Met O 11 Technical Note No. 18

# Objective analysis of the 100 mb. level

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## 1. Introduction

Objective computer analyses of contour charts now play an essential role in the production of numerical forecasts on an operational basis. The function of the objective analysis technique is to interpolate the initial values of contour height at each of the points forming the numerical grid from the station observations of height and wind. The initial analysis is then in a form which can be used directly in the forecast computations. Originally the grid point heights were extracted from subjectively analysed charts, but this is a very tedious, time-consuming process, and cannot be considered as a practical method for any operational numerical forecasting scheme which uses a large number of grid points.

Various objective analysis schemes are used in different countries, and the one developed in the Meteorological Office is based on the method first suggested by Gilchrist and Cressman (1). The approach is essentially two-dimensional (i.e. each level is analysed completely independently), and consists of fitting a quadratic surface to the observations in the vicinity of each grid point by least squares. The method has been described fully by Bushby and Huckle (2) and Corby (3). Regular use has shown that the results form a satisfactory basis for subsequent numerical integration; the technique also has the advantage of being entirely objective. Numerical forecasts are at present computed in the Meteorological Office using the Bushby-Whitelam three-parameter model (4), which requires data at 1000, 500 and 200 mb. As a result, the analyses have so far been restricted to these three levels, and to the field of 1000-500 mb. thickness. The convenience of machine analyses suggests that it would be worthwhile to apply similar techniques to other pressure surfaces, even though they are not needed immediately for numerical computations.

However, at levels above 200 mb. difficulties arise, due to the substantial errors which occur in the observations of geopotential height. This Note describes how it has been possible to adapt the objective analysis procedure to produce acceptable analyses at 100 mb.

## 2. Method of analysis

The analyses at 500 and 200 mb., which provide data for the routine numerical computations are carried out independently and the grid points are dealt with

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individually. In order to determine the contour height at a grid point, the computer selects the six nearest observing stations at which either a height, or wind, or both are reported, with the proviso that only those stations within six gridlengths (about 900 n. miles) are to be used in the interpolation. In areas of sparse data this may mean that less than six stations are chosen. A quadratic surface is fitted to these observations by the method of least squares. If the height of the surface of best fit in the vicinity of a grid point is denoted by hs, then:-

$$hs = ax^2 + by^2 + 2\,hxy + 2\,gx + 2\,fy + c \qquad (1)$$

where x, y are the co-ordinates, with the grid point at the origin.

Reported winds as well as contour heights can be taken into account when fitting the surface, since its slope at any point implies a certain geostrophic wind, which may be compared with the actual wind. The overall discrepancy between the quadratic surface and the height and wind observations (E) is defined by:-

$$E = \sum_{r=1}^{m} \left\{ P(h_s - h_o)^2 \right\}_r + T^2 \sum_{r=1}^{n} \left\{ P(\underline{V}_s - \underline{V}_o)^2 \right\}_r \qquad (2)$$

where ho = reported contour height

hs = height of quadratic surface at the station

m = number of height observations ($0 \leq m \leq 6$)

$\underline{Vo}$ = reported wind

$\underline{Vs}$ = geostrophic wind at the station obtained from the slope of the surface given by equation (1)

n = number of wind observations ($0 \leq n \leq 6$).

p is a distance weighting factor, the form of which is shown in Fig. 1. ($p = \frac{128}{1 + kr^4}$ where r is the distance between the observation and the grid point, in gridlengths, and k is a constant). Note that the value of p falls off rapidly as the distance between the observation and grid point exceeds two gridlengths, so that the major contribution will come from observations within this distance. $T^2$ is a dimensional weighting factor which balances the fitting of the height and wind observations. The optimum value of $T^2$ must be determined by experiment and will depend on the units in which the heights and winds are measured. $T^2 = 16\ \sec^2$ has been found to give the best overall results.

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To obtain the surface of best fit, the coefficients a, b, h, g, f and C in equation (1) must be chosen so that E is a minimum:-

$$\text{i.e.} \quad \frac{\partial E}{\partial a} = \frac{\partial E}{\partial b} = \frac{\partial E}{\partial h} = \frac{\partial E}{\partial g} = \frac{\partial E}{\partial f} = \frac{\partial E}{\partial C} = 0 \qquad (3)$$

This set of six linear simultaneous equations can be solved and each of the coefficients evaluated, but in practice if the co-ordinate system is chosen with the origin at the grid point under consideration, then from equation (1):-

$$\text{at } x = 0,\ y = 0 \qquad hs = C \qquad (4)$$

Now it is only necessary to compute C, the interpolated height for that particular grid point. Note that in general with six height and six wind observations, the quadratic surface is over-specified and the observations are not fitted exactly, so that a certain amount of smoothing is introduced at this stage.

Forecast contour heights can also be incorporated into the analysis scheme, thereby providing for some continuity between successive analyses. It will be evident later that this is an essential consideration at 100 mb. The use of forecast heights also ensures that the simultaneous equations can always be solved, even in areas of sparse data where there may not be six pieces of information available within six gridlengths. The expression to be minimised [equation (2)] now becomes:-

$$E = \sum_{r=1}^{m} \left\{P(h_s - h_o)^2\right\}_r + T^2 \sum_{r=1}^{n} \left\{P(\underline{V}_s - \underline{V}_o)^2\right\}_r + \sum_{r=1}^{l} \left\{q(h_s - h_F)^2\right\}_r \qquad (5)$$

where $h_F$ represents the forecast height at a grid point, and q is the corresponding distance weighting factor ($q = P/16$). The summation for the last term in equation (5) is effected over the nine grid points nearest to (and including) the one being analysed i.e. we take l = 9. The nine forecast values have about the same weight as a single height observation three gridlengths distant from the grid point, and consequently have no appreciable effect in regions of dense networks of reporting stations. The more sparse the data, the more important does the forecast field become.

Each grid point is dealt with in turn following the same procedure, until the complete grid has been analysed. The station height and wind observations are then compared with the values given at the station by this first analysis. Height observations which differ by more than 160 m. or wind observations with a component discrepancy along either grid axis of 40 kt. or more are rejected, since a discrepancy of this magnitude implies that the report is inconsistent either with neighbouring observations or with the forecast field (this check is not applied to weather ship reports). A correction can also be made to the reported winds at this stage which allows for the curvature of the flow. The observed wind may be identified with the gradient wind which is related to the geostrophic value by:-

$$\frac{V_{geo}}{V_{gra}} = 1 + \frac{V_{gra}}{rf} \qquad (6)$$

where Vgeo is the geostrophic wind speed

Vgra is the gradient wind speed

r is the radius of curvature of the flow (positive for cyclonic flow)

and f is the Coriolis parameter.

The right hand side of equation (6) can be calculated for each wind observation. r is taken as approximating to the radius of curvature of the contours computed from the first analysis. The observed winds used in the fitting process to derive the gradient of contour height are then multiplied by the factor Vgeo/Vgra so calculated.

A final analysis is produced in the same manner as the first, but without using any of the rejected data, and also incorporating this curvature correction. The results obtained using this scheme at 500 and 200 mb. have been found to be quite satisfactory and comparable in standard with subjectively analysed charts.

## 3. Problems of analysis at 100 mb.

Special difficulties arise in the analysis of charts at the 100 mb. level and above, due to the inconsistencies which occur between the observed winds and the gradients obtained from the reported contour heights. Errors occur in the observations of temperature and pressure, from which the geopotential heights are deduced, but below 100 mb. the errors are not sufficiently large to cause major problems of analysis. The errors in the reported heights can be divided into two components:-

### a. Systematic error

The systematic errors are associated with the different types of radiosonde and the various observation techniques in use throughout the

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world. The value is peculiar to the station and to the solar radiation encountered on the ascent, and depends on such factors as the method of measuring and correcting temperature, the type of radiation screen used in the sonde, and the different radiation corrections employed. Hawson and Caton (5) have made a close study of the errors in radio-sonde reports and their significance in the analysis of high-level charts, and have compiled a list of the errors in the 100 mb. height reports for all the stations over the present Central Forecasting Office (C.F.O.) analysis area. The values for a selection of stations are given in Table 1 (valid November 1963). These lists of errors have to be kept under constant review because of possible changes in the sondes or in the operating and correction techniques. It must be emphasised that the systematic corrections are designed to reduce the height observations to a common standard, and although the British soundings are used as a base this does not imply they are nearer the truth than the foreign ones. The systematic errors can be quite large, ranging from -240 m. (i.e. 240 m. too low) to +100 m. at 100 mb., and increasing with height. The values also differ greatly between 00Z and 12Z and depend on the season (i.e. the solar elevation).

b. <u>Random error</u>

Superimposed on these systematic differences, there are also random errors, which are peculiar to the individual sounding and depend on the variability between the sondes of any given type, and also include the normal errors of observation (including transmission errors.) Imperfections in the pressure element and peculiarities of the particular temperature element both contribute to the random error, which ranges from 30 to 80 m. at 100 mb., depending on the type of sonde (see Table 1). It is obvious from the figures in Table 1 that reported heights must be treated with caution when analysing a 100 mb. chart; however the standard vector error in the wind reports is comparatively small (e.g. 5 kt. for British land stations and 8.5 kt. for British weather ships), so that more reliance may be placed on the winds.

The first stage in the subjective analysis of a 100 mb. chart is to

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apply the known systematic height corrections to the reports, so that the observations are all reduced to a common standard. The random error component is still present, but contours can be drawn which give the best fit to the wind field and to the corrected height field. The contour patterns generally show considerable persistence in time, and a check on continuity is essential to ensure that the pattern develops in an orderly manner and is not dominated by the random fluctuations in the height observations. Even so, there is a fair element of subjectivity in the construction of any 100 mb. analysis, and this must be borne in mind when considering the application of objective methods to this level.

The 100 mb. chart is particularly important at present, since it is the basic chart from which the high level analysis (50 and 30 mb.) is built up. Also the height errors are related from level to level; the figures for 200, 300 and 500 mb. are respectively 60%, 35% and 10% of the values for 100 mb., and since the flow is usually smoother at 100 mb. and ageostrophic effects are relatively small compared with those at 200 and 300 mb., the errors are more immediately obvious at 100 mb. than at lower levels. It is therefore advantageous to determine the random errors in the height reports first by constructing the 100 mb. analysis using the method just described. Proportionate corrections may then be applied to the reported heights at lower levels.

4. <u>Objective analysis at 100 mb.</u>

The aim of this work was to adapt the scheme successfully used at 500 and 200 mb. to provide satisfactory analyses at 100 mb. The analyses were made for the 24 x 20 grid used in the daily operational numerical forecasts, and the area covered is shown in Fig. 2. All the computations were carried out on the Meteorological Office Ferranti computer, Meteor. The 100 mb. observations were taken from the plotted C.F.O. charts and no attempt was made to extrapolate a sounding to 100 mb. from lower levels if there was no height available for a particular station. The information used was therefore basically that which had been available to the C.F.O. analyst, and in assessing the computed charts the comparisons were generally made with the corresponding C.F.O. analysis, although for a few situations a special carefully drawn subjective chart was

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also available as a standard*. In most cases the C.F.O. analysis from 12 hours before was used as the forecast or background field (i.e. a 12-hour persistence forecast).

The observations and the forecast field were read into the computer on punched paper tape, and the analyses were printed as a rectangular array of contour heights. The appropriate systematic height corrections (00Z or 12Z) were automatically applied to the observations by the computer programme, and after the first analysis a list of the rejected height and wind observations was also printed out. Finally, the height fields were transferred to ordinary working charts (with the grid superimposed) and were drawn up by hand.

As a first approach, the method described in section 2 for 500 and 200 mb. was applied directly to the 100 mb. level (i.e. with a height rejection criterion, h, of 160 m., a wind rejection criterion of 40 kt. along each grid axis, T = 4 sec., and $q = \frac{P}{16}$ ). It will be convenient to refer to the magnitude of the forecast field weighting factor, $q$, in terms of the normal value used at 500 and 200 mb. (N) by writing $\frac{P}{16} = N$. Thus in this case $q = N$. However, the results were unsatisfactory, and a typical example of such an analysis for 00Z 17th July 1963, together with the corresponding C.F.O. analysis are shown in Figs. 3(b) and 3(a) respectively. Only the European and eastern Atlantic section of the chart has been reproduced here as the analysis is usually straightforward over America, where a standard sonde is used. Nearly all the wind observations, and the majority of the height observations (with the systematic corrections applied) are plotted in Fig. 3(a), so that the standard of the analyses may be readily assessed. The corrected heights are in dekametres with the thousand and hundred digits omitted, while the winds are plotted to the nearest 5 kt., with a half feather on the wind arrow representing 5 kt., a full feather 10 kt., and a solid pennant 50 kt. Contours are drawn at 6 dekametre intervals.

Inspection reveals that the computed chart is not so smooth as the C.F.O. analysis, and it is evident that the random errors in the reported heights produce local irregularities in the contour pattern which are not supported

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* Drawn by C. L. Hawson

the winds e.g. over Scandinavia and just to the south of Finland in Fig. 3(b). Obviously the first change necessary in the technique is to take account of the fact that normally more confidence can be placed on the winds than the heights at this level.

a. Optimum value of T

From the discussion in section 2 it will be recalled that T is the parameter which determines how closely the quadratic surface fits the winds relative to the heights, and that the optimum value for T at 500 and 200 mb. is T = 4 sec. It is to be expected that at 100 mb. T should be somewhat larger, so that the second term on the right-hand side of equation (5) becomes dominant, and the reported winds are fitted more closely. Therefore, to find the best interpolation procedure, analyses were computed for several situations for a range of T values, and compared statistically with the standard charts. Since at this stage the main interest was in the relative weights to be given to the winds and heights in the fitting process, the background field, which was the C.F.O. analysis from 12 hours before, was given a very small weighting of one eighth the normal value (i.e. $q = \frac{N}{8} = \frac{P}{128}$). Over the vast majority of the chart the effect of this field will have been negligible, but it must be included to ensure that the simultaneous equations can always be solved. Fifteen situations were analysed, each being computed for integral values of T ranging from T = 4 sec. to T = 10 sec. and the R.M.S. height and vector wind differences between the computed and standard analyses were evaluated. The results are recorded in Table 2, where the height differences are computed at the grid points, and the wind differences represent means over a grid square. It will subsequently be shown that a height reject criterion of about 70 m. rather than 160 m. is more appropriate at 100 mb. and the statistics in Table 2 do in fact refer to analyses produced using h = 70 m. Observations exceeding this limit are eliminated and therefore should not really be included when determining the most satisfactory relative weighting for wind and height observations. A graph of the overall R.M.S. height and wind differences as a function of T is plotted in Fig. 4,

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and indicates that the best results are obtained with T = 6 sec. at 100 mb., which is in accordance with the qualitative ideas expressed earlier.

The question arises whether the statistics are likely to differ greatly if another set of subjective analyses had been used as the standard charts. For cases 1, 2 and 6 in Table 2, two subjective versions constructed by different analysts were available, and in Table 3 are given the sets of statistics for the computed charts compared with each of these conventional analyses. There were significant differences between the subjective charts for case 6, but in cases 1 and 2 the sense of the variation with T was the same. Providing the statistics cover a reasonable number of cases to allow for the element of uncertainty usually present in 100 mb. analyses, and the comparisons are made with carefully drawn subjective charts, it is expected that results such as those given in Table 2 will give a reliable indication of the value of the parameter, T, which gives the most generally satisfactory analyses. The requirement that the objective charts should agree as closely as possible with the conventional analysis provides the only sound practical basis upon which their performance can be judged. The closeness of fit of the analysis to the individual station observations is certainly not a measure of its skill (even for wind reports). It is interesting to note that in each of the three cases in Table 3, the objective analyses did not agree so well with the analyses prepared by C.F.O. on an operational basis, as they did with those drawn by Hawson, who took as long as necessary in their construction.

b. <u>Height reject criterion</u>

An examination of analyses such as the one in Fig. 3(b) indicates that the criterion for rejecting height observations after the first analysis should be more selective. Only two or three heights were rejected on average with h = 160 m., and a number of observations which were obviously incompatible with neighbouring stations, and with continuity were retained for the re-analysis, to the detriment of the final product. The question arises as to why it is necessary to demand such a large discrepancy as 160 m. before rejecting heights at 500 and 200 mb. It is important to realise that a report may appear erroneous when compared with the first analysis solely because the quadratic surface which is fitted to the observations is incapable of representing the contour pattern adequately over an area of six grid lengths radius. For example, the centre of an

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intense vortex at 500 mb. is generally smoothed out slightly by the quadratic surface, which has a characteristic rounded shape in the vicinity of the contour height minimum, and a height report near the centre of the vortex consequently appears low when compared with the analysis. As a result, if the criterion is too strict there is a possibility of rejecting perfectly valid observations, so at 500 and 200 mb. this technique can only be used for detecting gross errors.

At 100 mb. however, the pattern is much smoother, and can normally be well-represented by a quadric over the six grid-length area surrounding each grid point. The error limit can therefore be decreased accordingly by an amount which ideally would result in just those heights being rejected which an experienced analyst would also reject by comparison with surrounding observations of height and wind, and on continuity. The most suitable limit was determined on a trial and error basis, but a reasonable estimate can first be made from a diagram such as Fig. 5, which is a plot of the apparent errors in the height reports on the first computer analysis against the apparent errors given by the subjective analysis (for Case 1). There is good correlation between these quantities, which suggests that this is a reliable method for detecting erroneous reports; also the spread of the points about the mean line indicates that a rejection criterion of 160 m. is unnecessarily liberal at 100 mb. Similar diagrams were prepared for Cases 2 and 3 with almost identical results.

The height criterion finally chosen was h = 70 m., and this proved to be quite satisfactory in subsequent use. Observations for which there is a marked discrepancy between the objective and subjective apparent errors almost invariably come into one of the following two categories:-

(1) cases where there is genuine uncertainty in the analysis

(2) cases where the height error is sufficiently large to have a significant effect on the first computer analysis. This is exactly the class of observation that needs to be eliminated, and the criterion h = 70 m. generally ensures that this is done. At the same time there is little possibility of rejecting a report which is definitely considered to be correct.

/Data

Data from about 200 stations are used in the objective analysis, and the number of heights rejected varies considerably from chart to chart, ranging from 3 to 40 in the cases so far run, and averaging about 12 per chart. Six heights and one wind observation were rejected for the situation shown in Fig. 3 viz:-

STN 02836 wind probably 180° in error

06447 60 m. high )
07145 140 m. low )
08495 110 m. low )
15120 60 m. high ) compared with subjective analysis (after application of the systematic error correction)
16596 40 m. high )
33658 130 m. low )

34300 210 m. high was not rejected since it was outside the analysis area.

Stations outside the analysis area which are used in the fitting process cannot be checked in this way. No change from the original wind criterion was found necessary, and normally only one or two wind observations are rejected per chart.

c. Continuity

Mention was made earlier of the importance of continuity at 100 mb., and how it can be incorporated into the analysis scheme through the forecast field. Changes at this level are usually slow, and a 12-hour persistence forecast (i.e. the previous analysis) provides a satisfactory background field, and ensures that the pattern develops in an orderly fashion. This to some extent simulates the procedure followed by a human analyst, who uses the preceding charts as a guide to the main features of the pattern, and to help assess the validity of the observations on the current chart. Since the persistence of features at 100 mb. tends to be greater than in the troposphere, it is probable that a much higher background field weighting could be used at this level, so that continuity has a significant influence even in areas of dense data coverage. This in effect results in a time-meaning of the observations over successive charts.

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To find the best forecast weighting, the first 12 cases listed in Table 2 were recomputed for the following values of q:-

q = N, 1.5N, 2N, 2.5N, 3N (i.e. ranging from $\frac{p}{16}$ to $\frac{3p}{16}$);

the previously determined optimum values of 70 m. and 6 sec. were taken for h and T respectively. The results are recorded in Table 4, and a graph of the overall R.M.S. height and wind differences as a function of q are plotted in Fig. 6. As q increases, the height differences reach a minimum at q = 2N, but increase again for weightings higher than this, while the wind differences which are probably more important, decrease quickly at first and then more slowly to a broad minimum in the region of q = 3N. There seems no point in increasing q beyond 2.5N since any improvement in the wind field will only be marginal, at the expense of the height values. Moreover, too large a persistence forecast weighting may prove restrictive especially in sparse data areas, with the result that the real variations in contour height may not be followed adequately. It is considered that a forecast weight of 2N or 2.5N is most suitable at 100 mb., and in subsequent work the former value was adopted. This problem basically involves the selection of a suitable interval for time-meaning the observations. The observed height-time profile at a station shows random fluctuations about the 'real' value, due to the random errors in the height reports. If a very small continuity or persistence factor is included, the analysis tends to follow these spurious fluctuations, while if the weighting is too large, the result is excessive damping of genuine changes in the pattern.

Examination of the objective charts showed that with q = 2N (and a 12-hour persistence forecast), a nice balance seems to have been found between these two extremes. Now that continuity is playing an essential role, particularly in areas of sparse data, it is possible to check weather ship reports against the first analysis in the same way as ordinary land observations. This was not possible previously, as the analysed value was dominated by the ship's own report. Fig. 3(c) shows the effect of these various modifications on the analysis for 00Z 17th July 1963. The pattern is somewhat smoother than the original version in

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Fig. 3(b), but the improvement is not so marked as in many of the other cases tested, and there are still some undesirable irregularities in the pattern over northern Europe which need adjustment.

d. Final analysis using wind data only

So far the emphasis has been placed on the evaluation of the contour height at individual grid points, and little has been said about relating adjacent heights in a more positive manner. It is clear from Fig. 3(c) that there is a need for some mutual adjustment between neighbouring points, particularly in areas of dense data such as Russia, where the observations used in the interpolation tend to be local to the grid point, and where the height reports are often particularly unreliable.

A significant improvement in the quality of the objective charts was achieved by the introduction of a third scan into the analysis procedure. Instead of taking the second analysis as the final version, it was used as the background field (with q = N) for a third analysis in which only the reported winds were used in the fitting process. Maximum use is made of the wind data in this way. The third scan incorporates the wind curvature correction, and also ignores winds rejected after the first analysis. The main features of the contour pattern are established in the first two analyses, and the purpose of the extra scan is to adjust the field to give an improved fit to the wind data, without influence from the reported heights, and also to give a certain degree of smoothing. The 12 cases listed in Table 4 were reanalysed in this way, and verified against the subjective charts. The results which are recorded in Table 5, show that both the height and wind fields agreed more closely with the standard analyses after the final wind scan.

5. Quality of the objective analyses

Fig. 3(d) shows the final version of the objective analysis for 00Z 17th July 1963, and it is immediately obvious that the additional wind scan has produced a significant improvement in the general appearance of the chart. A close check against the observations indicates a very satisfactory standard of analysis, with only minor variations from the corresponding subjective analysis in Fig. 3(a). Sixteen 100 mb. analyses have been prepared by the technique described in this report, and it is considered that their overall standard is as high as that of the analyses drawn in C.F.O. In fact, 100 mb. appears to be

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a level which is expecially suited to the quadratic fitting process, providing satisfactory methods can be found for sorting out the erroneous observations. It is interesting to compare the difference between the objective and subjective charts with the variations that occur between two subjective charts drawn by independent analysts, such as were available for Cases 1, 2 and 6:-

| CASE | TIME-DATE | RMS HT DIFF(M) | | | RMS V WIND DIFF(KT) | | |
|---|---|---|---|---|---|---|---|
| | | OBJ.-SUBJ.1 | OBJ.-SUBJ.2 | SUBJ.1-SUBJ.2 | OBJ.-SUBJ.1 | OBJ.-SUBJ.2 | SUBJ.1-SUBJ.2 |
| 1 | 00Z 15-11-62 | 25 | 28 | 30 | 10.6 | 11.0 | 10.5 |
| 2 | 00Z 20- 3-63 | 17 | 22 | 16 | 7.0 | 7.3 | 6.9 |
| 6 | 00Z 6- 6-63 | 14 | 30 | 30 | 7.4 | 10.7 | 12.8 |
| | OVERALL RMS DIFFERENCE | 23.4 | | 26.2 | 9.2 | | 10.3 |

Although the statistics are based on only three cases, it seems safe to conclude that the differences between the computed and subjective charts will be of the same order as the differences between two subjective analyses and the standards are therefore expected to be very similar.

It is to be noted that in the majority of cases the C.F.O. analysis from 12 hours before was used as the background field. The question arises as to whether the quality of the analyses may deteriorate in a series of charts where the previous objective analysis is used as the background field. Since it has been shown that the objective and subjective charts are comparable in standard this possibility appears unlikely, but confirmation must await trials on an operational day-to-day basis. A short test was made on six consecutive charts for the period 00Z 9-4-63 to 12Z 11-4-63, the C.F.O. analysis for 12Z 8-4-63 being used as the initial background field, and the previous objective analysis thereafter. No deterioration in the quality of the analyses could be detected over this short period, and the last two charts in the series together with the C.F.O. analyses are shown in Fig. 7 and Fig. 8 (the notation is the same as in Fig. 3, and the systematic height corrections have been applied). The number of height and wind reports rejected after the first analysis in these two cases were as follows:-

| CASE | OBSERVATIONS REJECTED | |
|---|---|---|
| | HEIGHTS | WINDS |
| 00Z 11-4-63 | 9 | 0 |
| 12Z 11-4-63 | 19 | 1 |

Approximately 50% more height observations were rejected in the three 12Z analyses

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of this run than in the corresponding 00Z analyses, which is in line with Hawson's statement (6) that in this part of the world the analysis of a 12Z chart is in general the less satisfactory of the two. Close examination of the fields does not reveal any serious discrepancies between the objective and subjective versions, and it is considered that there is very little difference in their quality. The only feature requiring comment in the analysis shown in Fig. 7, is the steep gradient drawn by the C.F.O. analyst on the western flank of the low centred near Iceland (Fig. 7(b)), which gives a geostrophic wind of almost 40 kt. at Keflavik, compared with the observed value of 5 kt. There seems no reason to doubt this wind report.

The objective analysis shown in Fig. 8(a) places the axis of the ridge over southern Sweden a little too far west on the reported winds in that area; also the wind at ship J could have been fitted slightly better, even though the subjective analysis in Fig. 8(b) has not fitted it closely either. There are some significant differences in the contour pattern over Europe, particularly Russia, where the objective contour pattern is generally about 60 m. lower than that drawn by C.F.O., but it is very difficult to say which is the better analysis.

The changes found necessary in the objective analysis procedure at 100 mb., compared with the method used at 500 and 200 mb., are now summarised; they are

a. Increase the wind-height weighting parameter (T) from 4 sec. to 6 sec.

b. Decrease the height rejection criterion after the first analysis from 160 m. to 70 m., but leave the wind criterion unaltered. Check ship reports in the same way as land stations.

c. Take the previous analysis as the forecast field with a weighting factor of $q = 2N$ (i.e. $q = P/_8$).

d. Re-analyse the field from the second analysis using only the wind observations.

Also the appropriate 100 mb. systematic height corrections must be applied to the observed heights.

6. <u>Future developments</u>

The immediate need is for an operational trial to see whether any additional problems arise when analysing a long series of charts. In such a test, the station data will have been extracted automatically and checked against other levels for hydrostatic consistency, so that some of the erroneous height observations will be eliminated before the analysis proper. Another

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useful data check for detecting gross errors, would be to test all height and wind observations against the previous analysis and reject those which differed by a wide margin - say, exceeding 200 m. for height and 40 kt. for wind. The general quality of the data available for the objective analysis should consequently be slightly improved with these additional checks.

A further modification which is likely to be beneficial, but which could not be tested readily on Meteor due to lack of space in the machine, would be to use a maximum of 10 or 12 stations (instead of 6) when fitting the quadratic surface around each grid point. This change should prove useful in dense data areas by providing more overlap between the stations used at neighbouring grid points, and thereby linking adjacent analysed values more closely to the reported winds. The effect in regions of moderate or sparse data coverage would be negligible, since the extra stations would be a long way from the grid point, and therefore would have little or no weight. The relative importance of the forecast field would be slightly reduced by the introduction of more stations into the fitting process, so in this case it is likely that the forecast weighting factor, q, should be increased to 2.5N.

At present the 100 mb. chart provides the basis for the high-level analysis at 50 and 30 mb. etc., and it is therefore especially important that this analysis should be of good quality. Objective analyses appear to fulfil the necessary requirements at 100 mb., and the question arises whether similar methods could also be used at 50 and 30mb. Taking the objective 100 mb. analysis as a basis, the 100-50 mb. thickness could be analysed on the computer and hence the 50 mb. analysis deduced. Since the geopotential errors are related from level to level, the errors in the observations on the 100 mb. chart may be used to determine the corrections in the 100-50 mb. thickness and in the 50 mb. height, following the procedure described by Hawson (6). The 30 mb. analysis may then be obtained from the 50 mb. analysis in a similar manner.

Finally it is worth noting that if a full objective upper-air routine is performed, the anomalies in the 100 mb. height reports as determined from the 100 mb objective analysis may be used to correct the 200 and 500 mb. heights, and thereby improve the analysis at these other levels.

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## 7. Acknowledgements

I wish to thank C. L. Hawson for his helpful advice and criticism during this work, and also for constructing some of the 100 mb. analyses.

## R E F E R E N C E S



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|---|---|---|---|---|
| 1. | Gilchrist and Cressman | 1954 | Tellus 6 | p.309 |
| 2. | Bushby and Huckle | 1957 | Q.J. 83 | p.232 |
| 3. | Corby | 1961 | Q.J. 87 | p.34 |
| 4. | Bushby and Whitelam | 1961 | Q.J. 87 | p.374 |
| 5. | Hawson and Caton | 1961 | Met.Mag.90 | p.336 |
| 6. | Hawson | Notes for the Central Forecast Office on Analysis at 100, 50 and 30 mb. levels (unpublished). | | |

## TABLE 1

### SYSTEMATIC AND RANDOM ERRORS IN 100 MB. OBSERVATIONS (NOV.1963)

| STATION | SYSTEMATIC ERROR(M)* | | RANDOM ERROR (M) |
|---|---|---|---|
| | 00Z | 12Z | |
| SCANDINAVIAN STATIONS | +20 | +50 | 50 |
| U.K./BRITISH O.W.S. | 0 | 0 | 40 |
| UNITED STATES/CANADA | 0 | 0 | 40 |
| RUSSIAN STATIONS | +50 | +100 | 70 |
| O.W.S. CIRRUS/CUMULUS | +10 | +100 | 50 |
| O.W.S. FRANCE I/FRANCE II | +30 | +90 | 70 |
| O.W.S. B, C, D, E | 0 | +20 | 50 |
| KEFLAVIK | 0 | +20 | 40 |
| DE BILT | +10 | +100 | 50 |
| FRENCH STATIONS≠ | +30 | +80 or +90 | 70 |
| GERMAN STATIONS | +30 or +40 | +50 or +60 | 30 or 40 |
| FUNCHAL/LISBON | -240 | -200 | 70 |
| WIEN | 0 | +20 | 40 |
| LAGENS | 0 | +20 | 40 |
| MALTA | 0 | -20 | 40 |

*A positive systematic error implies that the reported contour height is generally higher than the value which would be given by a U.K. sonde under the same conditions.

≠Apart from Chateauroux which is the same as Keflavik.

TABLE 2:- COMPARISON WITH STANDARD ANALYSIS FOR RANGE OF T VALUES (h = 70 m. g =N/8)

| CASE | TIME - DATE | R.M.S. HEIGHT DIFFERENCES (M) VALUE OF T (SEC) | | | | | | R.M.S. VECTOR WIND DIFFERENCES (KT) VALUE OF T (SEC) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 7 | 8 | 10 | 4 | 5 | 6 | 7 | 8 | 10 |
| 1 | 00Z 15-11-62 | 26 | 25 | 24 | 24 | 25 | 25 | 13.7 | 13.5 | 13.4 | 13.2 | 13.3 | 13.7 |
| 2 | 00Z 20- 3-63 | 23 | 19 | 18 | 20 | 20 | 21 | 11.0 | 10.6 | 10.3 | 10.6 | 10.7 | 11.2 |
| 3 | 00Z 17- 7-63 | 25 | 24 | 25 | 25 | 25 | 26 | 13.6 | 13.9 | 13.9 | 14.0 | 14.2 | 14.6 |
| 4 | 00Z 12- 1-63 | 39 | 39 | 37 | 37 | 37 | 37 | 18.9 | 18.9 | 18.9 | 19.0 | 19.2 | 19.8 |
| 5 | 00Z 6-10-63 | 32 | 32 | 32 | 32 | 31 | 31 | 13.8 | 13.7 | 13.9 | 14.0 | 14.0 | 14.5 |
| 6 | 00Z 6- 6-63 | 19 | 20 | 20 | 20 | 20 | 21 | 10.6 | 10.6 | 10.7 | 10.6 | 10.7 | 11.1 |
| 7 | 00Z 16- 2-63 | 36 | 35 | 35 | 35 | 35 | 38 | 17.9 | 17.8 | 17.9 | 18.3 | 18.5 | 19.3 |
| 8 | 00Z 15- 5-63 | 26 | 25 | 25 | 25 | 25 | 25 | 11.8 | 11.6 | 11.4 | 11.8 | 12.2 | 12.9 |
| 9 | 00Z 16- 8-63 | 22 | 21 | 21 | 22 | 22 | 24 | 11.0 | 10.7 | 10.7 | 11.0 | 11.3 | 11.8 |
| 10 | 00Z 16-12-63 | 26 | 25 | 24 | 24 | 25 | 26 | 12.6 | 12.3 | 12.3 | 12.2 | 12.3 | 12.6 |
| 11 | 00Z 9- 4-63 | 37 | 36 | 36 | 36 | 37 | 38 | 13.2 | 13.2 | 13.4 | 13.5 | 13.7 | 13.9 |
| 12 | 12Z 9- 4-63 | 39 | 39 | 40 | 40 | 41 | 42 | 18.4 | 18.3 | 18.6 | 19.2 | 19.5 | 19.7 |
| 13 | 00Z 10- 4-63 | 28 | 27 | 26 | 26 | 27 | 28 | 12.9 | 12.7 | 12.5 | 12.4 | 12.5 | 12.8 |
| 14 | 12Z 10- 4-63 | 29 | 25 | 26 | 28 | 29 | 30 | 11.2 | 10.8 | 10.6 | 10.9 | 11.0 | 11.3 |
| 15 | 00Z 11- 4-63 | 32 | 31 | 31 | 31 | 32 | 33 | 13.3 | 13.1 | 13.1 | 13.1 | 13.2 | 13.2 |
| OVERALL RMS VALUE | | 29.9 | 28.9 | 28.7 | 29.0 | 29.4 | 30.3 | 13.9 | 13.7 | 13.7 | 13.9 | 14.1 | 14.5 |

TABLE 3 - COMPARISON WITH DIFFERENT STANDARD ANALYSES ($h = 70$ m. $q = N/8$)

| CASE | COMPARISON ANALYSIS | R.M.S. HEIGHT DIFFERENCE (M) VALUE OF T (SEC) | | | | | | R.M.S. VECTOR WIND DIFFERENCES (KT) VALUE OF T (SEC) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 7 | 8 | 10 | 4 | 5 | 6 | 7 | 8 | 10 |
| 1 | STD ANALYSIS 1 | 31 | 30 | 29 | 30 | 30 | 31 | 14.0 | 13.8 | 13.6 | 13.5 | 13.6 | 13.9 |
| | STD ANALYSIS 2 | 26 | 25 | 24 | 24 | 25 | 25 | 13.7 | 13.5 | 13.4 | 13.2 | 13.3 | 13.7 |
| 2 | STD ANALYSIS 1 | 31 | 25 | 26 | 28 | 28 | 29 | 11.2 | 10.8 | 10.5 | 11.1 | 11.3 | 11.7 |
| | STD ANALYSIS 2 | 23 | 19 | 18 | 20 | 20 | 21 | 11.0 | 10.6 | 10.3 | 10.6 | 10.7 | 11.2 |
| 6 | STD ANALYSIS 1 | 29 | 28 | 28 | 27 | 27 | 27 | 13.5 | 13.5 | 13.4 | 13.1 | 13.1 | 12.9 |
| | STD ANALYSIS 2 | 19 | 20 | 20 | 20 | 20 | 21 | 10.6 | 10.6 | 10.7 | 10.6 | 10.7 | 11.1 |

STANDARD ANALYSIS 1 = CFO ANALYSIS

STANDARD ANALYSIS 2 = ANALYSIS CONSTRUCTED BY C. L. HAWSON (THESE VALUES USED IN TABLE 2)

TABLE 4 - COMPARISON WITH STANDARD ANALYSES FOR RANGE OF q VALUES (h = 70 m.T = 6 sec.)

| CASE | TIME - DATE | R.M.S. HEIGHT DIFFERENCES (M) VALUE OF q | | | | | | R.M.S. VECTOR WIND DIFFERENCES (KT) VALUE OF q | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N/8* | N | 1.5N | 2N | 2.5N | 3N | N/8* | N | 1.5N | 2N | 2.5N | 3N |
| 1 | 00Z 15-11-62 | 24 | 23 | 23 | 24 | 27 | 28 | 13.4 | 11.9 | 11.5 | 11.3 | 11.4 | 11.4 |
| 2 | 00Z 20- 3-63 | 18 | 17 | 18 | 18 | 19 | 20 | 10.3 | 9.0 | 8.8 | 8.7 | 8.4 | 8.7 |
| 3 | 00Z 17- 7-63 | 25 | 22 | 21 | 20 | 20 | 20 | 13.9 | 10.8 | 9.9 | 9.3 | 8.9 | 8.6 |
| 4 | 00Z 12- 1-63 | 37 | 34 | 33 | 33 | 33 | 34 | 18.9 | 14.6 | 14.1 | 13.8 | 13.4 | 13.3 |
| 5 | 00Z 6-10-63 | 32 | 28 | 28 | 26 | 26 | 27 | 13.9 | 12.7 | 11.8 | 11.4 | 11.2 | 11.2 |
| 6 | 00Z 6- 6-63 | 20 | 16 | 16 | 15 | 16 | 16 | 10.7 | 8.6 | 8.4 | 8.1 | 7.8 | 7.9 |
| 7 | 00Z 16- 2-63 | 35 | 40 | 40 | 40 | 41 | 41 | 17.9 | 16.9 | 16.6 | 16.3 | 15.9 | 15.9 |
| 8 | 00Z 15- 5-63 | 25 | 20 | 20 | 19 | 19 | 19 | 11.4 | 8.9 | 8.7 | 8.6 | 8.6 | 8.6 |
| 9 | 00Z 16- 8-63 | 21 | 18 | 17 | 17 | 17 | 16 | 10.7 | 9.1 | 9.0 | 8.8 | 8.6 | 8.5 |
| 10 | 00Z 16-12-63 | 24 | 24 | 23 | 23 | 24 | 25 | 12.3 | 12.2 | 12.2 | 12.2 | 12.3 | 12.1 |
| 11 | 00Z 9- 4-63 | 36 | 36 | 36 | 35 | 35 | 36 | 13.4 | 12.3 | 12.1 | 11.9 | 11.9 | 11.8 |
| 12 | 12Z 9- 4-63 | 40 | 34 | 34 | 33 | 33 | 33 | 18.6 | 12.0 | 11.4 | 11.2 | 11.0 | 11.1 |
| OVERALL RMS VALUE | | 29.0 | 27.2 | 26.9 | 26.4 | 26.9 | 27.4 | 14.1 | 11.8 | 11.5 | 11.2 | 11.0 | 11.0 |

*From Table 2

TABLE 5 - COMPARISON WITH STANDARD ANALYSES AFTER WIND SCAN (h = 70 m. T = 6 sec. q = 2N)

| CASE | TIME - DATE | R.M.S. HEIGHT DIFFERENCES (M) | | R.M.S. VECTOR WIND DIFFERENCES (KT) | |
|---|---|---|---|---|---|
| | | WITHOUT WIND SCAN* | WITH WIND SCAN | WITHOUT WIND SCAN* | WITH WIND SCAN |
| 1 | 00Z 15-11-62 | 24 | 25 | 11.3 | 10.6 |
| 2 | 00Z 20- 3-63 | 18 | 17 | 8.7 | 7.0 |
| 3 | 00Z 17- 7-63 | 20 | 19 | 9.3 | 8.5 |
| 4 | 00Z 12- 1-63 | 33 | 34 | 13.8 | 13.7 |
| 5 | 00Z 6-10-63 | 26 | 25 | 11.4 | 11.4 |
| 6 | 00Z 6- 6-63 | 15 | 14 | 8.1 | 7.4 |
| 7 | 00Z 16- 2-63 | 40 | 40 | 16.3 | 16.5 |
| 8 | 00Z 15- 5-63 | 19 | 18 | 8.6 | 7.5 |
| 9 | 00Z 16- 8-63 | 17 | 16 | 8.8 | 8.3 |
| 10 | 00Z 16-12-63 | 23 | 22 | 12.2 | 11.8 |
| 11 | 00Z 9- 4-63 | 35 | 35 | 11.9 | 12.4 |
| 12 | 12Z 9- 4-63 | 33 | 31 | 11.2 | 9.9 |
| OVERALL RMS DIFFERENCE | | 26.4 | 26.0 | 11.2 | 10.8 |

*From Table 4

FIG. 1

## DISTANCE WEIGHTING FACTOR (p)

$$p = \frac{128}{1 + 2^{-33} \times 10^{8} r^{4}}$$

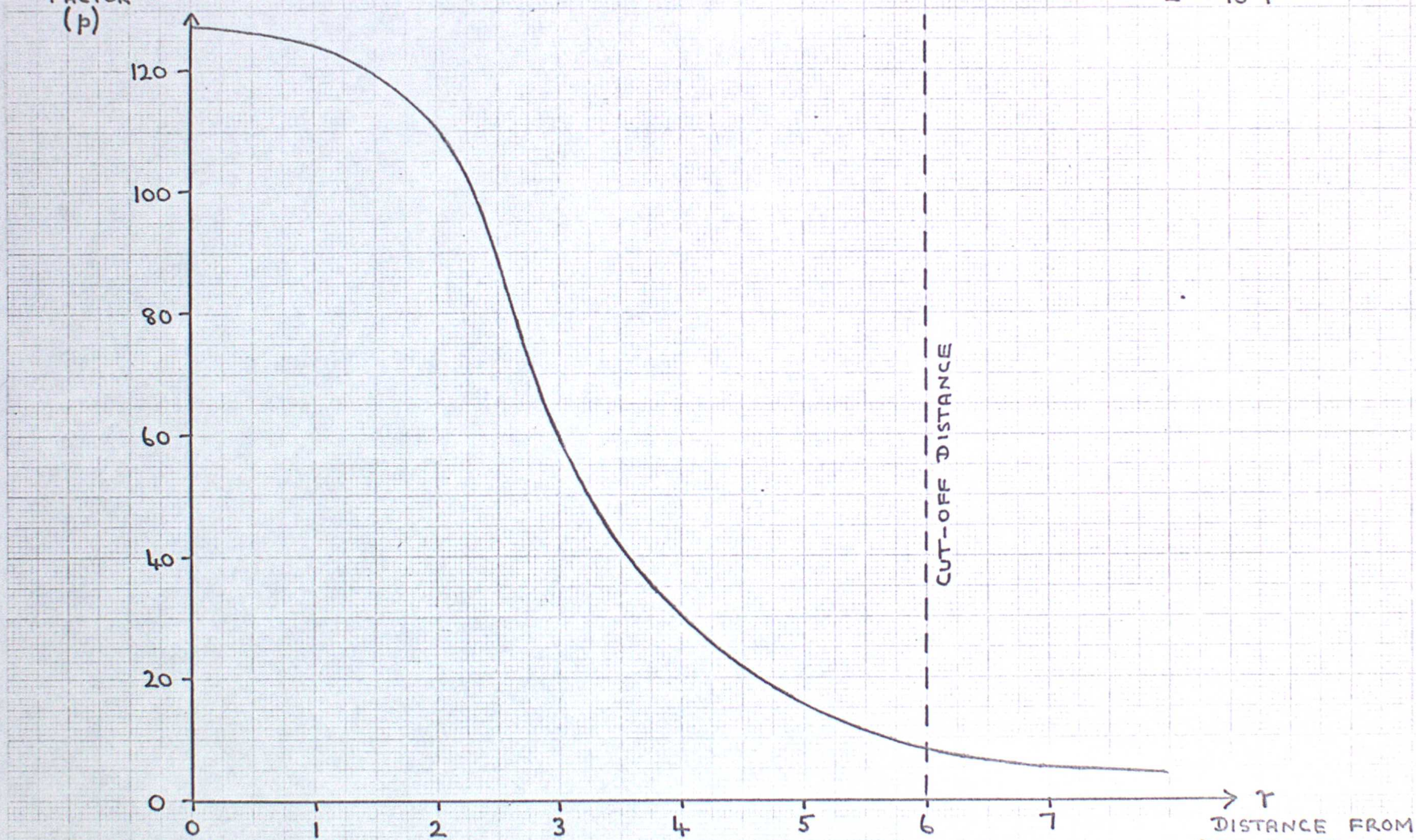


FIG. 1

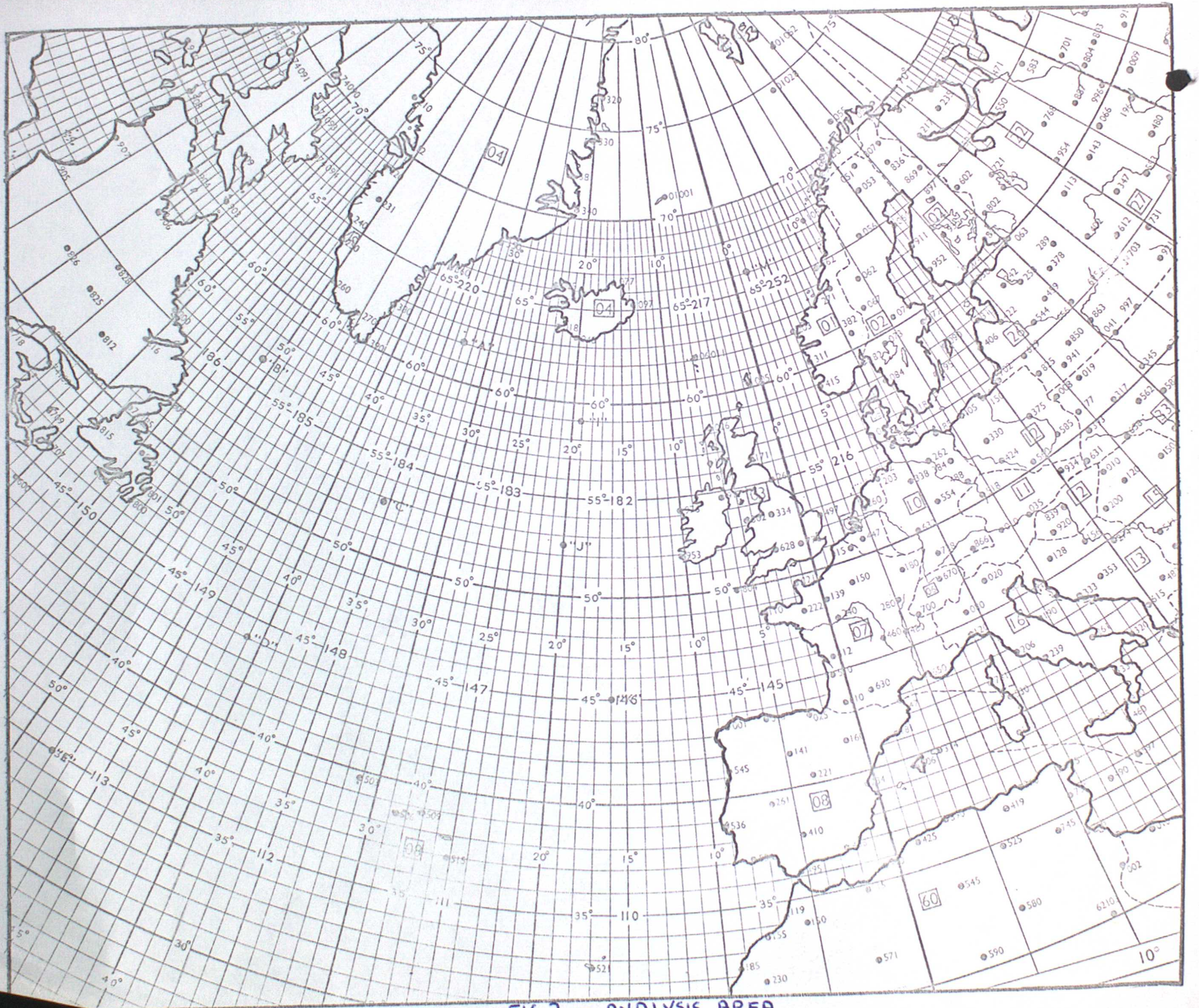


FIG. 2 – ANALYSIS AREA

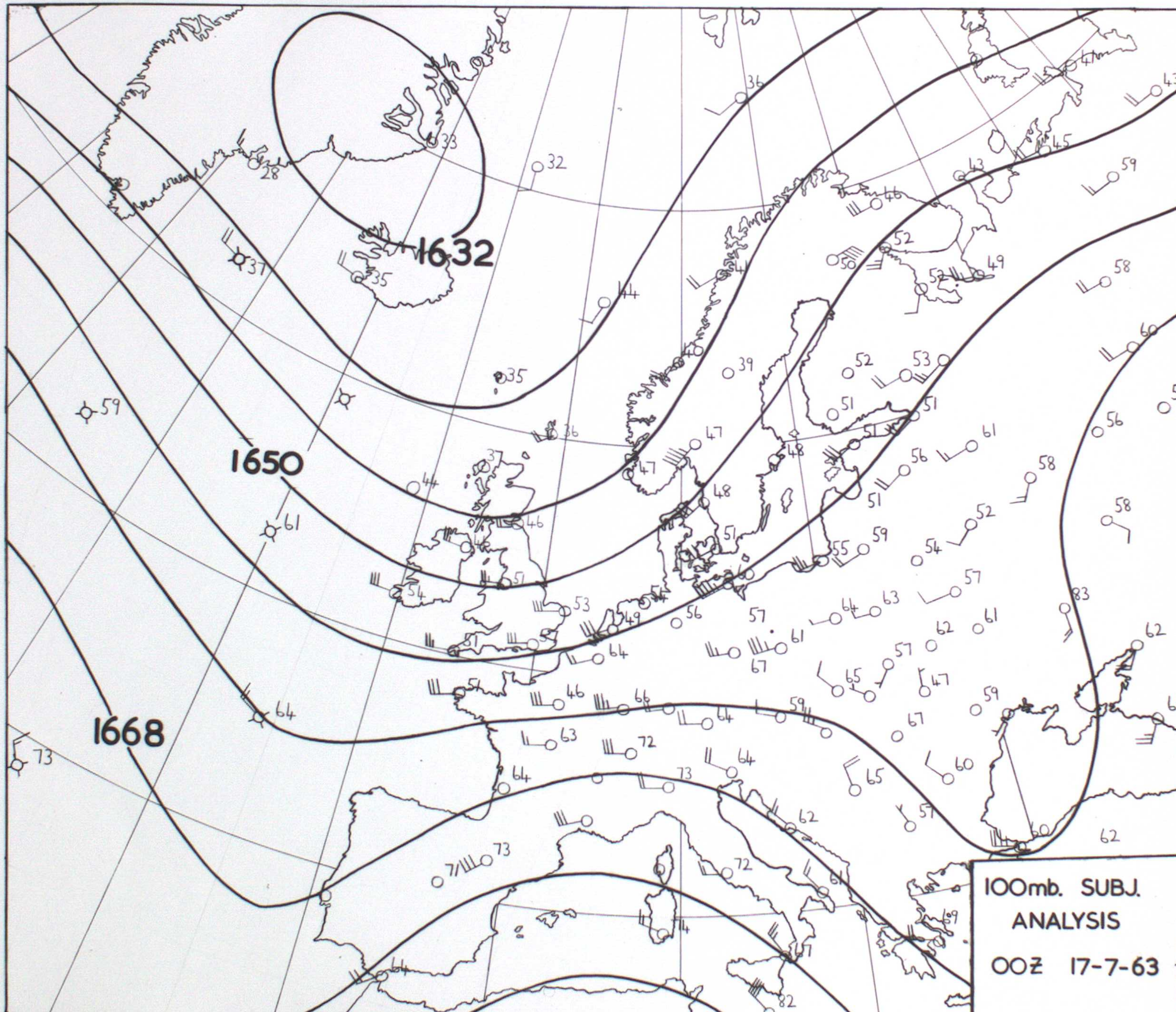


FIG 3(a)

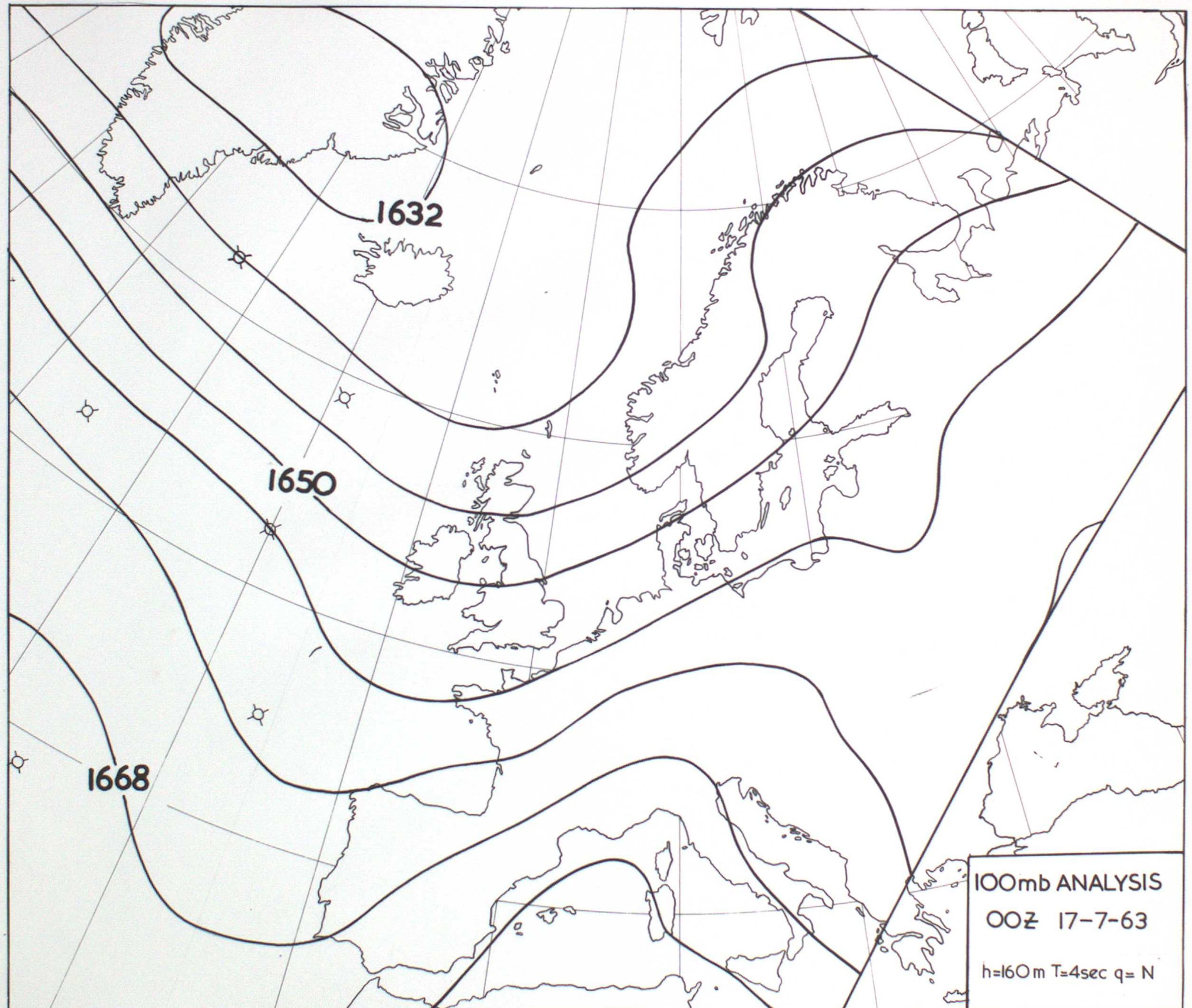


FIG 3(b)

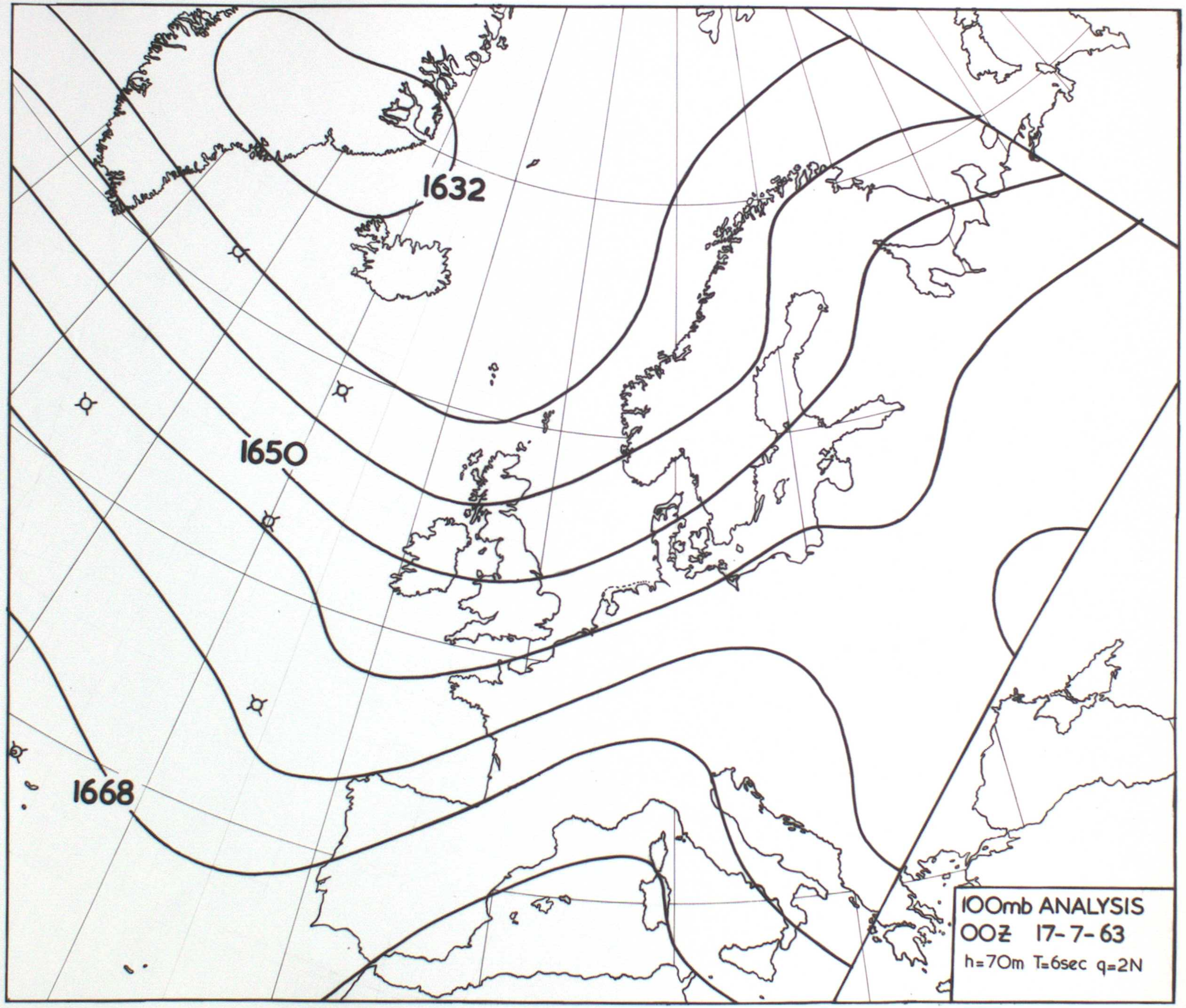


FIG 3(c)

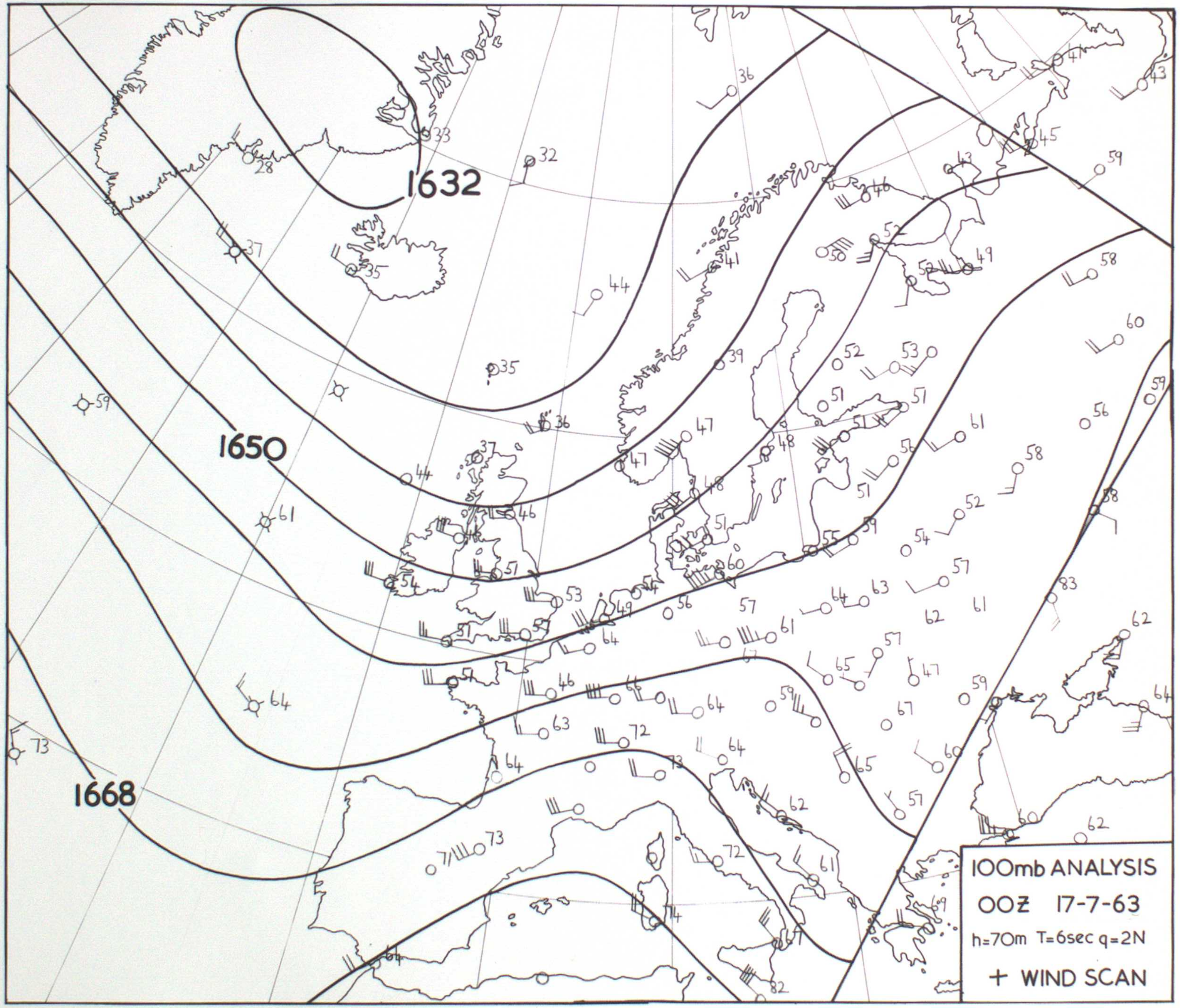
1632
1650
1668
100mb ANALYSIS
00Z 17-7-63
h=70m T=6sec q=2N
+ WIND SCAN

FIG 3(d)

FIG. 4

GRAPH OF R.M.S. DIFFERENCES BETWEEN COMPUTED AND SUBJECTIVE CHARTS AS A FUNCTION OF T

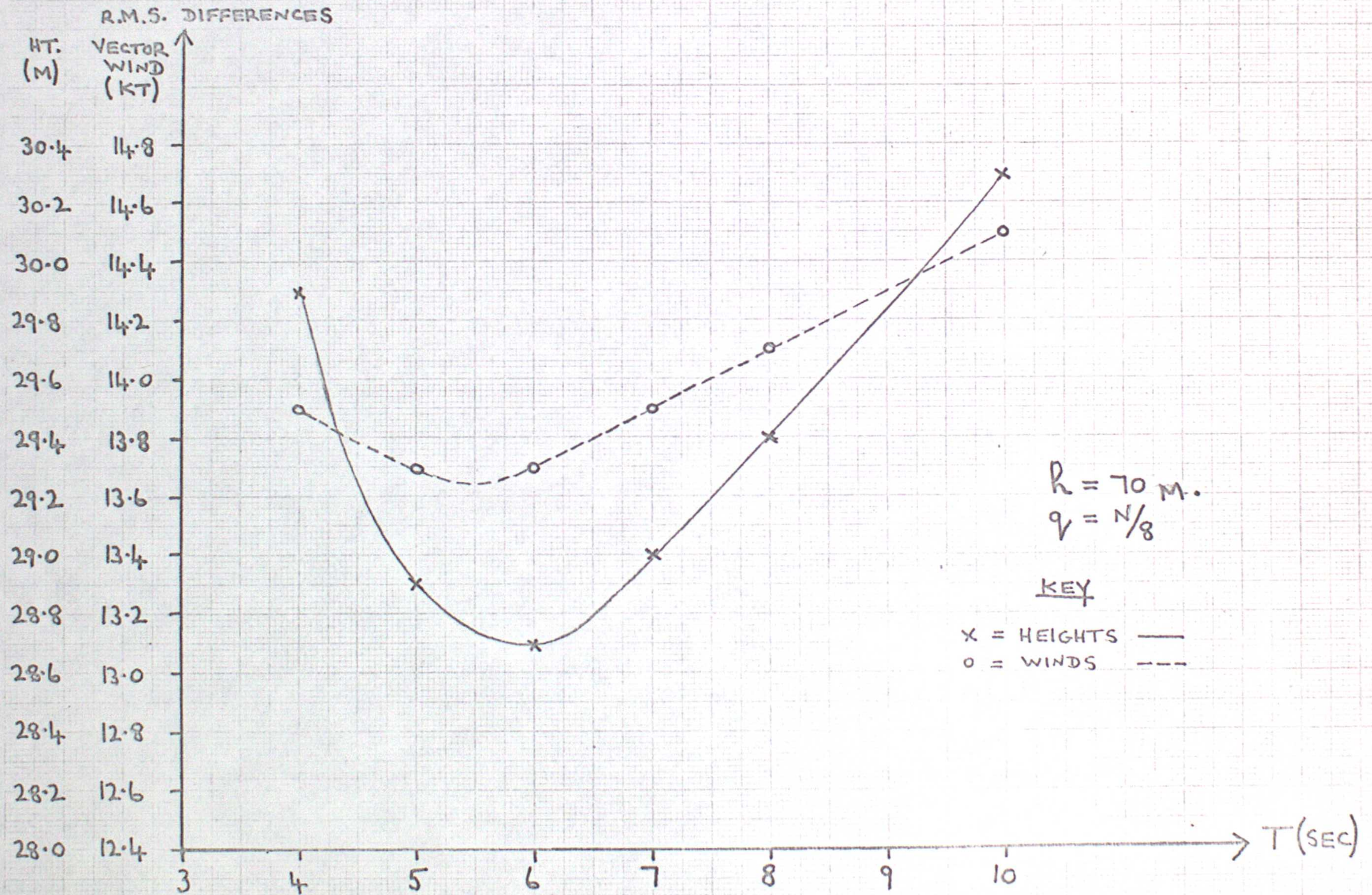


FIG. 4

APPARENT ERROR IN 100mb HTS - COMPUTER VS CFO ANALYSIS

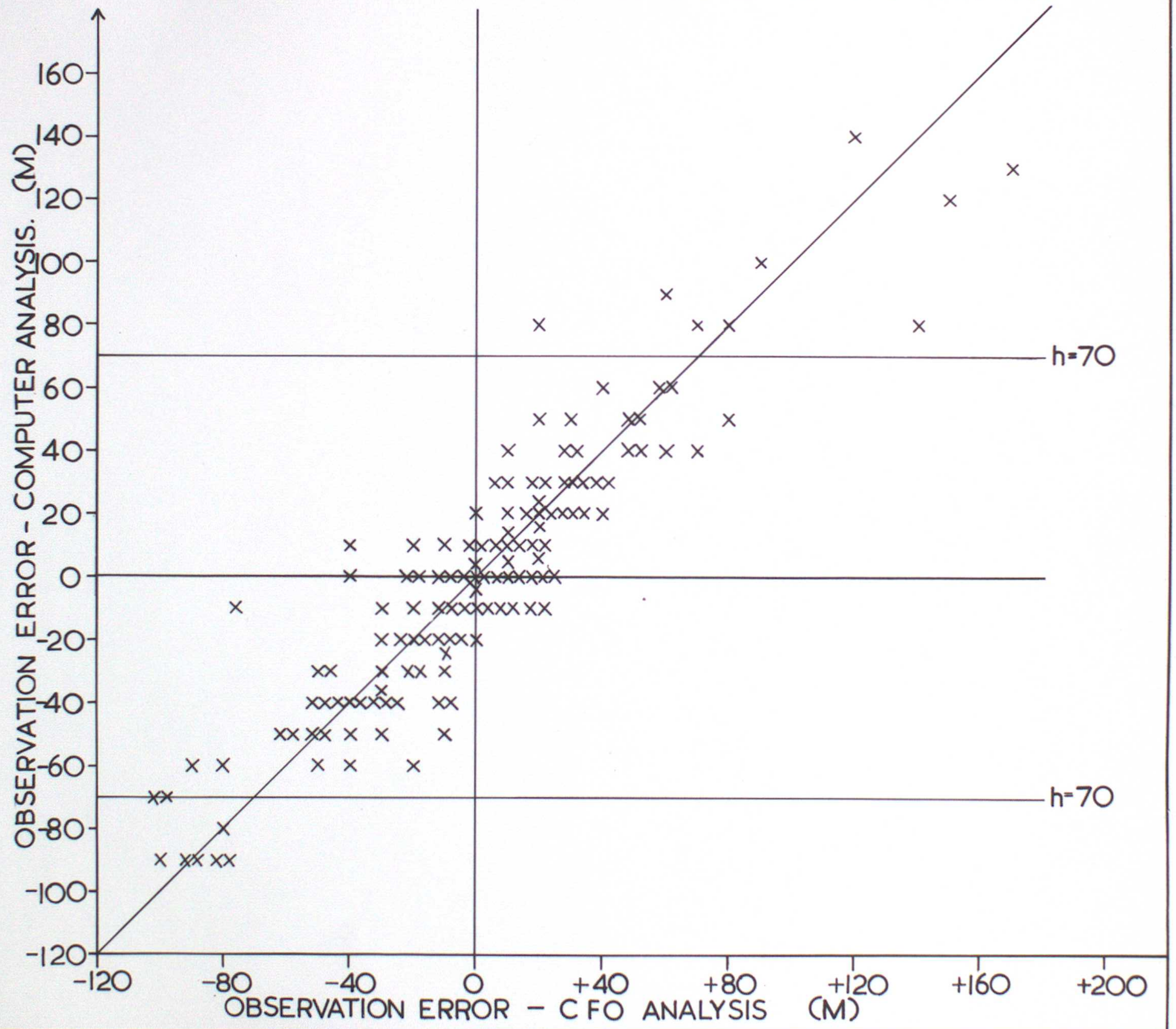


FIG 5

FIG. 6

GRAPH OF R.M.S. DIFFERENCES BETWEEN COMPUTED AND SUBJECTIVE CHARTS AS A FUNCTION OF $q$

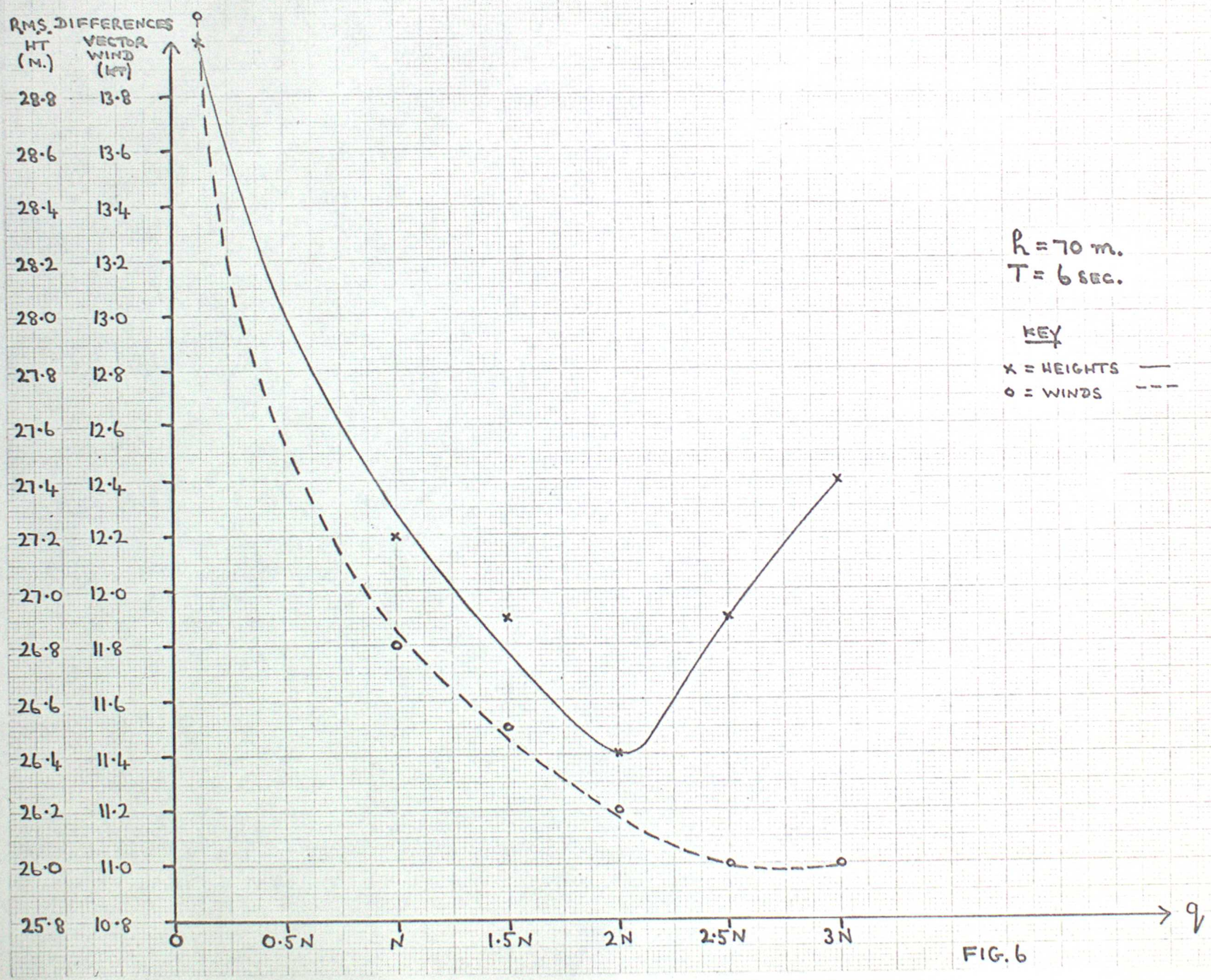


FIG. 6

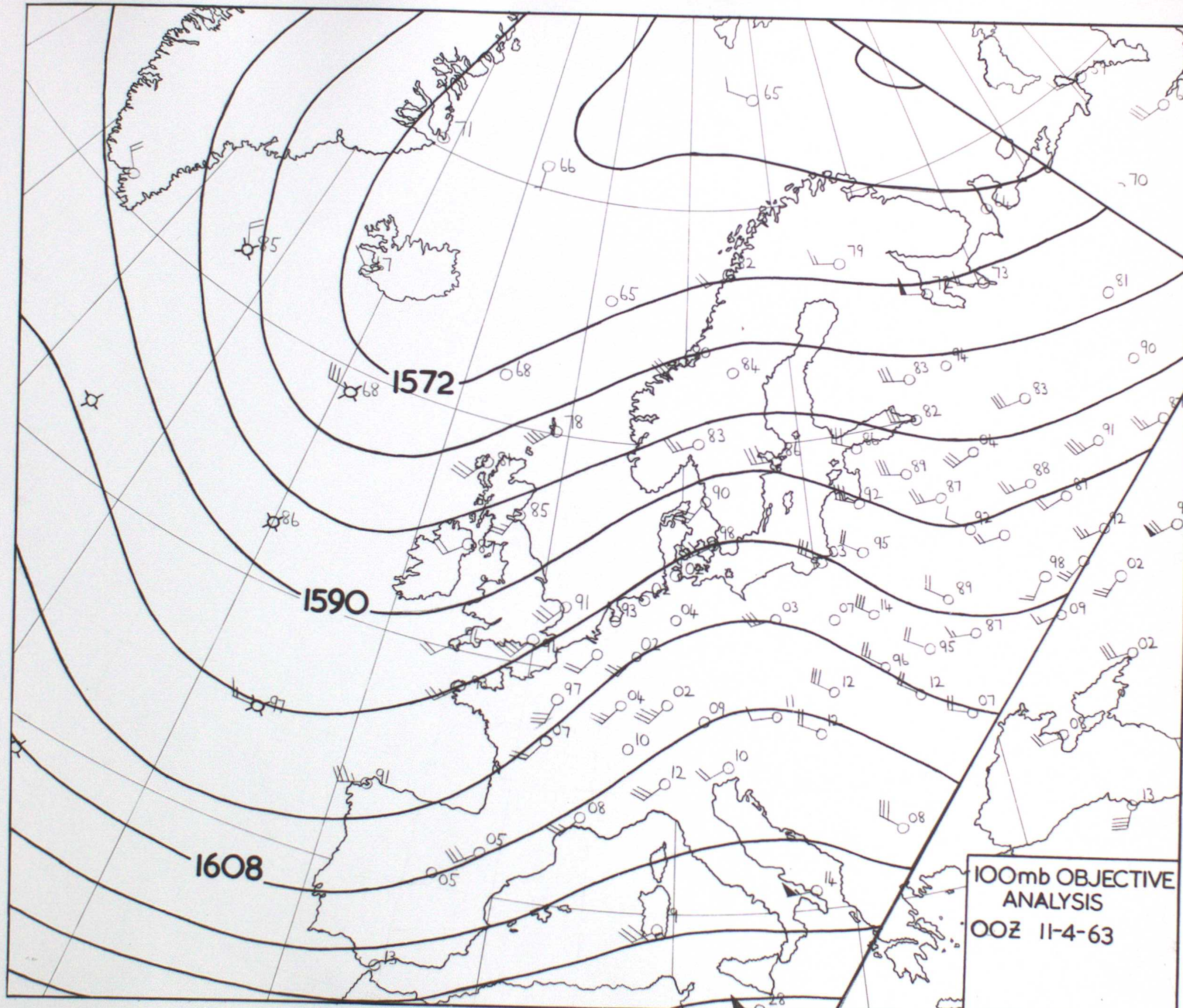


FIG 7(a)

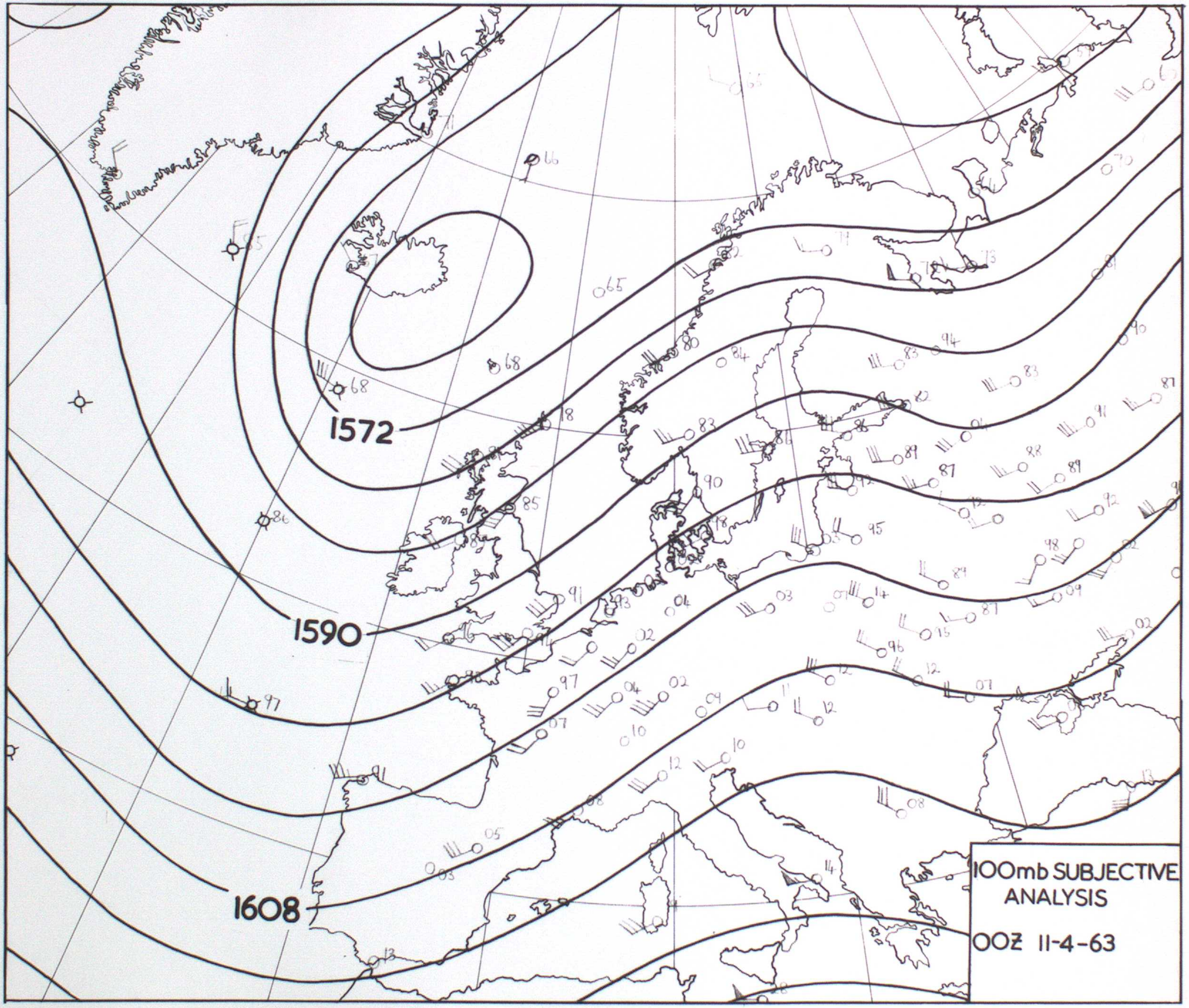


FIG 7(b)

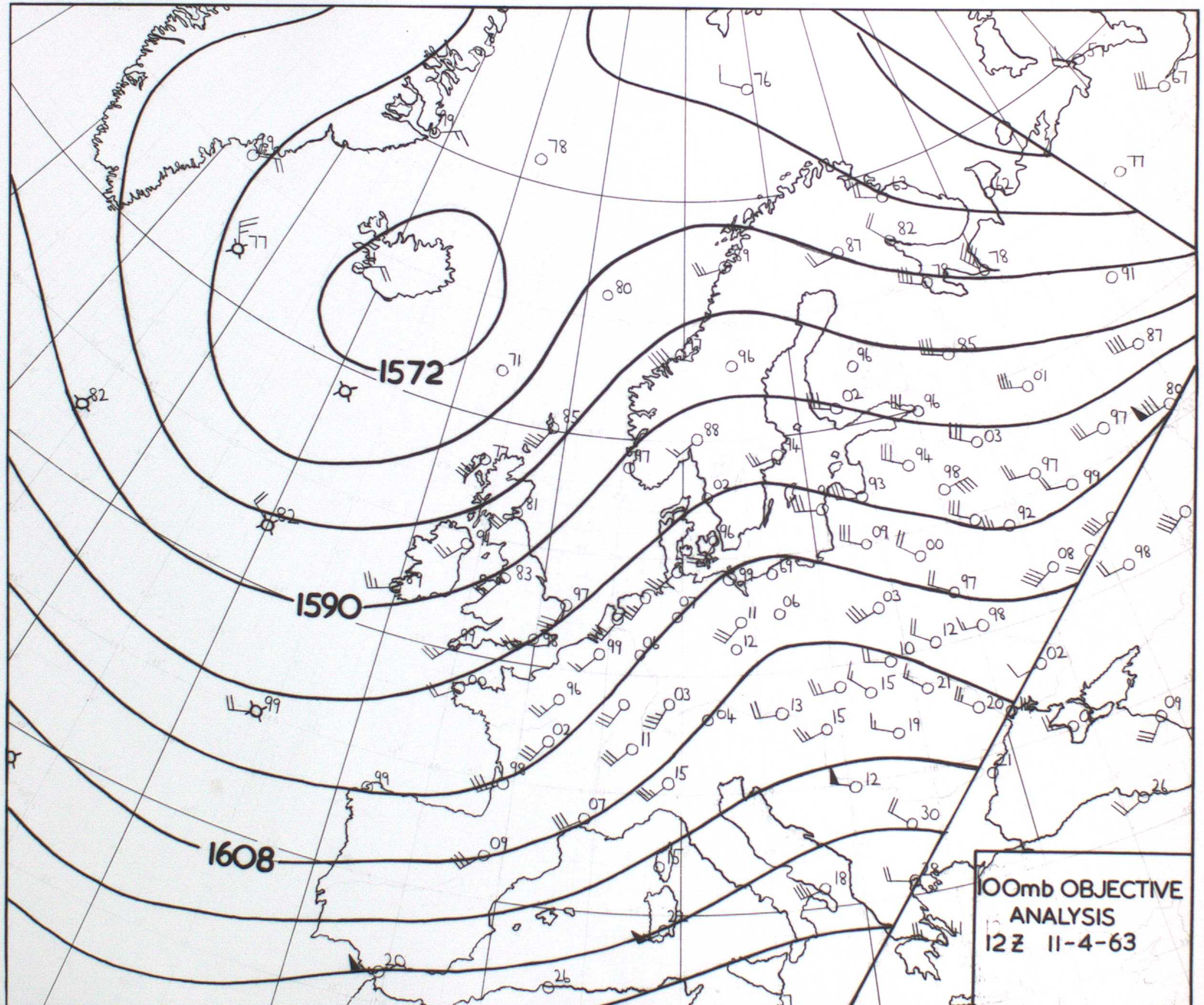


FIG 8(a)

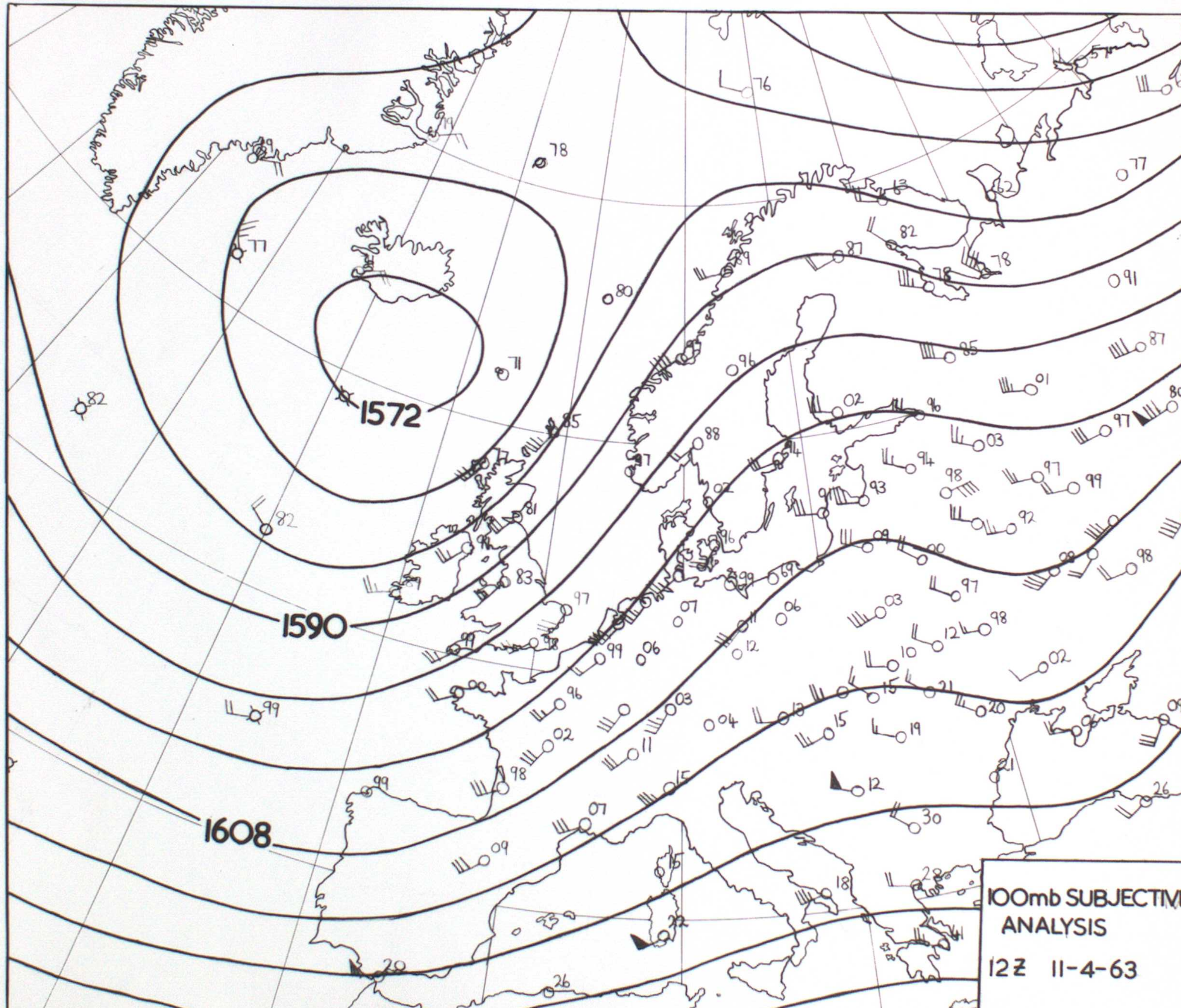


FIG 8(b)