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# THE RETRIEVAL OF 1,000 - 500 MB THICKNESSES FROM VTPR DIRECT READ-OUT DATA USING LINEAR REGRESSION METHODS

BY W H HAND AND B R MAY

## Abstract

This memorandum describes some results of retrievals of 1,000 - 500 mb thickness using linear regression methods from radiances measured by the Vertical Temperature Profile Radiometer over the north-eastern Atlantic. A brief description is given of the method of deducing the cloud-free radiances which are then related to co-located thicknesses from Central Forecasting Office Analyses in order to deduce the coefficients in the linear regressions. Results are presented, in statistical and chart form of comparisons of retrievals and CFO analyses on 43 days. The advantages and disadvantages of the methods are discussed and possible improvements are suggested.

## 1. Introduction

The Vertical Temperature Profile Radiometer (VTPR) is an eight-channel scanning radiometer on the polar-orbiting NOAA operational meteorological spacecraft (ref 1). Six of the channels measure the atmospheric radiance at wavelengths in the 15 micron $CO_2$ band which are used to deduce the atmospheric temperature profile. The seventh channel is in a water-vapour band near 18 microns and the remaining channel is situated in an atmospheric window at 11 microns.

Since December 1972 the US National Environmental Satellite Service (NESS) have been retrieving the SIRS operational soundings from VTPR radiances. The currently used retrieval method employs regression in which the temperature or thickness profile is expressed as a linear function of cloud free radiances; the linear coefficients are determined from samples of co-located radiances and radio-sonde soundings. The most recent comparisons by NESS indicate a standard deviation of about 3.5 gpdm in the 1,000 - 500 mb SIRS - sonde thickness difference.

In this paper we describe results of linear regression retrievals of the 1,000 - 500 mb thickness over the north-eastern Atlantic using clear radiances deduced from VTPR direct read-out data. Comparisons of (retrieved - actual) thicknesses have been made on 43 days for which statistics are given. For two days the retrieved and actual thickness charts are also compared.

## 2. Sources of Data

### a. Radiance Data

The NOAA operational spacecraft have the facility of transmitting VTPR radiance data in a coded form to ground receivers in real time (the direct read-out facility). On two days each week, usually Wednesday and Sunday, the VTPR telemetry is recorded at the Royal Aircraft Establishment reception station at Lasham (about 40 km south-west of Bracknell). The telemetry is transferred to Bracknell on magnetic tape where it is decoded into radiances using an algorithm and calibrations supplied by NESS and US Air Force orbital elements for the NOAA spacecraft are used to locate the radiances geographically. These radiances cover a circular area of radius about 4,000 km centred at Lasham which includes the northeast Atlantic.

The VTPR is a scanning instrument with a 60 km x 60 km field of view at the nadir elongating to 60 km x 90 km at the edges of the scan (each scan contains 23 observations). The radiances observed by the VTPR in cloud-free conditions are related to the mean temperature of the atmosphere as determined by the height of the weighing functions of the channels. The heights of the weighing functions of channels 1 to 6 are mainly determined by the known distribution of $CO_2$ in the atmosphere although tropospheric water-vapour modifies the shape of the functions of channels 4, 5 and 6. The approximate pressure at the peak of these weighing functions in average atmospheric conditions is given in table 1.

Table 1 VTPR $CO_2$ Weighing Functions

| Channel number | Approximate pressure at weighting function peak |
|---|---|
| 1 | 20 mb |
| 2 | 50 mb |
| 3 | 120 mb |
| 4 | 300 mb |
| 5 | 600 mb |
| 6 | 1,000 mb |

The peak of the weighting function of channel 7 is determined by the distribution of water vapour in the atmosphere but it is usually situated at the level above which there is 0.8 gm . $cm^{-2}$ of water-vapour. Channel 8 is situated in a spectral window and so the radiance depends mainly upon the temperature and proportion of the surface and clouds in the field-of-view.

The observations of radiance made by the VTPR are often affected by cloud and they are processed using a method similar to that described by Barwell and Rawlins (ref 2) in order to deduce the cloud free radiances. Briefly it is assumed that for any channel the radiance is linearly related to the fractional cloud cover in the field of view and so the radiances in any two channels are also linearly related. For channels 1 to 7 we can write that

$$R_i = a_i R_8 + b_i \quad \ldots \quad (1)$$

where the $a_i$ and $b_i$ can be determined by the least-square fitting of a straight line to the observations in an area (a VTPR "box") within which it is assumed that only the cloud amount varies. The VTPR boxes contain either 56 or 64 observations and are about 550 km square so that the $R_i$ are actually averages over areas of this size though they are regarded as point values at the centres of the boxes.

The calculation of the values of $R_8$ (clear) for use in equation 1 involves the determination of the transmission function profile (as described in ref 2) from the relevant temperature and humidity profile; in the operational retrieval of SIRS soundings, for instance, NESS use forecast profiles. We wish to avoid this complication so we represent the effect of the varying atmospheric transmissions by a set of eight fixed constants $\tau_i$, $i = 1, 8$ which are the average surface transmission for each channel. These values are given in table 2.

Table 2

Adopted surface transmission coefficients and wavenumbers for VTPR channels

| Channel number $i$ | $\tau_i$ | $\bar{\nu}_i$ ($cm^{-1}$) |
|---|---|---|
| 1 | 0.0 | 669 |
| 2 | 0.0 | 678 |
| 3 | 0.0 | 695 |
| 4 | 0.01 | 708 |
| 5 | 0.12 | 725 |
| 6 | 0.42 | 747 |
| 7 | 0.20 | 535 |
| 8 | 0.85 | 833 |

$\tau_8$ in table 2 is used to calculate $R_8$ (clear) from the equation

$$R_8 \text{ (clear)} = B(T_s, \bar{\nu}_8) \cdot \epsilon \cdot \tau_8 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $B(T, \bar{\nu})$ is the Planck function for the sea-surface temperature $T_s$ and wavenumber $\bar{\nu}$ and $\epsilon$ is the sea-surface emissivity, assumed to be 0.99. The value of $\tau_8 = 0.85$

was chosen so that equation 2 can represent both the attenuation of the surface radiation by the atmosphere and the addition of a small amount of radiation emitted by the atmosphere itself. $R_8$(clear) from equation 2 is used in equation 1 to calculate the $R_i$ (clear) i = 1, 7 where the $a_i$ and $b_i$ are derived from the cloudy observations as described previously. From each $R_i$ (clear) is subtracted the surface contribution $B(T_s, \bar{\nu}_i).\epsilon.\tau_i$ leaving the atmosphere radiances (referred to simply as $R_i$) to be used in the retrievals. Clear radiances can be obtained in this way only over the sea; overland $T_s$ and $\epsilon$ are not usually well enough known. Sea-surface temperatures for use in these processes are derived from ship measurements as described by May (ref 3). In this work radiances are quoted in units of $mW.m^{-2}sr^{-1}(cm^{-1})^{-1}$. (R.U.). The $\bar{\nu}$ for the VTPR channels are given in table 2.

b. 1,000 - 500 mb Thickness Data

A day's radiance data recorded at Lasham is received from several passes of the NOAA spacecraft over the direct read-out area. The sequences of passes is similar from day-to-day because the spacecraft is in a fixed local-time orbit; three or four southgoing passes between about 08 and 12Z are followed by three or four northgoing passes from 18 to 22Z.

The radiance data do not coincide in time with the main synoptic times (00 and 12Z) of radio sonde ascents and also very few clear radiances coincide in position with radio sonde stations. As a consequence it was decided to use the 12Z Central Forecasting Office subjective analysis as the source of thickness data with the following advantages and disadvantages.

Advantages

i. More coincident sets of radiances and thicknesses could be acquired in a given time interval.

ii. Possible errors in radio sonde ascents are suppressed by the smoothing involved in the objective analysis. This smoothing also makes the 1,000 - 500 mb thickness fields more compatible with the area averaged clear radiances.

iii. Meteorological data other than direct soundings (eg cloud photographs) and the continuity of pattern from one day to the next leads to improved analyses.

iv. A comparison of CFO analyses and radiances should result in retrievals of thickness which should be more compatable with further analyses.

Disadvantages

i. The 1:20 million north Atlantic CFO analyses may contain some influence of SIRS soundings derived by NESS from the identical radiances. However, judging from the CFO analyses these SIRS soundings are given little weight at latitude north of $40^{o}$N. Since the analyses are drawn subjectively, no numerical value can be attached to these weights, the SIRS soundings are given varying weight depending upon the judgement of the analyst.

ii. The VTPR radiances cover a period of about 14 hours in time compared with the roughly three hours spread of conventional observations used in the analysis. In order to obtain enough clear radiances (bearing in mind that there are no clear radiances in areas of widespread cloud) we were obliged to associate all of the day's radiances with one analysis which was chosen to be 12Z. It is believed that this makes the regression model more noisy.

3. Comparisons of Retrieved and Analysed thicknesses

i. Statistical results

Two linear regression relationships between radiances and thicknesses were studied, the first of which is

$$\Delta^{th}_{1000-500} = \sum^{i=1,7} A_i . \Delta R_i \quad \ldots\ldots\ldots (3)$$

where $\Delta$ denotes a deviation from a sample mean. This is referred to as model 1.

The $A_i$ in this equation were determined by a least square regression analysis of 458 coincident sets of radiances and thicknesses from days 7 January to 24 March 1976 inclusive. The radiances were chosen so that there would be approximately equal amounts in areas of large and small thickness to ensure that the regression coefficients would be representative over a large range of thickness. The effect of the zonal variation of the radiances upon the model was investigated but was found to be negligible. No extra weight was attached to radiances obtained from cloud-free areas nor to those close to radiosonde stations. The $A_i$'s are given in table 3 column 1.

Table 3 Coefficients in the Linear Regression Models 1 and 2

| Term | Coefficients $A_i$ in units of gpdm . $RU^{-1}$ (1) Model 1 | Coefficients $A_i$ in units of gpdm . $RU^{-1}$ (2) Model 2 |
|---|---|---|
| $\Delta R_1$ | +0.04 | -0.08 |
| $\Delta R_2$ | -0.58 | +0.13 |
| $\Delta R_3$ | +0.06 | -0.84 |
| $\Delta R_4$ | -4.85 | +2.56 |
| $\Delta R_5$ | +10.14 | +10.57 |
| $\Delta R_6$ | -4.37 | -3.47 |
| $\Delta R_7$ | -0.18 | +5.17 |
| $\Delta R_4 \Delta R_7$ | - | -0.08 |
| $\Delta R_5 \Delta R_7$ | - | -0.02 |
| $\Delta R_6 \Delta R_7$ | - | -0.01 |

The $A_i$ in column 1 show that the 1,000 - 500 mb thickness is most sensitively related to changes in the radiance in channels 4, 5 and 6 which have weighting functions which peak in the troposphere (see table 1). The impact of changes in the stratospheric radiances, in channels 1, 2 and 3, is much smaller even though there are likely to be significant correlations between atmospheric temperatures in the two regions. Judging from the magnitude of $A_5$, the channel 5 radiance is most important of all in determining changes in thickness but its effect in practice is counterbalanced by the opposite sign of $A_4$ and $A_6$ and the positive correlation between $\Delta R_4$, $\Delta R_5$ and $\Delta R_6$ due to the overlap of the weighting functions.

These regression coefficients were used to retrieve thicknesses from radiances observed on 43 days in the period 12 November 1975 to 7 January 1976 and from 19 May to 18 August 1976. The mean difference (in the sense actual-retrieved), its standard error and the standard deviation of the differences (about 50, distributed uniformly over the chart) on each day are shown in figure 1a. The standard deviation of the differences averages about 5.5 gpdm during this period with daily values ranging from 4.0 to 7.0 gpdm, compared with the value currently achieved by NESS of 3.4 gpdm at mid latitudes based on their regular SIRS - sonde comparisons (private communication). The relative constancy of the standard deviation indicates that the regression relationship is inherently stable though noisy. In contrast the daily mean difference shows a strong seasonal variation with large differences of about +11 gpdm during summer but near zero in the winter. This seasonal variation arises because the $A_i$ were determined from a winter sample of radiances and thicknesses and do not strictly apply to summer conditions.

The seasonal change in the mean difference could be regarded as indicating that the regression coefficients need to be re-calculated for different seasons of the year. However it is noticeable that there is no sign of a seasonal change in the standard deviation which is a measure of the ability of the radiances to represent the pattern of the thickness field. It may be adequate simply to retain a fixed set of coefficients such as those in table 3 column 1 and simply to add to the retrieved thicknesses a seasonally varying correction factor. The standard errors of the mean differences in figure 1a indicate that it would be adequate to use a correction factor determined from a previous days' comparisons.

It was mentioned previously that the weighting functions of channels 4, 5 and 6 are affected by the presence of water vapour in the troposphere possibly resulting in non-linearities in the regression model. Now $R_7$ contains information about atmospheric water vapour so that the slightly more complicated model (model 2)

$$\Delta th_{1000-500} = \sum_{i=1,7} A_i \Delta R_i + A_8 \Delta R_4 . \Delta R_7 + A_9 \Delta R_5 . \Delta R_7 - A_{10} \Delta R_6 . \Delta R_7 \quad \ldots \ldots (4)$$

was investigated.

The regression analysis to determine the $A_i$, i = 1, 10 was carried out as before on the same sample of radiances and thicknesses. The $A_i$ are given in table 3, column 2.

The coefficients of the cross-product terms are very small indicating that non-linearities in the model resulting from the effects of water vapour on $CO_2$ weighting functions are negligible. This is confirmed by the mean (actual retrieved) difference and its standard error and the standard deviation of the differences on each day as shown in figure 1b, which behave in a near identical fashion as those for the simpler model. The average standard deviation is slightly smaller, at 4.9 gpdm, than previously (5.5 gpdm) though a statistical f-test reveals that these two values are not significantly different. The mean difference is about 2.5 gpdm less. Further possible sources of error are discussed later in this paper.

ii. Results in chart form

The main purpose of this work is to retrieve from VTPR radiances 1,000 - 500 mb thicknesses to supplement the sparse upper air sounding data in the north-east Atlantic area. In this section we given two examples of thickness charts derived from radiances **alone** and compare them with the corresponding CFO analyses. The thicknesses from which the charts were drawn were retrieved using the second of the linear regression equations. They were adjusted by the addition of a uniform correction in order to bring their general level into agreement with the CFO analysed charts; this does not change the pattern of the retrieved thicknesses.

Case 1 - 20 June 1976 (figure 2)

On this day the CFO analysed 1000 - 500 mb thickness pattern showed a marked trough at about 40°W with the axis roughly NW - SE and a cut-off cold pool at 53°N 35°W. To the east of this trough lay a ridge off the west coast of Ireland with a further trough over southern Scandinavia.

The retrieved thickness pattern shows only moderate agreement with the features of the CFO analysis, the trough south of Greenland is retrieved as a weak feature and the alignment of the contours to the west side of the trough are nearly perpendicular. The shape of the ridge west of Ireland is retrieved well between latitudes 50° and 60°N but poorly to the south. The trough over Scandinavia is not well retrieved and there is considerable disagreement btween retrieved and analysis south of 40°N. The standard deviation of the difference between the retrieved and analysed charts based on comparisons at 64 well distributed points, is 3.9 gpdm.

Case 2 - 7 April 1976 (figure 3)

A strong south-westerly flow south of Greenland, a strong north-westerly flow over the UK, a very flat area south-west of Ireland and a trough extending south-west over Spain are the main features of the analysed thickness pattern on this day. The retrieved thickness pattern shows all of these features with the trough over Spain and the cut-off low being particularly well reproduced. Visually the agreement between the retrieved and analysed patterns on this day appear to be better than on 20 June (case 1) but the standard deviation of the difference (from 68 points) is slightly larger with a value of 4.8 gpdm.

The overall assessment of the results of comparisons on 43 days is that the agreement (judged visually) between retrieved and actual thickness charts is rather more often of the lower standard represented by case 1, than case 2. We now discuss reasons for this poor quality of the retrievals and suggest possible improvements.

## 4. Possible improvements in the retrievals

### i. Clear radiances

The results of a comparison of clear column radiances deduced by the method described in section 2a and radiances calculated directly from co-located sonde ascents indicates that the clear-column radiances have a persistent error which increases with cloud-top height and cloud amount (ref 4). Discussions with the staff of NESS reveal that this is caused by the presence of multiple layers of cloud which modifies the linear relationship between cloud amount and radiance. An improved method of deducing clear radiances based on that used by NESS for the SIRS soundings has been adopted in Met O 19 since the work described in this paper was completed.

An alternative is to use directly observed VTPR radiances from areas which are apparently cloud-free. Such areas can be seen in cloud pictures from the Scanning Radiometer which accompanies the VTPR on the NOAA spacecraft. A possible difficulty here is that extensive cloud-free areas tend to be associated with anticyclonic conditions which may result in difficulties in compiling suitably balanced samples of the thickness and radiances.

ii. Transmission Coefficients

It was mentioned in section 2a that constant surface transmission coefficients were adopted to avoid having to calculate an appropriate temperature and humidity profile for each radiance observation. Recent calculations indicate that possible changes in transmission coefficients over the direct read-out area can be considerable so that the use of a constant set plus only one regression equation for the whole area is unwarranted. The obvious alternatives are to have several sets of transmission coefficients and/or several sets of regression coefficients chosen on a latitude basis.

iii. Asynoptic Radiance Observations

A further small improvement in accuracy may be obtainable by interpolating within the clear radiances deduced from the southgoing passes (08Z to 12Z) and from the northgoing passes (18 to 22Z) to determine radiances for 12Z to coincide with the timing of the CFO analysed chart.

References:-


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3. May B R — "The Processing of Sea-Surface Temperature measurements for use in the Met O 19 VTPR retrieval programme". Met O 19 Branch Memorandum No 21.

4. Hand W H et al — "Experiences in the Use of VTPR Direct Read-out Radiances" Paper presented at COSPAR Symposium C on "Meteorological Observations from Space: Their contributions to the FGGE". Philadelphia June 1976.

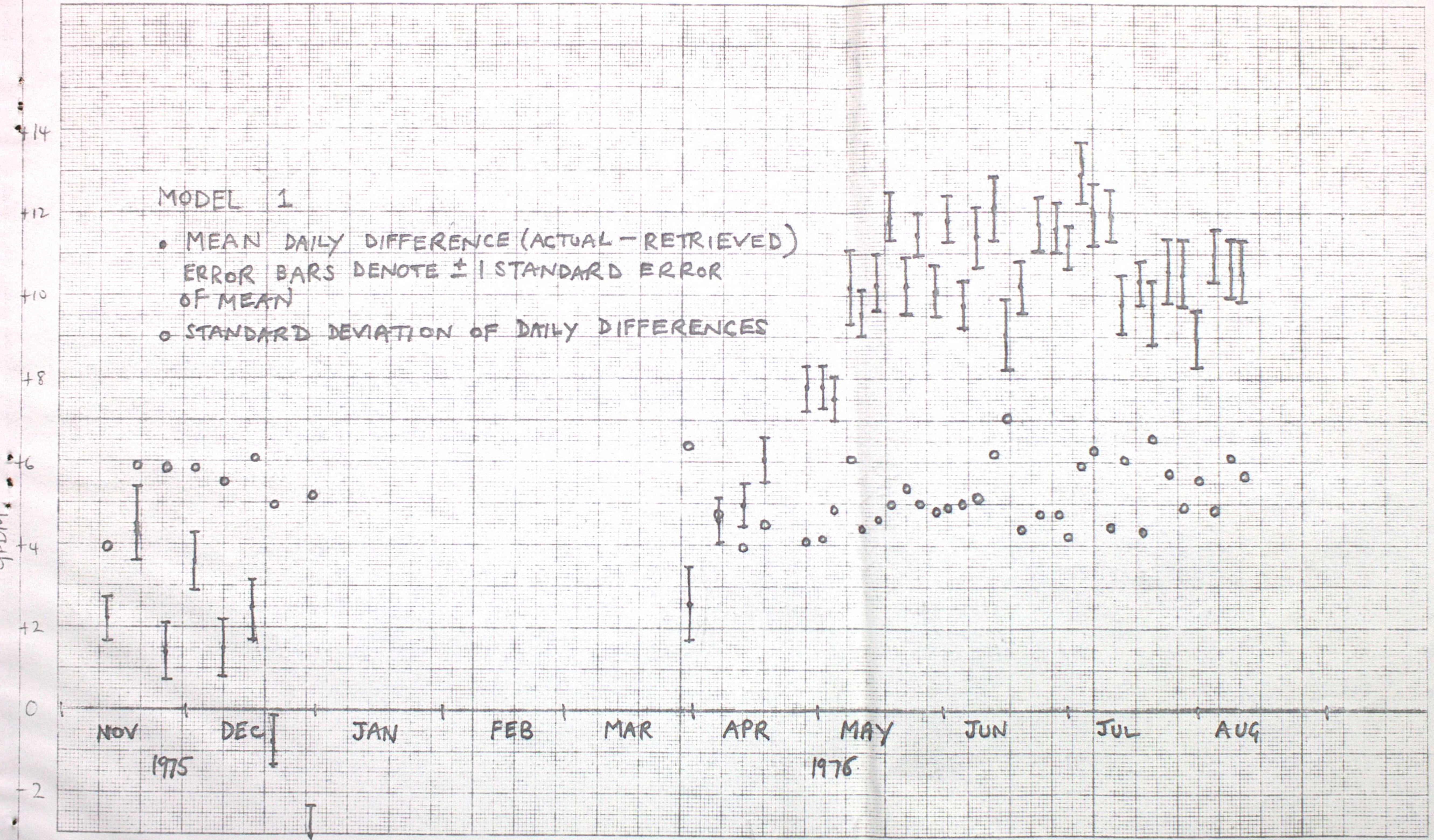


FIGURE 1a MEAN, STANDARD ERROR AND STANDARD DEVIATION OF DAILY MEAN DIFFERENCES (ACTUAL – RETRIEVED) OF 1000 – 500 MB THICKNESS FROM REGRESSION MODEL 1.

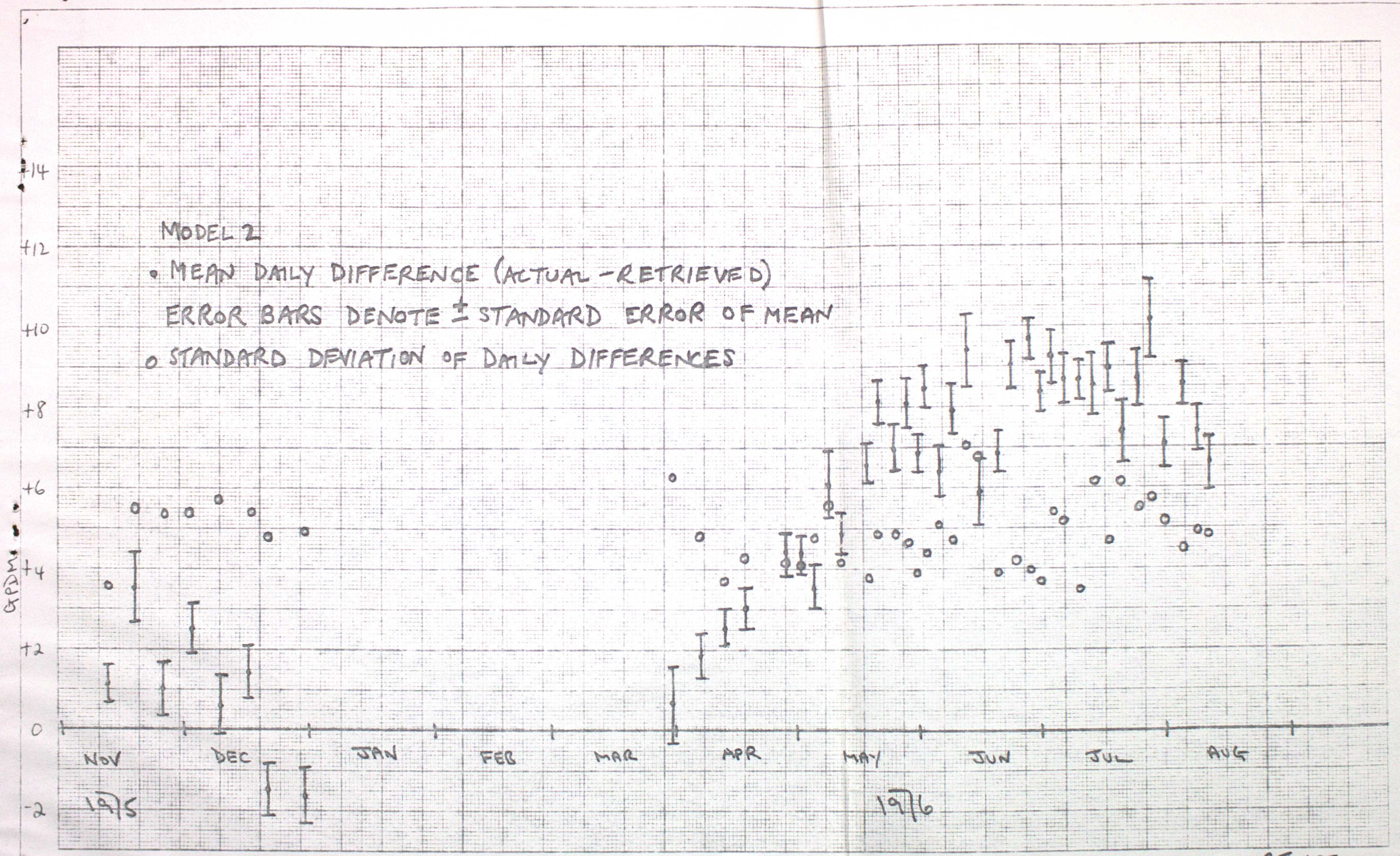


FIGURE 1b MEAN, STANDARD ERROR AND STANDARD DEVIATION OF DAILY MEAN DIFFERENCES (ACTUAL - RETRIEVED) OF 1000-500MB THICKNESS FROM REGRESSION MODEL 2.

540
534
546
552
558
564
570
1000-500MB THICKNESS IN GPDM
12Z 20 JUNE 1976
RETRIEVED
CFO ANALYSIS


FIGURE 2

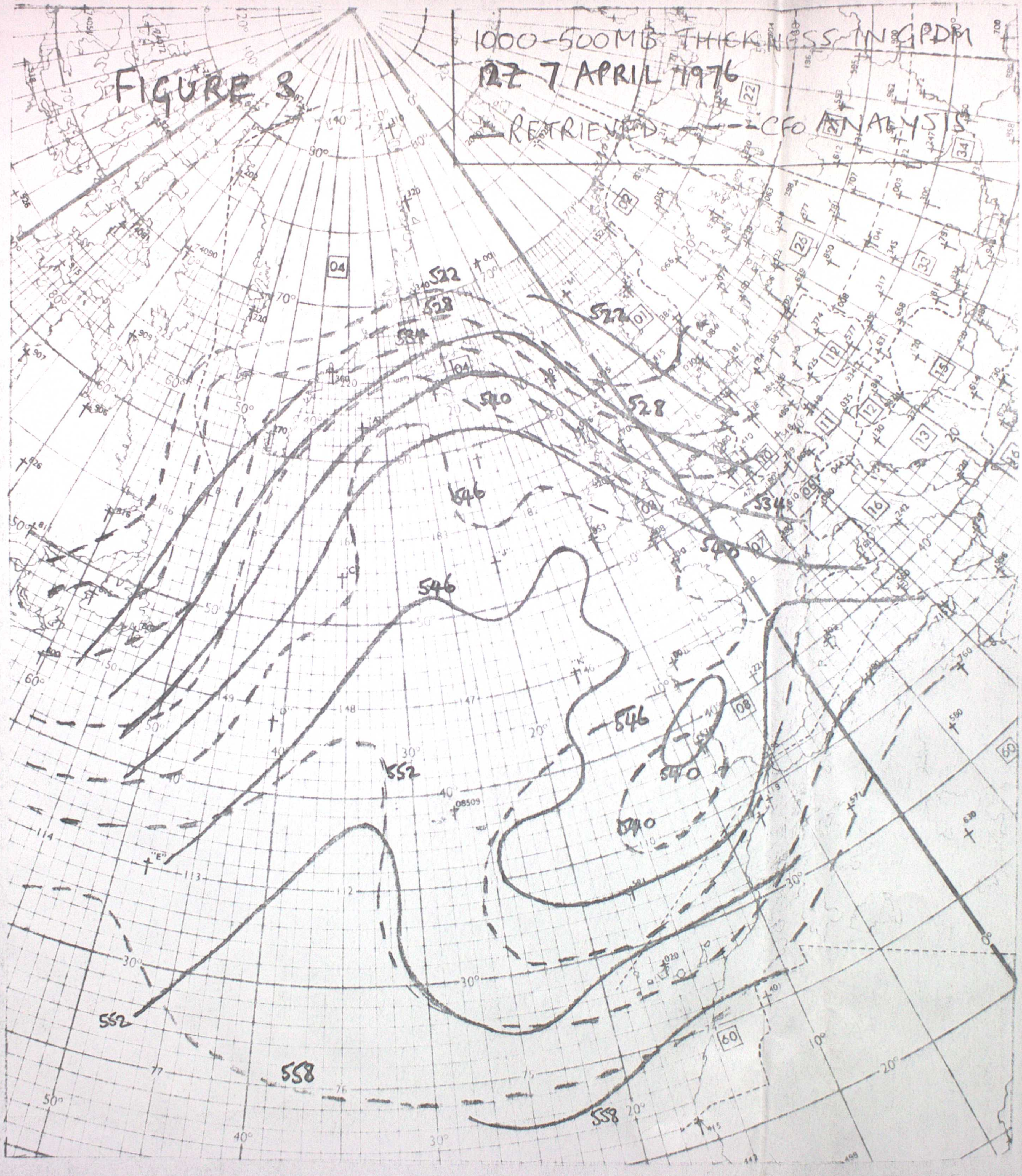

FIGURE 3
1000-500MB THICKNESS IN GPDM
12Z 7 APRIL 1976
—— RETRIEVED
— — — CFO ANALYSIS
522
528
534
540
546
552
558