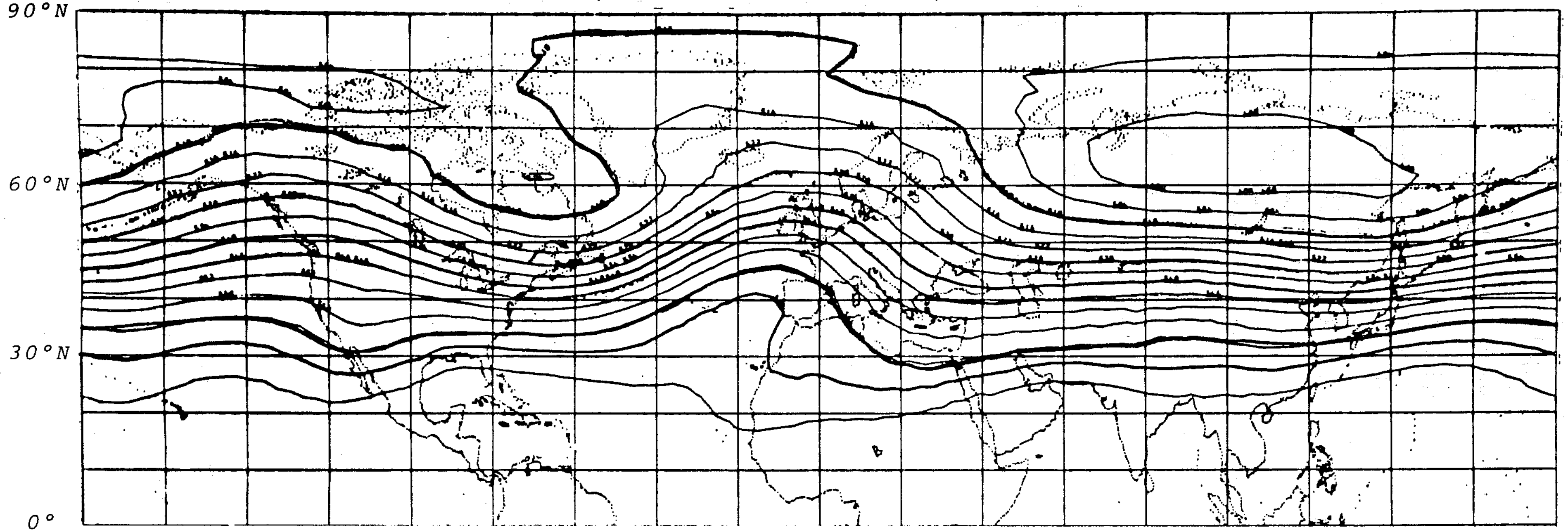
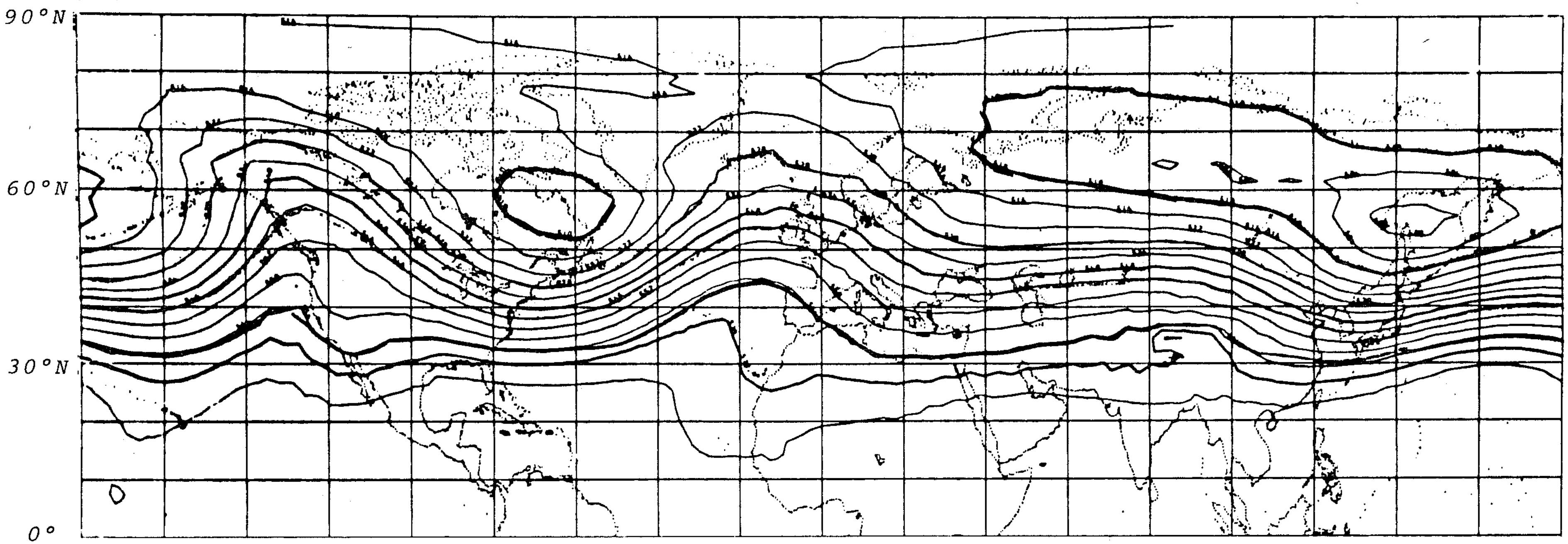


Fig. 3a

MEAN OF 4 DEC '76 EXPTS. WITH DOUBLED TOPOGRAPHY H500



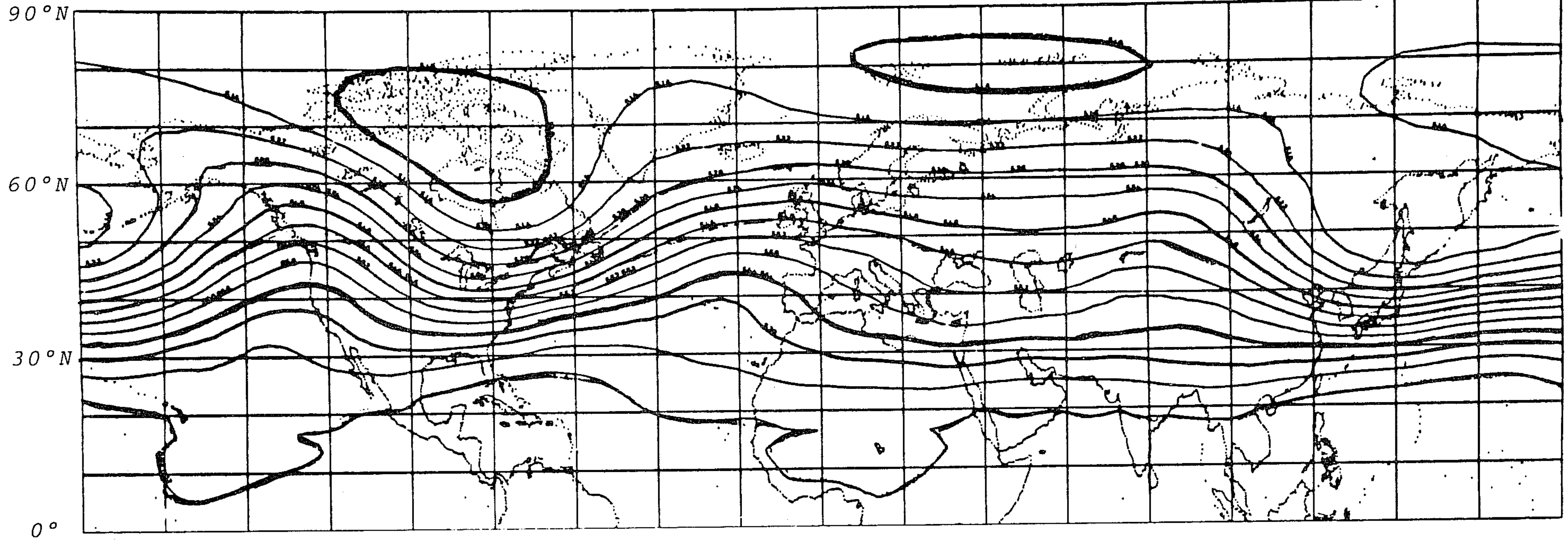


Fig. 3c

MEAN DEC '76 EXPTS. MINUS MEAN WITH DOUBLED TOPOGRAPHY THIK

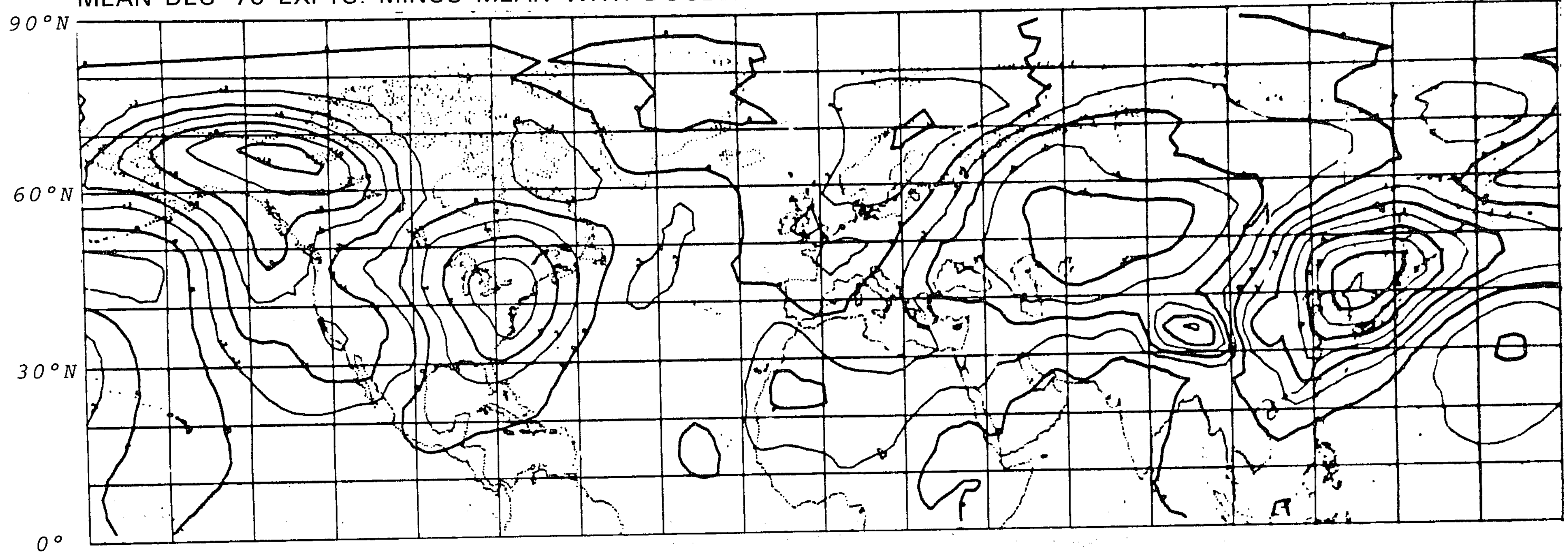
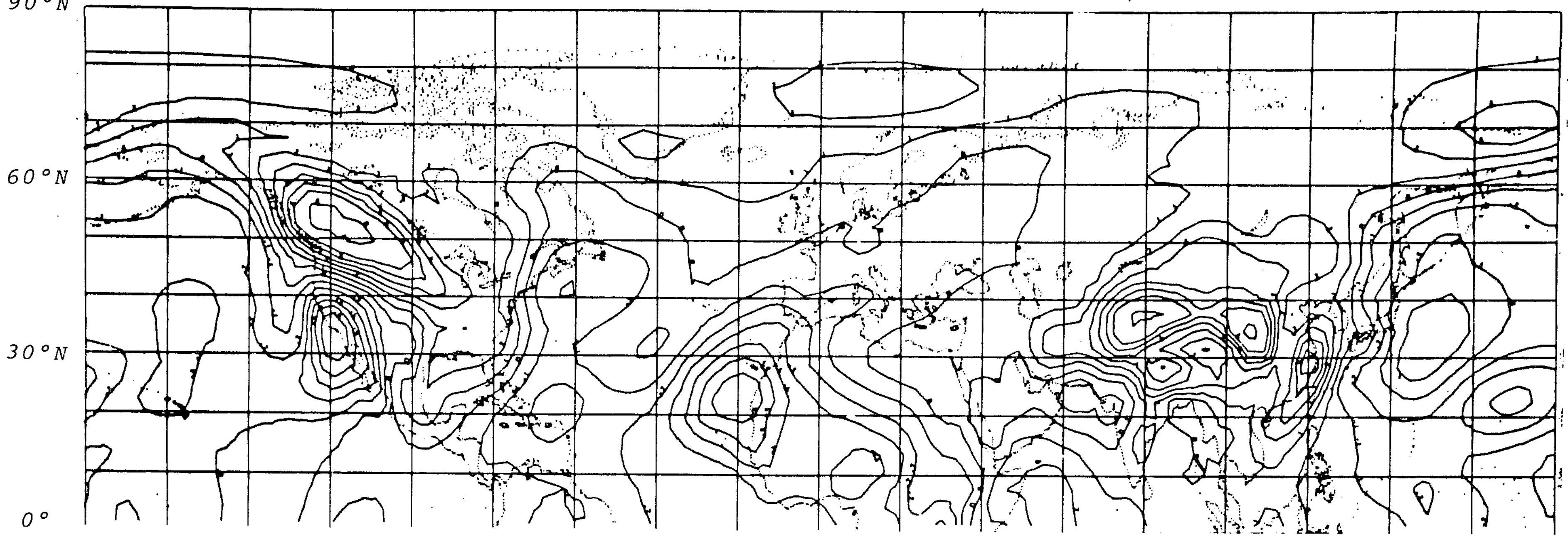


Fig. 4

T STATS DBLE/TOP MS CON DEC '76 EXP (755.754.753.745-660.661.662.663) D21T050 PMSL



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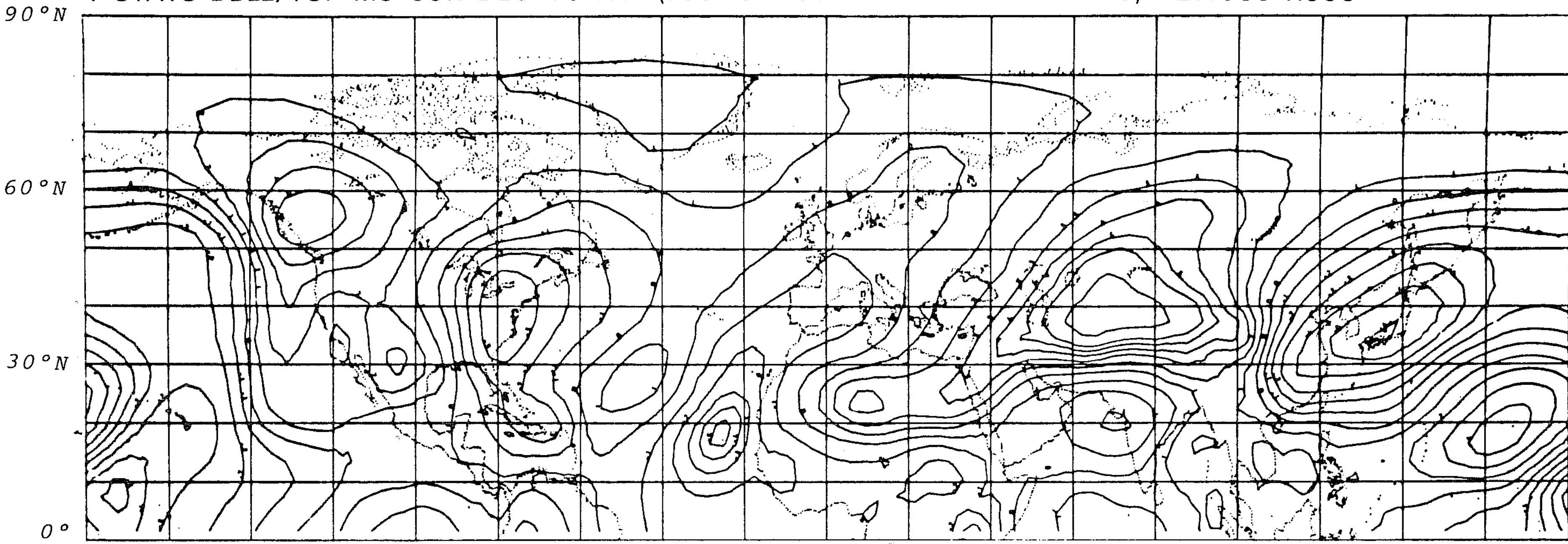


Fig. 5

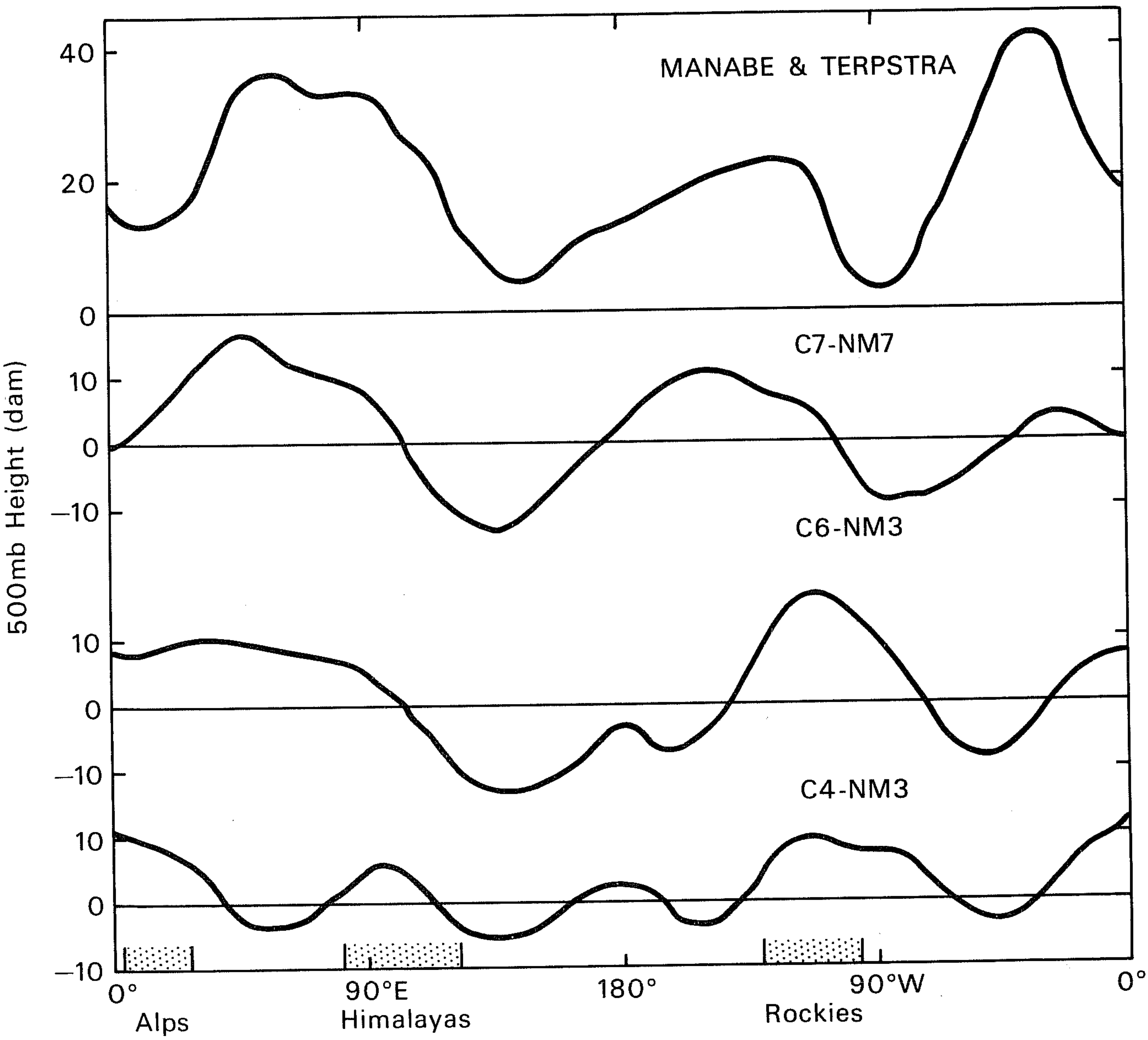
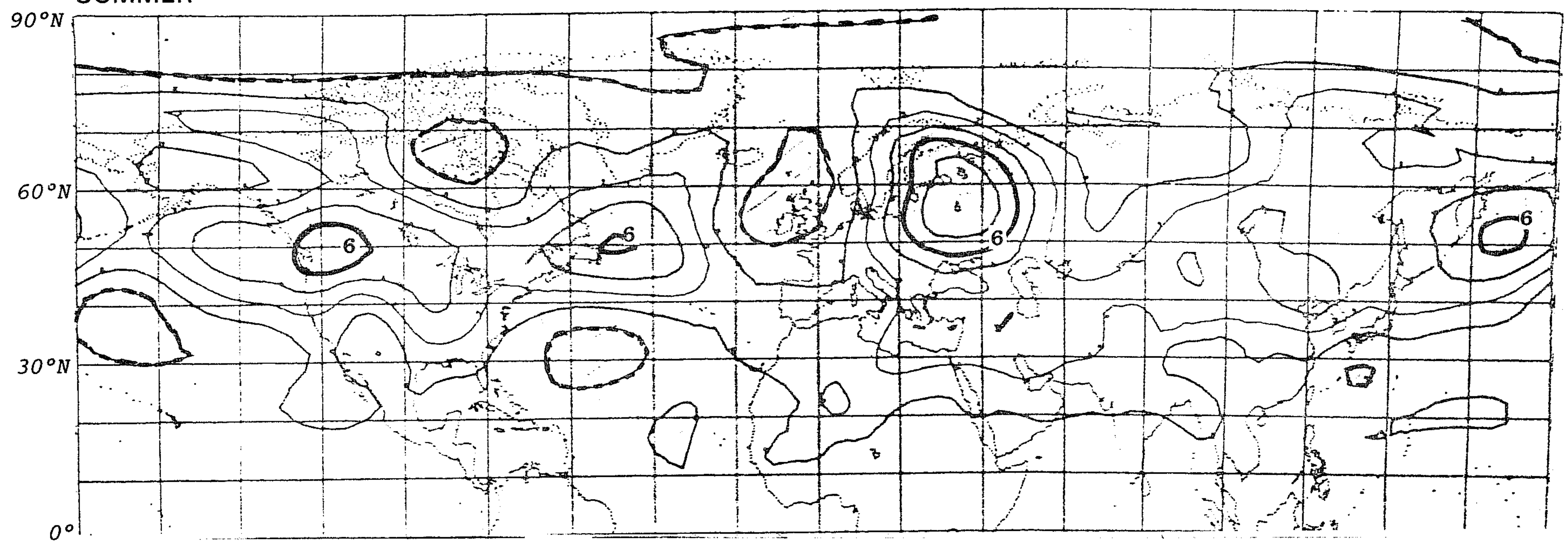


Fig. 6 Changes in 500mb along $49\frac{1}{2}^{O}$N by inclusion of mountains (from Rowntree (1975)).

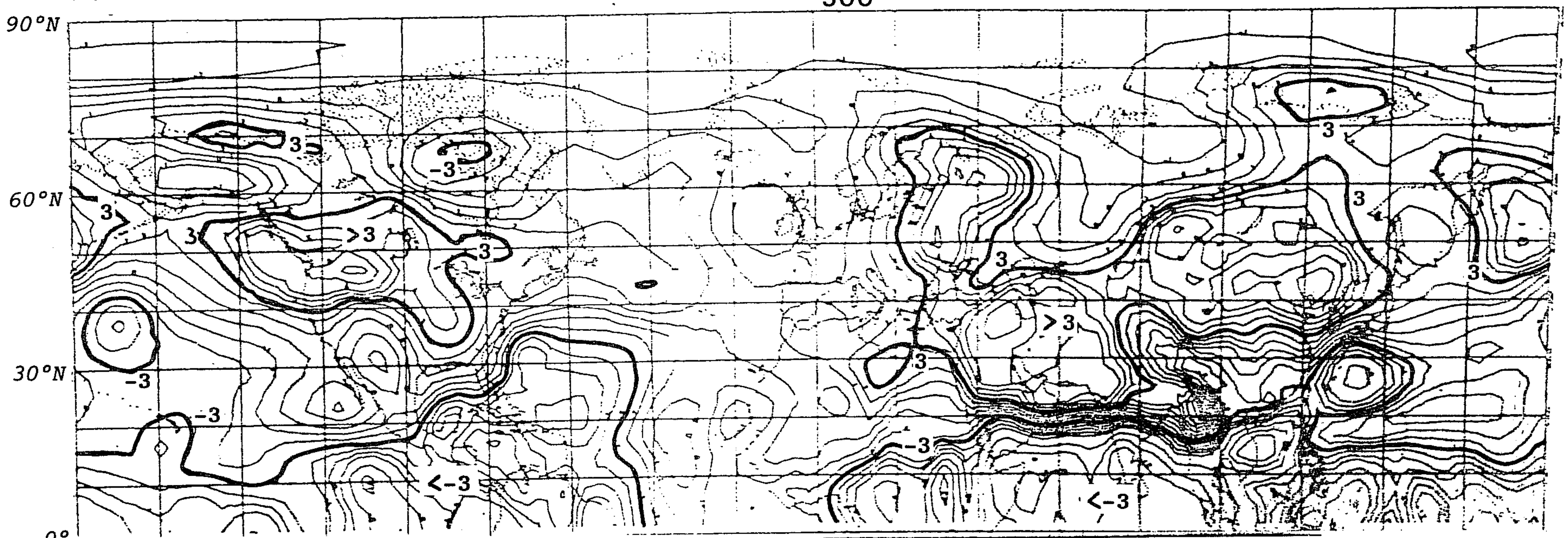
DIFFERENCES OF MEANS OF H_{500} BETWEEN ENHANCED AND STANDARD OROGRAPHY EXPERIMENTS FOR SUMMER



-2 dam contour is dashed. $\pm$6 dam contours are darkened. Contour interval: 2 dam.

Fig. 7

t-STATISTICS FOR DIFFERENCES BETWEEN MEANS OF H_{500} FOR SUMMER EXPERIMENTS



$\underline{+}3$ isopleths are darkened. Contour interval is 1 with 7 omitted.

Fig. 8