Space Science and Engineering Center
University of Wisconsin-Madison

A Final Report

for

Technical Development to Improve Satellite Soundings
over Radiatively Complex Terrain

A REPORT from the

Cooperative Institute for Meteorological Satellite Studies

A Final Report

for

Technical Development to Improve Satellite Soundings over Radiatively Complex Terrain

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SUMMARY

The major effort of the ALPEX project at the University of Wisconsin Space Science and Engineering Center was software development of TOVS processing on the Man-computer Interactive Data Access System (McIDAS) initially based on the IBM 4341 and now on the IBM 4381. This work included: (1) the addition of a high resolution topography, (2) formulation and implementation of a new surface skin temperature calculation technique, (3) improvement in the method of handling HIRS and MSU limb correction, and (4) improvement in the method of accounting for MSU surface emissivity. These modifications as well as the implementation of the simultaneous solution physical retrieval technique have measurably improved the quality of TOVS retrievals over the complex terrain of the Alps.

I. INTRODUCTION

This grant was for partial support from the National Aeronautics and Space Administration to improve satellite vertical sounding retrievals over complex terrain conditions as they related to ALPEX. Those features which are unique to complex land conditions are (1) the variable elevation of the terrain, (2) the large differences between surface air and surface skin conditions, and (3) the variability of surface emissivity at microwave wavelengths. In the following section, each of these three points will be mentioned very briefly. The reader will be referred to specific appendices for more detailed explanations.

II. DISCUSSION

A. SOFTWARE DEVELOPMENT

A major development undertaken through this contract was the acquisition and application of high resolution topography on the McIDAS system. The previous 100 km resolution terrain file was improved to 15 km, which is better than the resolution of the HIRS instrument and therefore adequate for mesoscale sounding applications. The high resolution topography is necessary for evaluating the surface contribution term of the radiative transfer equation which is required for the proper interpretation of the radiance measurements in terms of atmospheric profiles. It is also important in establishing a reference level for the pressure height profile.

A new technique for finding the surface skin temperature in the presence of cloud and reflected sunlight was implemented in the ALPEX retrieval software. The method uses the three window channels for 2 FOV and involves the minimization of a function relating surface temperature, cloud temperature, cloud amount and reflectance (Smith, et al., 1983; Appendix A).

The statistical limb correction used in operational TOVS processing is known to be deficient. Because a random sample of cloud conditions are included in the regression dependent data base, the statistical correction tends to overestimate the limb correction for cloudy fields of view and underestimate it for clear fields of view. As a consequence, the statistical limb correction produces noise in the adjacent cloudy and clear fields of view. The ALPEX software was modified to account for the angular dependence of the radiances measured in the IR and MSU channels in a physical (rather than statistical) manner (Appendix A and C, Smith, et al., 1983 and LeMarshall and Schreiner, 1985).

An algorithm for calculating the surface emissivity for the microwave channels has also been developed for the ALPEX algorithm. A detailed description of the algorithm and evaluation is given in Appendix A.

In all of the ALPEX processing it was intended that we maintain a standard benchmark version of the retrieval system against which to measure improvements. The benchmark version was essentially an operational iterative retrieval algorithm which does not include the refinements carried out under this grant. Our four principal ALPEX orbits were processed with the benchmark version and reprocessed with several of the improvements. A systematic evaluation of each of the improvements was not performed, although comparisons of the benchmark version versus the "new and improved" iterative algorithm are described in Appendix A.

In addition to the "new and improved" iterative algorithm, the ALPEX grant was used in developing the "matrix inversion" retrieval algorithm (Smith, et al., 1984; Appendix D). Briefly, this algorithm provides a simultaneous solution for temperature and water vapor profiles and surface skin temperature from radiance observations. This approach has been shown to be more independent of the first guess than the iterative algorithm and also to yield greatly improved moisture profiles.

A feasibility study comparing single field of view (FOV) TOVS retrievals versus the box of 3x3 fields of view most TOVS software uses. The advantage of one FOV soundings would be in describing the atmosphere on a mesoscale level in the mountainous terrain. It was found that the single FOV was most advantageous at the borders of mountains in two cases. The single FOV retrievals showed close agreement to 3x3 retrievals in areas of homogenous terrain. Results of this experiment are detailed in Appendix B (Loechner, 1983).

As part of the verification effort, software was developed to process ECMWF data (level II and III) on the McIDAS. These data can also be used to provide a first guess temperature profile though to date all retrievals have been made using a statistical first guess based on the NESDIS operational retrieval coefficients.

It should be noted that the new ALPEX related algorithm development has been largely accomplished on the new McIDAS IBM 4381. The performance of this contract has provided the major impetus for transferring the TOVS man-interactive software to the new machine and thereby is providing continuity in the SSEC satellite retrieval research effort.

B. DATA

Level 1-B data containing the raw radiances for all HIRS and MSU channels for NOAA-6 and 7 from the period 1 March - 30 April 1982, which corresponds to the first special observing period, were collected and preprocessed to produce earth located calibrated radiances. In addition, the ECMWF level III-a and level II-a data for specific cases were received and are available on magnetic tape. The periods covered are: Level IIa; 1-10 March 1982 and 21-30 April

1982, Level IIIa; 1-9 March 1982 and 21-26 April 1982. In this case level IIa refers to a global observation data set for the area 30N-60N and 30W-37E. Level IIIa designates the operational global analysis for 0000, 0600, 1200 and 1800 GMT on 1.875° latitude/longitude grid for the standard levels from 1000 mb to 10 mb.

In support of the research carried out under this contract, the University of Wisconsin sent out the following data sets to the various international ALPEX working groups. A total of eight NOAA-7 overpasses or four pairs were used. Two pairs, each covering the continent of Europe at the nominal time of 4 March 1982 1300 GMT and 5 March 1982 0300 GMT; and two pair covering the Tasman Sea from the east coast of Australia to the International Date Line for the times 0300 GMT and 1500 GMT on 28 October 1982. In addition, software and coefficient files to read and process the ingested NESDIS TOVS 1-B data sets were included.

Meteosat data covering the period 4-5 March 1982 were requested of the European Space Agency and received. From these data cloud drift and water vapor winds were derived and are available on magnetic tape.

III. CONCLUSIONS

The purpose of this two year grant was to develop retrieval algorithms to deal with the unique problems of satellite retrievals over complex terrain. To a large extent this has been accomplished. In addition, this grant provided the impetus for transferring software from the McIDAS/Harris system to the McIDAS/IBM-4341 and, most recently the IBM 4381 network. Also, International TOVS Processing Package (ITPP) versions I and II have been made available to users around the world. Finally, much of the research work performed under this grant at the University of Wisconsin was in support of the First and Second International TOVS Conferences held in Igls, Austria.

Data sets using both algorithms (ITPP versions I and II) have been generated and statistics calculated comparing the retrieval results to ECMWF analyses. The results will be available in the Technical Proceedings of the Second International TOVS Conference. Cloud drift winds as well as water vapor winds for Meteosat data over the Alpine region on March 4 and 5, 1982 have been generated and are available to interested users.

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Appendix A: Physical Retrieval TOVS Export Package

W. L. Smith, et al.

excerpted from

The Technical Proceedings of the First International TOVS Study Conference (editor P. Menzel)

THE PHYSICAL RETRIEVAL TOVS EXPORT PACKAGE

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1. Introduction

The satellite sounding radiance data received at the University of Wisconsin is converted into meteorological parameters using a physical solution of the radiative transfer equation, rather than empirical regression, in order to account for the influences of surface variables (i.e., terrain elevation, emissivity, and temperature) in the profile solutions and to permit the infrared data to be utilized for overcast as well as clear or partly cloudy sky conditions. These attributes of the physical solution are particularly important for the CIMSS applications of the data to real-time mesoscale weather analysis and forecasting for the North American region.

The initial "TOVS Export Package" developed by the CIMSS, and made available to numerous direct readout data users, has been modified to include the physical retrieval algorithm. As in the previous version, the new package produces temperature and moisture profiles from a 3 x 3 array of HIRS radiances and spatially interpolated MSU observations. Thus, the resultant linear resolution and spacing is about 75 km. In addition, the new Physical Retrieval TOVS Export Package provides a measure of total ozone concentration based upon the stratospheric carbon dioxide and ozone channel (emission to space) radiance observations. Advantages of the physical retrieval algorithm over the prior statistical regression method are:

a. surface parameters such as skin temperature, emissivity, and elevation are treated as variables and therefore accounted for explicitly in the profile solutions;

b. the reflected solar contribution to the shortwave window channels is determined and accounted for in the solution for surface temperature;

c. the effect of clouds on the infrared channel observations is determined, thereby permitting the use of an optimum number of infrared observations under all cloud conditions;

d. the radiance data is not "limb-corrected", thereby eliminating a potential source of error in the data processing (the preprocessor (PROGRAM TOVPRE) now permits the user to specify whether or not limb corrections are to be made);

e. the solutions are in no way related to radiosonde data so that their accuracy is much more independent of geographical location and observation time than statistical regression solutions (with the exception of the regression first guess option).

In this paper, prepared for the participants of the First International TOVS Study Conference, the physical algorithm is presented, its performance on the Alpex and Tasman Sea NOAA-7 orbits chosen for the conference is described, and the documentation needed to implement the new software is given.

2. Physical Retrieval System

This document assumes the reader is already familiar with the observational characteristics of the TOVS; if not, the reader is referred to the articles provided in the bibliography. As a quick review, Table I shows the characteristics of the TOVS (HIRS and MSU) channels. Figure 1 shows a schematic of the TOVS Physical Retrieval Processing System. The ingest, calibration, and earth location are the same as given in the original version. In the physical retrieval system there is no need to angle or "limb-correct" the measurements since the weighting (i.e., atmospheric transmittance) functions can be computed for the angle of observation as described in section 2 i.

a. First guess profiles

The physical retrieval algorithm solves for a departure of the true atmospheric temperature, moisture, and ozone profiles from a "guess" condition as a function of the departure of the observed radiances from those calculated for the "guess" profiles. The guess options included are: a latitude and time interpolation of the ten "Standard Atmospheres" (one for each of five latitude zones in winter and summer), by regression estimates from the non-cloud-contaminated radiances (microwave and stratospheric infrared); estimates produced by a dynamical forecast model. The first two options are available in the physical retrieval export package; since accessing forecast-model output is highly machine- and installation-specific, each user must provide his own interface.

b. Selection of "clearest" radiances

The profiles are produced from 3 x 3 arrays of 26 kilometer resolution HIRS fields-of-view (the courser resolution microwave data having been interpolated to the HIRS locations). The "clearest" observations are selected on the basis of the 11 μm window channel brightness temperature being within 3°K of the maximum observed amongst the 9 measurements. The average of all the "clearest" observations is generated for the sounding retrieval process. For the microwave channels and the stratospheric sounding infrared channels, the average is taken over all nine fields-of-view without regard to the 11 μm window brightness temperature. A check is made to determine whether the "clearest" observations are too cloud contaminated to afford an accurate profile retrieval. Using the 11 μm brightness temperature and the "guess" temperature profile, if the former is colder than the guess 500 mb temperature no retrieval is attempted. This check also safeguards against the use of precipitation attenuated microwave observations in the profile solutions.

c. Surface data

The accuracy of the retrieved profiles can be affected significantly through the use of surface data. The surface parameters required for radiative transfer calculations are surface pressure, surface skin temperature, and surface emissivity. The "shelter" temperature and humidity are desired as constraints on the retrieved temperature and humidity profiles.

(i) pressure

Surface pressure is computed hydrostatically using an estimated 1000 mb height, an estimated 1000 mb temperature and assumed lapse rate of 5°C/km, and an estimate of the surface elevation for the radiance observation location. That is

$$P_s = 1000 \text{ EXP} \quad -\frac{g}{R}\int_{Z_{1000}}^{Z} \frac{dZ}{T_{1000} + \gamma(Z - Z_{1000})} \qquad (1)$$

Where g is gravity, R is the gas constant for air, and γ the assumed lapse rate. The 1000 mb height and temperature are estimated from either an analysis of station observations reduced to the 1000 mb level, a forecast (as in the case of first-guess generation, the user must provide the interface to such data), or climatology. The height of the observed surface is obtained from 10 nautical miles horizontal resolution topographical data (this high-resolution topography is, at present, available for the Northern Hemisphere only: elsewhere, the previously supplied 60 nautical mile resolution information must be used). The elevation for each HIRS field-of-view is obtained through a field-of-view response weighting, and subsequently the elevation for each field-of-view is spatially averaged in the same manner as the radiances themselves, as described in (2b).

(ii) air temperature and humidity

The surface air temperature is estimated from an analysis of station observations reduced to 1000 mb by using the assumed lapse rates for the reduction to 1000 mb and the actual height of the observed topography. Surface humidity is estimated from an analysis of surface dewpoint depression. If station data is not used, then the surface air temperature and dewpoint are left as unknowns in the profile retrieval process.

(iii) skin temperature

The surface skin temperature is estimated from both longwave (11 μm) and shortwave (3.7 μm and 4.0 μm) window channels of the HIRS. During the day, the shortwave windows must be corrected for reflected sunlight contributions prior to the surface temperature retrieval. Assuming that the surface reflectivity is constant within the 3.7 - 4.0 μm region it can be shown (Smith, 1980) that

$$\frac{R(3.7\mu m) - B(3.7\mu m,T_B)}{R(4.0\mu m) - B(4.0\mu m,T_B)} = \frac{B(3.7\mu m,T_{SUN})}{B(4.0\mu m,T_{SUN})} = K \qquad (2)$$

provided that the atmospheric transmittance is the same for both spectral channels. In (2), R is the observed radiance for HIRS window channel, B the Planck radiance, and T_{SUN} is the effective radiating temperature of the sun, assumed to be 5800°K. The only unknown in (2) is the effective radiating temperature of the earth-atmosphere for the 3.7 - 4.0 μm region, T_B. Rearranging (2) gives

$$f(T_B) = KB(4.0\mu m,T_B)-B(3.7\mu m,T_B) = KR(4.0\mu m)-R(3.7\mu m) \qquad (3)$$

Thus, $f(T_B)$ is calculated once and for all, and tabulated to permit rapid determination of T_B from actual observations of R(4.0 μm) and R(3.7 μm) observations (Channels 18 and 19 of Table 1).

The effective surface temperature for the 4.0 μm and 11 μm regions is then calculated from the observed (solar corrected) brightness temperatures using the relation

$$T_S = T^n_S + \frac{T_B - T_B^n}{\tau(p_o)} \qquad (4)$$

where T_B^n refers to the brightness temperature computed for a "guess" surface temperature, T_S^n, and atmospheric temperature and moisture profile condition, and $\tau(p_o)$ is the transmittance of the atmosphere above the surface pressure level, p_o. Equation (4) is derived from a form of the radiative transfer equation in which the Planck radiance dependence upon temperature is linearized using a first order Taylor expansion. Since (4) is not exact, the solution is iterated several times until $|T_s^{n+1} - T_s^n| < 0.01$°K. The initial value for T_s is obtained from the "split window" approximation, $T_s^{(0)} = T_B(11\ \mu m) + 0.5[T_B(11\ \mu m) - T_B\ (8\ \mu m)]$. As shown in Figure 1, the temperature and moisture profiles used for the final determination of T_s are provided by the microwave brightness temperatures and HIRS water vapor channel radiances as described later. The longwave (11 μm) and shortwave (4 μm) surface temperature values are checked for consistency and used to diagnose the presence of cloud contamination. Provided the results are reasonable for cloudfree sky conditions, they are used separately for the calculation of longwave (15 μm) and shortwave (4.3 μm) radiances in the infrared temperature profile retrieval process. The differences between the two surface temperatures are attributed to surface emissivity differences for the two spectral regions.

(iv) microwave emissivity

Unlike the emissivity of the earth's surface at infrared wavelengths, the surface emissivity at microwave frequencies can depart drastically from unity, depending upon surface moisture conditions. Thus, the surface emissivity must be determined and used explicitly in the calculation of outgoing radiance. The microwave "window" channel at 50 GHz (Table I) was included in the TOVS specifically for determining the effects of surface emissivity and liquid water on the microwave sounding channel radiance . It can be shown that the surface emissivity, ε_s, is given by the expression

$$\varepsilon_s = \frac{T_B + \int_0^{p_o} T(p) \left[1 + \frac{\tau^2(p_o)}{\tau^2(p)} \frac{d\tau(p)}{dp} \right] dp}{T_s \tau(p_o) + \int_0^{p_o} T(p) \frac{\tau^2(p_o)}{\tau^2(p)} \frac{d\tau(p)}{dp} dp} \qquad (5)$$

where $\tau(p)$ is the transmittance of the atmosphere above pressure level p. For the microwave window region (50 GHz), the atmospheric (integral) quantities are small compared to the observed brightness temperature and surface term; thus the result is weakly dependent upon the temperature profile condition assumed. If a poor first guess temperature profile condition is used (e.g., climatology) the entire surface emissivity and microwave temperature profile retrieval process is repeated.

d. Microwave temperature profile retrieval

The temperature profile is calculated from the microwave brightness temperatures observed in MSU channels 2,3, and 4, using the iterative solution (Smith, 1970)

$$T^{n+1}(p) = T^n(p) + \frac{\sum_{i=2}^{4} [T_B(\nu_i) - T_B^n(\nu_i)] W(\nu_i, p)}{\sum_{i=2}^{4} W(\nu_i, p)} \qquad (6)$$

where T_B^n is the brightness temperature calculated from the temperature profile $T^n(p)$, and $W(\nu_i, p) = d\tau(\nu_i, p)/dp$. In the calculation of $T^n(p)$, the surface emissivity calculated from the 50 GHz brightness temperature measurement, the surface temperature given by the HIRS 8 µm and 11 µm brightness temperatures using the "split window" approximation, and the surface pressure obtained from the high resolution topographical data are used as boundary conditions. The solution for T(p) is iterated until the condition

$$|T_B^n(\nu_i) - T_B^{n-1}(\nu_i)| < 0.05°K$$

is satisfied for all channels. If surface air temperature observations are being used, the profile below the 700 mb pressure level is adjusted in a linear fashion to blend into the observed air temperature at the surface.

e. Initial water vapor profile estimate

The initial profile of water vapor is derived using the mean relative humidity solution given by Smith and Zhou (1980). Assuming the relative humidity is constant within each layer sampled by the HIRS water vapor channels (10, 11, and 12), then

$$Rh[(p(\nu_i,p)] = Rh^{\circ} EXP \frac{R(\nu_i)-R^{\circ}(\nu_i)}{\int_0^{P_o} W^{\circ}(\nu_i,p)dp} \tag{7}$$

where $p(\nu_i)$ is the pressure level of maximum water vapor sensitivity for the water vapor channel ν_i, Rh° is a guess layer relative humidity value (a value of 0.5 is used initially), $R^{\circ}(\nu_i)$ is the radiance calculated for the guess humidity condition, and $W^{\circ}(\nu_i)$ is the water vapor weighting function given by

$$W^{o}(\nu_i,p) = g \frac{U^{o}(p)}{q^{o}(p)} \frac{\partial\tau(\nu_i,p)}{\partial p} \frac{\partial B(\nu_i,T)}{\partial p}$$

where $U^{\circ}(p)$ is the integrated precipitable water above the pressure p, and $q^{\circ}(p)$ is the mixing ratio as implied by the guess relative humidity condition, and the atmospheric temperature profile (which, at this point, has been derived from the MSU brightness temperature observations). For the HIRS water vapor channels 10, 11, and 12, the pressures of maximum sensitivity are assumed to be 800, 600, and 300 mb, respectively. Given these three relative humidity values from (7) a profile of relative humidity is constructed by linear interpolation with respect to pressure. If surface data is available, it is used to interpolate between the surface and the 800 mb level, otherwise the relative humidity is assumed to be constant below the 800 mb level. The relative humidity above 300 mb is also assumed to be constant. The solution given by (7) is repeated after the infrared brightness temperatures are used to derive an improved estimate of the temperature profile, using the relative humidity values obtained initially. Although the layer mean relative humidity approximation is not an exact simultaneous solution for the relative humidity profile from the three water vapor channel radiances, it is a stable approximation in that the influence of cloud or measurement errors is minimal.

It should be noted that, even if the atmosphere is cloudy, a relative humidity profile is derived. In this case, the solution is produced by using the microwave temperature profile and the 11 μm brightness temperature to estimate the cloud pressure and temperature. These cloud parameters are then used in the calculation of $R^{o}(\nu_i)$. The relative humidity results below the cloud level are a consequence of linear interpolation between the relative humidity sensed above the cloud level and the observed surface value.

f. Infrared temperature profile retrieval

After deriving the water vapor profile, the surface skin temperatures for the short and long wavelength temperature sounding channels are obtained by iterating (4). These together with the microwave specified temperature profile are used to calculate the "expected" values of the brightness temperatures observed in the 4.3 μm and 15 μm temperature sounding channels (Table I). If the visible channel reflectance is less than 25% and the longwave surface temperature is greater than a threshold of five degrees below the observed or microwave retrieved surface air temperature, then <u>all</u> the infrared channels are presumed to be free of cloud contamination, and are used in the temperature profile retrieval process. If the "clear test" fails, then an attempt is made to determine which of the infrared channels are free of cloud contamination. By assuming that clouds always reduce the brightness temperatures by a magnitude dependent upon the transmissivity of the spectral channel, all channels of equal or greater opacity than a given channel are presumed to be clear if the deviation between the observed and calculated brightness temperature for that channel is greater than or equal to zero. If HIRS channel 7 satisfies this criterion, all shortwave and longwave channels are presumed to be unaffected by the cloud and used in the retrieval process. If, however, this criterion is not satisfied by channel 7, then only the longwave channels satisfying the criterion are used; the shortwave channels are not used because of the difficulty in accurately correcting these measurements for cloud-reflected sunlight contributions.

Having determined the infrared channels unaffected by cloud contamination, the temperature profile is given by the iterative solution

$$T^{n+1}(p) = T^n(p) + \frac{\sum_{i=1}^{m} [T_B(\nu_i) - T_B^{\,n}(\nu_i)] W(\nu_i, p)}{\sum_{i=1}^{m} W(\nu_i, p)} \tag{8}$$

where m is the number of cloud free infrared channels and the weighting function is given by the relative contribution function

$$W(\nu_i p) = \frac{B[\nu_i, T^n(p)]}{R(\nu_i)} \frac{d\tau(\nu_i, p)}{dp}$$

If any longwave channel, ν_i, is presumed to be cloud contaminated, then $T_B^{\,n}(\nu_i)$ is presumed to be equal to $T_B(\nu_i)$ in equation (8), in order to blend the solution into the microwave retrieval below the cloud level. The iteration is terminated as soon as the criterion

$$T_B^{\,n}(\nu_i) - T_B^{\,n-1}(\nu_i) < 0.05°K$$

is satisfied for all channels. The temperature profile retrieved from the infrared brightness temperatures, using the microwave result as the initial guess, is the "final" estimate.

g. Final water vapor profile estimate

The final water vapor profile is calculated using (7) with the infrared temperature profile and the final surface temperature estimates being used in the calculation of $R^\circ(\nu_i)$ and $W^\circ(\nu,p)$. The Rh° values are taken as the estimates initially derived on the basis of the microwave temperature profile.

h. Ozone retrieval

The total ozone concentration is retrieved from the ozone channel brightness temperature using the method of Ma, Smith, and Woolf (1984). In a manner analogous to the water vapor solution, the ozone concentration is given by the inverse solution of the radiative transfer equation,

$$O(p_o) = O^o(p_o)\,\mathrm{EXP}\;\frac{R(\nu_i) - R^o(\nu_i)}{\int_o^{P_o} W^o(\nu_i,p)\,dp} \qquad (9)$$

where ν_i is channel 9 (Table I) and

$$W\,(\nu^o,p) = g\,\frac{O^o(p)}{m\,\varrho(p)}\;\frac{\partial\tau^o(\nu_i,p)}{\partial p}\;\frac{\partial B(\nu_i,T)}{\partial p}$$

$O(p)$ is the ozone concentration profile, and $m(p)$ is the ozone mixing ratio profile. The initial ozone mixing ratio and concentration profile is obtained using regression relations developed from a large sample of ozonesondes and radiances for the stratospheric HIRS channels (1-4) synthesized by radiative transfer calculations, from the ozonesonde temperature profile data. Thus the temperature profiling channels are used to specify the gross vertical structure of the ozone profile (via temperature-ozone correlation), and the ozone channel radiance is used to estimate the absolute magnitude of the total concentration. If a cloudy condition prevails, the surface pressure used in (9) is the cloud pressure determined from the 11 μm window brightness temperature and the final temperature profile.

i. Calculation of transmittances

An essential ingredient of any physical retrieval scheme is the availability of accurate and computationally efficient ("fast") procedures for calculating profiles of atmospheric transmittance in the various spectral intervals represented by the infrared (HIRS) and microwave (MSU) sounding channels. These procedures must account for variations in spectral response, atmospheric composition and state (temperature and moisture dependence), and departure from vertical viewing (slant path or zenith-angle dependence).

The requirement for computational speed precludes the employment, in routine processing, of so-called "exact" (in the spectroscopic sense),or line-by-line, methods. Therefore, models have been developed (McMillin and Fleming, 1976; Fleming and McMillin, 1977; Weinreb and Neuendorffer, 1973; Weinreb et al., 1981) to satisfy the dual requirements of speed and accuracy--the latter being defined in terms of degree of agreement with exact calculations. The first three references cited above describe the algorithms developed for the infrared; the first relates these specifically to HIRS, and also discusses the method used with MSU.

When the design decision was made to apply the physical retrieval algorithm to non-limb-corrected TOVS data, it was determined that the existing MSU transmittance model would not suffice. For an arbitrary scan angle, it entails calculation of transmittance profiles for a number of angles, followed by convolution with the antenna gain pattern--a computationally costly process. Therefore, a variation of the model was developed, in which a separate set of regression coefficients, relating absorption to temperature and moisture, is generated for each of six equally spaced scan angles. The influence of the antenna pattern is incorporated into the absorption profiles used for the regression. Coefficients for arbitrary scan angles are obtained dynamically by linear interpolation. The model has been verified by comparing antenna temperatures calculated from "exact" and regression-estimated transmittance profiles; agreement is very good.

Transmittances for the ozone retrieval are computed using the method of Gruenzel (1978), with contributions from water vapor lines and continuum obtained by the procedures described in Weinreb, et al. (1981).

The transmittances are adjusted in order to minimize differences between observed and calculated radiances. The adjustments are made assuming that

$$\ln\tau(\nu_i p) = \gamma(\nu_i)\ln\hat{\tau}(\nu_i, p)$$

where $\gamma(\nu_i)$ is the adjustment factor and $\hat{\tau}(\nu_i, p)$ is the unadjusted transmittance. The adjustment factors have been determined on the basis of a very large sample (several thousand) of "coincident" radiosonde and radiance observations. The γ's are calculated so as to minimize the RMS difference between observed and calculated radiances for all atmospheric conditions and latitude zones. The values assumed for all NOAA satellites in the TOVS Export Package are given in Table 2.

3. Results From NOAA-7 ALPEX Orbits

The Physical Retrieval Export Package was applied to the NOAA-7 orbits chosen for the TOVS Study Conference. The program options used were "Regression Guess" and "With Surface Data". The regression coefficients used were the NESDIS operational for the overcast cloud (Path 3) condition. The surface data was obtained from station reports for the ALPEX orbits and from Australian Bureau of Meteorology analyses for the Southern Hemisphere orbits. The effect of the different program options upon the results are discussed in section 5 of this report.

The actual retrieval values and radiosonde data for the Alpex orbits are given in an Appendix. Also, the retrieval values and contour analyses for the Southern Hemisphere orbits chosen for the Study Conference are given in an Appendix. The geopotential thickness values are for the layers specified in the Study Conference invitation and are given in decameters.

In this section we present comparisons of the various TOVS geopotential thickness analyses with those of radiosonde data produced by the European Center for Medium range Weather Forecasting (ECMWF) for the ALPEX orbits. The analysis of the TOVS retrievals is produced by Barnes interpolation (Barnes, 1973) at a spatial resolution of 75 Km. The ECMWF analyses are based on optimal interpolation (Bengtsson, 1981) at a spatial resolution of 200 Km. The different resolutions are consistent with the different horizontal spacings between TOVS and Radiosonde sounding data (see the Appendix).

Figures 2-6 show the analysis comparisons for geopotential thickness. As may be seen from these figures, the patterns of the two different analyses produced from TOVS (SAT) and from Radiosonde (ECMWF) data are nearly identical, however, there are significant differences in the horizontal scale and gradients resolved by the two data/analysis systems. In particular, smaller horizontal scales seem to be resolved in the TOVS analyses. For example, the shortwave ridge in the 1000-700 mb thickness along the east-coast of Spain in the 03Z TOVS analysis (Figure 2c). Also, the amplitude of the trough and ridge axes over the Oceanic areas are definitely greater in the TOVS analyses; for example, the ridge axis over the ocean between Spain and England in the 1000-500 mb thickness at 03Z on 5 March (Figure 3c). On the other hand, at upper tropospheric levels there is a definite weakening of the horizontal gradient of TOVS derived thicknesses relative to the radiosonde data. For example, the horizontal gradient of the 300-100 mb thickness across Italy for 00Z on 5 March is about 180 meters for the ECMWF analysis, compared to about 90 meters for the SAT analysis. The magnitude of the high over the Mediterranean also differs by about 40 meters, the SAT analysis being weaker than the ECMWF analysis. The loss of horizontal resolution of the TOVS soundings relative to radiosondes with altitude is due to the loss of vertical resolution of satellite soundings with increasing altitude. The relatively low vertical resolution of the satellite soundings in the tropopause region leads to large bias and relative differences with radiosonde observations (section 4).

Figure 7 shows the twelve hour change of precipitable water above 1000, 700, and 500 mb levels as retrieved from the TOVS data. One can see good continuity with time and with the thickness patterns displayed in Figures 2-6.

Finally, Figure 8 shows the total ozone retrieved from the NOAA-7 TOVS observations for 4 and 5 March, 1982. Unfortunately, the ground truth data was not available to verify the absolute accuracy of these retrievals. Of particular interest is the very rapid movement of the high ozone center over the English channel at 13Z on 4 March to the Mediterranean at 03Z on 5 March. This movement, and in fact the entire ozone pattern, is highly correlated with the patterns and time displacements seen in the 300-100 mb thickness shown in Figure 6. This correlation is presumably due to the relation between ozone concentration and geopotential thickness in this layer to tropopause height and temperature. High stratospheric ozone concentrations should be associated with low tropopause height and low tropopause height are associated with warm tropopause temperatures or geopotential thicknesses. Thus, there is a strong positive correlation between the geopotential thickness of the tropopause layer (i.e., 300-100 mb) and the stratospheric ozone concentration. This correlation is clearly seen in the TOVS retrievals (compare Figures 8 and 6).

4. Error Statistics

Figure 9 presents bias and standard deviations between the analyses of TOVS retrieved temperatures and radiosonde temperature observations (ECMWF) as well as the bias and standard deviations of each of these analyses with respect to actual radiosonde observations. Because of occasional large digital transmission errors in the radiosonde data, observations which exceeded 2° (Figure 9c) or 5° (Figure 9d) deviation from the ECMWF analysis were discarded from the error statistics. No filtering of TOVS data was performed. The reader is reminded that the TOVS retrievals were produced using a stratospheric HIRS and MSU channel regression "first guess" and incorporated surface data. The TOVS and ECMWF analyses were performed with grid spacings of 75 km and 200 km, respectively.

As may be seen by comparing Figure 9(b) with 9(c) or 9(d), the bias and standard deviations between radiosonde observations and the TOVS and ECMWF analyses are comparable, except in the tropopause regions. This result is somewhat surprising since the TOVS analyses are completely independent of the radiosonde data whereas the ECMWF analyses are completely dominated by radiosonde observations over the European region studied. One explanation for the comparability of the magnitudes of the standard errors is (a) the lack of small horizontal scale detail in the ECMWF analyses (i.e., horizontal smoothing) and (b) the inherent vertical smoothing of the TOVS profiles relative to radisonde observations. The much larger bias error in the TOVS retrievals in the tropopause region merely demonstrates that vertical smoothing is more detrimental than horizontal smoothing in this region of sharp vertical temperature variation. The combination of the error statistics shown in figure 9 indicate that the TOVS level temperature retrieval errors are generally less than 2°C. Errors in thickness temperatures should be less than the error of level temperature values because of the vertical smoothing inherent in the TOVS retrievals.

5. Impact of Profile Guess and Surface Data

The influence of profile first guess and surface data options of the retrieval program were studied using the western orbit of 4 March, 1982. Figure 10 shows the bias and standard deviations of the TOVS level temperature values with respect to the ECMWF analyses for four different program options; (a) regression guess with surface data, (b) climate guess with surface data, (c) regression guess without surface data, and (d) climate guess without surface data. As may be seen, the main influence of the various options is upon the bias error distribution of the retrievals. The major influence of surface data is below the 700 mb level where standard deviation and bias error improvement of more than 1°C can be seen. The influence of the profile first guess (regression vs. climate) seems to greatly impact the bias error for the case where surface data is utilized. This may be due to the structure differences created by blending the "first guess" profile into the surface observations. Surprising is the fact that without surface data (Figures 10c and 10d), little difference is produced by the profile first guess. Comparisons of horizontal analyses of the level temperatures for the various first guess options (not shown) revealed little difference in the patterns but significant differences in the absolute temperature values as suggested in Figure 10. The authors believe that the most reliable retrievals are produced for the regression guess with surface data option. Certainly, surface observations are extremely valuable when dealing with complex terrain conditions.

6. Summary and Future Improvements

The physical retrieval "Export Package" has been described. Analyses of its performance on the NOAA-7 orbits chosen for the TOVS study conference indicate satisfactory performance. A major improvement yet to be implemented is the use of full resolution AVHRR data to better define surface skin temperature and to account for the influence of clouds upon the TOVS sounding channel radiances. An effort is now underway at the CIMSS to implement the AVHRR option to the TOVS sounding processing system.

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Channel Number	Channel Central Wavenumber	Central Wavelength (μm)	Principal Absorbing Constituents	Level of Peak Energy Contribution	Purpose of the Radiance Observation
1	668	15.0	CO_2	30 mb	Temperature Sounding. The 15 μm band channels provide better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3 μm band channels. Radiances in Channels 5, 6, and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
2	679	14.7	CO_2	60 mb	
3	691	14.5	CO_2	100 mb	
4	704	14.2	CO_2	250 mb	
5	716	14.0	CO_2	500 mb	
6	732	13.7	CO_2/H_2O	750 mb	
7	748	13.4	CO_2/H_2O	900 mb	
8	898	11.1	Window	Surface	Surface Temperature and cloud detection.
9	1028	9.7	O_3	25 mb	Total Ozone concentration.
10	1217	8.3	H_2O	900 mb	Water Vapor Sounding. Provide water vapor corrections for CO_2 and window channels. The 6.7 μm channel is also used to detect thin cirrus cloud.
11	1364	7.3	H_2O	600 mb	
12	1484	6.7	H_2O	400 mb	
13	2190	4.57	N_2O	950 mb	Temperature Sounding. The 4.3 μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15 μm band channels. Also, the short-wavelength radiances are less sensitive to clouds than those for the 15 μm region.
14	2213	4.52	N_2O	850 mb	
15	2240	4.46	CO_2/N_2O	700 mb	
16	2276	4.40	CO_2/N_2O	600 mb	
17	2361	4.24	CO_2	5 mb	
18	2512	4.0	Window	Surface	Surface Temperature. Much less sensitive to clouds and H_2O than 11 μm window. Used with 11 μm channel to detect cloud contamination and derive surface temperature under partly cloudy sky conditions. Simultaneous 3.7 μm and 4.0 μm data enable reflected solar contribution to be eliminated from observations.
19	2671	3.7	Window	Surface	
20	14,367	0.70	Window	Cloud	Cloud Detection. Used during the day with 4.0 um and 11 μm window channels to define clear fields of view.

MSU	Frequency (GHz)	Principal Absorbing Constituents	Level of Peak Energy Contribution	Purpose of the Radiance Observation
1	50.31	Window	Surface	Surface Emissivity and Cloud Attenuation determination.
2	53.73	O_2	850 mb	Temperature Sounding. The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3 μm and 15 μm sounding channels.
3	54.96	O_2	500 mb	
4	57.95	O_2	100 mb	

TABLE 1. Characteristics of TOV Sounding Channels

Table 2. Transmittance - adjustment exponents ("gammas") for use in SUBROUTINE TAUGAM

HIRS		MSU	
Channel	Gamma	Channel	Gamma
1	1.069	1	1.000
2	0.942	2	1.019
3	1.108	3	0.999
4	1.031	4	0.899
5	0.972		
6	0.965		
7	0.909		
8	1.000		
9	1.000		
10	1.120		
11	1.032		
12	1.035		
13	1.115		
14	1.028		
15	1.057		
16	1.002		
17	1.480		
18	1.000		
19	1.000		

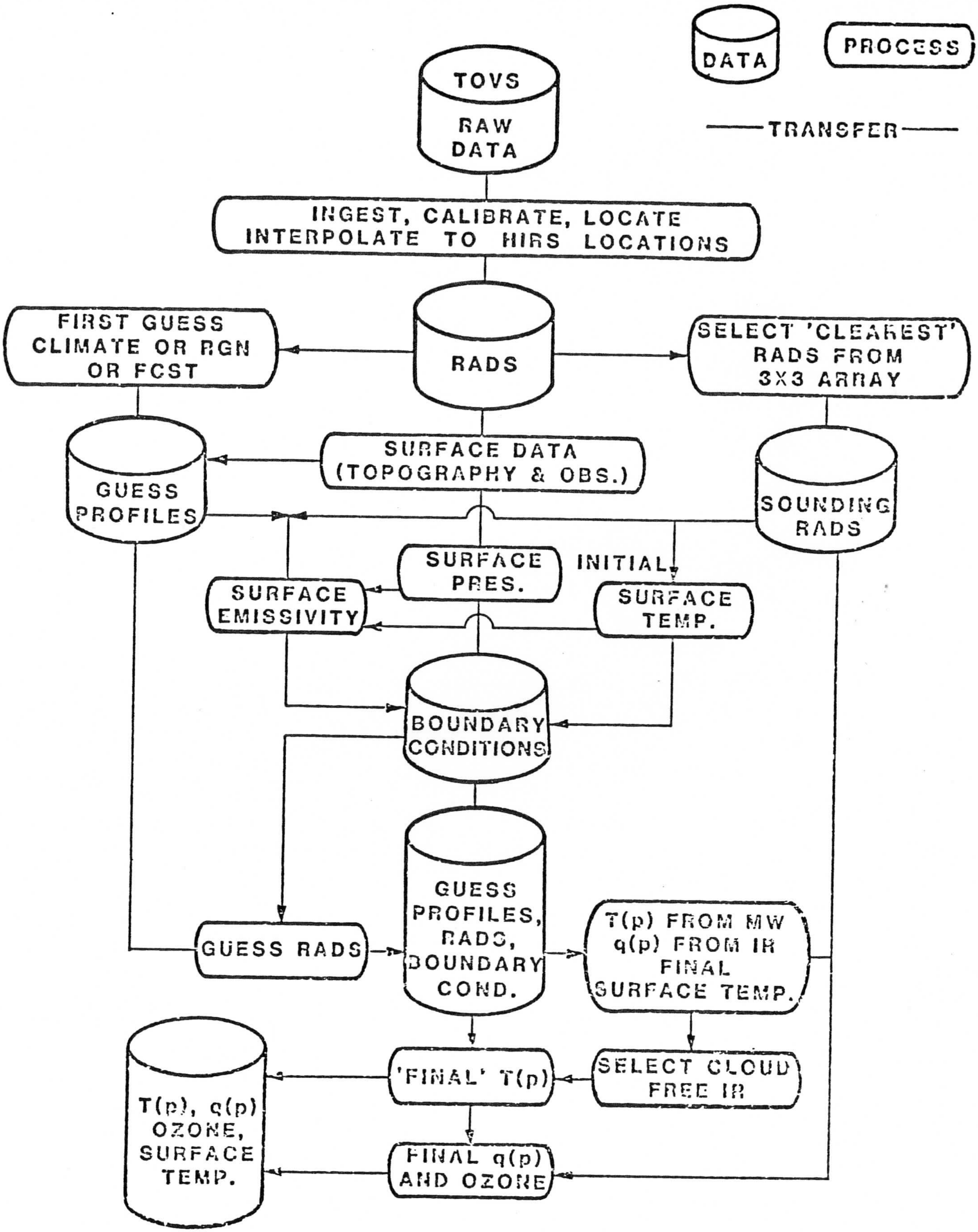


Figure 1. Schematic of the TOVS Physical Retrieval Processing System.

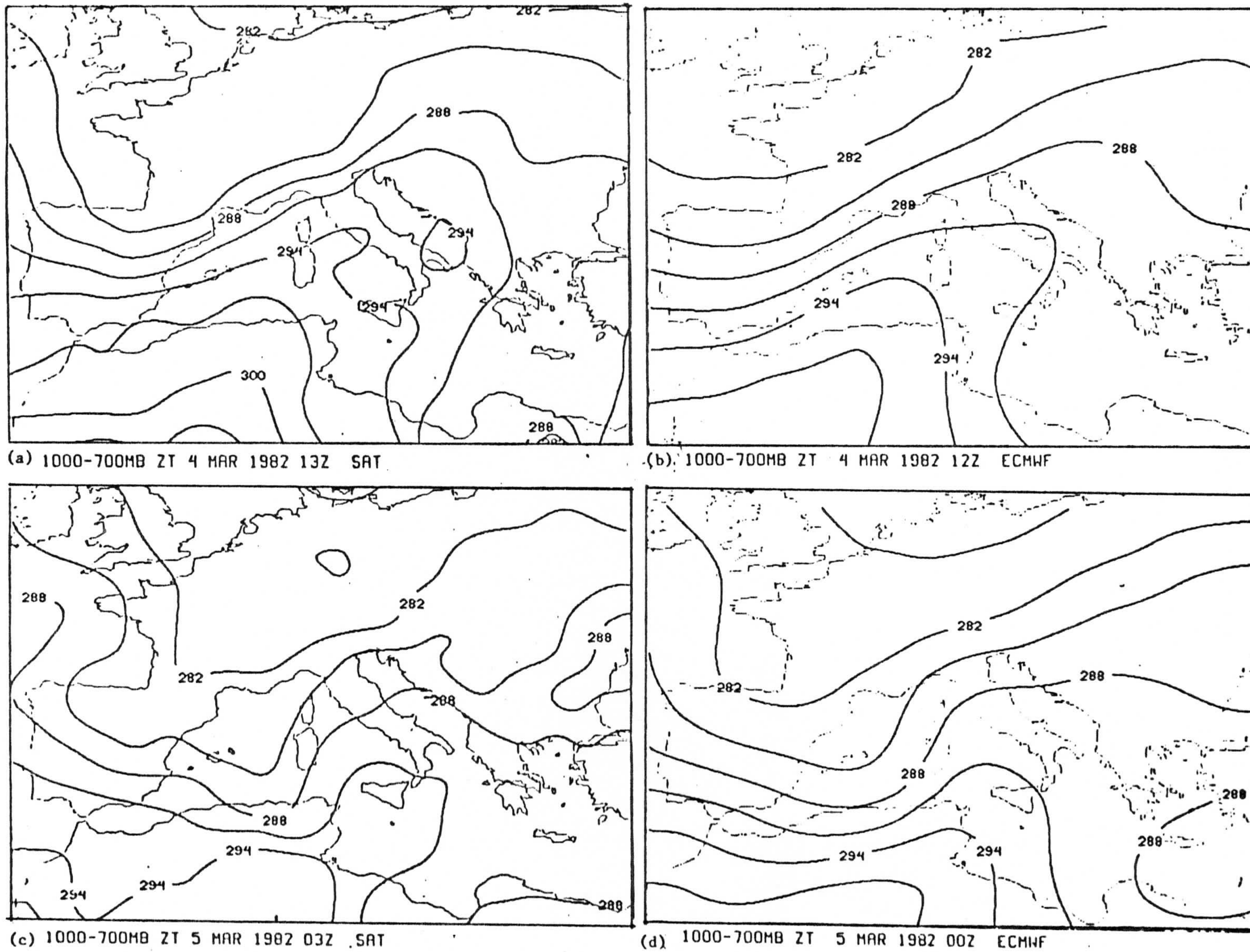


Figure 2. Analyses of TOVS (SAT) and Radiosonde (ECMWF) 1000-700mb geopotential thickness (decameters).

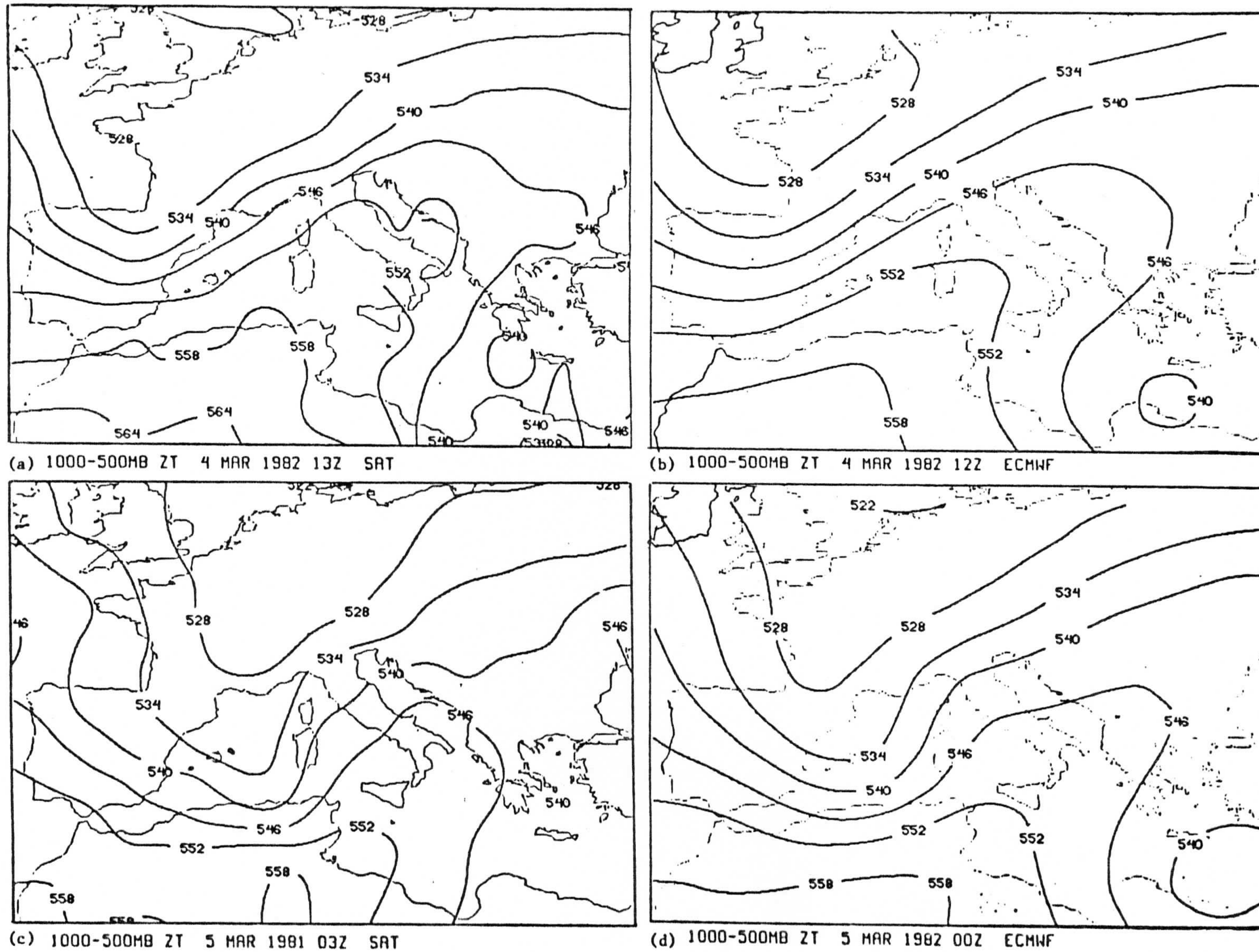


Figure 3. Analyses of TOVS (SAT) and Radiosonde (ECMWF) 1000-500 mb geopotential thickness (decameters).

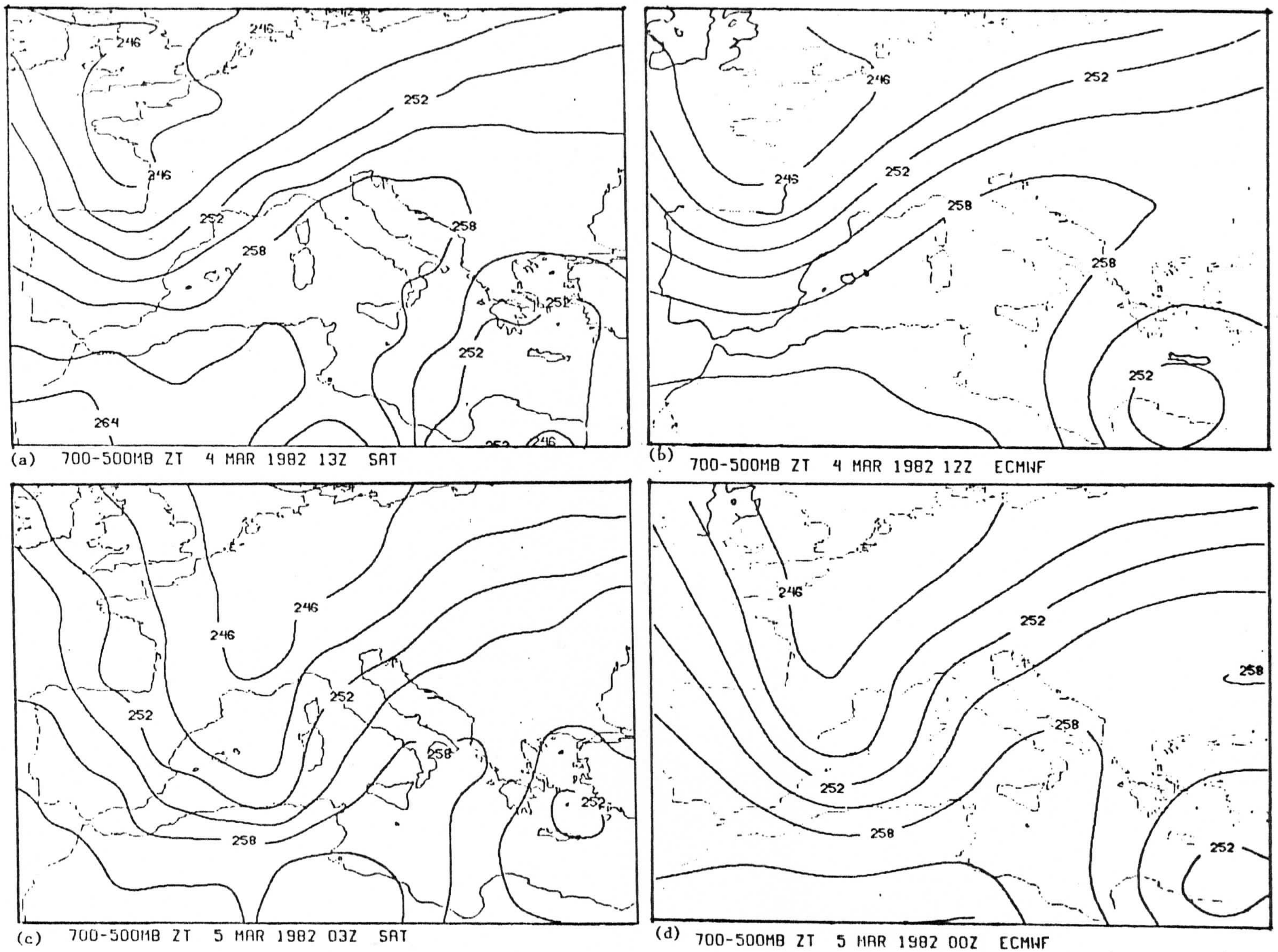


Figure 4. Analyses of TOVS (SAT) and Radiosonde (ECMWF) 700-500 geopotential thickness (decameters).

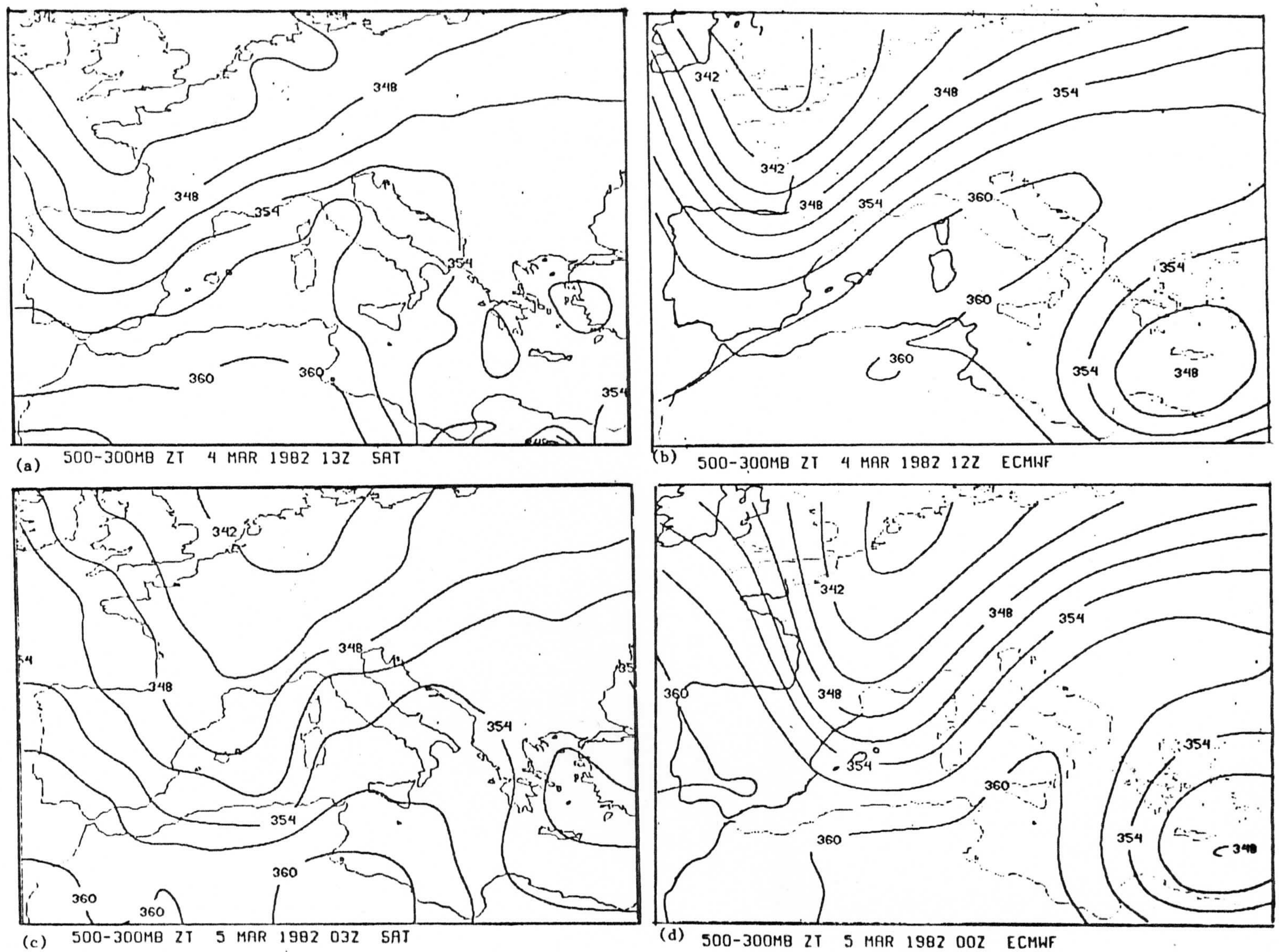


Figure 5. Analyses of TOVS (SAT) and Radiosonde (ECMWF) 500-300 geopotential thickness (decameters).

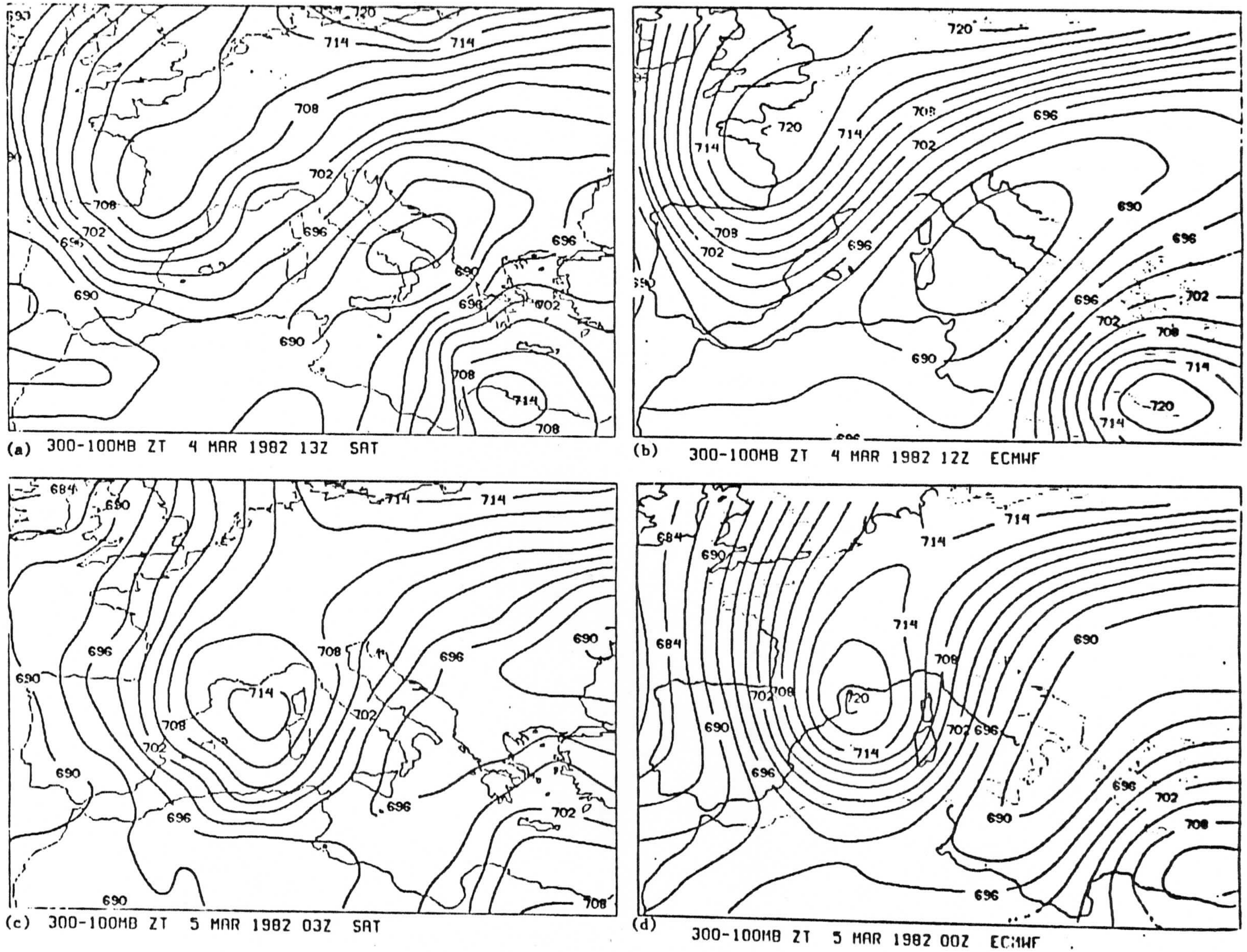


Figure 6. Analyses of TOVS (SAT) and Radiosonde (ECMWF) 300-100 mb geopotential thickness (decameters).

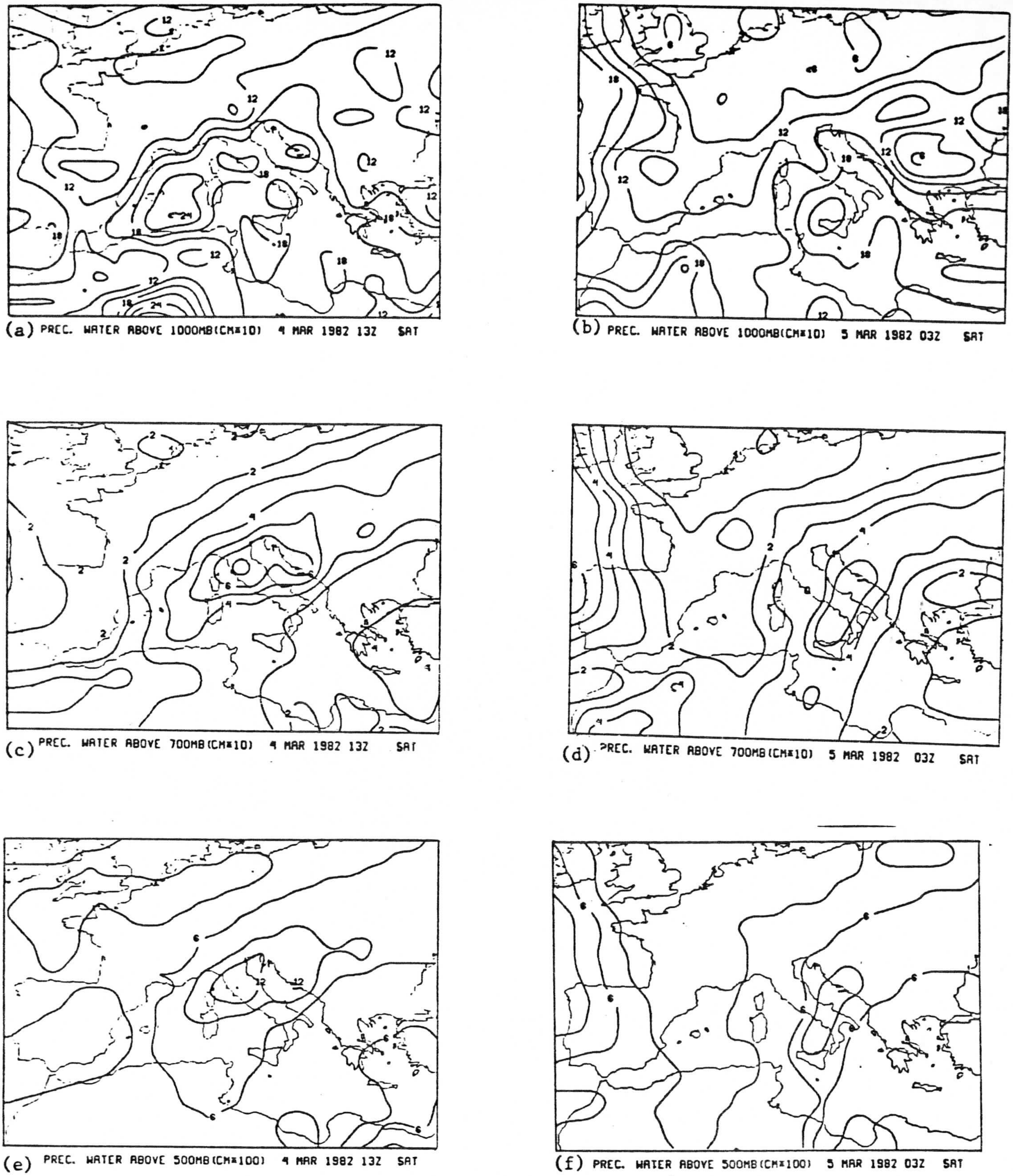
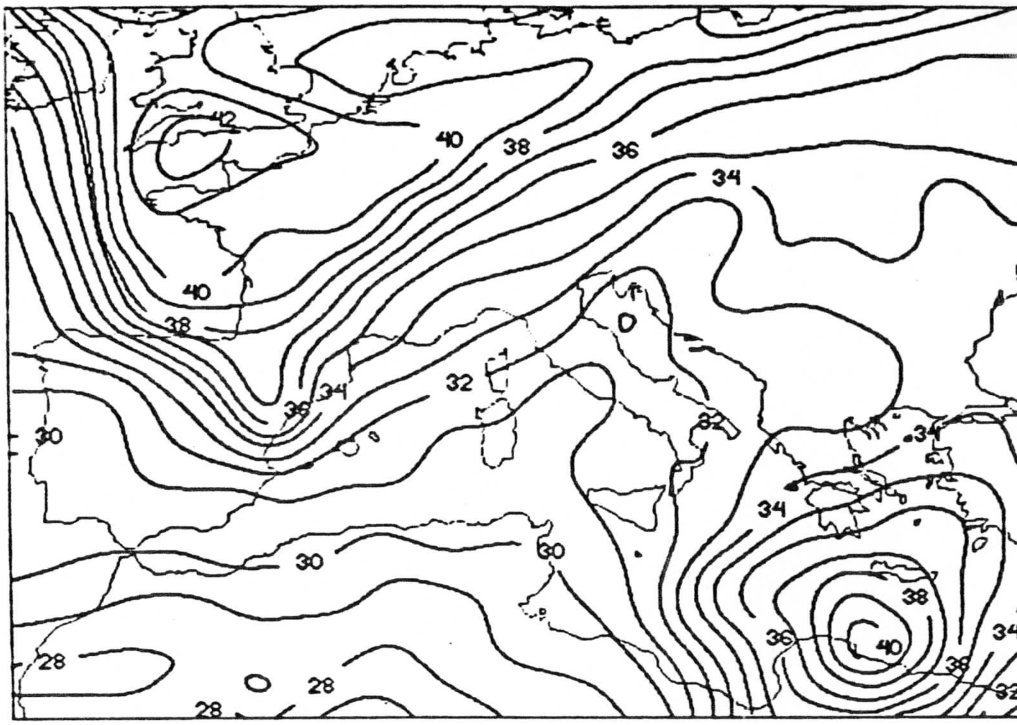
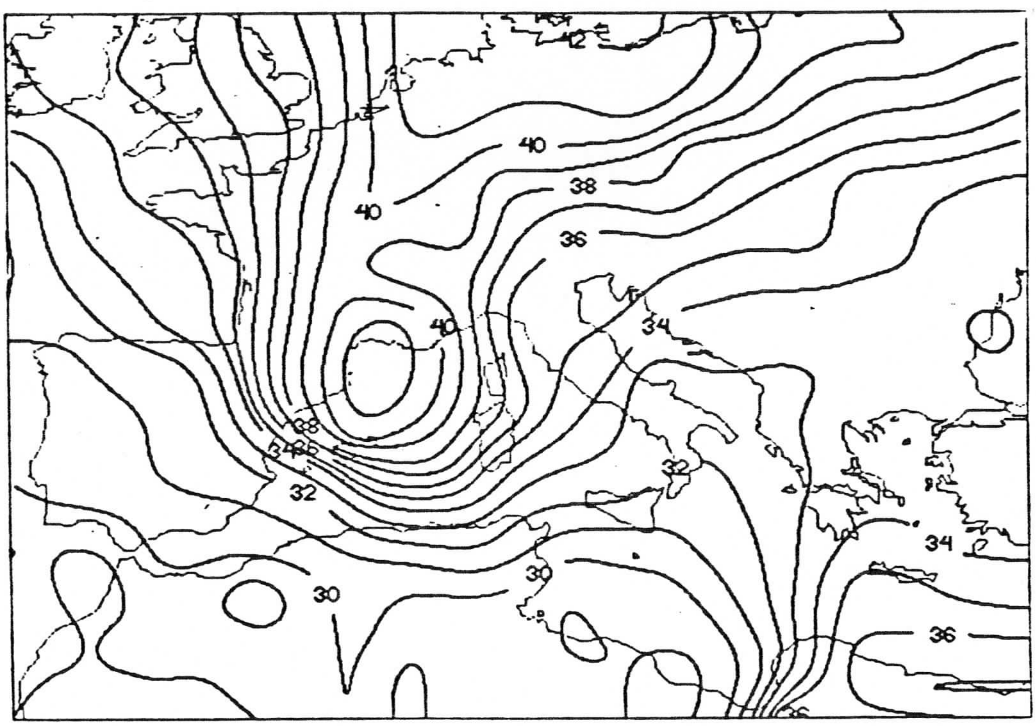


Figure 7. Analyses of TOVS (SAT) Total Precipitable Water for the Atmospheric Column above (a) and (b) 1000 mb, (c) and (d) 700 mb, and (e) and (f) 500 mb.



(a) TOTAL OZONE(DU*10) 4 MAR 1982 13Z SAT



(b) TOTAL OZONE(DU*10) 5 MAR 1982 03Z SAT

Figure 8. Analyses of TOVS (SAT) Total Ozone Concentration (deca-Dobson units) for (a) 4 March and (b) 5 March, 1982.

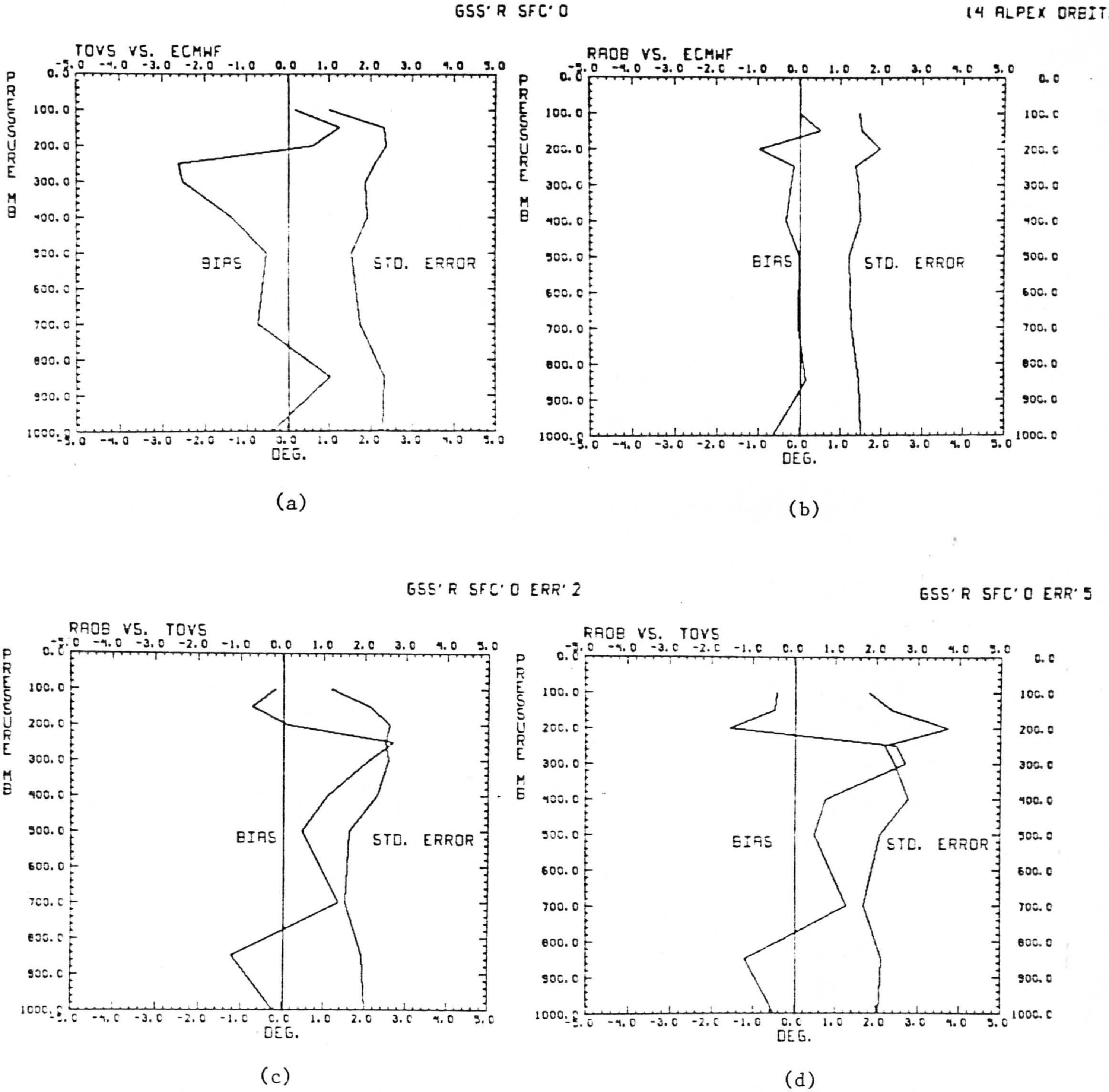


Figure 9. Bias and Standard Deviation (Errors) between TOVS, ECMWF analyses and radiosonde observations of level temperatures. Radiosonde used in figures (c) and (d) were within 2°C and 5°C of the temperature of the ECMWF analyses.

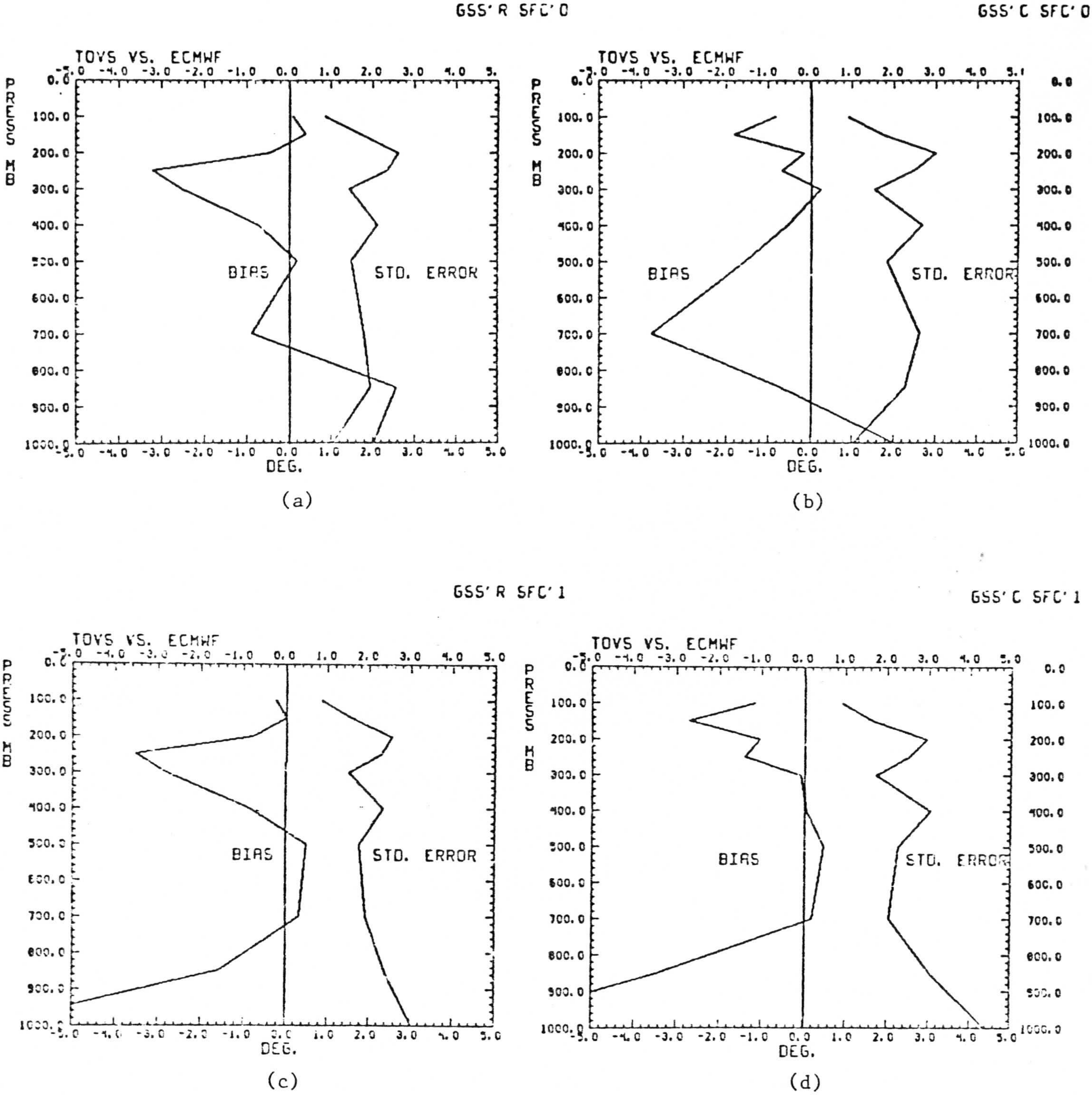
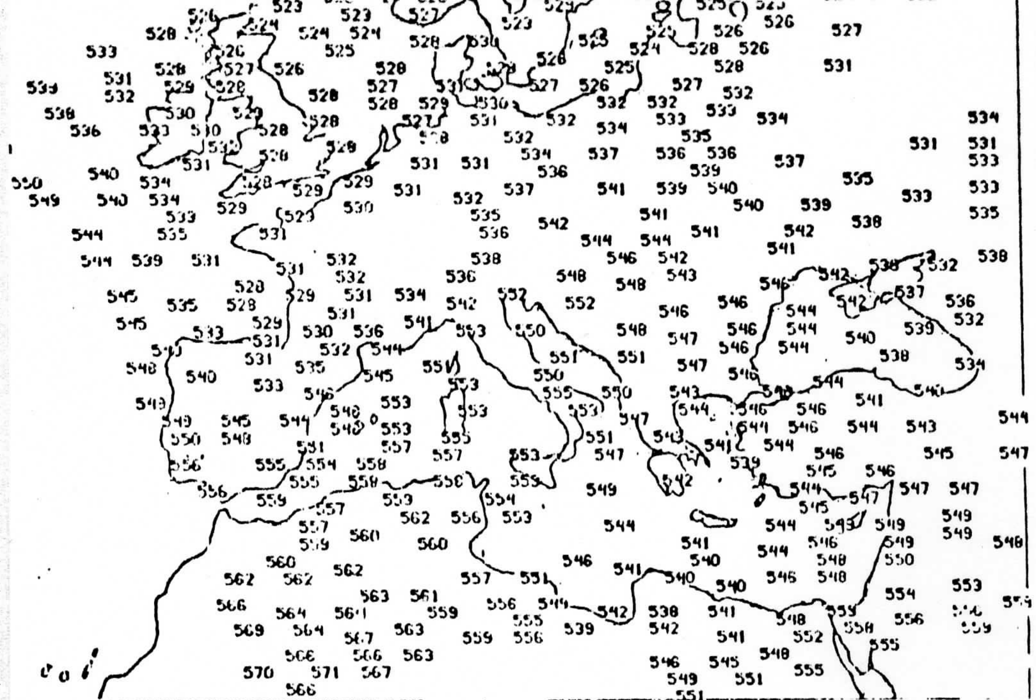


Figure 10. Bias and Standard Deviations between ECMWF analyses of radiosonde data and TOVS level temperature values produced for four different program options. (a) regression guess with surface data, (b) climate guess with surface data, (c) regression guess without surface data, (d) climate guess without surface data.

Appendix to Smith et al

The following pages contain plots of TOVS and radiosonde geopotential thickness (decameters) and precipitable water (cm x 100) for the TOVS Study Conference NOAA-7 orbits. For the southern hemisphere, TOVS data and analyses are also given. Documentation for the TOVS Export Package software and data are included at the end of this Appendix.



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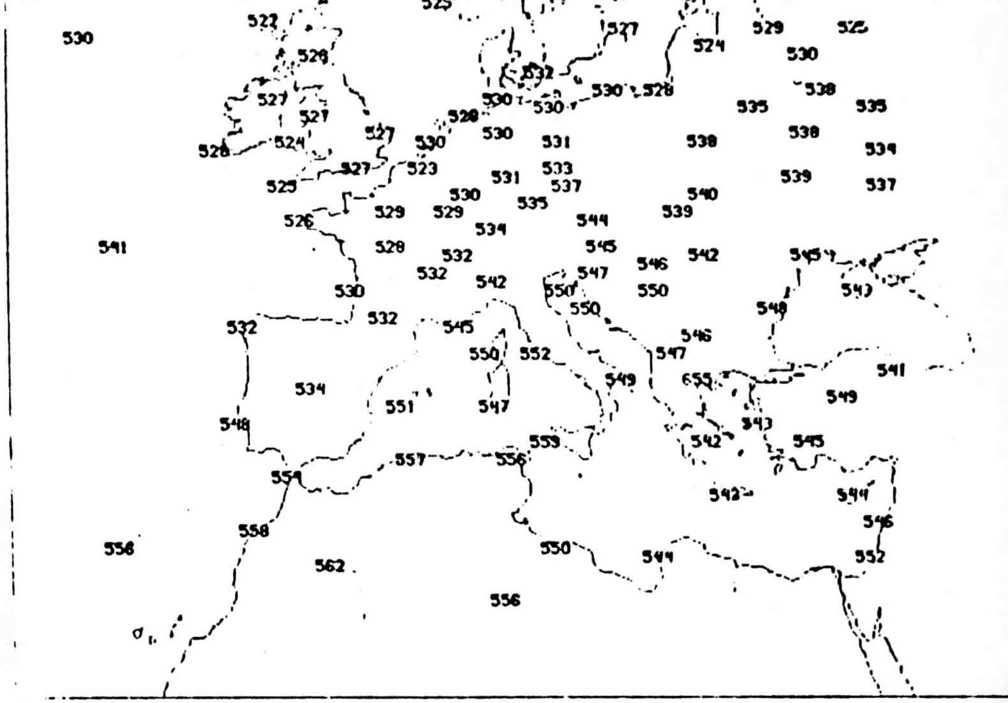

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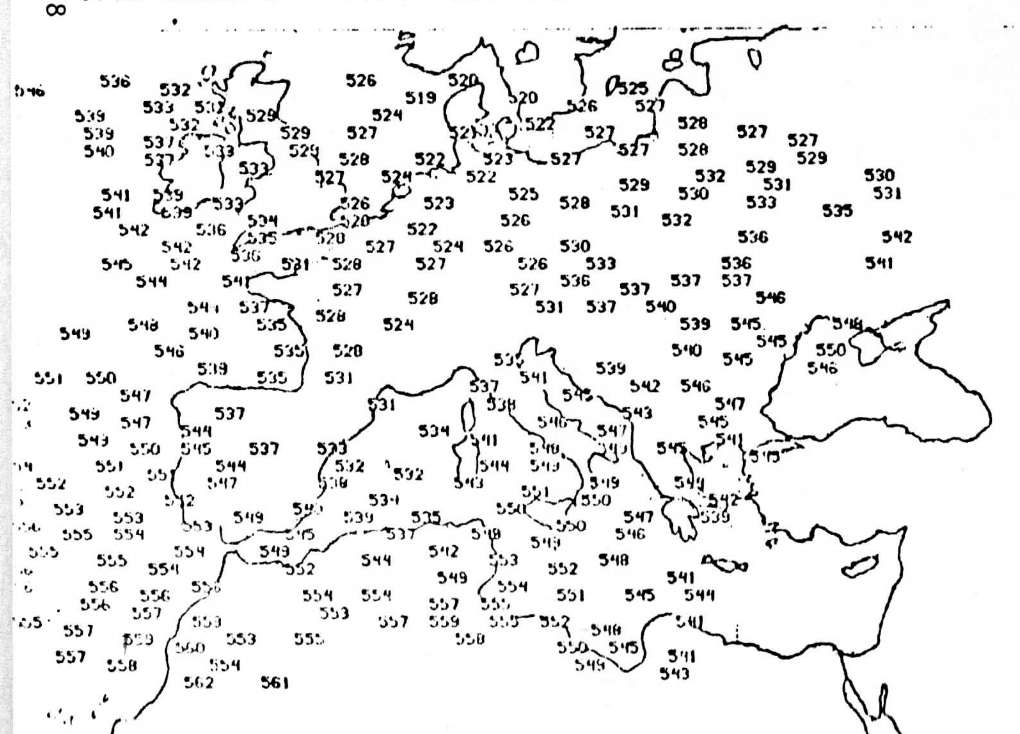

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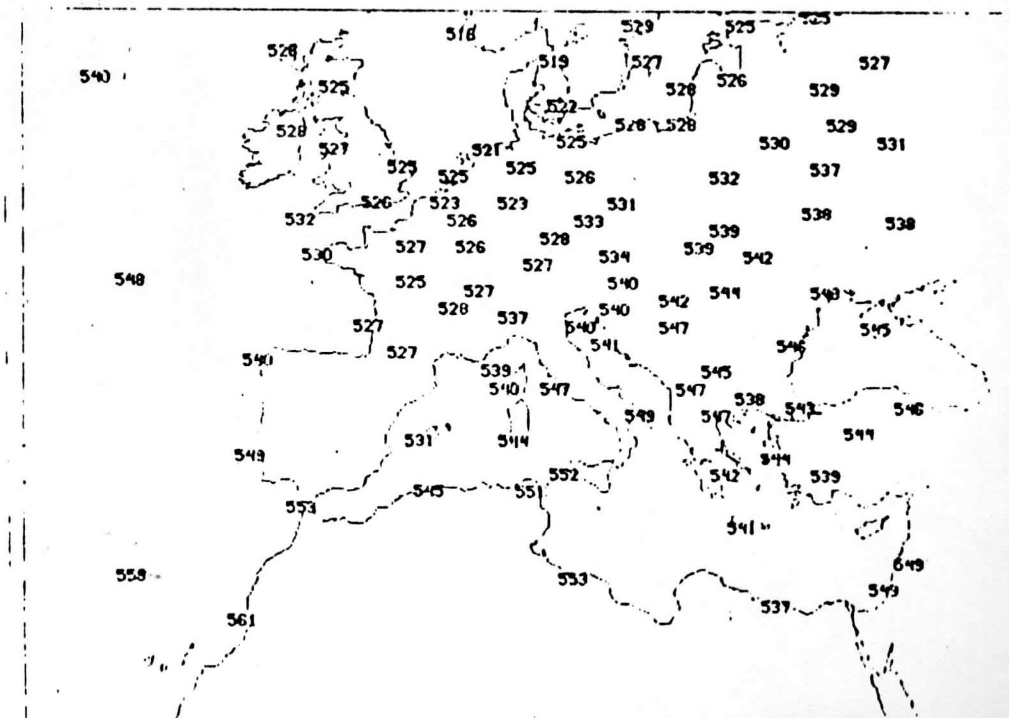

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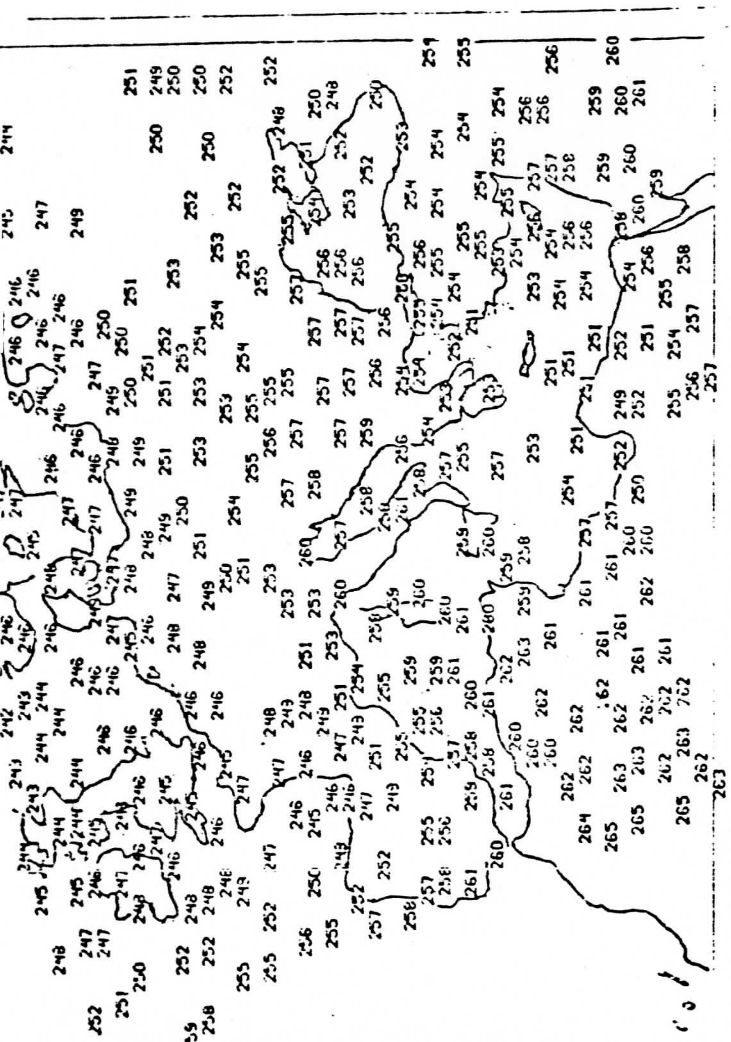

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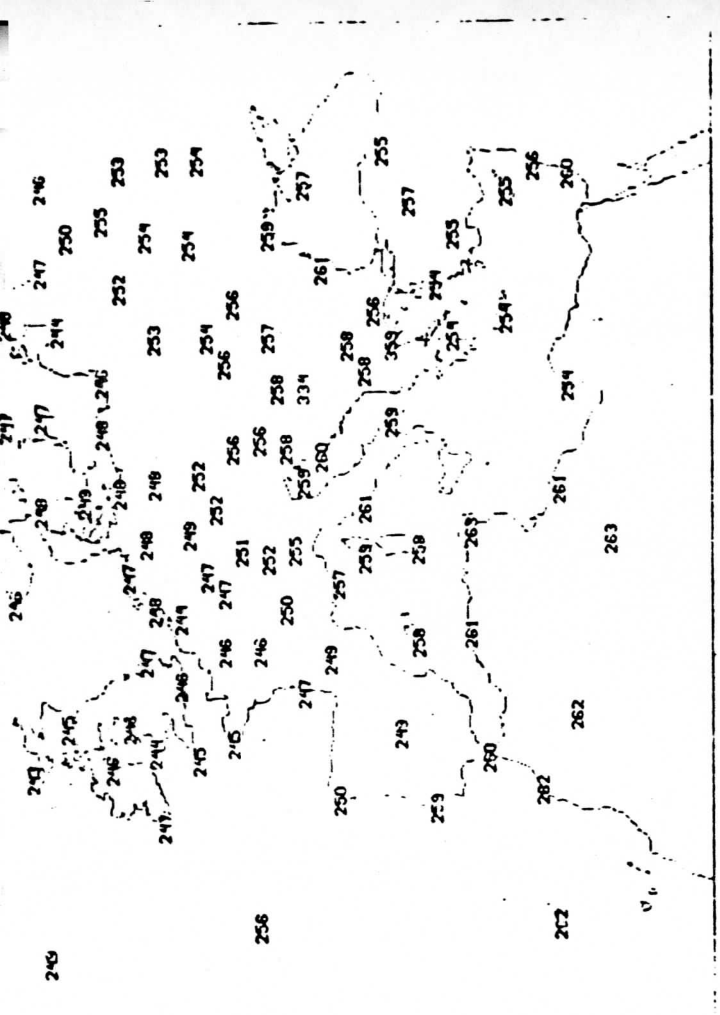

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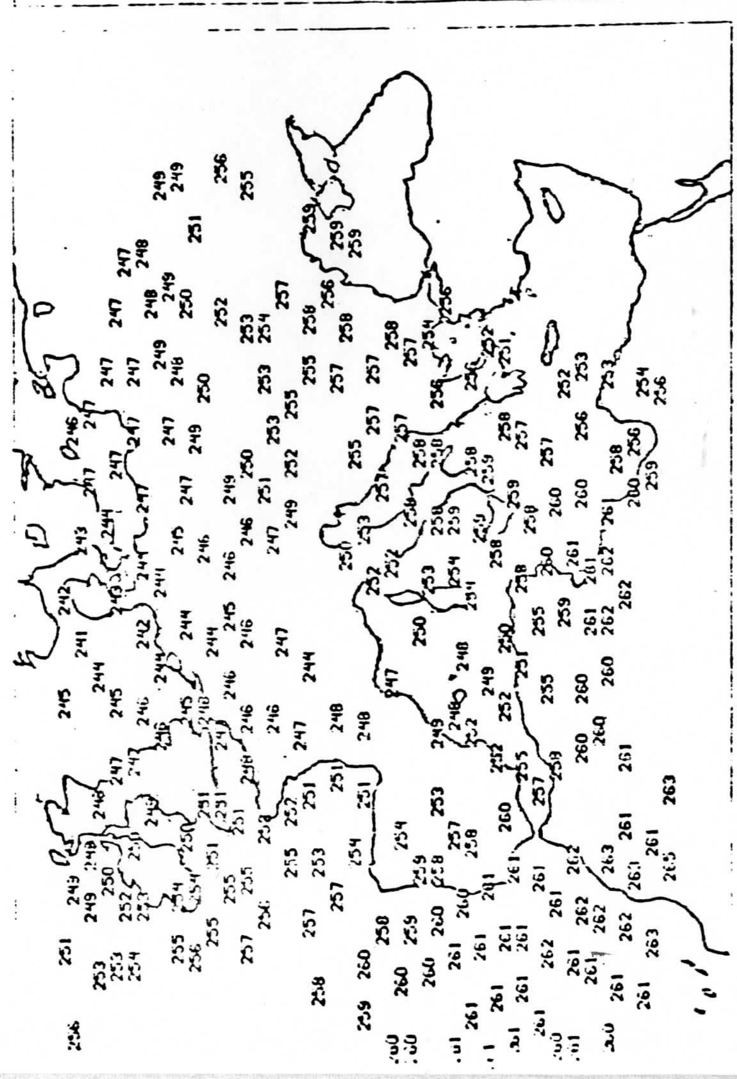

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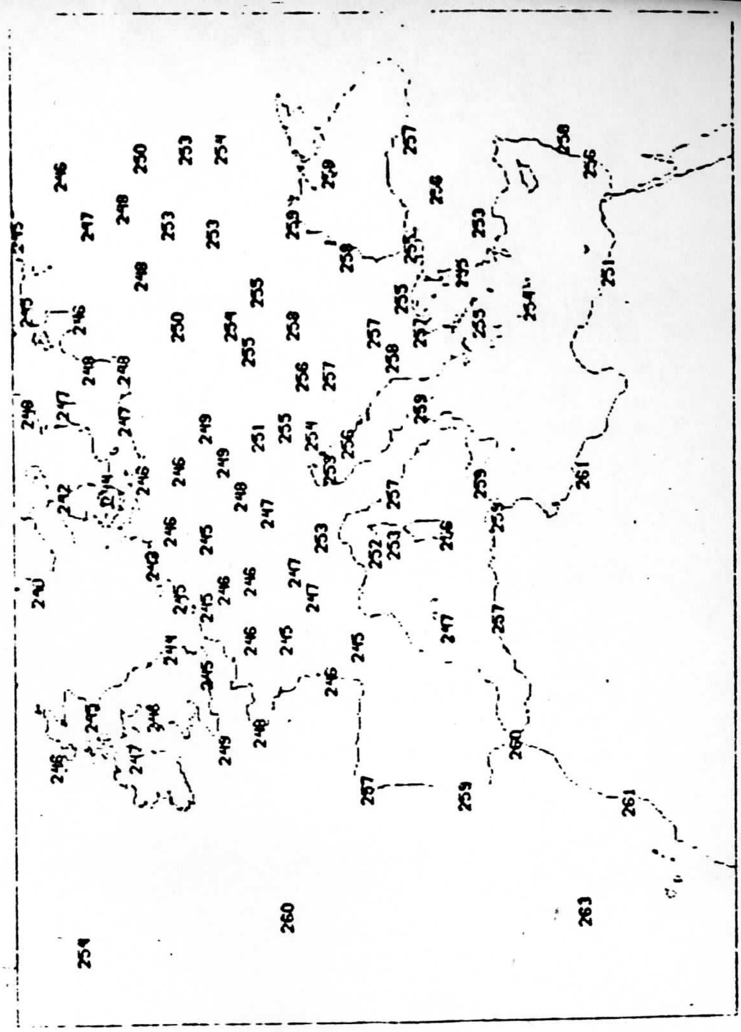

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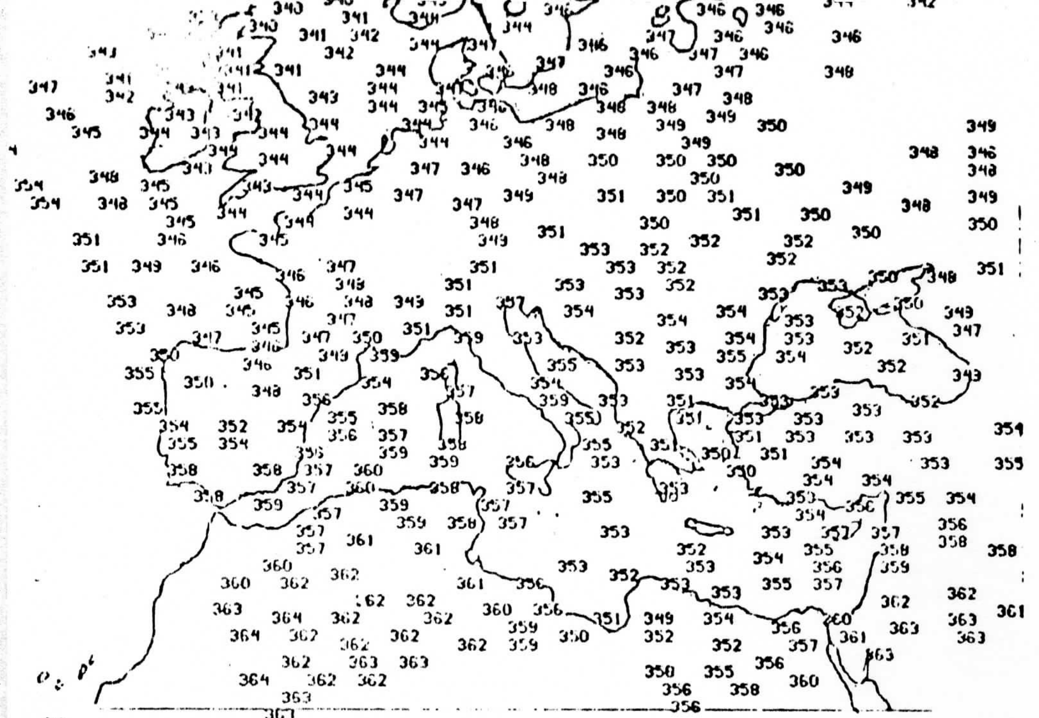

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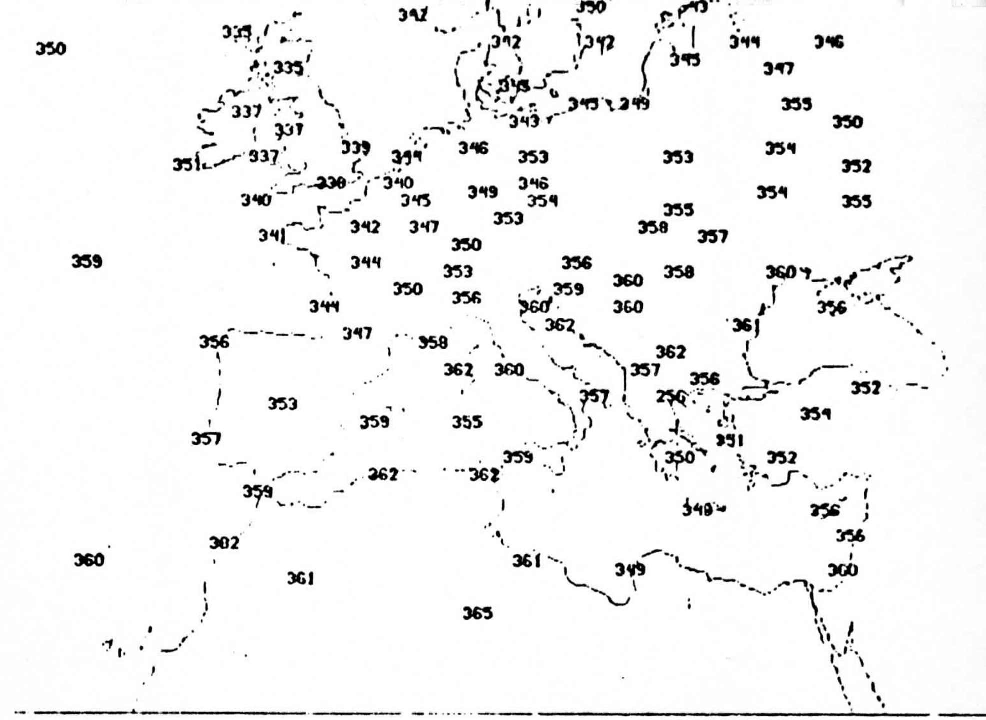

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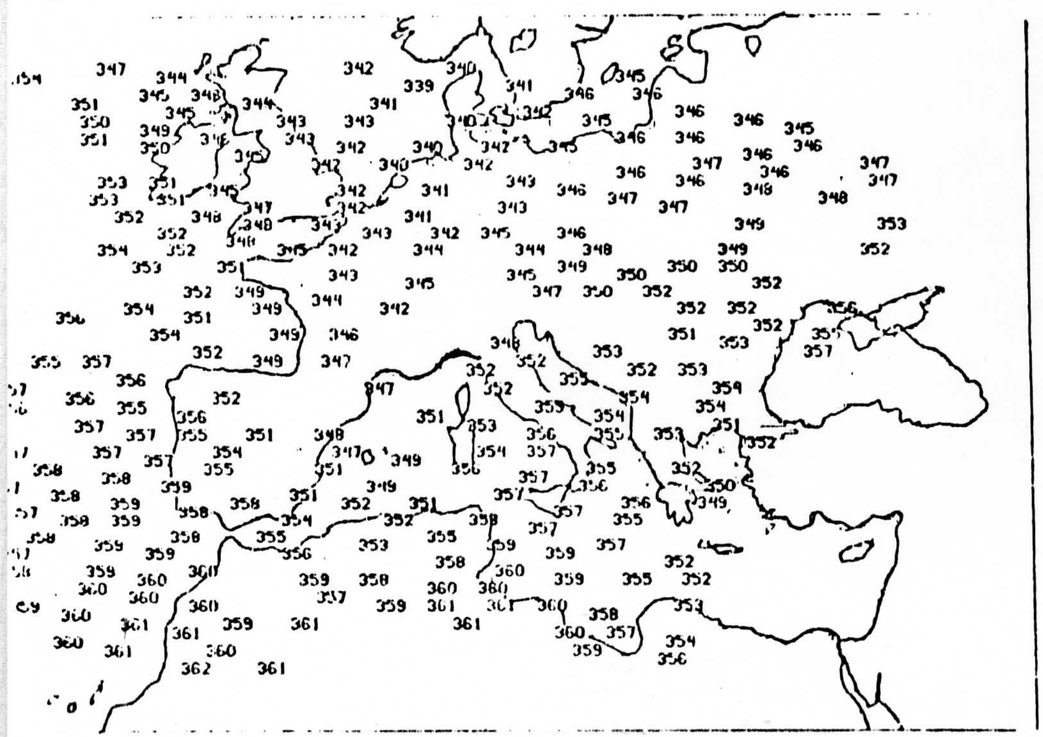

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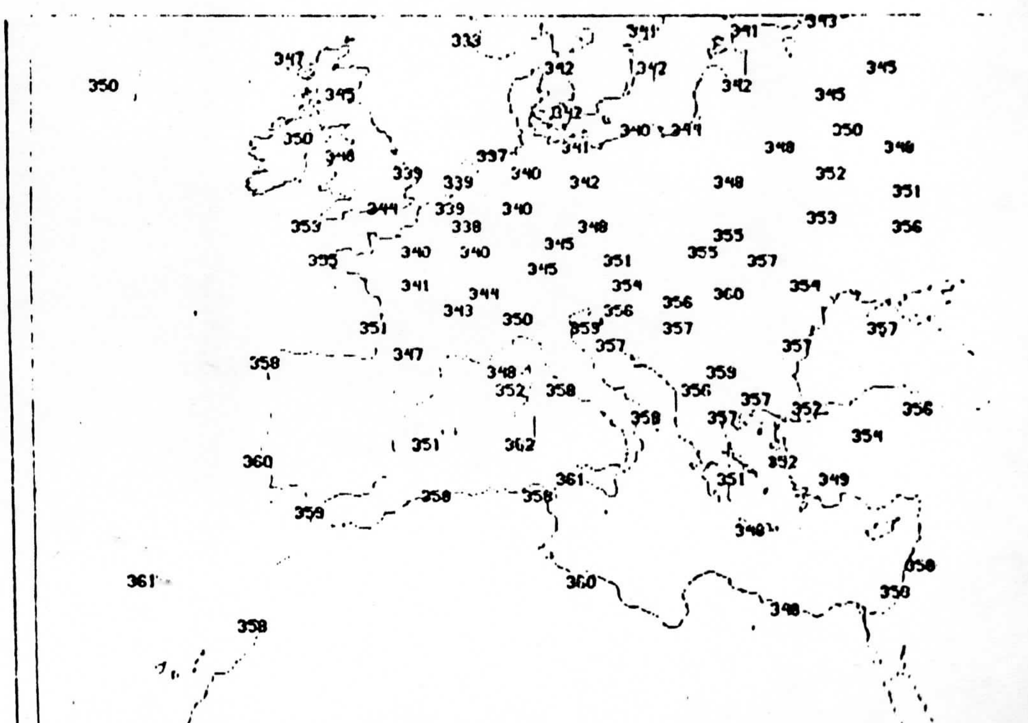

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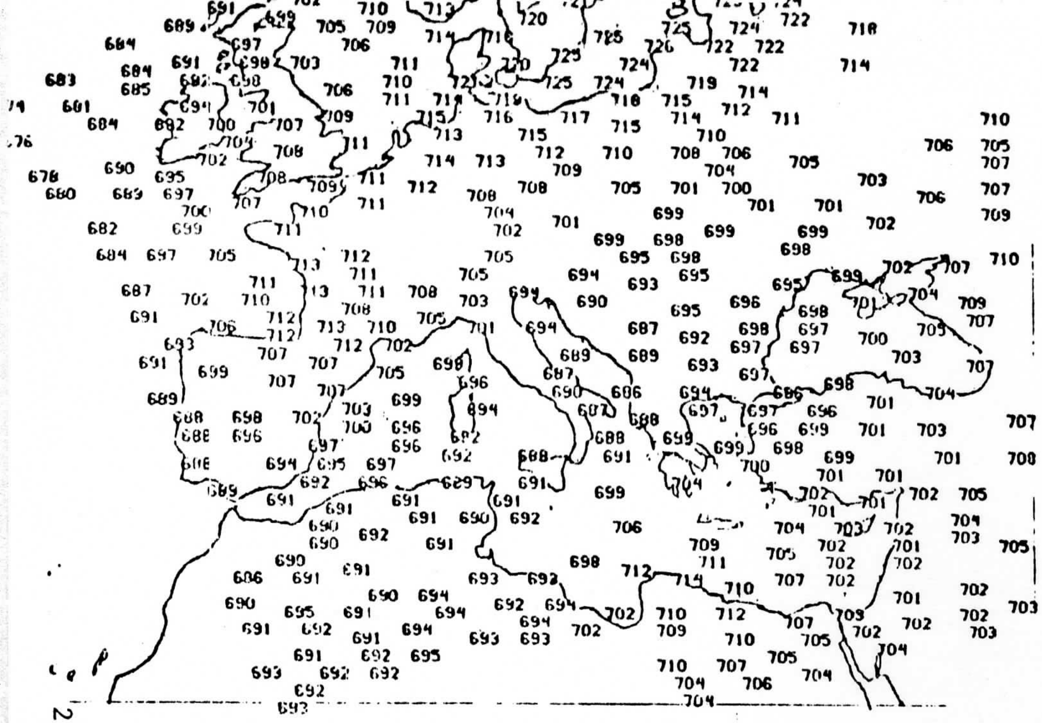

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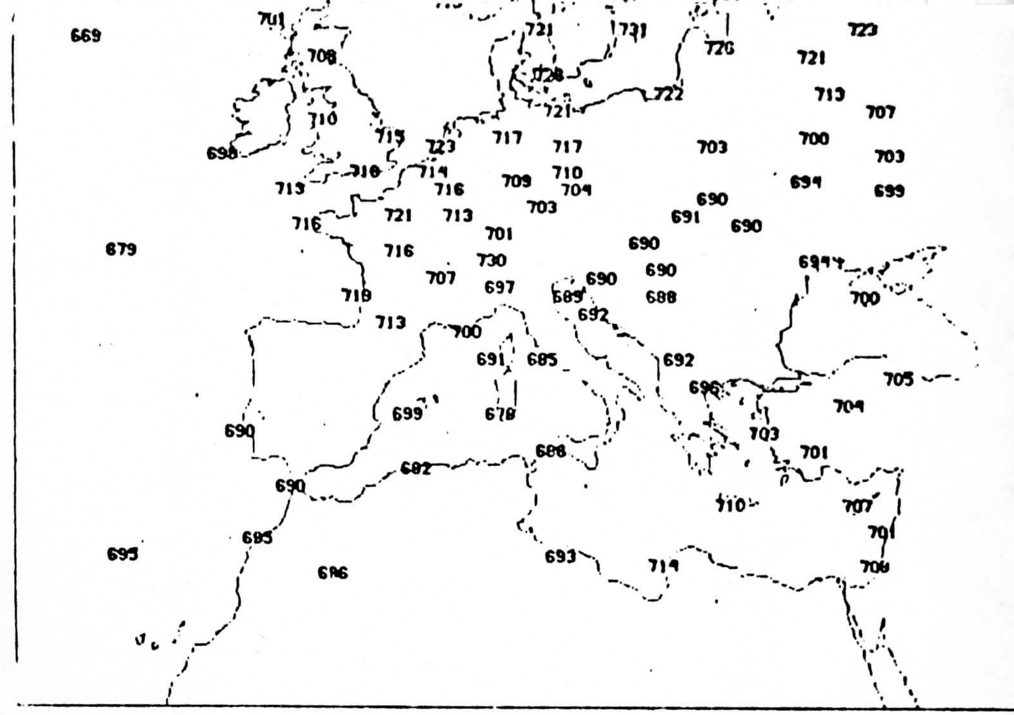

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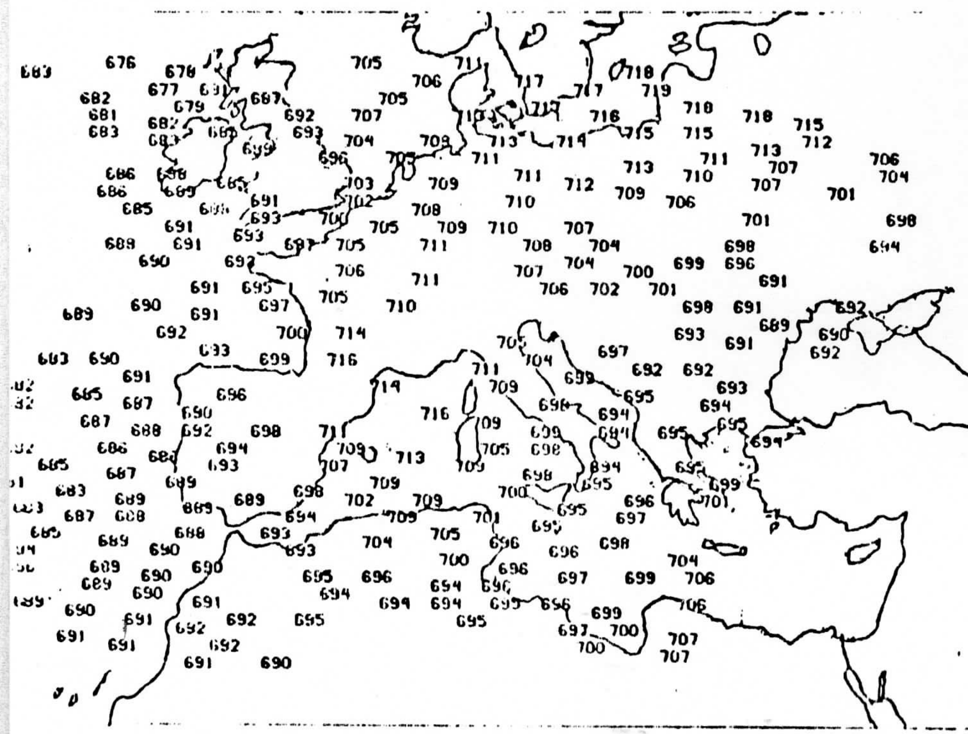

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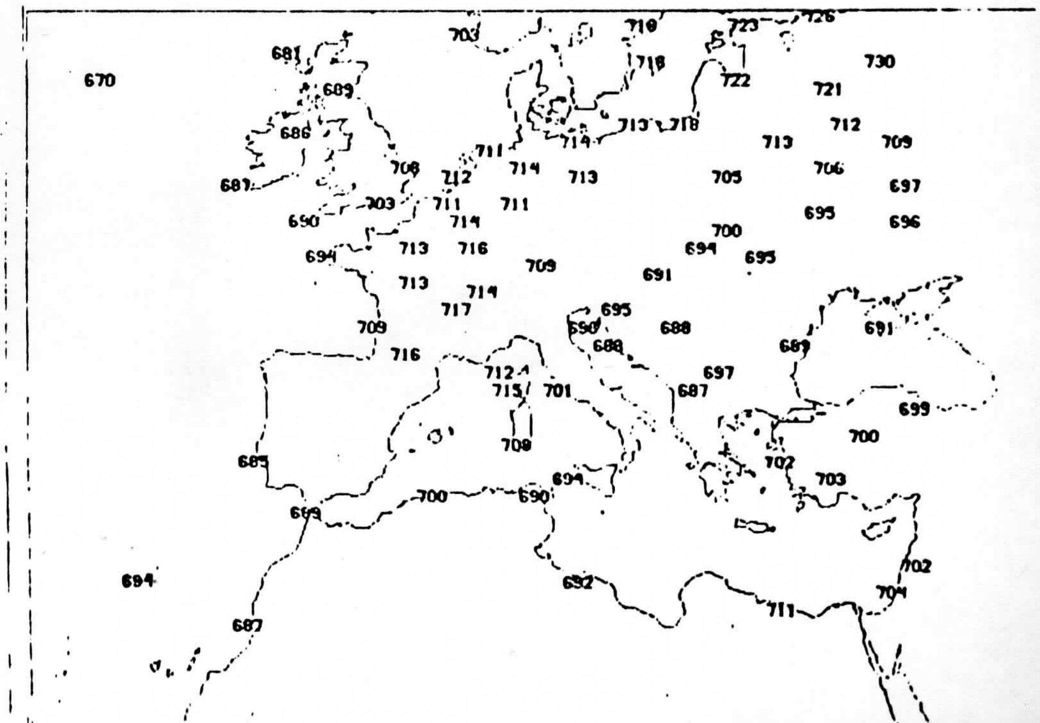

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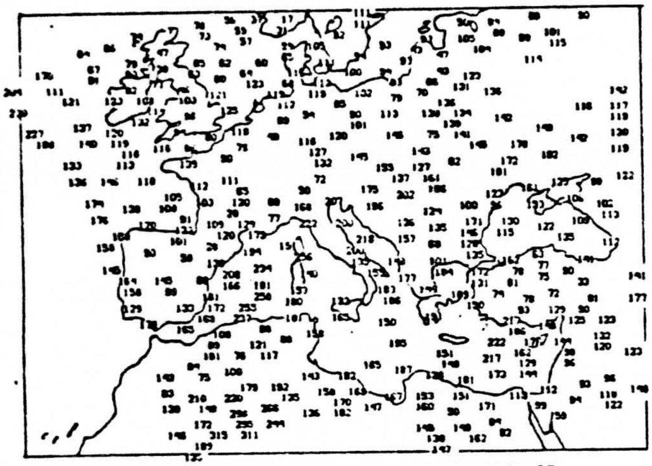

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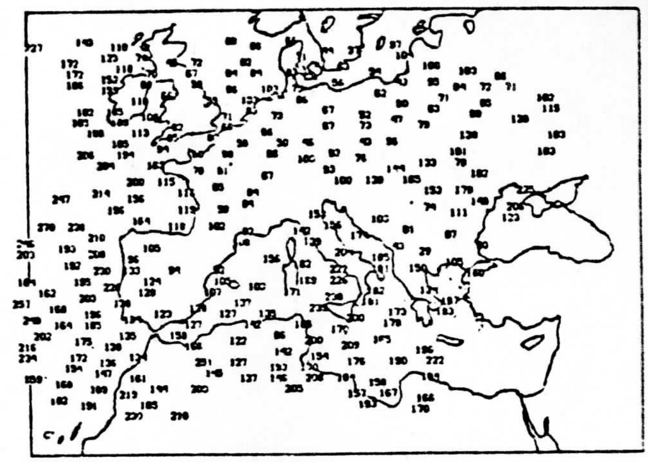

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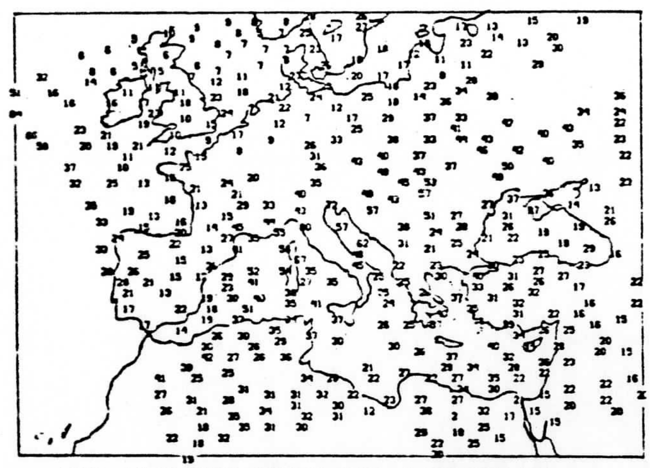

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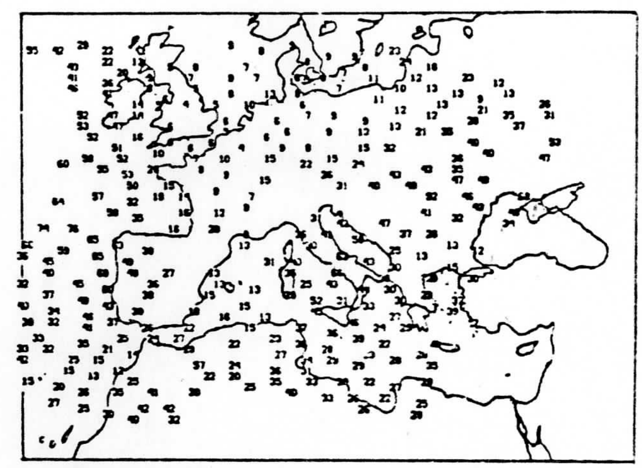

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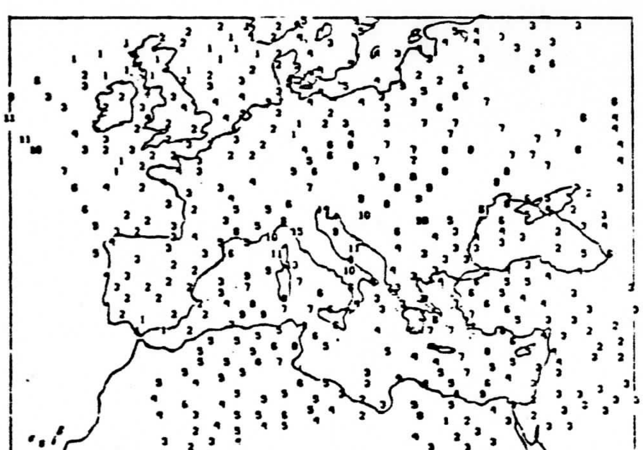

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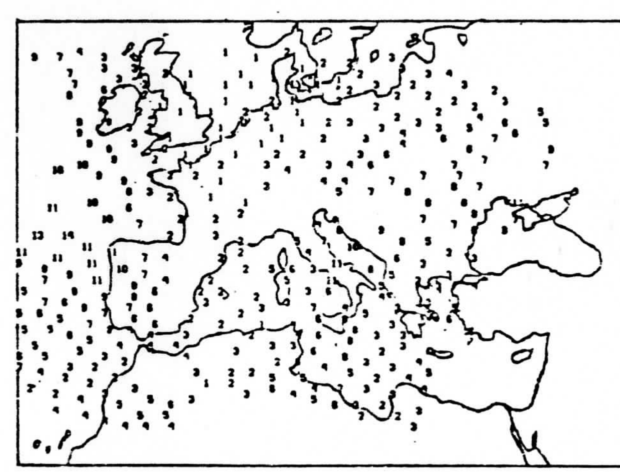

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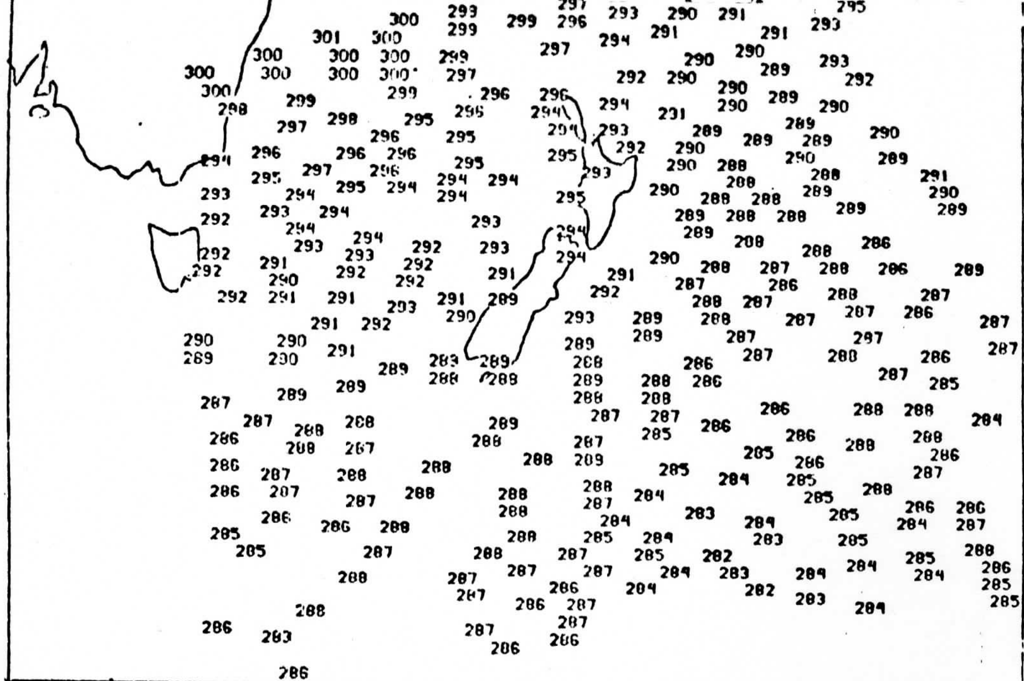

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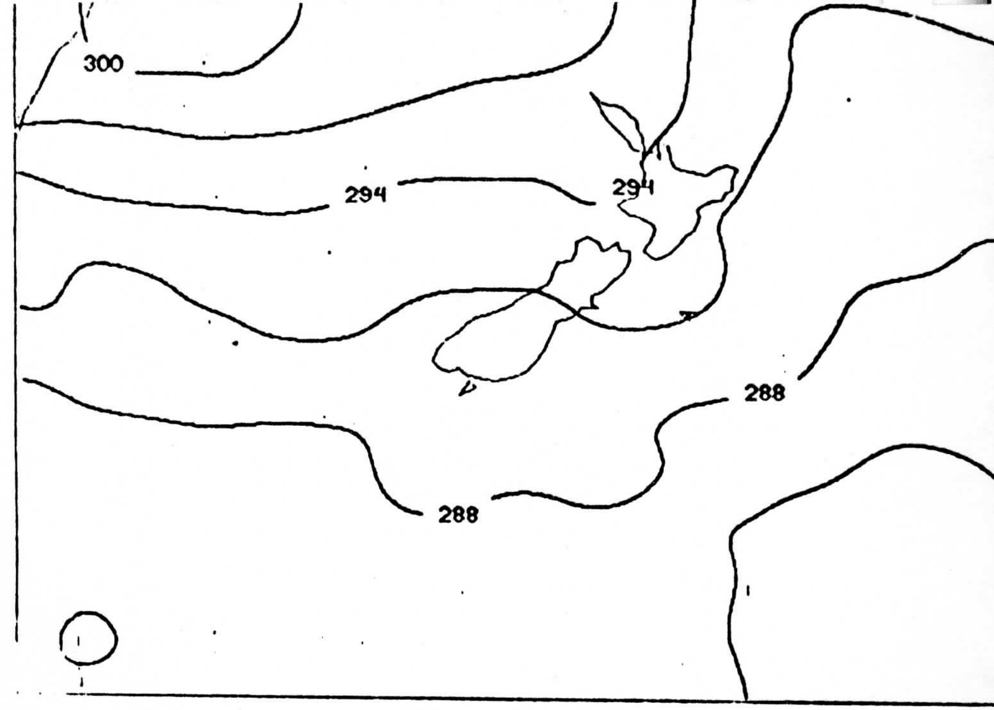

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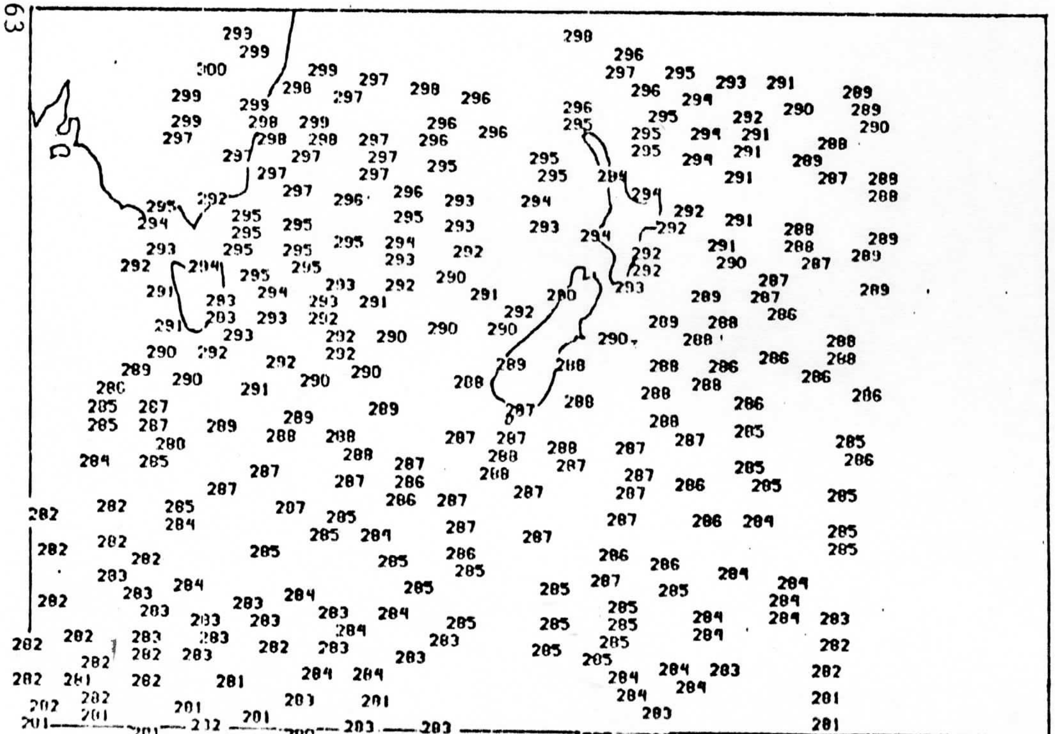

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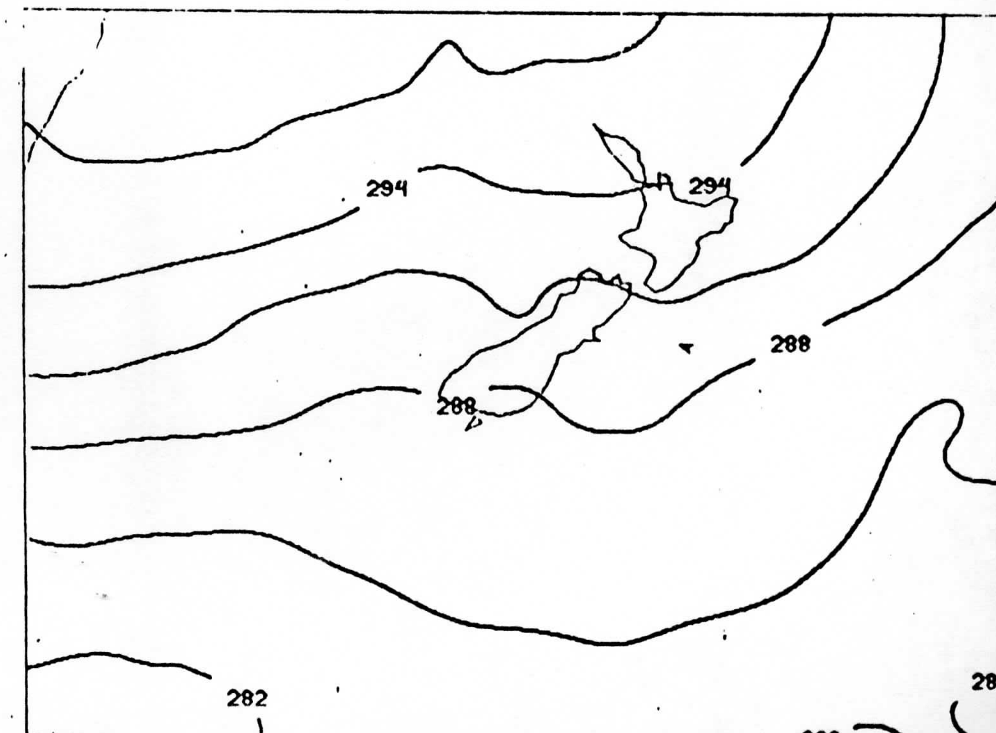

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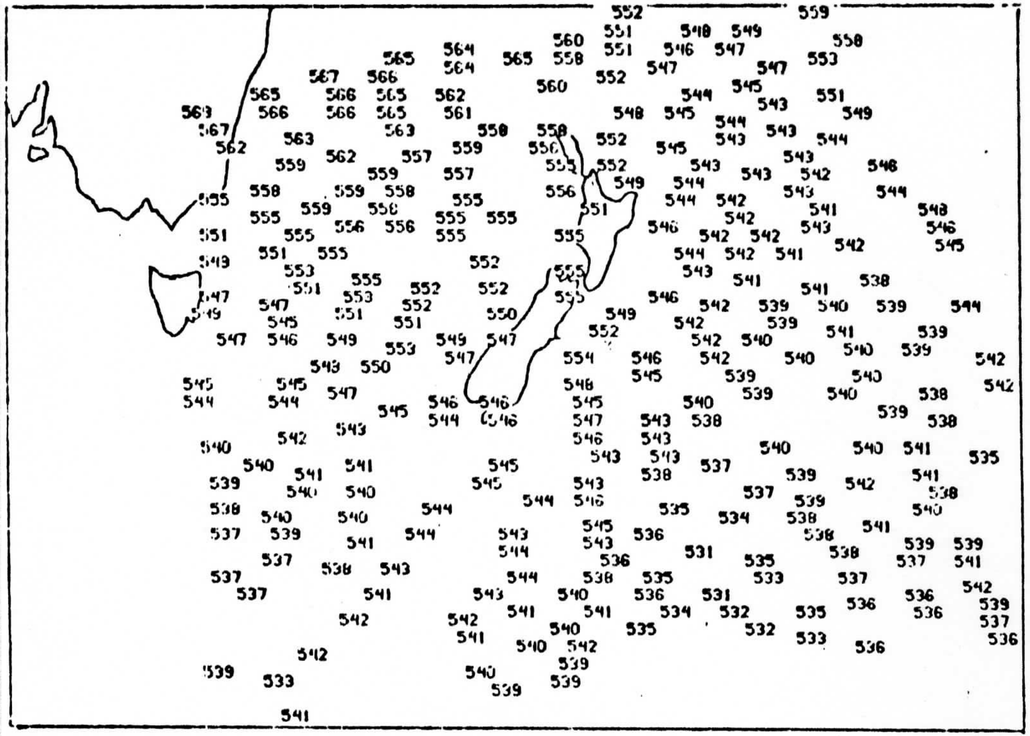

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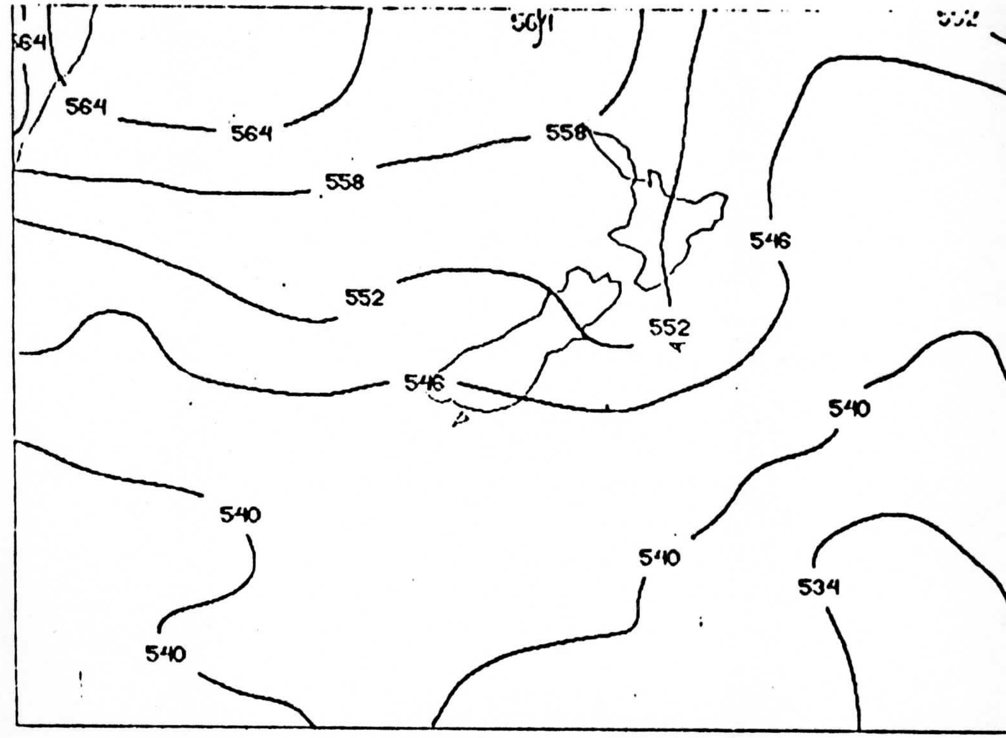

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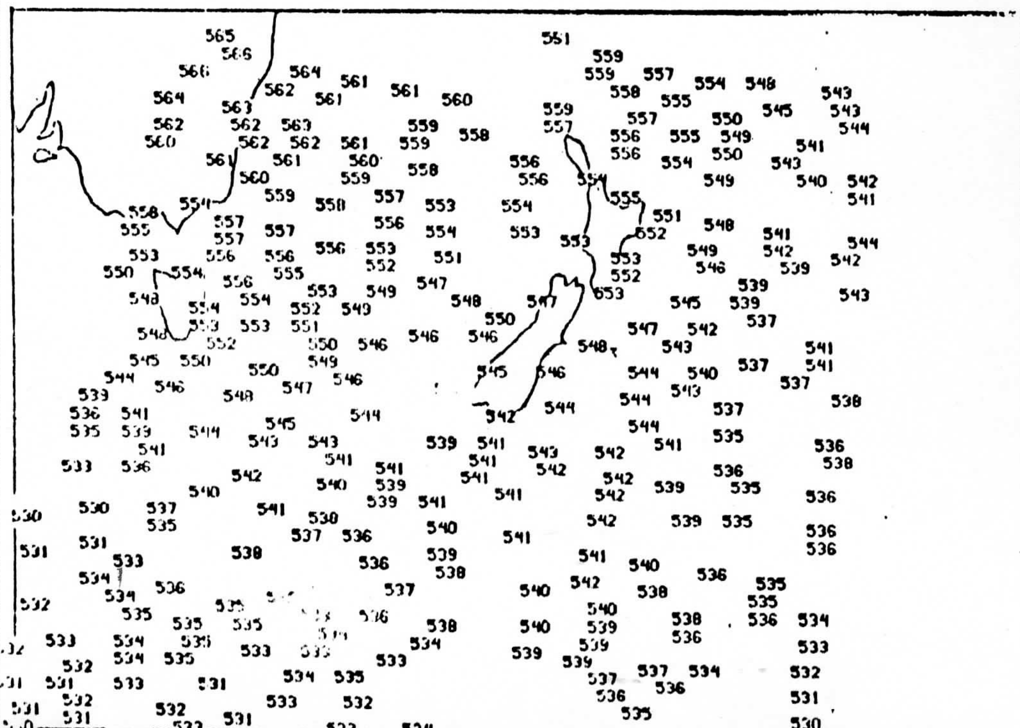

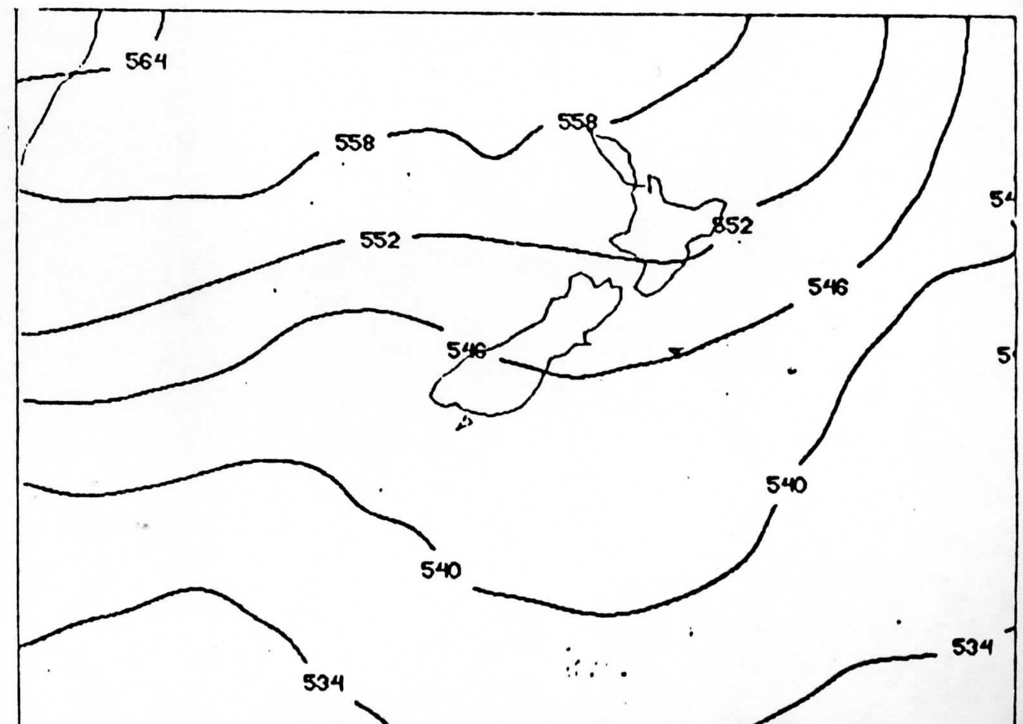

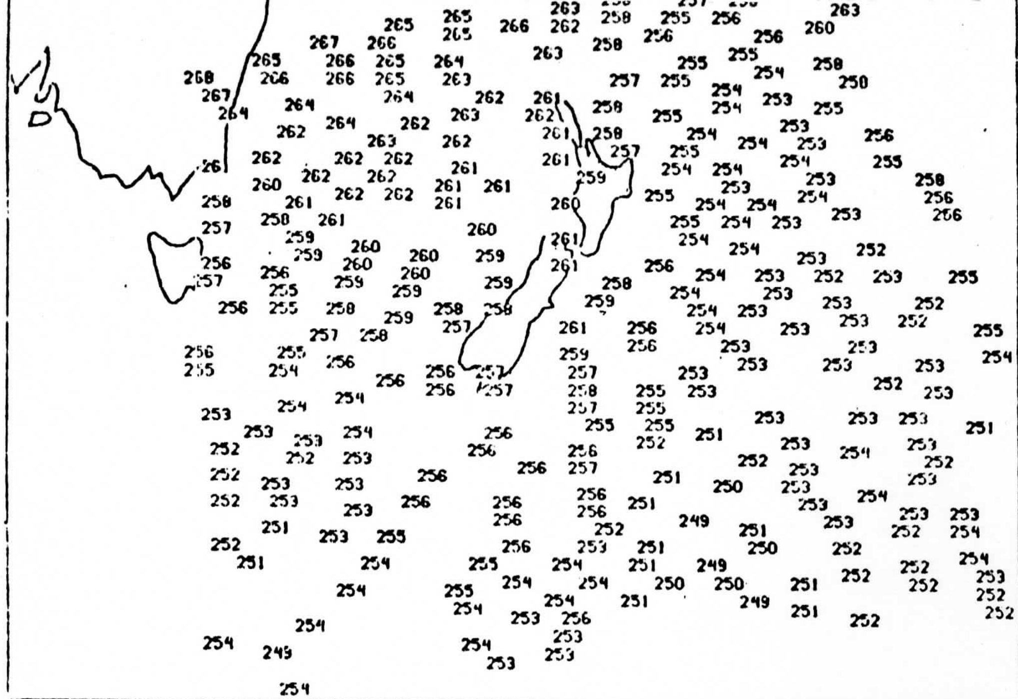

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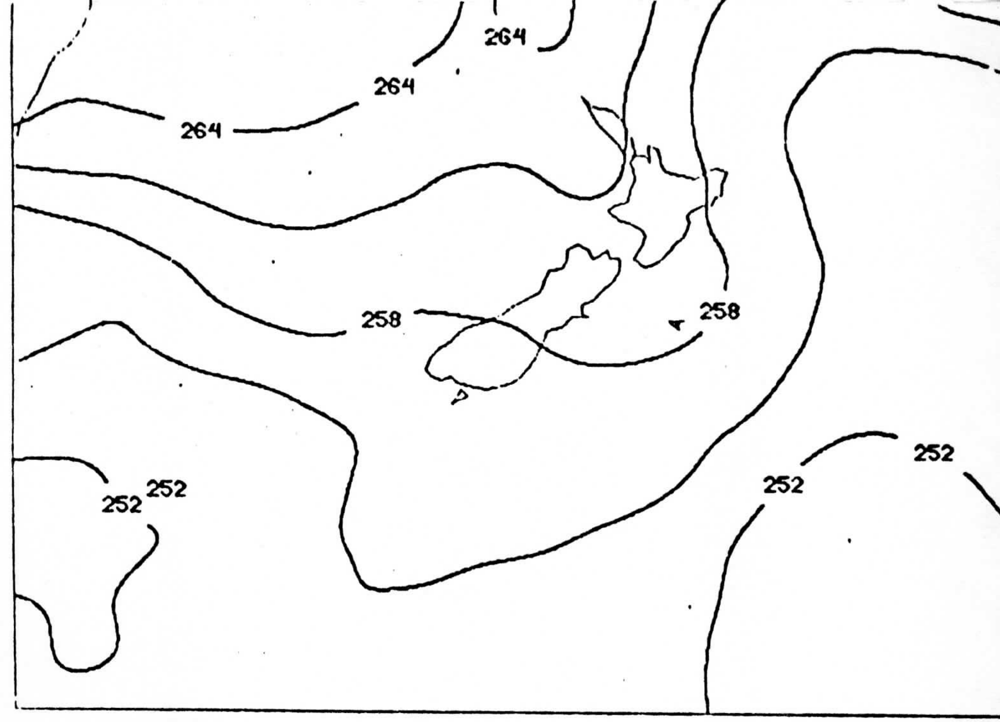

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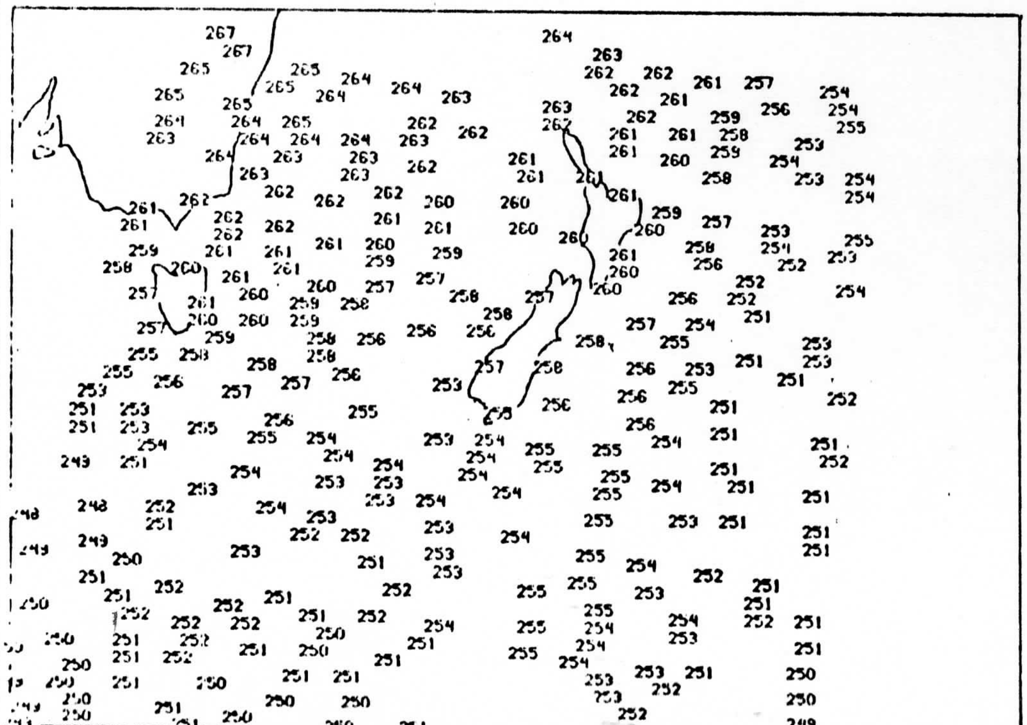

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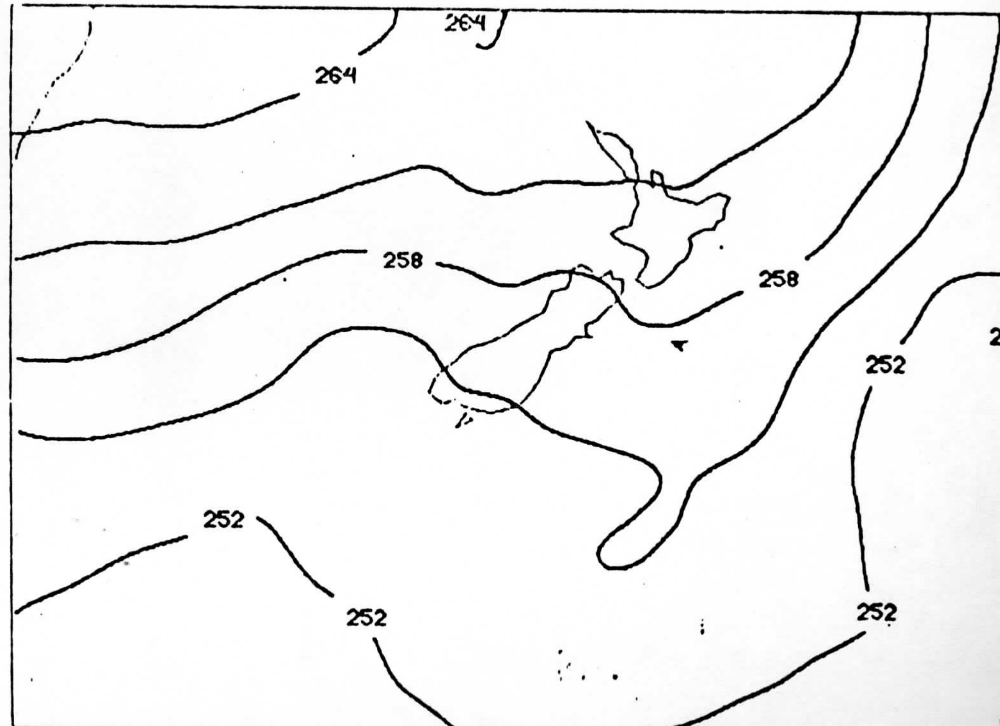

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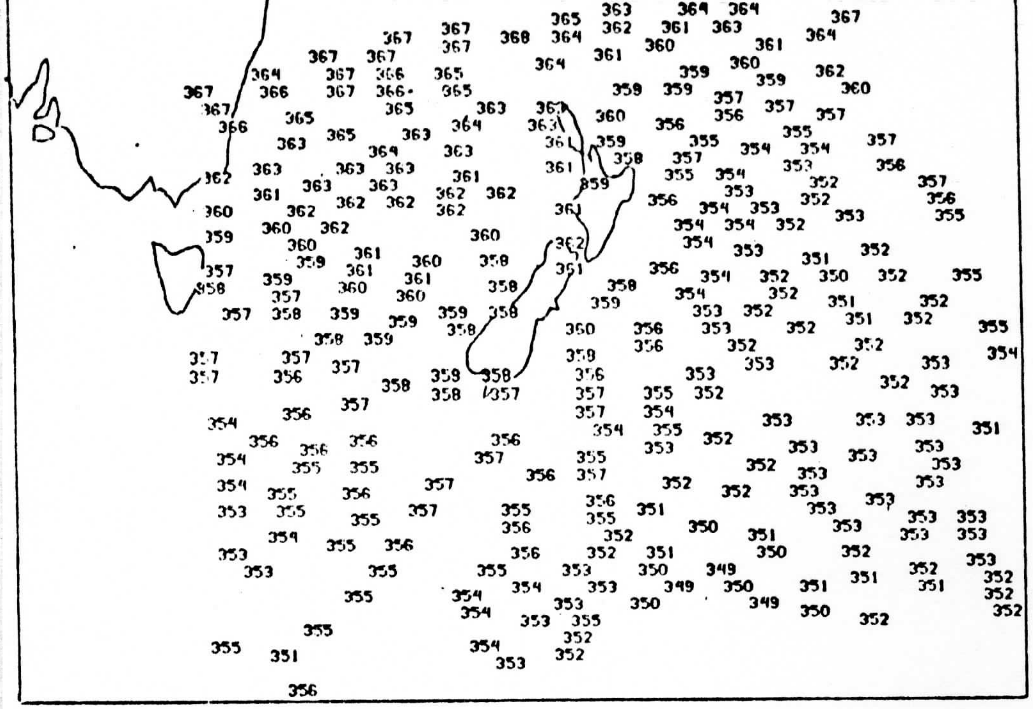

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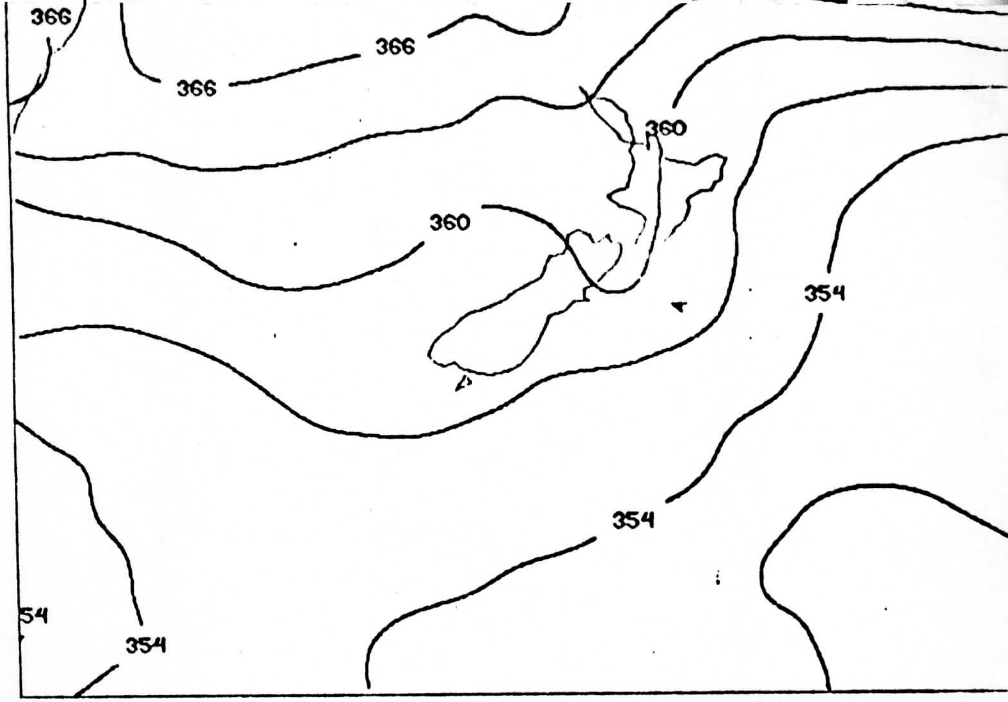

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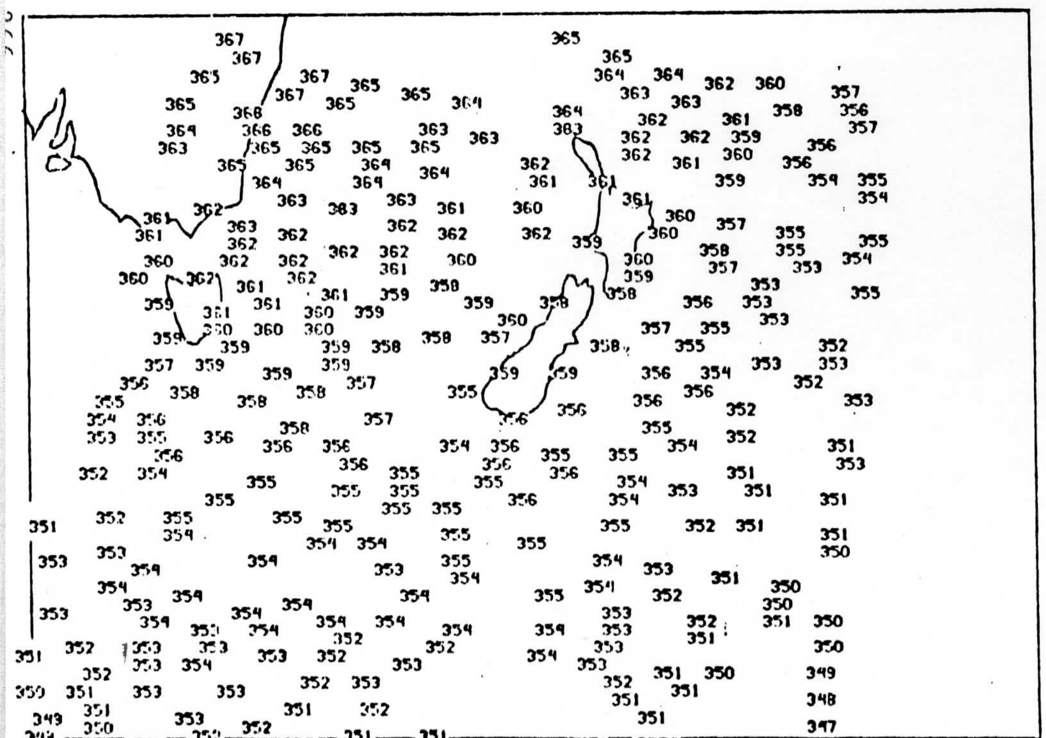

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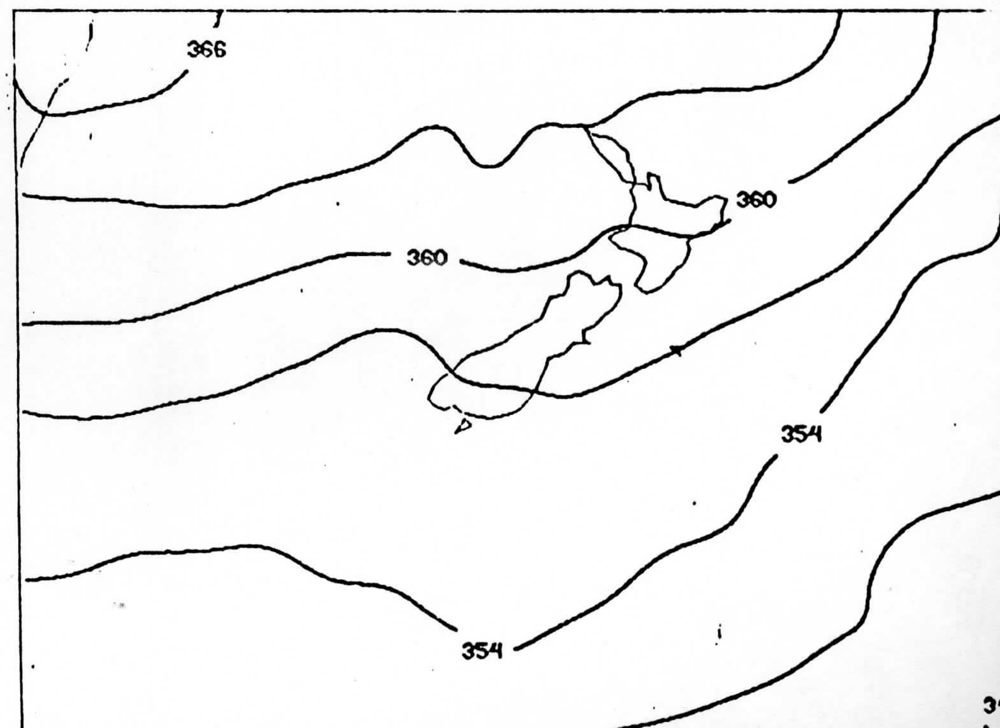

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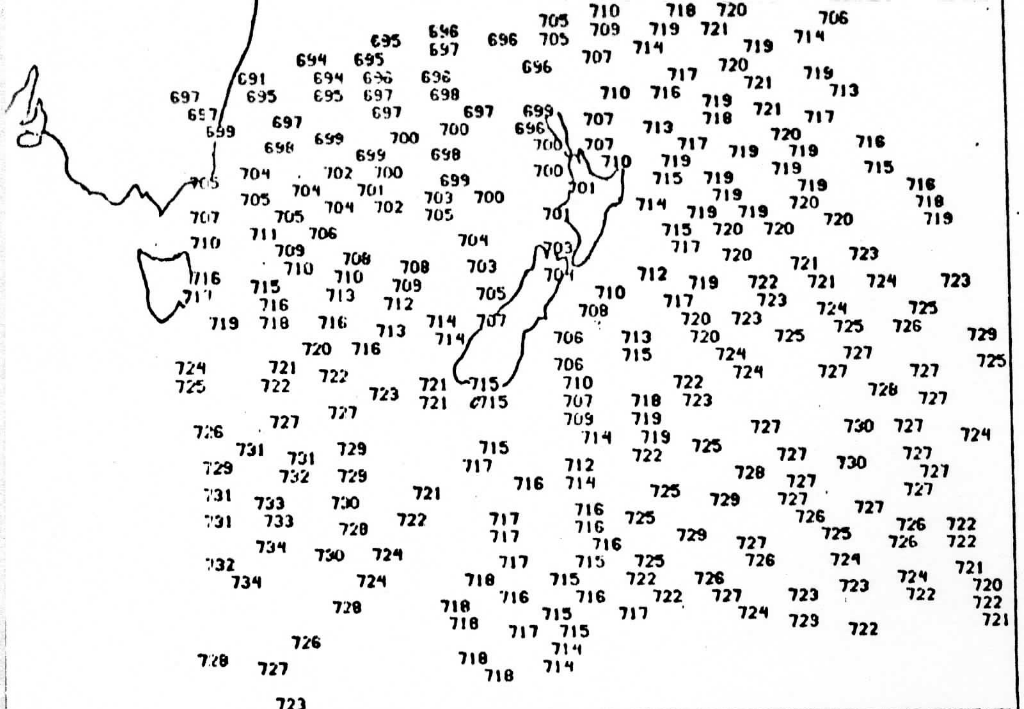

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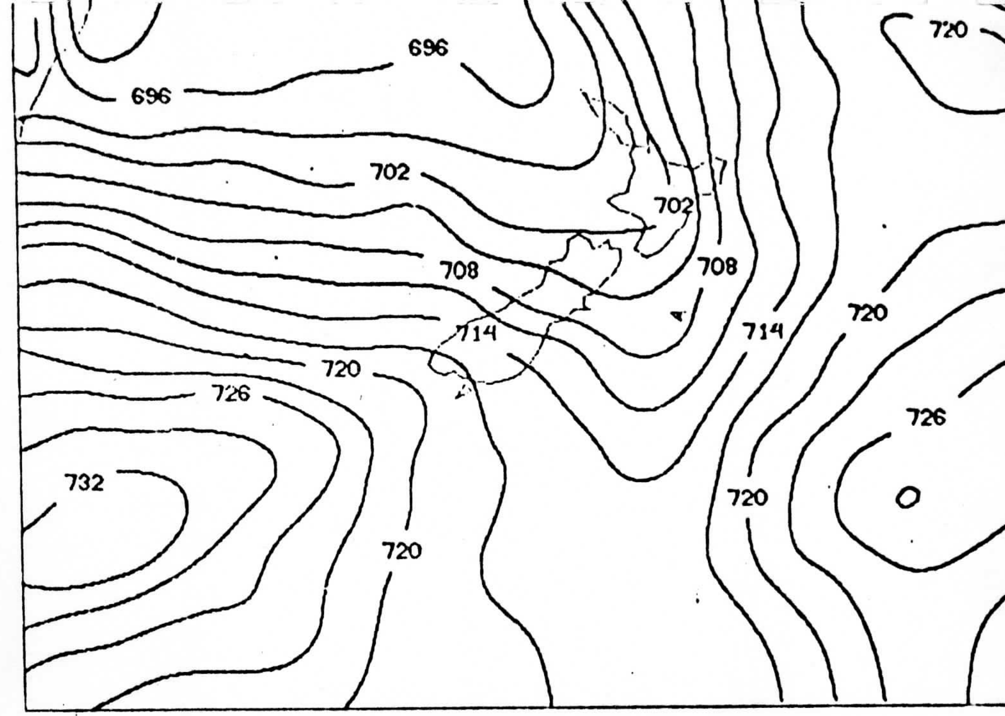

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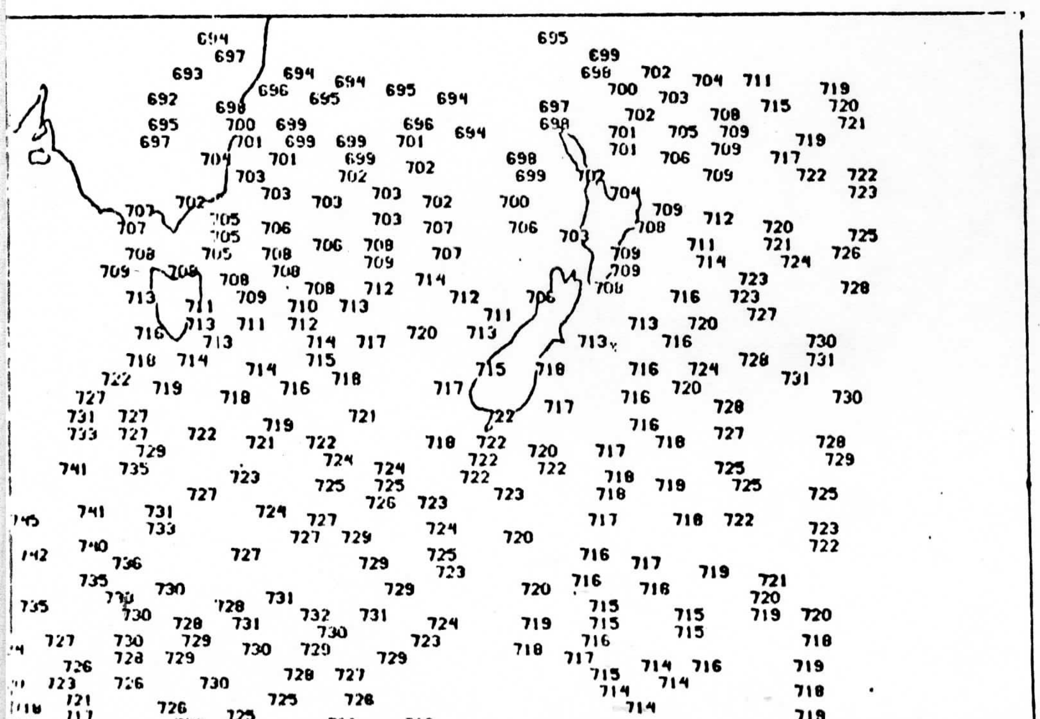

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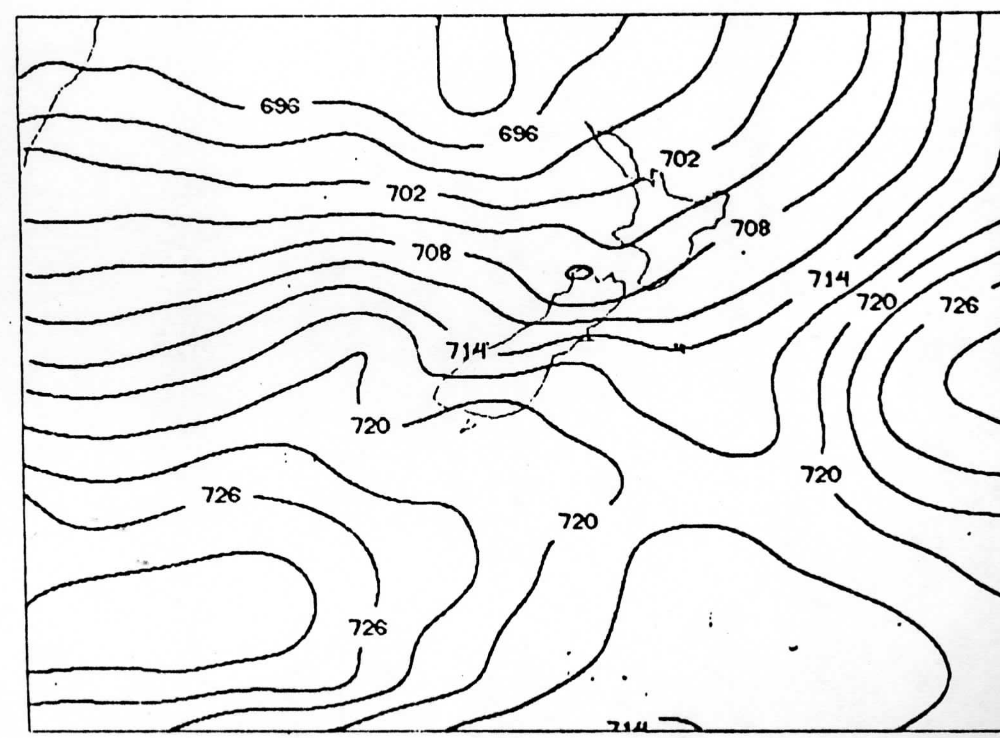

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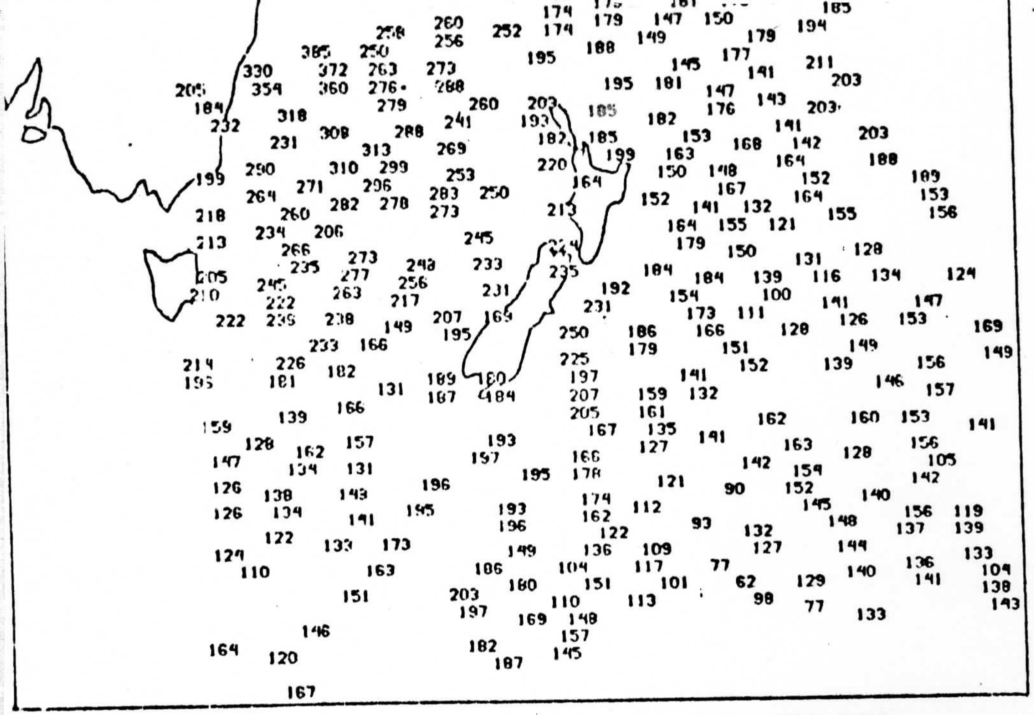

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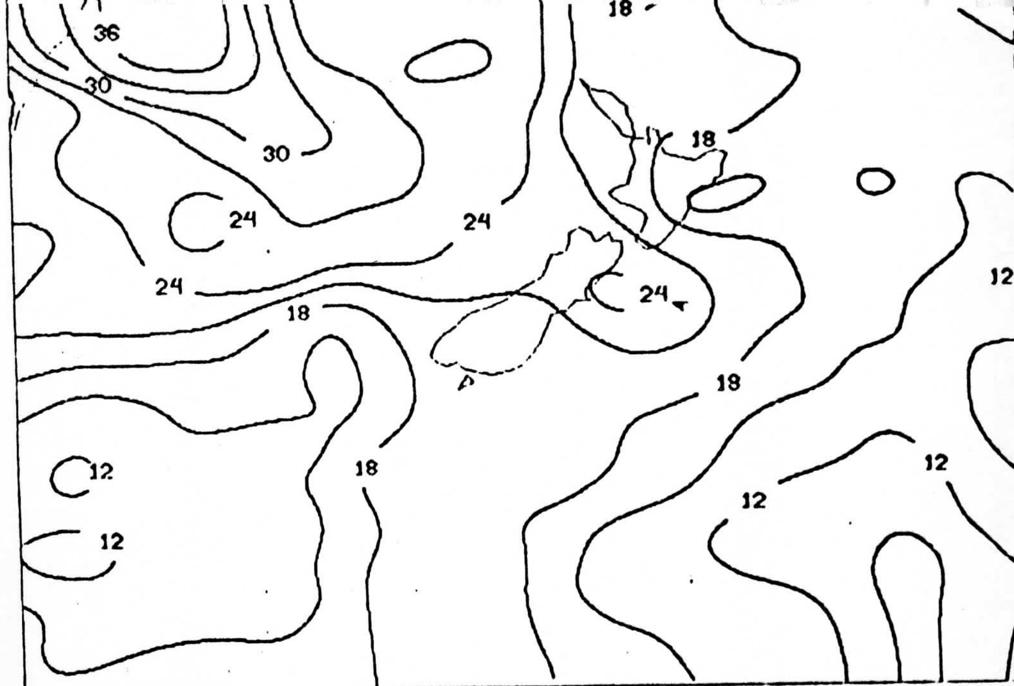

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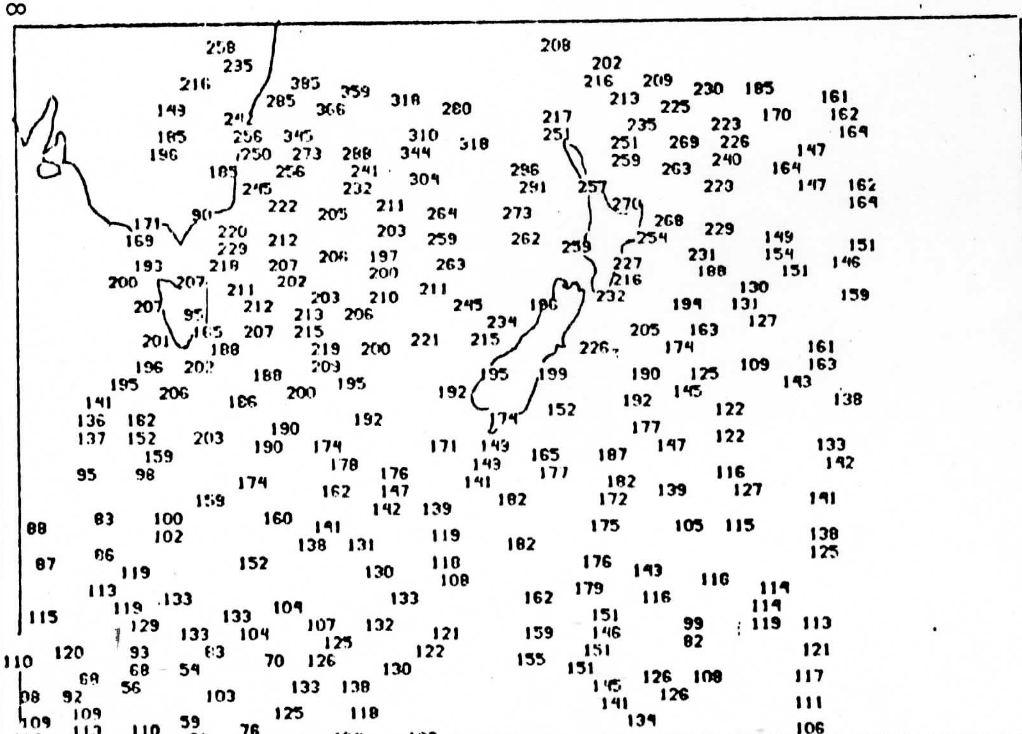

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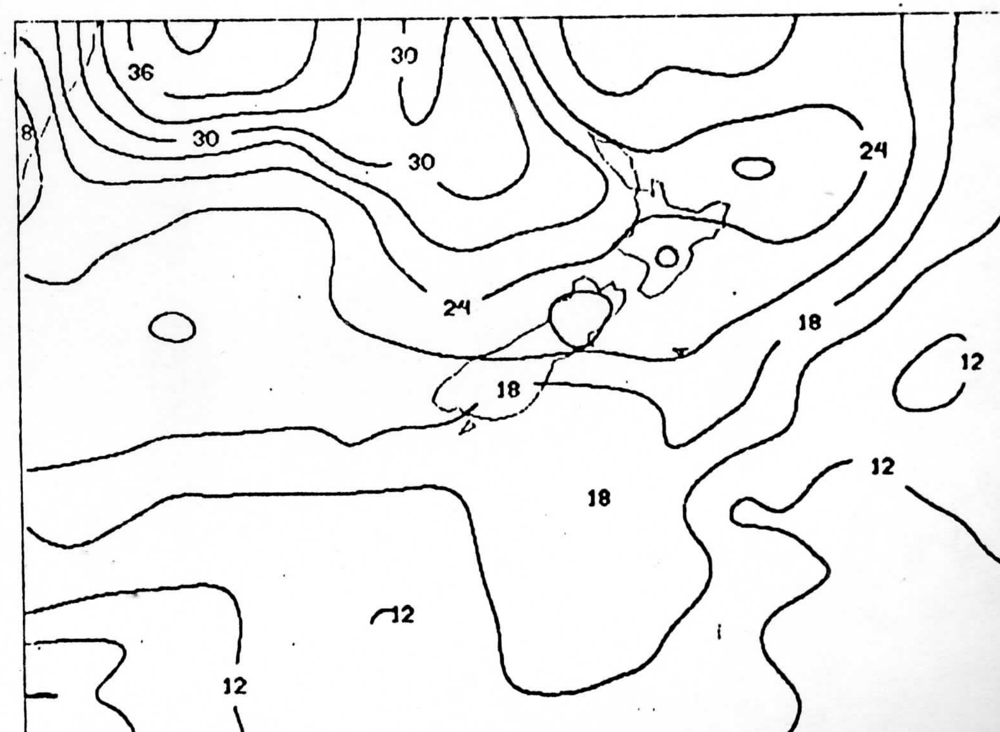

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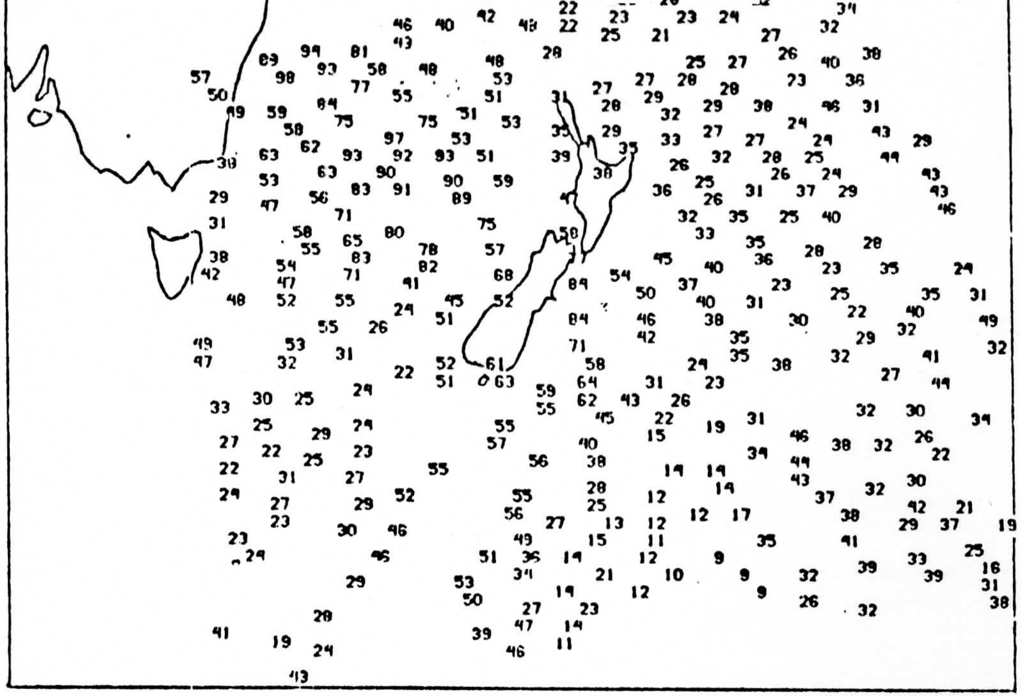

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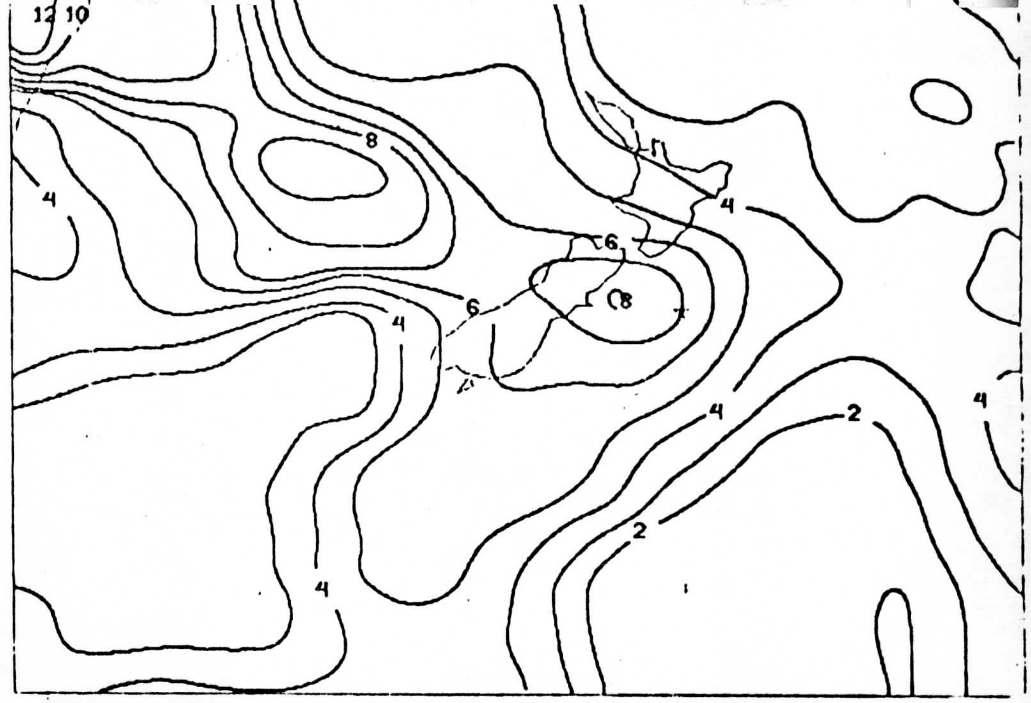

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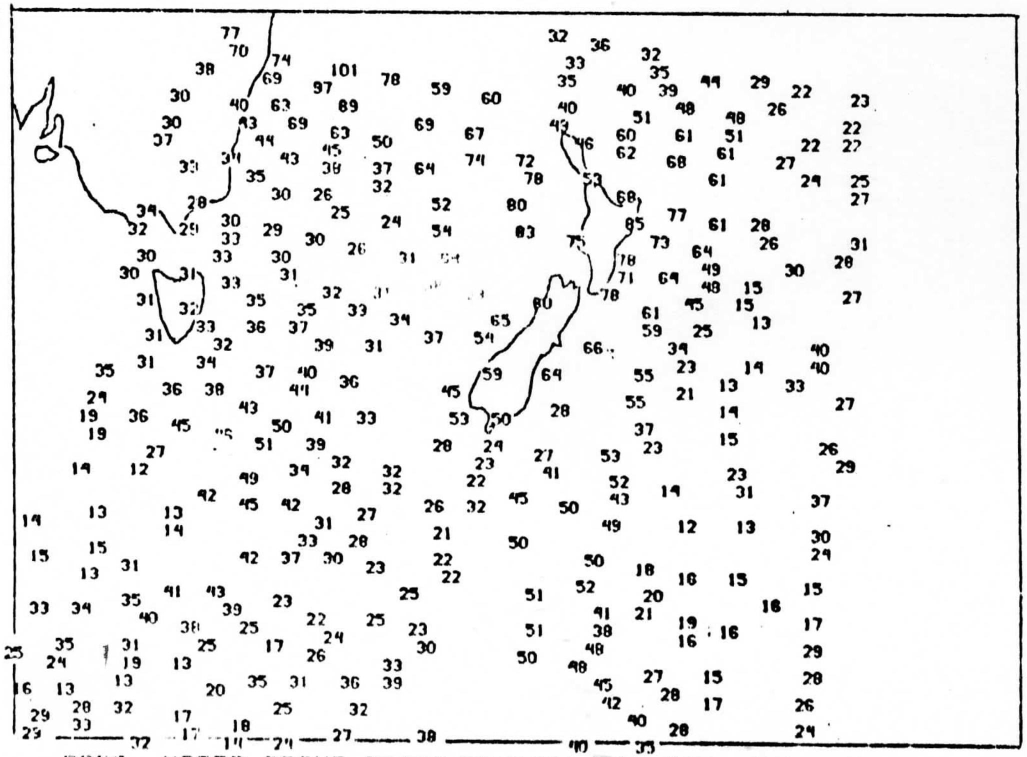

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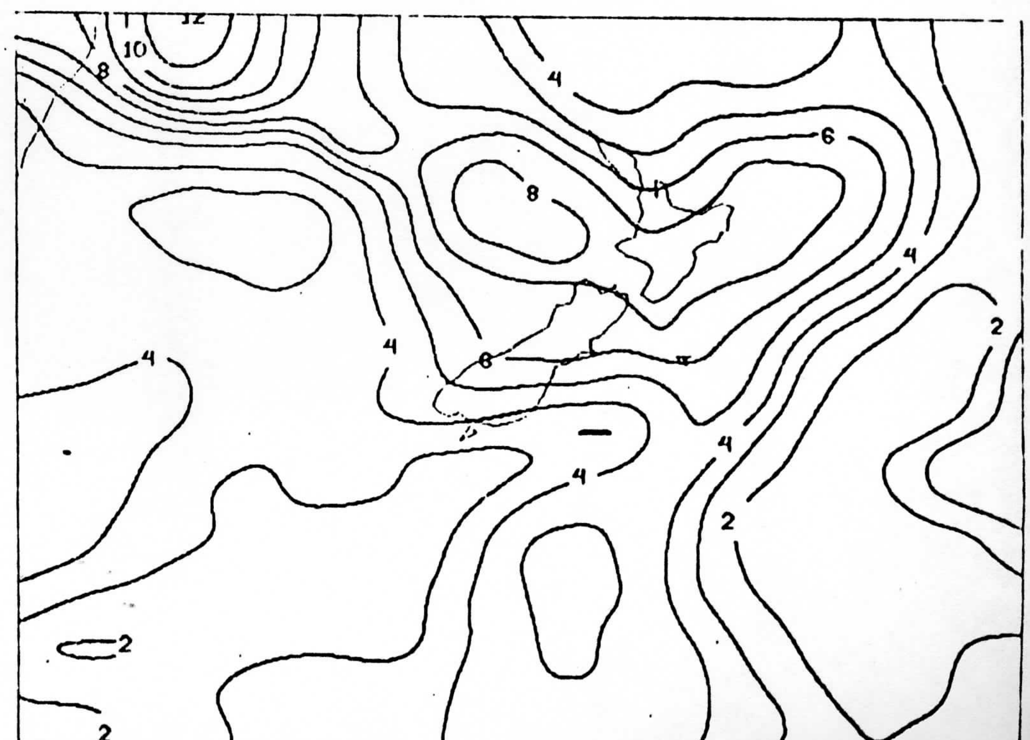

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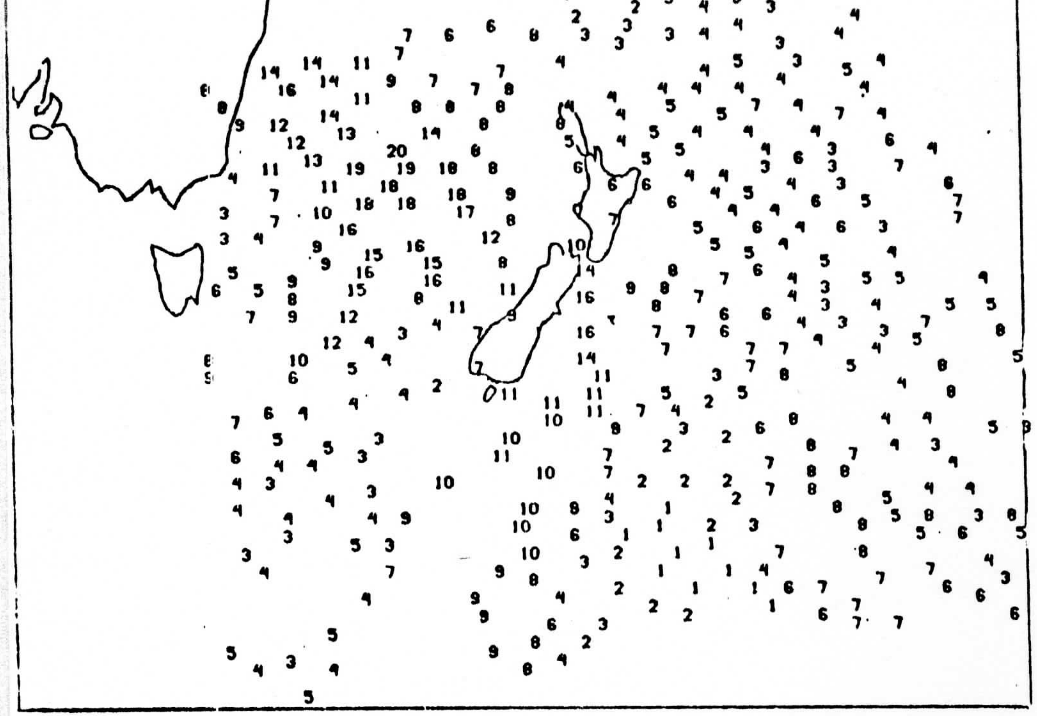

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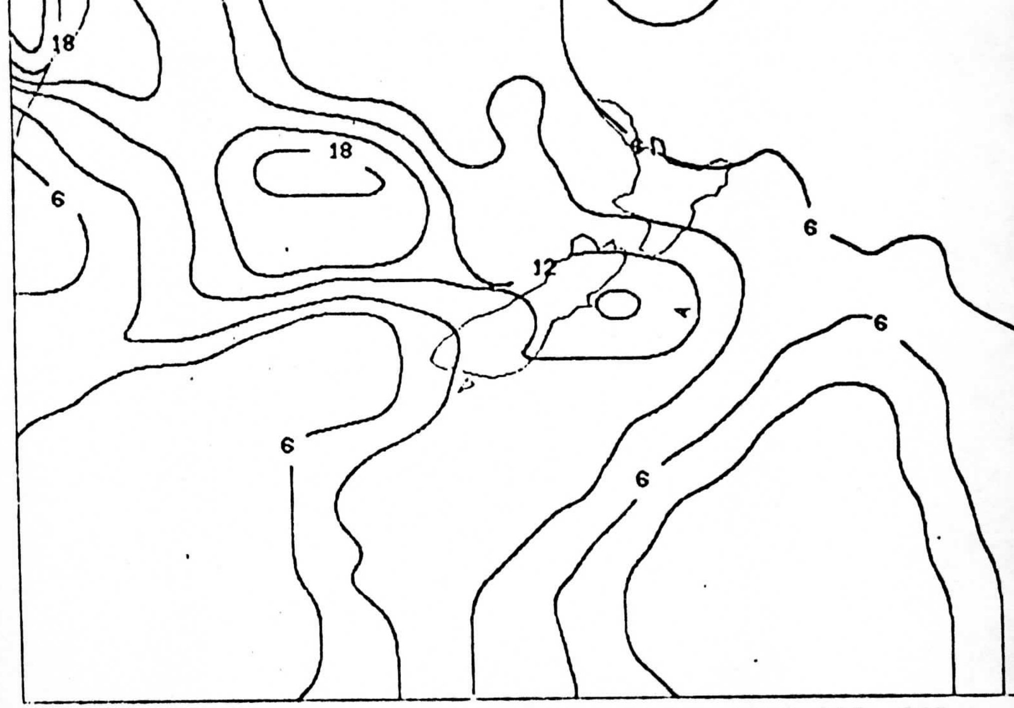

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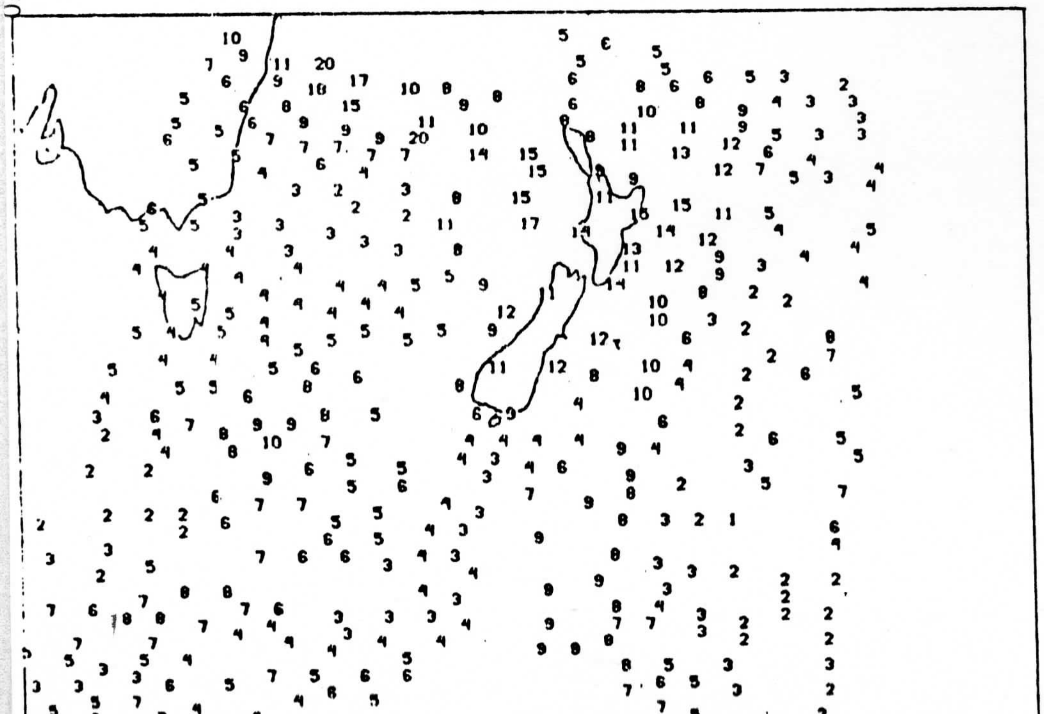

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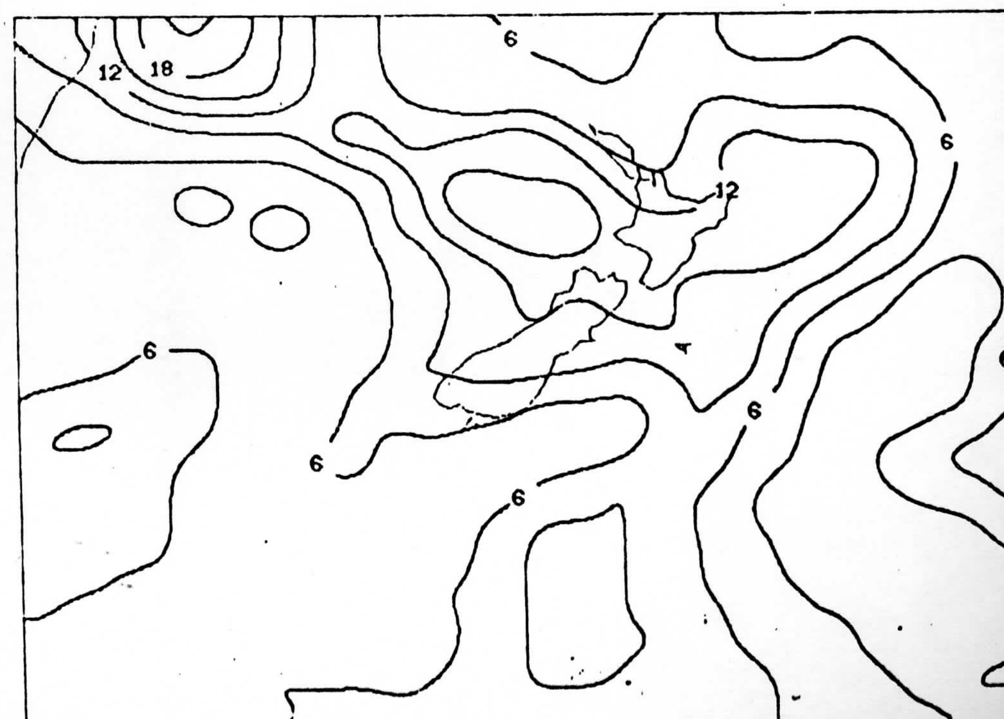

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DOCUMENTATION FOR TOVS-EXPORT SOFTWARE/DATA PACKAGE

VERSION OF 24 SEP 83

THIS DOCUMENT DESCRIBES, IN BRIEF OUTLINE FORM, PROCEDURES FOR ESTABLISHING A LOCAL/REGIONAL SYSTEM FOR PROCESSING TOVS (HIRS+MSU) SOUNDING DATA FROM THE TIROS-N/NOAA SERIES OF POLAR-ORBITING SPACECRAFT, USING THE SOFTWARE AND SUPPORTING DATA CONTAINED IN SUBSEQUENT FILES ON THIS TAPE. THE ALGORITHMS AND DATA-PROCESSING TECHNIQUES WERE ORIGINALLY DEVELOPED FOR 'MCIDAS' (MAN-COMPUTER INTERACTIVE DATA ACCESS SYSTEM) AT THE SPACE SCIENCE AND ENGINEERING CENTER OF THE UNIVERSITY OF WISCONSIN IN MADISON (UW/SSEC). INITIALLY BASED ON THE HARRIS 'SLASH-6' MINICOMPUTER, MCIDAS HAS RECENTLY BEEN IMPLEMENTED ON THE IBM 4341. THE SOFTWARE HEREIN SUPPLIED HAS BEEN CONFIGURED FOR AN IBM-OS SYSTEM TO PROVIDE THE MOST PORTABLE SYSTEM FEASIBLE, GIVEN THE RESOURCES AVAILABLE TO THOSE RESPONSIBLE FOR MAINTENANCE OF THE SYSTEM.

QUESTIONS AND/OR COMMENTS CONCERNING THE SYSTEM AND ITS IMPLEMENTATION, ESPECIALLY IN REGARD TO POSSIBLE ERRORS, SHOULD BE ADDRESSED TO

MR. HAROLD M. WOOLF
NOAA-NESDIS DEVELOPMENT LABORATORY
UW/SSEC, ROOM 219
1225 WEST DAYTON STREET
MADISON, WISCONSIN 53706
TELEPHONE ... (608) 264-5325
TWX/TELEX ... (910) 286-2771

CONTENTS OF THE REMAINING FILES ON THIS TAPE

- FILE 2. IBM FORTRAN SOURCE FOR MAIN PROGRAMS
- FILE 3. IBM FORTRAN SOURCE FOR SUBPROGRAMS
- FILE 4. IBM ASSEMBLER SOURCE FOR I/O ROUTINE 'FFIO'
- FILE 5. ORBITAL ELEMENTS FOR SATELLITE 1 (CURRENTLY NOAA-7)
- FILE 6. ORBITAL ELEMENTS FOR SATELLITE 2 (CURRENTLY NOAA-8)
- FILE 7. INGEST PARAMETERS FOR SATELLITE 1 (CURRENTLY NOAA-7)
- FILE 8. INGEST PARAMETERS FOR SATELLITE 2 (CURRENTLY NOAA-8)
- FILE 9. COEFFICIENTS FOR HIRS RADIATIVE-TRANSFER COMPUTATIONS
- FILE 10. COEFFICIENTS FOR MSU RADIATIVE-TRANSFER COMPUTATIONS
- FILE 11. COEFFICIENTS FOR HIRS LIMB-CORRECTION
- FILE 12. COEFFICIENTS FOR MSU LIMB-CORRECTION
- FILE 13. LOW-RESOLUTION (60 NAUT.MI.) EARTH TOPOGRAPHY & LAND-SEA FLAGS
- FILE 14. REAL-DATA COEFFICIENTS FOR USE WITH PGMS 'TOVRET' & 'ENHRET'
- FILE 15. COEFFICIENTS FOR MSU ANGLE-DEPENDENT RADIATIVE-TRANSFER
- FILE 16. SYNTHETIC COEFFICIENTS FOR USE WITH PGM 'FXTIRO'
- FILE 17. REAL-DATA COEFFICIENTS FOR USE WITH PGM 'FXTIRO'
- FILE 18. HIGH-RESOLUTION (10 NAUT.MI.) GLOBAL TOPOGRAPHY

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NOTES ON FORTRAN SOURCE (FILES 2 AND 3)
*****
   THE FIRST CARD OF EACH MAIN PROGRAM IN FILE 2 IS A FORTRAN COMMENT OF
THE FORM
C      MAIN PROGRAM 'XXXXXX'
   EACH MAIN PROGRAM, SUBPROGRAM, OR COLLECTION OF RELATED SUBPROGRAMS,
CONTAINS A COMMENT CARD NEAR ITS BEGINNING OF THE FORM
C   *** VERSION OF DD MMM YY (DAY MONTH YEAR)
   USERS FOR WHOM THIS IS NOT THE FIRST PACKAGE SUPPLIED SHOULD FIND
THESE 'VERSION-DATES' A CONVENIENT MEANS OF DETERMINING WHICH ROUTINES
HAVE BEEN CHANGED SINCE THEIR INITIAL IMPLEMENTATION.  ALTHOUGH IN THE
PAST UPDATES TO THE PACKAGE HAVE BEEN PROVIDED IN THE FORM OF SELECTED
SOFTWARE AND COEFFICIENTS, THE MOST RECENT CHANGES ARE TOO EXTENSIVE,
AND THE NUMBER OF USERS WORLD-WIDE TOO GREAT, TO PERMIT SUCH 'LIMITED-
EDITION' UPDATING.  HEREAFTER, UPDATES - TO SOFWARE, COEFFICIENTS, OR
BOTH - WILL BE IN THE FORM OF A NEW TOTAL-PACKAGE TAPE.  IT WILL BE THE
RESPONSIBILITY OF THE INDIVIDUAL USER TO DETERMINE WHICH 'NEW ITEMS' ARE
RELEVANT TO HIS INSTALLATION.
*****
*****
NOTES ON SUPPORTING-DATA FILES
*****
   THE COEFFICIENTS IN FILES 7 THROUGH 12 ARE DETERMINED INITIALLY FOR
EACH SATELLITE, AND CAN BE CONSIDERED FIXED FOR ITS OPERATIONAL LIFETIME
UNLESS MAJOR CHANGES OCCUR IN THE PERFORMANCE OF ONE OR MORE SPECTRAL
CHANNELS.*  THIS IS ALSO TRUE FOR THE COEFFICIENTS IN FILES 15 AND 16.
THE RETRIEVAL COEFFICIENTS IN FILES 14 AND 17 ARE UPDATED WEEKLY BY
NESDIS OPERATIONS AND CAPTURED FOR INCLUSION IN THIS PACKAGE.  ORBITAL
ELEMENTS SUPPLIED IN FILES 5 AND 6 ARE ALSO UPDATED WEEKLY.  THESE ARE
NEEDED FOR NAVIGATION (EARTH-LOCATION) OF REAL-TIME DATA OBTAINED VIA
DIRECT READOUT OF THE SPACECRAFT (BEACON).  THE REAL-DATA COEFFICIENTS
AND ORBITAL ELEMENTS ARE PROVIDED TO ASSIST IN THE INITIAL IMPLEMENTA-
TION; THE USER MUST MAKE HIS OWN ARRANGEMENTS FOR CONTINUED ACQUISITION
OF SUCH INFORMATION FOR REAL-TIME APPLICATIONS.
    OCCASIONALLY, SOME OF THE MSU CALIBRATION QUALITY-CONTROL LIMITS IN
    FILES 7 AND 8 MAY NEED TO BE ADJUSTED TO AVOID DISCARDING GOOD DATA
    AS A RESULT OF CHANGES IN GAIN OR OTHER INSTRUMENT CHARACTERISTICS.
*****
*****
CONSTRUCTING THE TOVS DATA-PROCESSING SYSTEM
*****
    THE SYSTEM MAKES EXTENSIVE USE OF DISK FILES, BOTH SEQUENTIAL AND
DIRECT-ACCESS, FOR EFFICIENCY IN I/O OPERATIONS.  TO ASSIST IN ESTAB-
LISHING THE PERMANENT DATA FILES (ORBITAL ELEMENTS, COEFFICIENTS, AND
TOPOGRAPHY), PROGRAMS HAVE BEEN PROVIDED (IN FILE 2) TO READ THE DATA
FROM TAPE AND WRITE TO DISK.

    PROGRAM       TAPE FILE(S)       DISK LUN       TYPE**
    -------       ------------       --------       ----
    PUTELE        5,6                11,12          D,D
```

PUTPAR	7,8	15	S
HIRTCFTD	9	13	D
MSUTCFTD	10	14	S
HIRLCFTD	11	15	S
MSULCFTD	12	16	S
TOPOGFTD	13	17	D
RTVLCFTD**	14	25	D
MSZTCFTD	15	18	S
RTVCFOTD***	16	25	D
RTVCFSTD	17	26	D
TOPOGHTD+	18	19	D

NOTES:
LUN = FORTRAN LOGICAL UNIT NUMBER
* S = SEQUENTIAL, D = DIRECT-ACCESS (IBM BDAM)
** PROGRAM 'RTVLCFTP' IS PROVIDED TO PERMIT EXTRACTION OF RETRIEVAL COEFFICIENTS FROM THE GENERAL COEFFICIENT-DATABASE TAPE THAT IS AVAILABLE FROM NESDIS OPERATIONS UPON SPECIAL REQUEST.
*** PROGRAM 'RTVLCXTP' IS ANALOGOUS TO 'RTVLCFTP', BUT PROVIDES THE RECORD STRUCTURE REQUIRED FOR INPUT TO PROGRAM 'FXTIRO'.
+ PROGRAM 'SUBTOP' IS PROVIDED TO CREATE A SUBSET OF THE GLOBAL HIGH-RESOLUTION TOPOGRAPHY FOR USE IN PROGRAM 'FXTIRO'. IT IS ASSUMED THAT MOST USERS WOULD NOT BE ABLE TO MAINTAIN THE ENTIRE DATASET ON DISK, SINCE IT CONTAINS 16200 RECORDS, EACH 288 BYTES IN LENGTH.

TWO PROGRAMS, 'RAOBHIRS' AND 'RAOBMSU' (AND ASSOCIATED SUBPROGRAMS) ARE SUPPLIED TO DEMONSTRATE THE PROCEDURES FOR CALCULATING, FROM RADIOSONDE TEMPERATURE AND HUMIDITY PROFILES, HIRS RADIANCES AND BRIGHTNESS (EQUIVALENT-BLACKBODY) TEMPERATURES, AND MSU ANTENNA OR BRIGHTNESS TEMPERATURES, RESPECTIVELY. THE REMAINDER OF THE SOFTWARE CONTAINED IN FILES 2, 3, AND 4 IS FOR PROCESSING HIRS AND MSU DATA TO OBTAIN PROFILES OF ATMOSPHERIC TEMPERATURE, HUMIDITY, GEOPOTENTIAL HEIGHT, AND GEOSTROPHIC WIND, AND FOR DISPLAYING AND MANIPULATING THOSE PROFILES IN VARIOUS WAYS. ESSENTIAL TASKS ARE 'INGEST', 'PREPROCESSING', AND 'RETRIEVAL'. THE TERM 'RTC' MEANS 'RADIATIVE-TRANSFER COEFFICIENTS', AND 'LCC' STANDS FOR 'LIMB-CORRECTION COEFFICIENTS'.

*****

*****
INGEST
*****

FUNCTION: PRODUCE CALIBRATED, EARTH-LOCATED HIRS AND MSU RADIOMETRIC MEASUREMENTS FROM TOVS 'TIP' DATA. TWO VERSIONS ARE PROVIDED; THE ESSENTIAL DIFFERENCE IS IN THE TYPE OF INPUT DATA THEY ARE DESIGNED TO HANDLE - EITHER ARCHIVAL ('LEVEL 1-B') OR DIRECT-READOUT (REALTIME).

LEVEL 1-B: DATA THAT HAS BEEN THROUGH PRELIMINARY PROCESSING BY NESDIS OPERATIONS' TOVS GROUND SYSTEM, AND IS PROVIDED ON STANDARD COMPUTER TAPE TO USERS, UPON REQUEST, BY THE SATELLITE DATA SERVICES BRANCH OF NESDIS. SUCH TAPE CONTAINS, IN ADDITION TO VALUES (IN DIGITAL COUNTS) REPRESENTING RADIOMETRIC MEASUREMENTS, EARTH-LOCATION INFORMATION AND CALIBRATION PARAMETERS REQUIRED TO TRANSFORM THE RAW DATA VALUES INTO

RADIANCE OR BRIGHTNESS TEMPERATURE. THREE PROGRAMS ARE SUPPLIED FOR THIS TYPE OF OPERATION:

```
   PROGRAM       INPUT(S)           OUTPUT(S)        ( ) = LUN
   *******       *********          *********
   INVTAP        1-B TAPE(10)       PRINTOUT OF DATA TYPE, TIMES, AND
                 DATA CARD          LOCATIONS FOR EACH FILE

   TOVTAP        1-B TAPE(10)       SELECTED HIRS(11) AND MSU(12) DATA ON
                *DATA CARD          DISK; PRINTOUT OF RELEVANT INFORMATION

   TOVING        HIRS DISK(11)      CALIBRATED, LOCATED DATA ON DISK(20);
                 MSU DISK(12)       PRINTOUT
                 HIRS RTC(13)
               **DATA CARD
```

NOTES:

* NUMBER OF FILES TO READ; PROGRAM TERMINATES ON DOUBLE EOF IF ENCOUNTERED BEFORE COUNT IS SATISFIED.

** PHYSICAL FILE NUMBERS OF HIRS AND MSU DATA, PLUS BEGINNING AND ENDING TIMES.

*** SATELLITE NUMBER (1 FOR NOAA-7, 2 FOR NOAA-8); REQUIRED BECAUSE INFORMATION IN TAPE HEADER RECORDS MAY BE AMBIGUOUS.

DIRECT-READOUT: DATA OBTAINED ON-SITE BY DIRECT DOWNLINK FROM THE SPACECRAFT. THE SSEC SYSTEM USES DATA FROM THE VHF (137MHZ) BEACON. SUCH DATA CAN ALSO BE ACQUIRED BY EXTRACTING 'TIP' FROM AN HRPT DATA-STREAM; CREATION OF THE NECESSARY SOFTWARE IS THE RESPONSIBILITY OF THE USER. PROCESSING OF DIRECT-READOUT DATA IS MUCH MORE COMPLEX THAN THAT OF LEVEL 1-B, SINCE THE USER MUST DO EVERYTHING - DECOMMUTATION OF RAW DATA, NAVIGATION OR EARTH-LOCATION, AND IN-FLIGHT CALIBRATION. TWO PROGRAMS ARE PROVIDED:

```
   PROGRAM        INPUT(S)          OUTPUT(S)
   *******        *********         *********
   PREING         DATA TAPE(9)      DISK FILE(10) CONTAINING DECOMMUTATED
                  DATA CARD            HIRS AND MSU DATA
                                    PRINTOUT

   INGTOV         DECOM DATA(10)    CALIBRATED, LOCATED DATA ON DISK(20)
                **ORB-ELEM(11,12)   PRINTOUT
                  HIRS RTC(13)
                  ING-PARAM(15)
```

NOTES:

* FILE TO PROCESS, IF MORE THAN ONE ON TAPE; FLAG FOR DETAILED (DIAGNOSTIC) MSU PRINT.

** UPDATED BY PROGRAM 'PUTELE' WITH DATA OBTAINED FROM DIRECT READOUT USER SERVICES.

THE DATA IN FILE 20 WILL HAVE THE SAME FORMAT, REGARDLESS OF THE SOURCE AND TYPE OF INGEST. THIS FILE SERVES AS INPUT TO THE NEXT STEP.

PREPROCESSOR

FUNCTION: TRANSFORM CALIBRATED, EARTH-LOCATED HIRS AND MSU MEASUREMENTS PRODUCED BY INGEST, INTO DATASETS FOR DISPLAY AND RETRIEVAL.

PROGRAM	INPUT(S)	OUTPUT(S)
TOVPRE	INGEST OUTPUT(20)	IMAGER FILE(22)
	HIRS RTC(13)	SOUNDER FILE(23)
	HIRS LCC(15)	PRINTOUT
	MSU LCC(16)	
	LO-RES TOPOG(17)	
	DATA CARD	
TOVMAP	IMAGER FILE(22)	PRINTOUT OF DATA IN (LINE,ELEMENT) COORDINATES
	DATA CARD - SPECIFY PARAM(S), STARTING LINE	

NOTE:
SPECIFY WHETHER DATA ARE TO BE 'LIMB-CORRECTED' OR NOT (SEE BELOW)

THE PREPROCESSOR PERFORMS THE FOLLOWING FUNCTIONS:

- IF THE MSU 'LIMB-CORRECTION' FLAG IS ON, MSU DATA ARE CORRECTED FOR
  - ANTENNA PATTERN (TRANSFORM ANTENNA TEMP. TO BRIGHTNESS TEMP.);
  - LIMB EFFECTS (NORMALIZE TO THETA = 0);
  - SURFACE REFLECTIVITY (NORMALIZE TO SFC.EMIS. = 1);
  - LIQUID WATER (PRECIPITATING CLOUD) ATTENUATION.
- IF THE HIRS 'LIMB-CORRECTION' FLAG IS ON, HIRS DATA ARE CORRECTED FOR
  - LIMB EFFECTS;
  - WATER VAPOR ATTENUATION IN THE WINDOW CHANNELS.
- IN ADDITION, HIRS CHANNELS 17 AND 18 ARE CORRECTED, IN DAYLIGHT, FOR FLUORESCENCE AND REFLECTED SUNLIGHT, RESPECTIVELY, REGARDLESS OF THE STATE OF THE LIMB-CORRECTION FLAG.
- MSU AND HIRS ARE COLOCATED BY INTERPOLATING THE MSU OBSERVATIONS TO THE HIRS SCAN PATTERN.
- OUTPUT FILE 22 HAS ALL DATA FOR ONE PARAMETER CONTIGUOUS ON DISK, AND THUS IS OPTIMIZED FOR IMAGING;
- OUTPUT FILE 23 HAS ALL DATA FOR ONE SCAN SPOT CONTIGUOUS ON DISK, AND THUS IS OPTIMIZED FOR SOUNDING.

RETRIEVAL

FUNCTION: DETERMINE, FROM PREPROCESSED HIRS AND MSU DATA, VERTICAL PROFILES OF ATMOSPHERIC TEMPERATURE, HUMIDITY, AND GEOPOTENTIAL HEIGHT, AS WELL AS TOTAL OZONE AND STABILITY PARAMETERS, AT HIGH SPATIAL RESOLUTION. SEE NOTE ON 'SURFACE DATA' AT THE END OF THIS DOCUMENT. THERE

ARE TWO VERY DIFFERENT RETRIEVAL PROGRAMS INCLUDED IN THIS PACKAGE: STATISTICAL ('TOVRET') AND PHYSICAL ('FXTIRO').

```
   PROGRAM         INPUT(S)          OUTPUT(S)
   -------         ---------         ---------
   TOVRET          HIRS RTC(13)      RETRIEVAL FILE(24)
                   LO-RES TOPOG(17)  PRINTOUT
                   SOUNDER FILE(23)
                  *RTVL COEF(25)
```

*THIS PROGRAM REQUIRES BOTH HIRS AND MSU TO HAVE BEEN LIMB-CORRECTED.

NOTE:

COEFFICIENTS STAGED TO DISK BY 'RTVLCFTD' OR 'RTVLCFTP'.

```
   PROGRAM         INPUT(S)          OUTPUT(S)
   -------         ---------         ---------
   FXTIRO          HIRS RTC(13)      RETRIEVAL FILE(24)
                   MSU RTC(14)       PRINTOUT
                  +HIRS LCC(15)
                  +MSU LCC(16)
                   LO-RES TOPOG(17)
                  *MSU RTC(18)
                 **HI-RES TOPOG(19)
                   IMAGER FILE(22)
                   SOUNDER FILE(23)
                ***RTVL COEF(25)
                ***RTVL COEF(26)
                ***DATA CARD
```

*THIS PROGRAM CAN OPERATE ON HIRS AND MSU DATA THAT HAVE BEEN LIMB-CORRECTED OR NOT ... THE LATTER SEEMS TO GIVE BETTER RESULTS.

NOTES:

THE RTC IN FILE 14 ARE FOR LIMB-CORRECTED MSU DATA; THOSE IN FILE 18, FOR NON-LIMB-CORRECTED DATA.

\+ NEEDED FOR REGRESSION ESTIMATION OF FIRST-GUESS TEMPERATURE AND OZONE PROFILES.

* PRESUMED TO BE A REGIONAL DATASET CREATED BY 'SUBTOP'. IF THE GLOBAL DATASET IS TO BE USED, REPLACE SUBROUTINE 'HRTOPX' (IN 'NTOPO') WITH 'HRTOPO'.

** FILE 25 CONTAINS 'REAL-DATA' COEFFICIENTS OBTAINED FROM NESDIS/OPERATIONS; FILE 26, 'SYNTHETIC' COEFFICIENTS - SEE NOTES UNDER DESCRIPTION OF INITIAL-DATA-STAGING PROGRAMS.

*** SPECIFY VARIOUS OPTIONS TO CONTROL EXECUTION OF PROGRAM - SEE SOURCE CODE FOR PARAMETERS AND THEIR MEANINGS.

FILTERING

FUNCTION: ELIMINATE SOUNDINGS OF QUESTIONABLE RELIABILITY BY OBJECTIVE ANALYSIS OF DIFFERENCES BETWEEN INFRARED AND MICROWAVE RETRIEVALS FOR THE SAME LOCATION, AND OF VARIABILITY IN 1000-500MB THICKNESS AND LONGWAVE-WINDOW VS. SURFACE TEMPERATURE.

```
   PROGRAM        INPUT(S)           OUTPUT(S)
   *******        ********           *********
   FILRET         RTVL FILE(24)      RTVL FILE(24), WITH 'FAILED'
                  DATA CARD             SOUNDINGS FLAGGED
                                     PRINTOUT

NOTE:
   TO CONTROL FILTERING PARAMETERS ... SEE SOURCE CODE FOR DETAILS

 *****
 *****
ENHANCEMENT
 ***********
   FUNCTION: ADD MICROWAVE-ONLY SOUNDINGS IN AREAS WHERE INFRARED
RETRIEVALS WERE NOT MADE, OWING TO HEAVY CLOUDINESS, OR WERE FLAGGED
'FAILED' BY THE FILTER PROGRAM.  THIS PROGRAM WAS ORIGINALLY DEVELOPED
WHEN ONLY STATISTICAL RETRIEVALS COULD BE MADE (BY 'TOVRET'); IF THE
PHYSICAL RETRIEVAL ('FXTIRO') IS USED, ENHANCEMENT SHOULD NOT BE NEEDED.

   PROGRAM        INPUT(S)           OUTPUT(S)
   *******        ********           *********
   ENHRET         LO-RES TCPOG(17)   RTVL FILE(24)
                  SOUNDER FILE(23)
                  RTVL FILE(24)
                  RTVL COEF(25)

NOTE:
   SAME COEFFICIENTS AS USED WITH 'TOVRET'

 *****
 *****
GEOSTROPHIC WINDS
 *****************
  FUNCTION: DETERMINE GEOSTROPHIC WINDS FOR 'GOOD' SOUNDINGS IN RETRIEV-
AL FILE, BY LEAST-SQUARES OBJECTIVE ANALYSIS OF HEIGHT FIELDS.

   PROGRAM        INPUT(S)           OUTPUT(S)
   *******        ********           *********
   WINRET         RTVL FILE(24)      RTVL FILE(24)
                  DATA CARD

NOTE:
   TO CONTROL QUANTITY OF PRINTOUT

 *****
 *****
REDUNDANCY ELIMINATION
 **********************
   FUNCTION: ELIMINATE REDUNDANT INFRARED RETRIEVALS, BASED ON VARIABIL-
ITY IN SELECTED HIRS CHANNELS.
```

PROGRAM	INPUT(S)	OUTPUT(S)
*******	*********	*********
REDRET	RTVL FILE(24)	RTVL FILE(24)
	DATA CARD	

NOTE:
TO SPECIFY OTHER THAN DEFAULT (BUILT-IN) CONTROL PARAMETERS

*****
*****

RETRIEVAL PLOTTERS
****

FUNCTION: TO PLOT VARIOUS QUANTITIES FROM THE RETRIEVAL FILE. INPUT CONSISTS OF THE RETRIEVAL FILE(24) AND DATA CARDS TO CONTROL THE LOCATION AND PARAMETERS PLOTTED ... SEE SOURCE CODE FOR DETAILS.

PROGRAM	PRODUCT
*******	*******
TOVPLFIL	IR-MW SOUNDING DIFFERENCES, WITH CHARACTERS APPENDED TO DENOTE RESULTS OF 'FILRET' AND 'REDRET'
TOVPLDIF	IR-MW DIFFERENCES
TOVPLTEM	IR-RETRIEVAL TEMPERATURES
TOVPLDEW	IR-RETRIEVAL DEWPOINTS
TOVPLTBB	SOUNDING TBB'S FOR SPECIFIED CHANNELS

'TOVPLFIL' SHOULD BE RUN BEFORE THE NEXT PROGRAM TO BE DESCRIBED ('COMRET'); THE OTHER PLOTTERS SHOULD BE RUN AFTER FILE-COMPRESSION.

*****
*****

FILE COMPRESSION
****

FUNCTION: COMPRESS THE RETRIEVAL FILE BY DELETING SOUNDINGS THAT HAVE BEEN FLAGGED BY 'FILRET' AND/OR 'REDRET', AND MOVING THE REMAINING SOUNDINGS TO REPLACE THE 'EMPTY' RECORDS.

PROGRAM	INPUT(S)	OUTPUT(S)
*******	*********	*********
COMRET	RTVL FILE(24)	RTVL FILE(24)

*****
*****

NOTE ON 'SURFACE DATA'

PROGRAMS 'TOVRET' AND 'ENHRET' INVOKE SUBROUTINE 'RTV', WHICH IN TURN CALLS SUBROUTINE 'GETSFC'. IN LIKE MANNER, THE ROUTINE 'GETSFX' IS CALLED FROM WITHIN 'FXTIRO'. IT IS OBVIOUS FROM INSPECTION OF THE SOURCE CODE THAT THESE ARE DUMMY ROUTINES. THE USER SHOULD PROVIDE AN INTERFACE TO ACTUAL SURFACE DATA (1000MB HEIGHT, TEMPERATURE, AND DEWPOINT) IF SUCH INFORMATION IS AVAILABLE AT HIS INSTALLATION.

*****
*****

END OF DOCUMENT

Appendix B: Temperature Retrievals over Mountains Using One FOV

Frank Loechner

excerpted from

The Technical Proceedings of the First International
TOVS Study Conference (editor P. Menzel)

TEMPERATURE RETRIEVALS OVER MOUNTAINS USING ONE FOV

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1. Introduction

Most of the TOVS software uses boxes of 3x3 fields of view (FOVs) to evaluate clear-column radiances. This restricts the horizontal resolution of the results to 100x70 km in the subsatellite point. If we can reduce this resolution to one FOV, TOVS retrievals would be an important tool in mesoscale investigations. Therefore temperature profiles were calculated using 3x3 boxes and one FOV at sites with different terrain, and compared with conventional data. This work was done at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in Madison together with C. M. Hayden and A. J. Schreiner.

2. Technique

Single FOV retrievals are possible only in cloud free situations. For 5 March 1982 the AVHRR picture of channel 2 (Figure 1) shows clear sky over parts of western Europe and snowcovered Alps. This is the overpass of 1330 GMT, the only one, for which DFVLR received AVHRR data. Preliminary comparisons between single FOV and 3x3 retrievals over the North Sea and France showed excellent agreement.

The single FOV retrievals were calculated with the program MXTI, the 3x3 retrievals with the related software MYTI. Both were developed at CIMSS. They use the iterative scheme and topographical data of 10 nautical miles horizontal resolution. A regression without conventional surface data was chosen as a first guess. The main results do not change, if other first guess or surface data are applied.

For the comparisons in mountains, the following groups of adjacent FOV's were chosen (Figure 2):

a. Lac Leman, an easy terrain without high mountains, with a weather station nearby at Payerne and a contiguous FOV in the mountains,

b. three sites with high mountains at Pontresina, Umbrail pass, and Fluchthorn,

c. four sites around Innsbruck, two of them at the border of the mountains, which can be regarded as mixed terrain. Weather stations are at Hohenpeissenberg and Garmisch-Partenkirchen.

3. Results

The comparison between the radiosonde soundings of Payerne (Figure 3) and the retrievals using single FOV and 3x3 boxes at Lac Leman (Figure 4) shows good agreement. Details at 550 mb and 300 mb are not reproduced by the computations as expected. The deviation of the temperature at 850 mb is smaller for the single FOV retrieval.

The adjacent FOV at Sion is located in high mountains. In spite of the different terrain, the single FOV results for Lac Leman and Sion (Figure 5) are very similar.

There are no radiosonde data for Umbrail pass, Pontresina, and Fluchthorn. Assuming that 3x3 retrievals produce correct results, if the type of the terrain is the same for all FOV's, only small deviations are found for single FOV retrievals (Figure 6).

In the comparison between adjacent FOV's with high mountains, Umbrail and Pontresina (Figure 7), Pontresina and Fluchthorn (Figure 8), good agreement is obtained for single FOV computations.

Problems arise at the border of the mountains with 3x3 retrievals. Large differences are seen between the profiles of Lac Leman and Sion (Figure 9). They were not found for the single FOV calculations and are due to the results at Sion. Here the retrievals for single FOV and 3x3 boxes disagree again (Figure 10). The comparison with the measurements at Payerne favour the single FOV result.

A similar but less severe situation emerge at Mittenwald for single FOV and 3x3 retrievals (Figure 11). The observations of Hohenpeissenberg (Figure 12) prefer the single FOV profile. Again almost no deviations were found, when the single FOV profiles of Mittenwald and the adjacent site Zugspitze are compared (Figure 13).

The reason for the differing results with 3x3 computations seems to be the average value of the elevation of the terrain. If the elevations assigned to the FOV's used to calculate a 3x3 retrieval differ considerably, problems arise. In contrast, retrievals using one FOV produce consistent temperature profiles over snow-covered mountains, and at the border of mountains as well.

Figure 1. AVHRR picture, Channel 2, 5 March 1982, 1330 GMT.

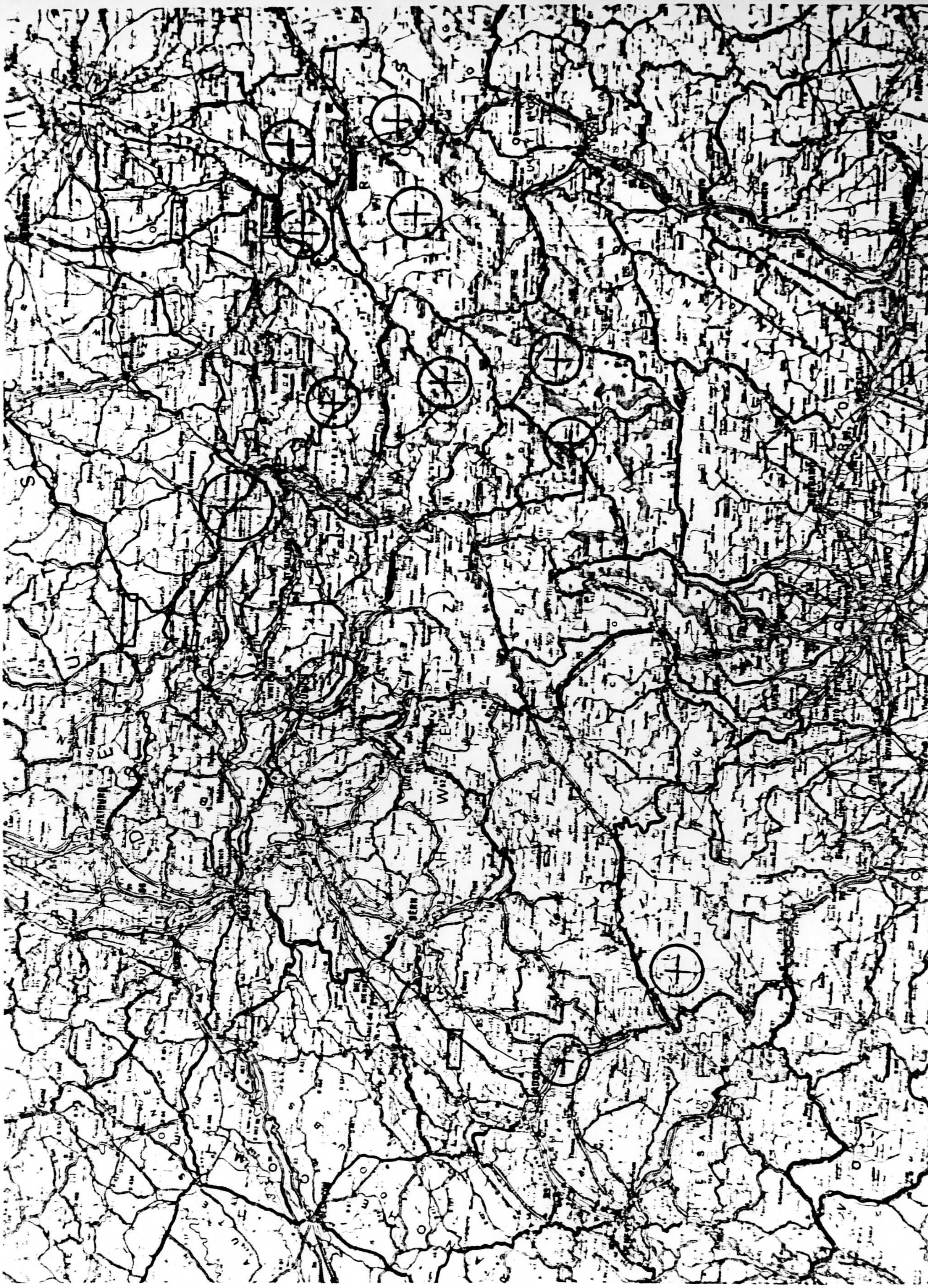


Figure 2. Fields of view selected for comparisons in mountains. The diameter of the circles is approximately 20 km.

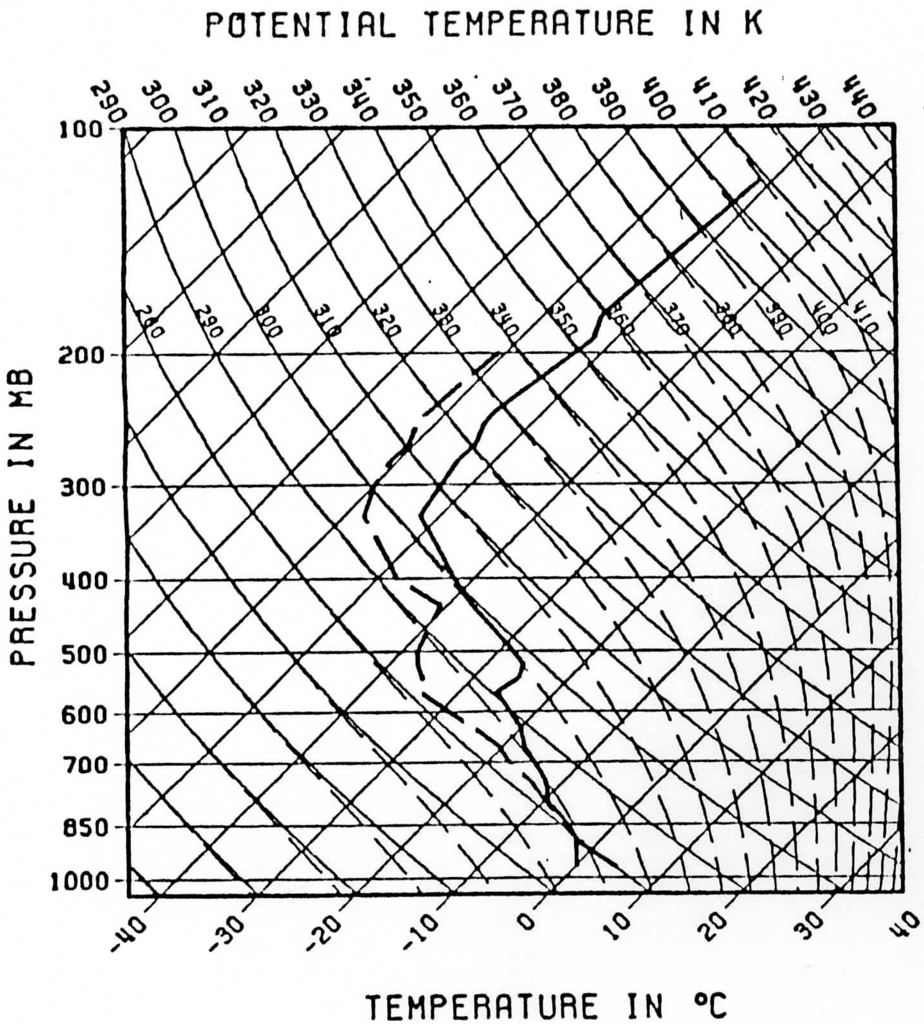


Figure 3. Radiosonde observation of Payerne, 5 March 82, 12 GMT.

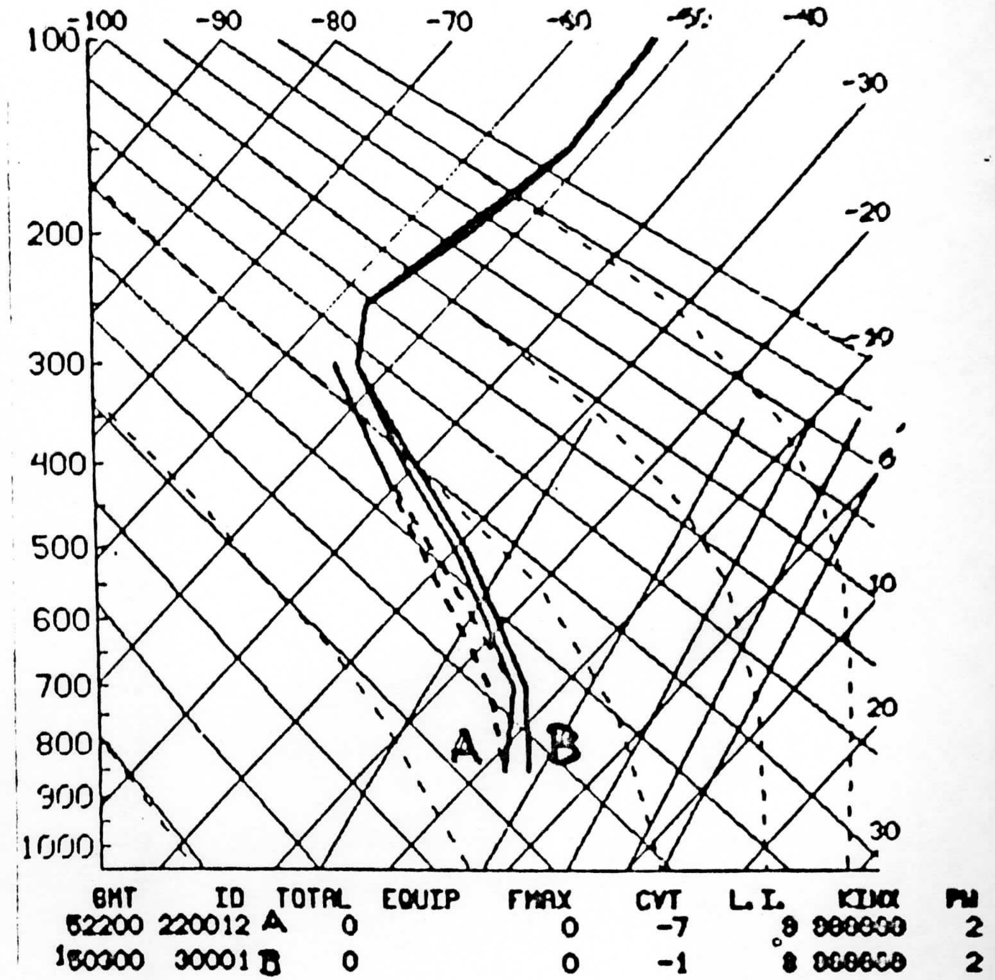
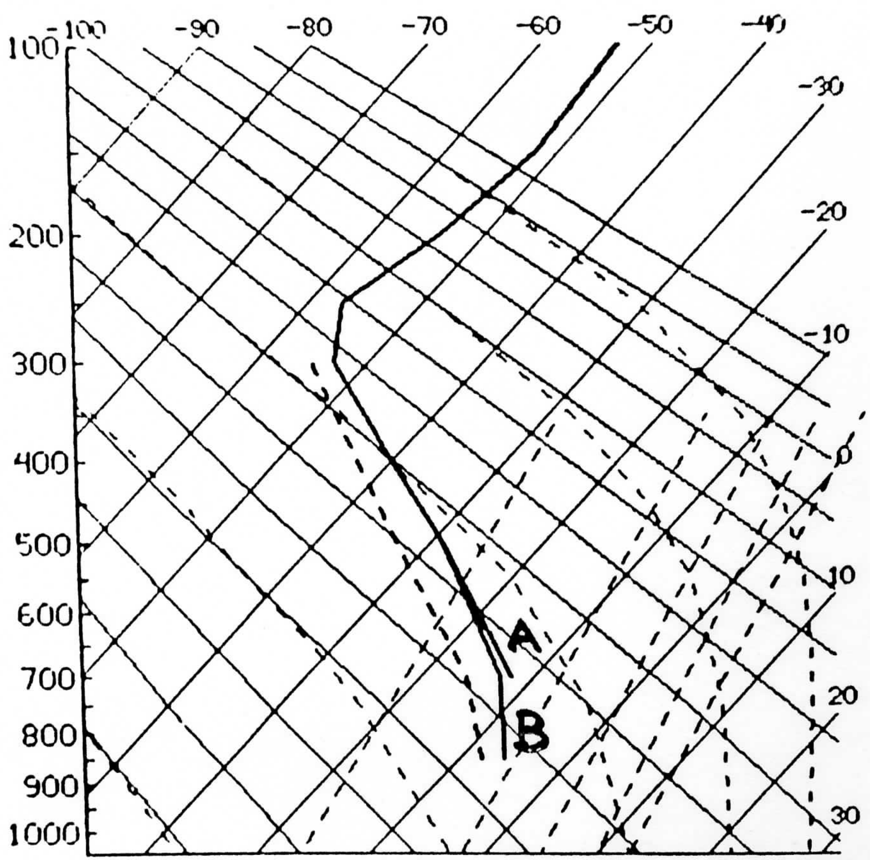
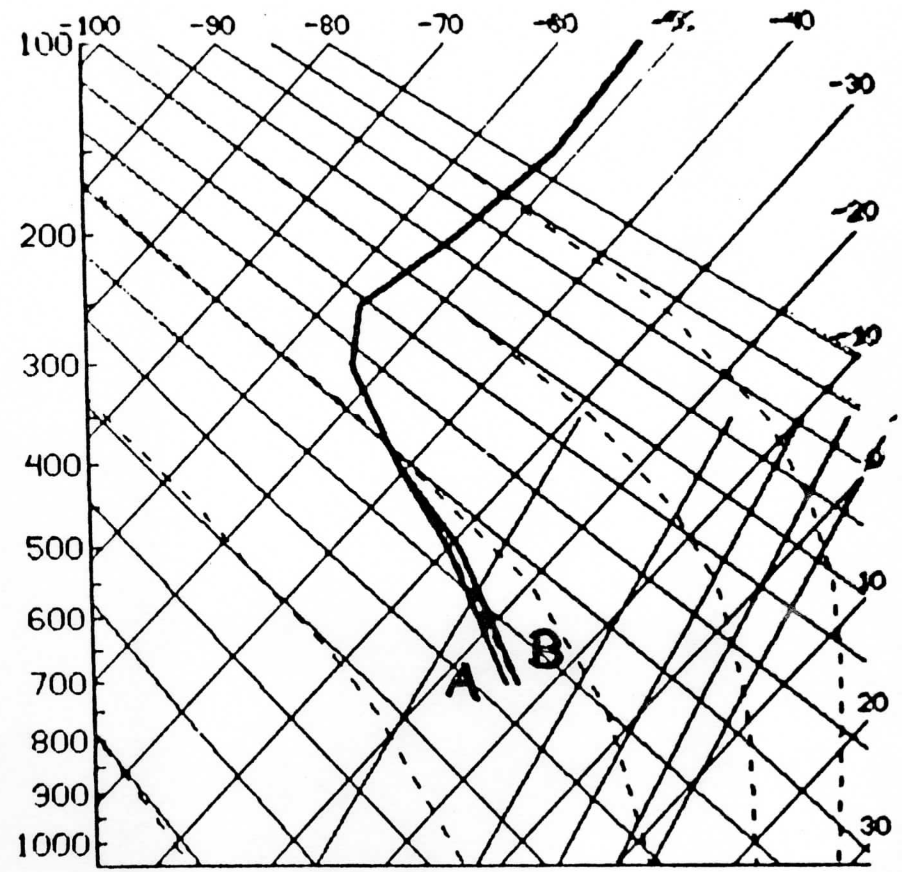


Figure 4. 3x3 (A) and single FOV (B) retrievals at Lac Leman, solid lines are temperatures.



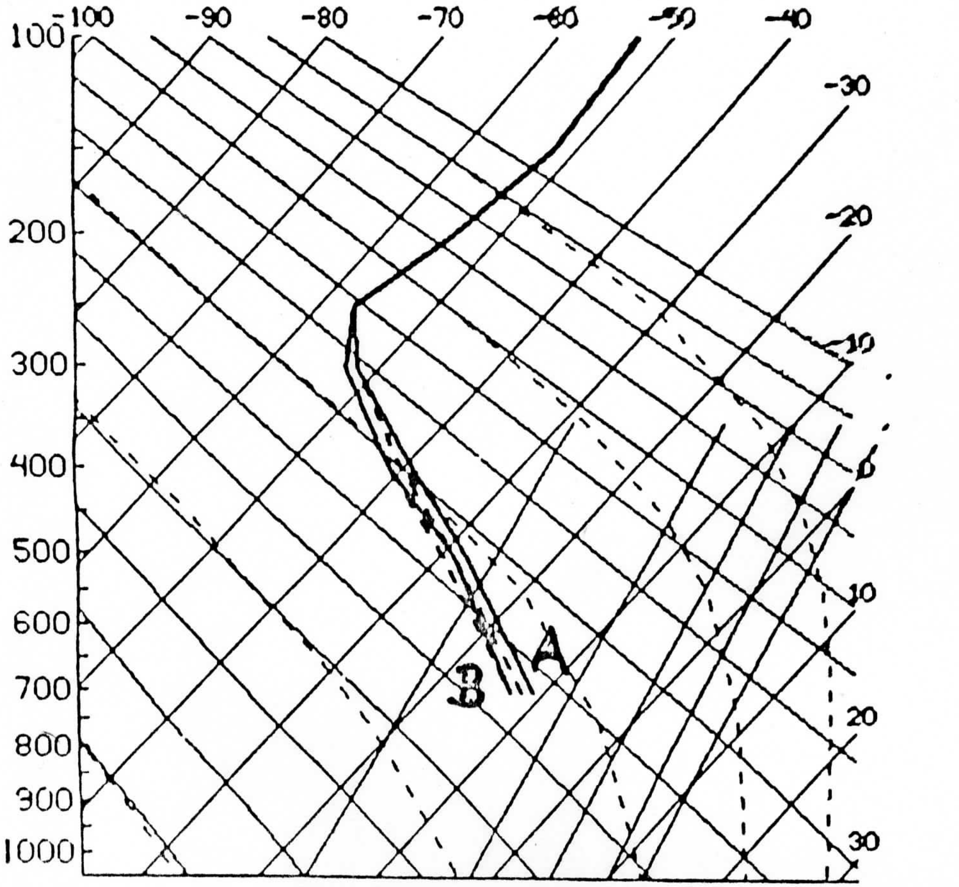
GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
50300	30001 B	0		0	-1	8	888888	2
1150300	30002 A	0	0	0	-10	3	888888	1

Figure 5. Single FOV retrievals at Sion (A) and Lac Leman (B), solid lines are temperatures.



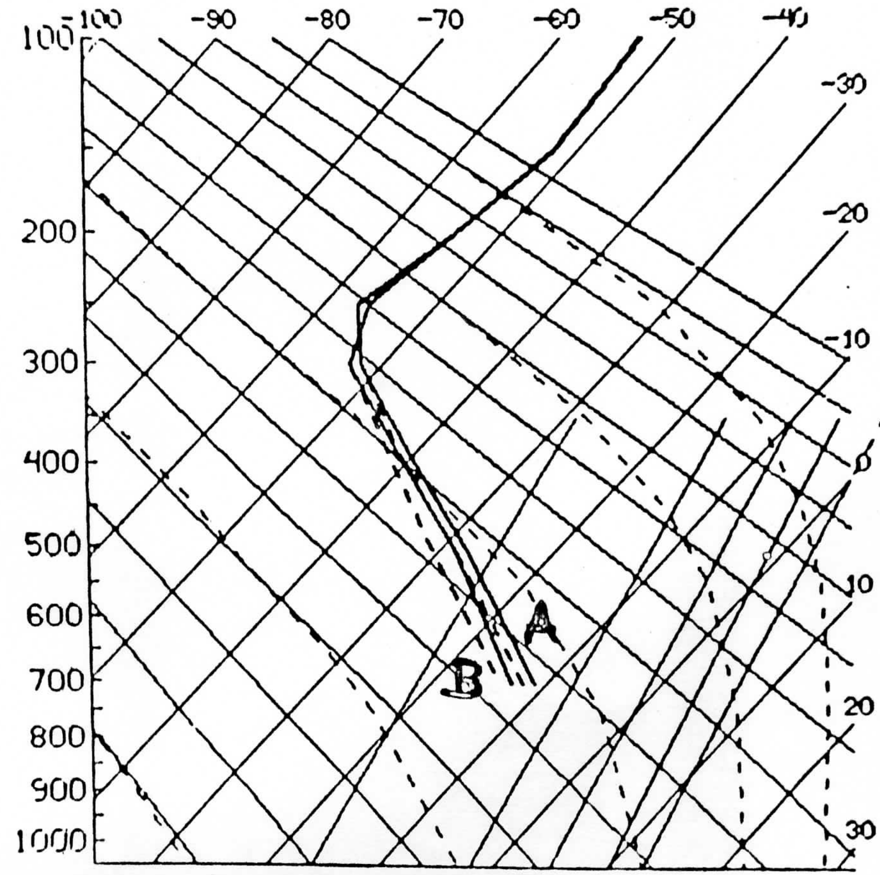
GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
52200	220014 A	0	0	0	-12	3	888888	1
151800	180003 B	0	0	0	-11	3	888888	1

Figure 6. 3x3 (A) and single FOV (B) retrievals at Umbrail pass, solid lines are temperatures.



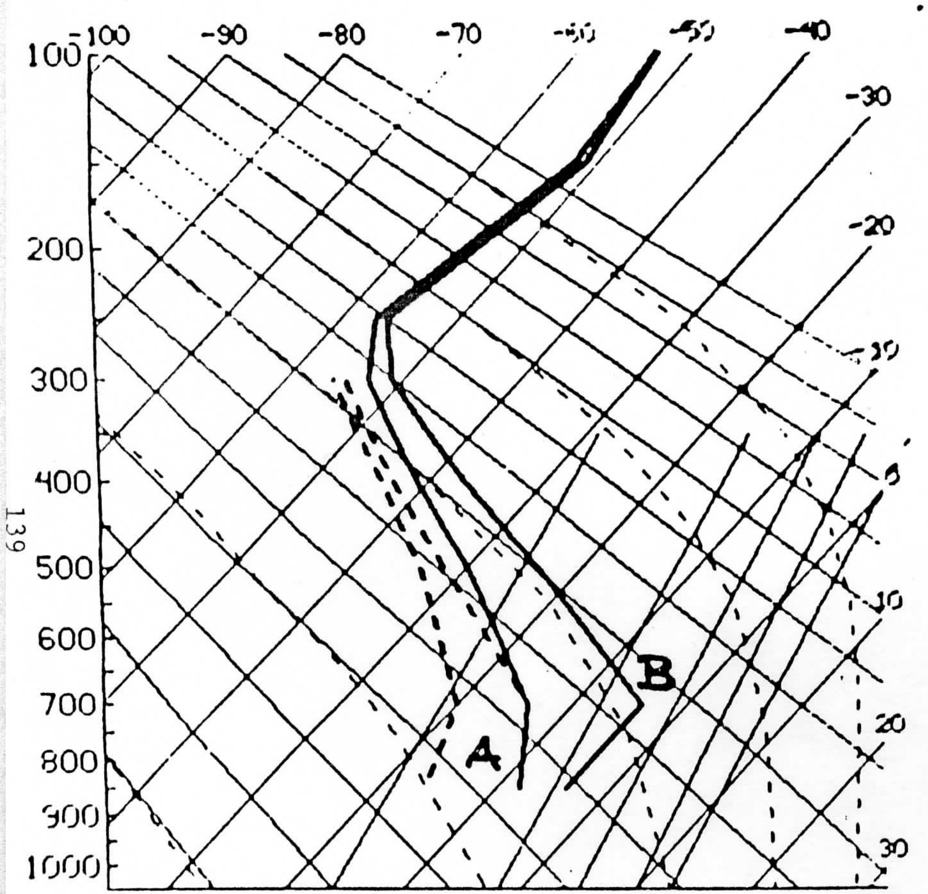
GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
51800	180001 A	0	0	0	-9	3	888888	1
551800	180003 B	0	0	0	-11	3	888888	1

Figure 7. Single FOV retrievals at Pontresina (A) and Umbrail Pass (B), solid lines are temperatures.



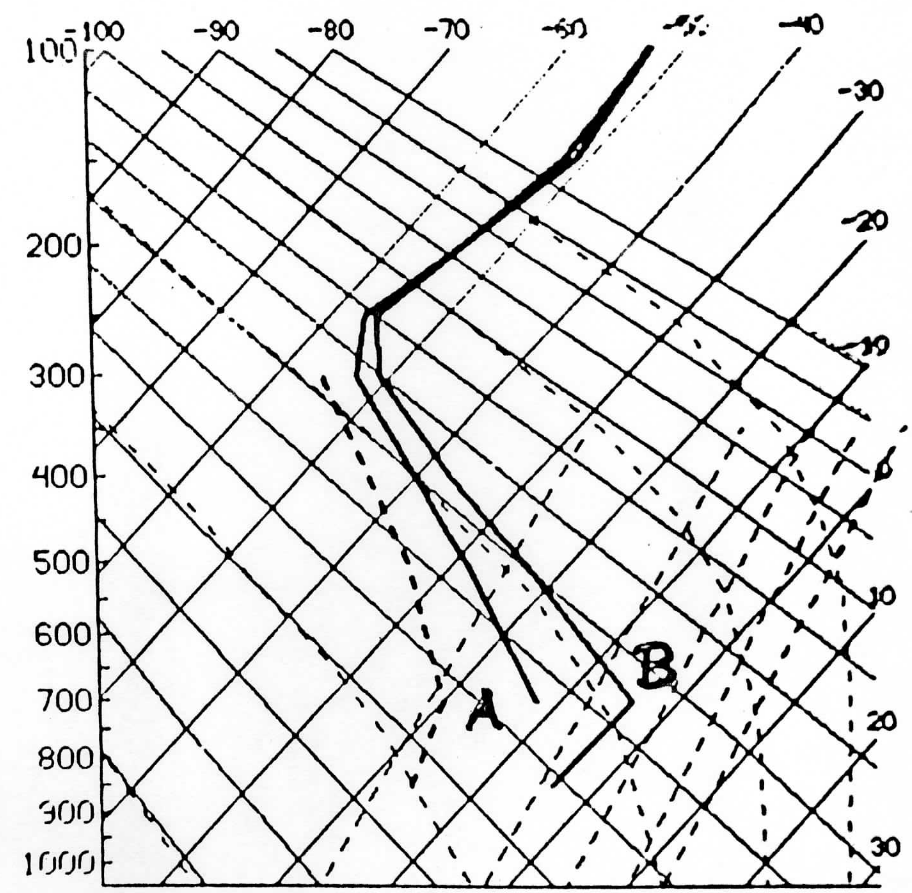
GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
51800	180001 A	0	0	0	-9	3	999999	1
1151800	180002 B	0	0	0	-10	3	888888	1

Figure 8. Single FOV retrievals at Pontresina (A) and Fluchthorn (B), solid lines are temperatures.



GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
52200	220012 A	0		0	-7	9	888888	2
152200	220013 B	0	0	0	16	11	888888	1

Figure 9. 3X3 retrievals at Lac Leman (A) and Sion (B), solid lines are temperatures.



GMT	ID	TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
52200	220013 B	0	0	0	16	11	888888	1
160400	30002 A	0	0	0	-10	3	888888	1

Figure 10. Single FOV (A) and 3X3 (B) retrievals at Sion, solid lines are temperatures.

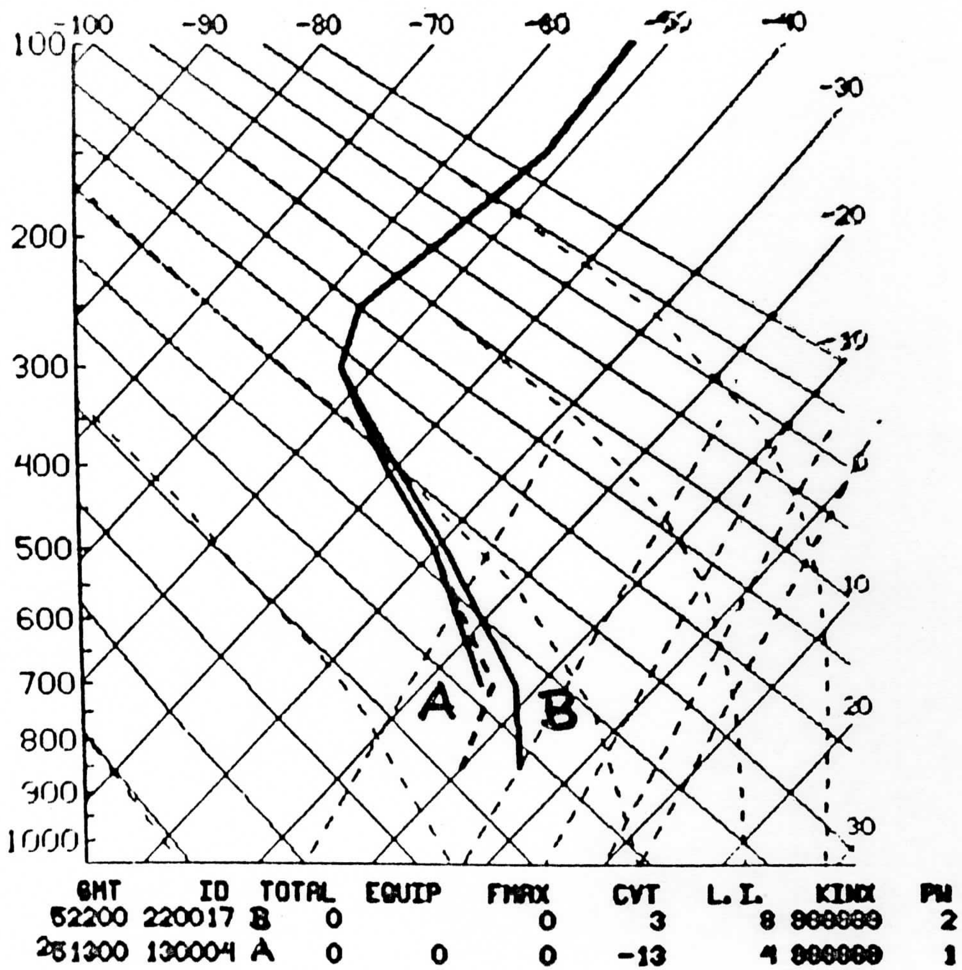


Figure 11. Single FOV (A) and 3x3 (B) retrievals at Mittenwald, solid lines are temperatures.

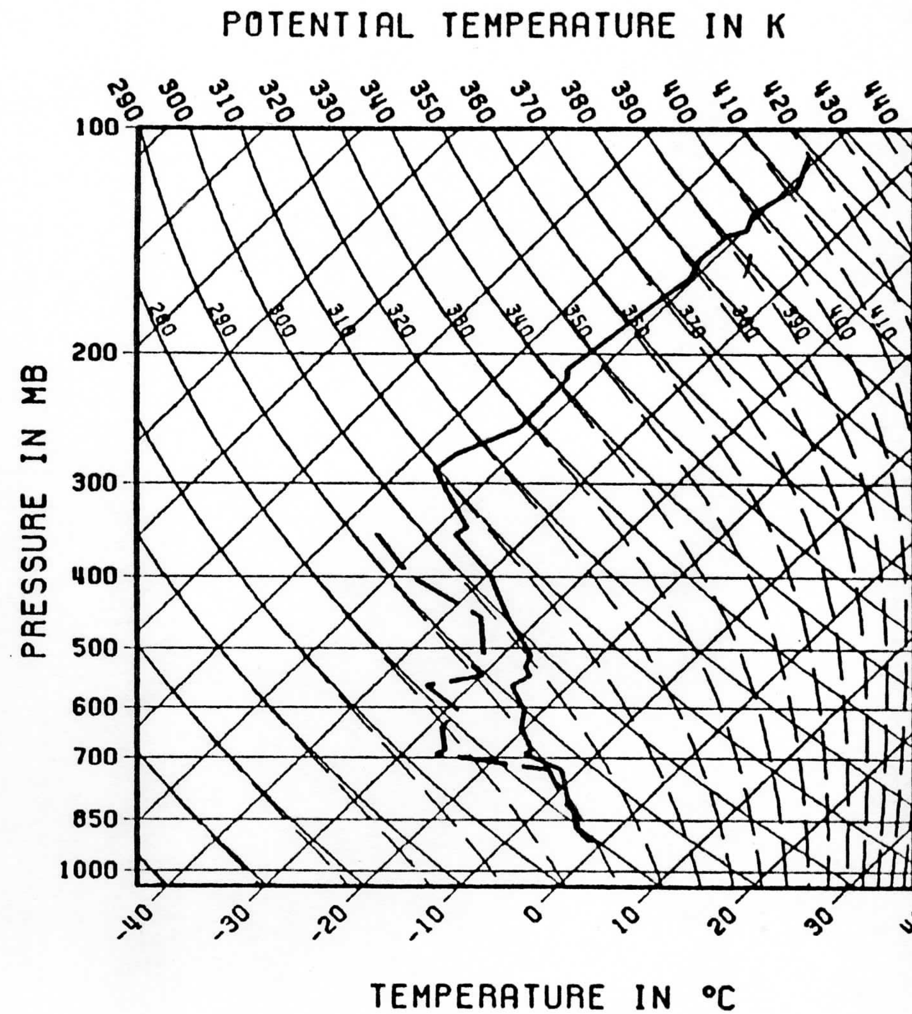
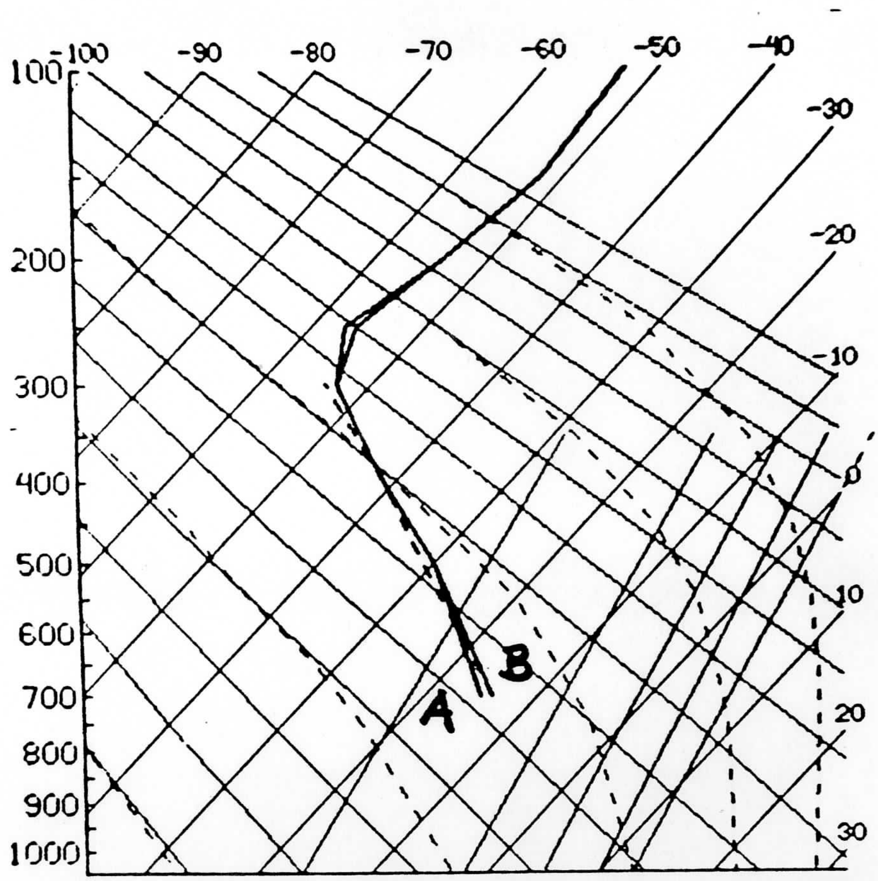


Figure 12. Radiosonde observation of Hohenpeissenberg, 5 March 1982, 1050 GMT.



6MT	ID		TOTAL	EQUIP	FMAX	CVT	L.I.	KINX	PW
51300	130001	B	0	0	0	-12	4	999999	1
1151300	130004	A	0	0	0	-13	4	999999	1

Figure 13. Single FOV retrievals at Mittenwald (A), and Zugspitze (B), solid lines are temperatures.

Appendix C: Limb Effects in Satellite Temperature Sounding

J. LeMarshall and A. Schreiner

LIMB EFFECTS IN SATELLITE TEMPERATURE SOUNDING

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2/JFL1/12

Abstract

To date, operational satellite temperature retrievals from the TIROS-N/NOAA A-G series of satellites and a large percentage of those produced for research purposes have used statistical techniques to estimate limb effects in satellite observed radiances. In this study temperature profiles have been derived using the radiative transfer equation in a form which properly takes into account the angle of observation. These temperature profiles have then been compared to those derived using the radiative transfer equation with "nadir radiances" produced by a statistical limb correction technique similar to those now used operationally. This comparison has shown significant differences in the derived temperature profiles at large viewing angles, particularly in the case of strong meridional temperature gradients. Overall, the results suggest that for the calculation of temperature profiles from non-nadir observations, the more proper physical solution is the preferred procedure for deriving temperature fields.

1. Introduction

During the "First International TOVS Study Conference" at Igls, Austria in 1983, stress was put on the use of physically based rather than empirical algorithms in future temperature retrieval procedures (Menzel and Lynch, 1983). In this spirit and also because of the widespread operational use of statistically limb corrected data, a study was undertaken to gauge the differences between temperature soundings generated from a full physical solution of the radiative transfer equation taking into account slant path, as opposed to those derived using a statistical correction to the slant path radiances followed by a physical solution of a nadir form of the radiative transfer equation.

Two adjacent orbits starting at 1200 GMT and 1340 GMT on 4 March 1982 were used for the study. These were chosen as they had been extensively studied at the "First International TOVS Study Conference," overlaid an area with a good conventional data base and, most importantly, exhibited a strong meridional temperature gradient. This strong gradient provided a means of examining any loss of information as a result of the limb modelling procedures.

2. The Retrieval Technique

The retrieval technique used produces temperature, moisture and ozone profiles which are a full solution of the radiative transfer equation. The solution methodology is described in detail in Smith et al. (1983). Briefly, the physical retrieval algorithm solves for a departure of the true atmospheric temperature, moisture, and ozone profile from a "guess" condition, as a function of the departure of observed radiances from those calculated for the "guess" profile. In this study a climatological first guess was used, tied to a surface air temperature and surface pressure derived from conventional surface data, to constrain the lowest levels of the soundings.

3. The Limb Correction Techniques

3.1 Statistical

The statistical limb correction technique is similar to that used operationally (Werbowetski, 1981) and was of the form used in the "First TOVS Export Package." The statistical limb correction coefficients, which are applied to non-nadir radiance observations to give nadir radiances, were generated using synthetic radiance data in a manner described by Smith et al. (1974). A global representation of 100 temperature and water vapor mixing ratio profiles was used to generate synthetic radiances and brightness temperatures at nadir and non-nadir angles. In the case of High-resolution Infra-Red Sounder (HIRS) observations, each profile was used with a variety of cloud heights and amounts to produce the radiances. For the Microwave Sounding Unit (MSU) data, although land and water surfaces are treated separately, hybrid samples were used for every fifth profile and one in ten soundings over land had randomly introduced precipitating clouds. In addition, the effect of sidelobes and emissivity was removed from the nadir MSU radiances. Limb brightness temperature correction coefficients were then computed using stepwise multiple linear regression, with the differences between the vertical path and slant path synthetic data being predictands and the product of the synthetic non-nadir channel brightness temperature and secant of the local zenith angle as well as the secant itself being predictors.

3.2 Physical

The radiative transfer equation was used with non-limb corrected data to generate temperature profiles by utilizing a computationally efficient transmittance model which provided transmittances appropriate for the atmospheric path at the angle of observation. The model algorithm is similar to that described by McMillin and Fleming (1976). For the MSU transmittances, the effects of side lobes on the transmittances has been computed by a regression technique rather than using the computationally costly process of convolving the antenna gain pattern with transmittances for a number of angles (Smith et al., 1983).

4. The Retrievals

As previously described, the test orbits were processed using statistically limb corrected radiances and non-nadir radiances in conjunction with transmittances appropriate to a slant path. The temperatures were then analyzed at standard levels using the Barnes analysis scheme (Barnes, 1973). Figure 1 shows the analyzed 500 mb temperature fields, their differences, and the corresponding archived field from ECMWF. It can be seen the thermal gradients in the satellite only and ECMWF analyses show good agreement, although a bias of 1.5 degrees at 500 mb is evident for these orbits (Smith et al., 1983). An examination of the western edge of the 1340 GMT orbit shows the strong thermal gradient region has been best depicted by the full physical scheme. The differences between the two satellite analyses show little deviation in the center and become quite significant at larger angles. The differences at 700 mb and 250 mb are shown in Figure 2. Again, the differences increase at the edge and the large differences appear more frequently as one moves from 250 mb to 700 mb. The satellite analyses also show a difference over northern Africa where we believe the statistical limb correction to be less reliable because of extreme surface conditions. The distribution of differences was found to be similar for the eastern orbit.

The analyzed temperature fields were compared to the 1200 GMT radiosonde data. The differences in the root mean square error and the standard error between the limb corrected (LC) and statistically non-limb corrected (NLC) fields (LC-NLC) are shown in Figure 3. In general, both the root mean square error and standard error are reduced by using the full physical scheme. At the lowest levels the differences are small, partially as a result of surface temperature and pressure constraints on the at those levels, while for the rest of the levels a positive impact is seen as a result of the full physical retrieval scheme.

5. Conclusions

It has been shown in this study that there appear to be systematic differences between soundings generated from statistically limb corrected data using a scheme similar to that now used operationally and those generated using transmittance functions appropriate to the angle of view. These differences can be significant at larger viewing angles. It appears from the sample examined, physical retrievals which account for the angle of view explicitly are more realistic and appear to better maintain temperature gradients in the limb. Overall, it would appear that the physical modelling of limb effects in the transmittance terms of the radiative transfer equation is the preferred method for temperature retrieval.

Acknowledgments

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Figure Captions

Figure 1:

a) 500 mb temperature analysis at 1344 GMT on 4 March 1982 derived using observed radiances (NLC) and the full physical retrieval technique.

b) 500 mb temperature analysis at 1344 GMT on 4 March 1982 derived using statistically limb corrected radiances (LC).

c) 500 mb temperature analysis from ECMWF for 1200 GMT on 4 March 1982.

d) Differences in 500 mb temperature between non-limb corrected (NLC) and statistically limb corrected (LC) retrievals.

Figure 2:

a) Differences in 700 mb temperature between non-limb corrected (NLC) and statistically limb corrected (LC) retrievals.

b) Differences in 250 mb temperature between non-limb corrected (NLC) and statistically limb corrected (LC) retrievals.

Figure 3: The differences in root mean square and standard error compared to radiosondes between statistically limb corrected (LC) retrievals and the non-limb corrected (NLC).

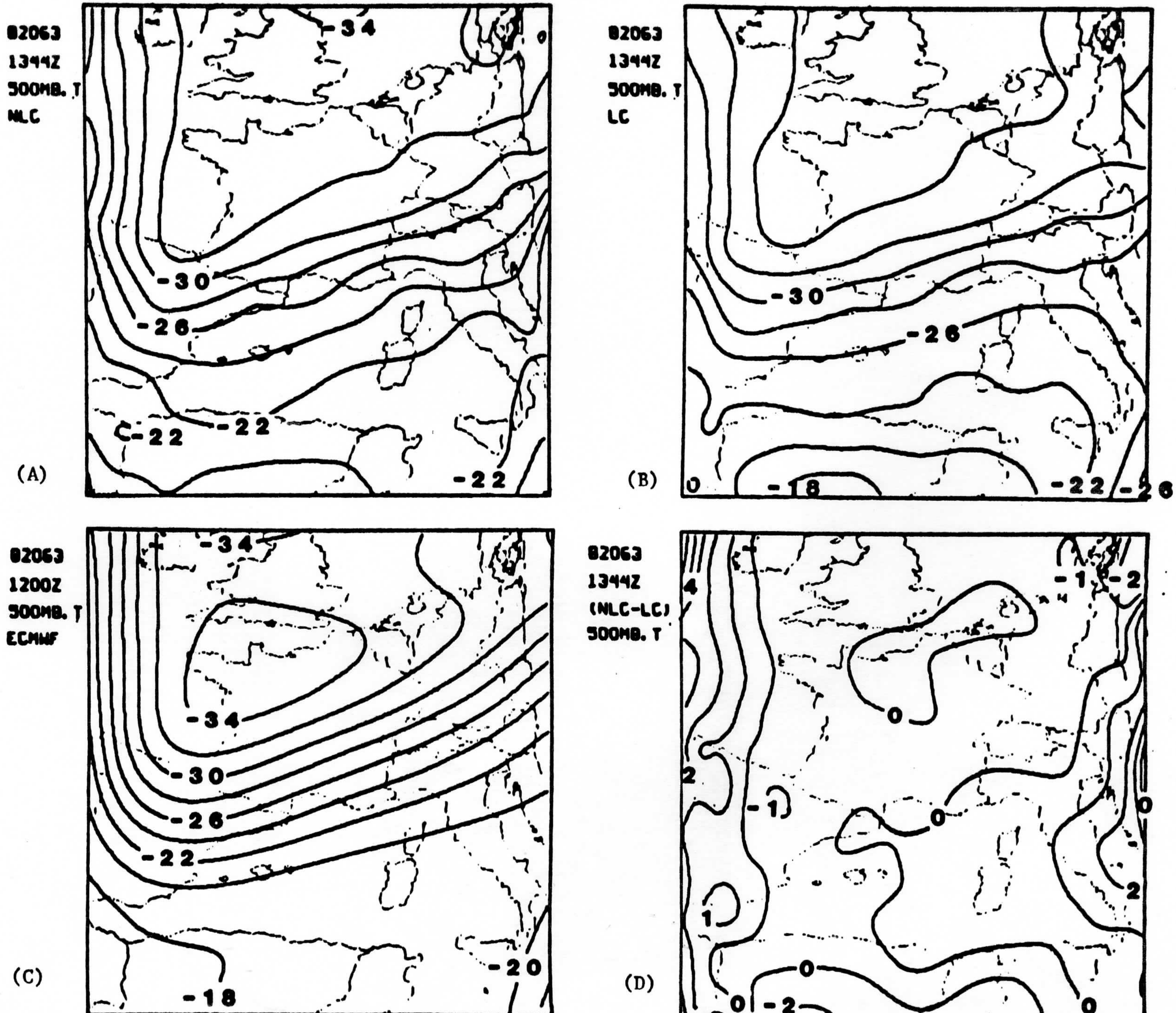
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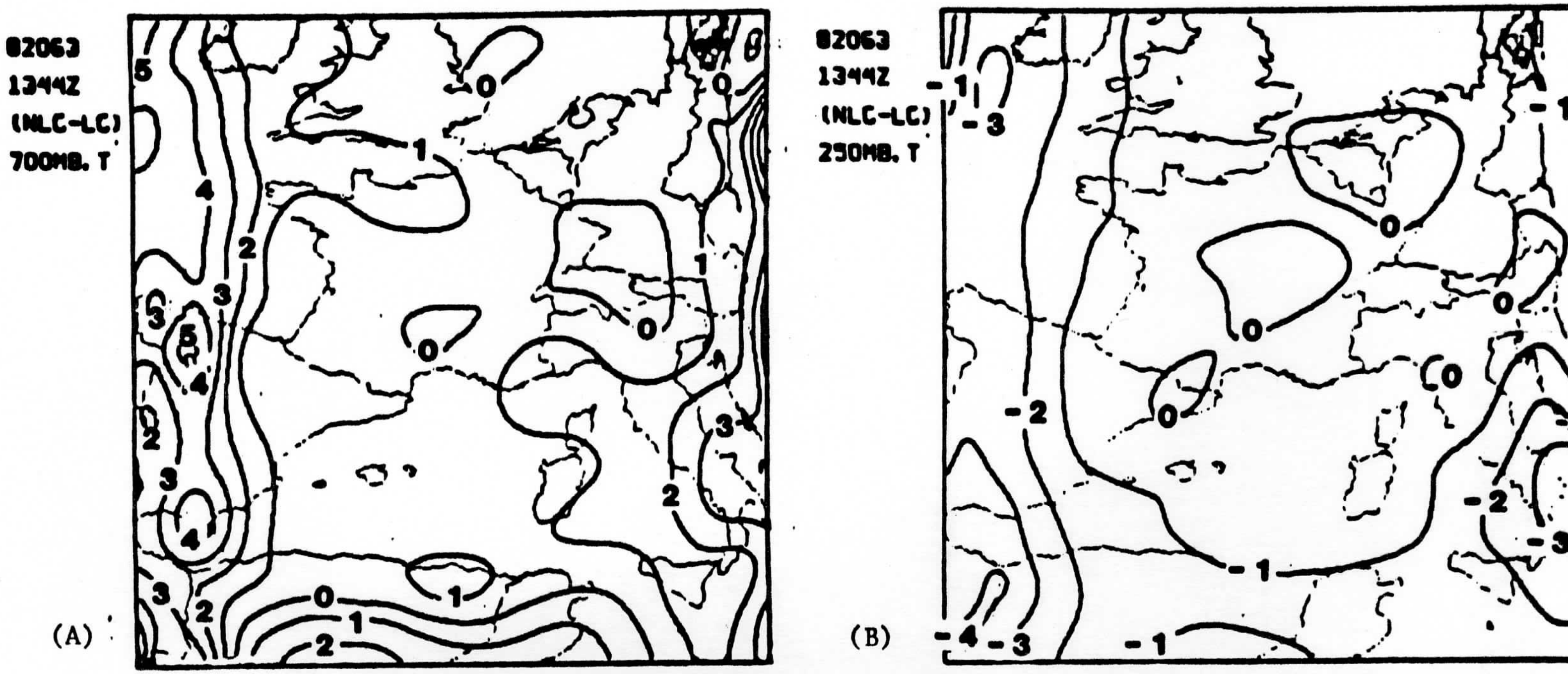
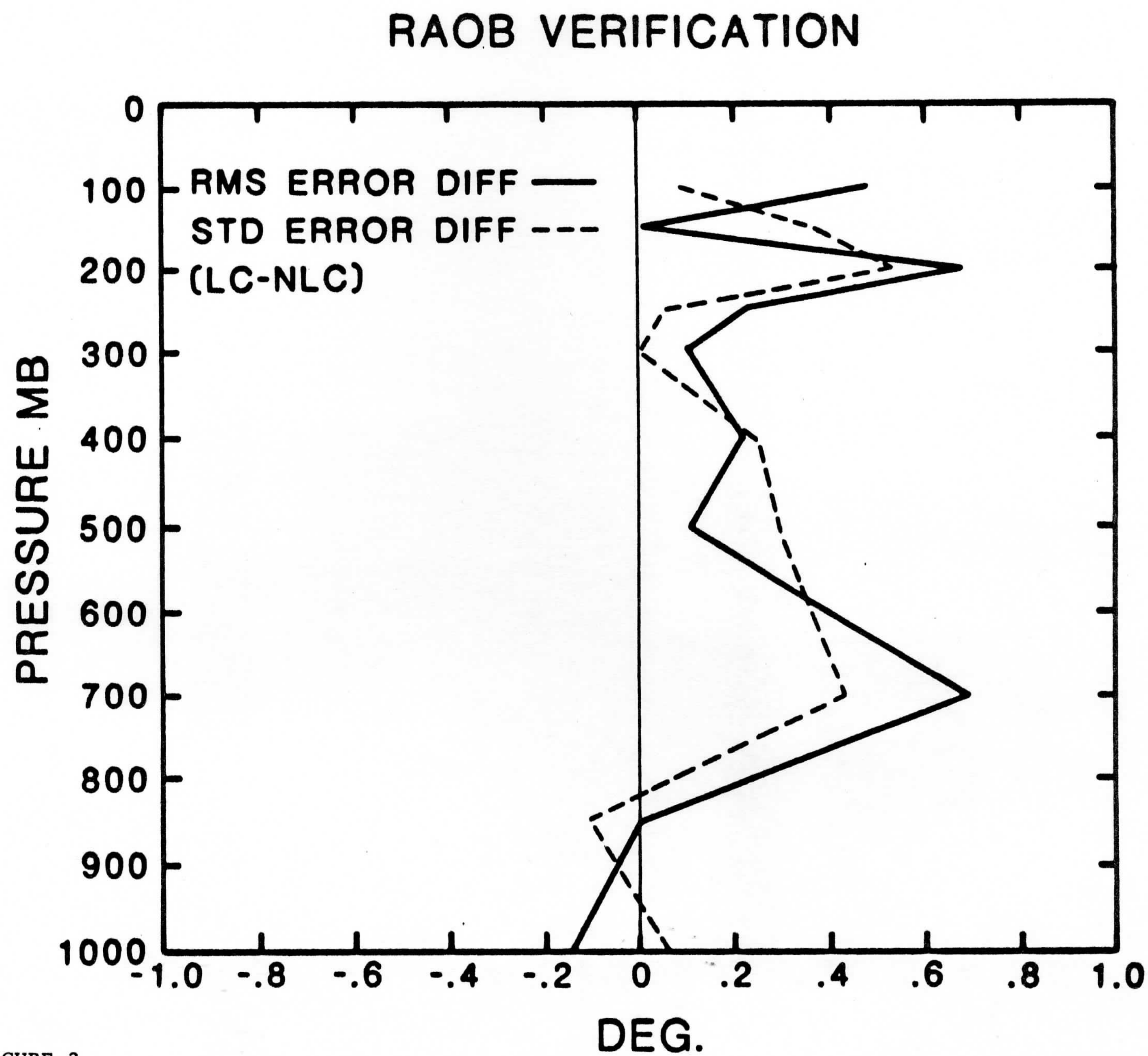
FIGURE 1



(A) (B)

FIGURE 2


RAOB VERIFICATION
RMS ERROR DIFF
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0
.2
.4
.6
.8
1.0
DEG.

FIGURE 3

Appendix D: The Simultaneous Retrieval Export Package

W. L. Smith et al.

excerpted from

The Technical Proceedings of the Second International TOVS Study Conference (editor, P. Menzel)

THE SIMULTANEOUS RETRIEVAL EXPORT PACKAGE

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1. INTRODUCTION

As part of the "First International TOVS Study Conference", a description of a physical algorithm for retrieving temperature and moisture soundings from TOVS radiance data was described (Smith et al., 1983). This algorithm was incorporated into the "TOVS Export Package" made available by CIMSS to direct readout users of TOVS data. The physical algorithm consisted of the application of the Smith-Iterative Solution (Smith, 1970) for temperature and moisture profiles. In that approach, (1) an initial profile for temperature and water vapor is specified from climatology, statistical regression, or from an NWP model, (2) radiances are calculated from the initial profiles, (3) the temperature profile is adjusted in an iterative manner until there is agreement between the observed and calculated radiances in the cloud insensitive microwave O_2 channels, (4) the infrared window channels are used to define either the surface skin temperature or the temperature of cloud within the instrument's field of view and the cloud level is defined using the microwave specified temperature profile, (5) the guess moisture profile is adjusted to reflect the existence of cloud by assuming 100% relative humidity at the cloud level and then further adjusted in an iterative manner in order to achieve convergence between observed and calculated radiance for the water vapor channels, and (6) the temperature profile is then further adjusted in an iterative manner in order to achieve convergence between the radiances observed and calculated in the infrared CO_2 channels.

Since the first Igls conference, a new retrieval algorithm has been developed which permits the simultaneous retrieval of surface-skin (or cloud) temperature, and the temperature and moisture profiles. The advantage of the "simultaneous solution" is two-fold: (1) the radiances observed in all channels are used to solve for all parameters simultaneously, thus alleviating the problem of the interdependence of the radiance observation upon the three parameters, and (2) since a direct analytical solution is employed, the process is computationally efficient.

In this paper the new algorithm now incorporated in the "TOVS export package" is described. As with the prior "iterative" algorithm, the physical nature of the solution permits the influence of surface variables (i.e., terrain elevation, emissivity, and temperature) and cloudiness to be accounted for in the profile determinations. The cloud handling algorithm is modified to enable the infrared data to be utilized in partly cloudy as well as cloud overcast sky conditions. The low sensitivity of the simultaneous solution to the initial guess profile and the improved performance of the simultaneous retrieval method compared to the previously established iterative technique (Smith et al., 1983; Susskind, 1984) are demonstrated from TOVS orbits over Europe obtained during the ALPine EXperiment (ALPEX) as selected by the International Radiation Commission's TOVS Working Group for the intercomparison of retrieval methods. The physics for treating surface emissivity, terrain elevation, and reflected sunlight are not described here since these aspects have been provided in the previous report (Smith et al., 1983).

2. DIRECT PHYSICAL SOLUTION

An important advance in the profile retrieval methodology is the simultaneous temperature and water vapor solution (Smith and Woolf, 1984). In order to achieve the simultaneous solution, the integral form of the radiative transfer equation is integrated by parts and treated in the perturbation form:

$$\delta T^* = \int_0^{P_s} \delta U \frac{\partial T}{\partial p} \frac{\partial \tau}{\partial U} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dp - \int_0^{P_s} \delta T \frac{\partial \tau}{\partial p} \frac{(\partial B/\partial T)}{(\partial B/\partial T^*)} dp + \delta T_s \frac{(\partial B_s/\partial T_s)}{(\partial B/\partial T^*)} \quad (1)$$

where T^* is brightness temperature, U is precipitable water vapor, B is Planck radiance, T is temperature, T_s is surface-skin temperature, τ is transmittance, and p is pressure. The perturbation, δ, is with respect to an a-priori estimated or mean condition. The pressure dependence of all integrand variables is to be understood. In order to solve (1) for δU, δT, and δT_s from a set of spectrally independent radiance observations, the perturbation profiles are represented in terms of arbitrary pressure functions, $\phi(p)$:

$$\delta q(p) = g \sum_{i=1}^{N} \alpha_i q_0(p) \phi_i(p) \quad (2a)$$

$$\delta T(p) = - \sum_{i=N+1} \alpha_i \phi_i(p) \quad (2b)$$

where q(p) is the water vapor mixing ratio and g is gravity. The zero subscript indicates the a priori condition. Equation 2a implies from the gas law and hydrostatic equation that

$$\delta U(p) = \sum_{i=1}^{N} \alpha_i \int_0^{P} q_0(p) \phi_i(p) dp \ . \quad (2c)$$

Substituting representations (2b) and (2c) into (1) and letting $\alpha_0 = \delta T_s$ yields for each spectral radiance observation, δT_j^*, for a set of K spectral channels:

$$\delta T_j^* = \sum_{i=0}^{M} \alpha_i \Phi_{ij} \qquad j=1,2,\ldots,K \tag{3}$$

where

$$\Phi_{0,j} = \frac{\partial B_j / \partial T_s}{\partial B_j / \partial T_j^*} \tau_{s,j}$$

$$\Phi_{i,j} = \int_0^{P_s} \left[\int_0^{P} q_0 \phi_i \, dp\right] \left[\frac{\partial T}{\partial p} \frac{\partial \tau_j}{\partial U} \frac{\partial B_j / \partial T}{\partial B_j / \partial T_j^*}\right] dp \qquad i \leq N \tag{4}$$

$$\Phi_{i,j} = \int_0^{P_s} \phi_i \left[\frac{\partial \tau_j}{\partial p} \frac{\partial B_j / \partial T}{\partial B_j / \partial T_j^*}\right] dp \qquad N < i \leq M .$$

The $\Phi_{i,j}$ quantities are calculated from the <u>a- priori</u> estimated or mean profile conditions. Written in matrix form

$$t^* = \Phi\alpha \tag{5}$$

where t^* is a row vector of K radiance observations, α is a row vector of M+1 coefficients, and Φ is a matrix having dimensions $(K \times M+1)$. Assuming that $K \geq M+1$, then the least squares solution of (5) is employed to give

$$\alpha = (\Phi^T \Phi)^{-1} \Phi^T t^* \approx (\Phi^T \Phi + \gamma I)^{-1} \Phi^T t^* \tag{6}$$

where $(\ )^T$ indicates matrix transposition and $(\ )^{-1}$ indicates matrix inverse. The γI term, where γ (nominally 0.1) is a scalar and I is the identity matrix, is incorporated to stabilize the matrix inverse. Once the α_i's are determined, δT_s, δq, and δT are specified from (2) and added to the <u>a-priori</u> estimates to yield the final solutions for surface-skin temperature and the water vapor mixing ratio and temperature profiles.

The choice of pressure basis functions $\phi(p)$ is arbitrary. For example, empirical orthogonal functions (i.e., eigenvectors of the water vapor and temperature profile covariance matrices) can be used in order to include statistical information in the solution. However, here for its application to the TIROS Operational Vertical Sounder (TOVS) data and the VISSR Atmospheric Sounder (VAS) observations, physical functions, the profile weighting functions ($d\tau/d\ln p$) of the radiative transfer equation, are used as the basis functions.

Ancillary information such as surface observations can be easily incorporated into the profile solutions. For example for surface observations it follows from (2) that

$$q(p_s) - q_0(p_s) = g \sum_{i=1}^{N} \alpha_i q_0(p_s) \phi_i(p_s)$$

and

$$T(p_s) - T_0(p_s) = - \sum_{i=N+1}^{M} \alpha_i \phi_i(p_s)$$

have the same form as (3) and therefore can be added to the set to yield K+2 equations to solve for M+1 unknowns (α).

The main advantage of the "simultaneous" retrieval method is that it enables the temperature and water vapor profiles and the surface skin temperature to be determined simultaneously using all the radiance information available. This solution alleviates the problem associated with water vapor radiance dependence upon temperature and the dependence of several of the carbon dioxide channel radiance observations used for temperature profiling, on the water vapor concentration. The dependence of the radiance observations on surface emissions is accounted for in the simultaneous solution by the inclusion of surface temperature as an unknown. Also, since only a single matrix inversion is required for the specification of all parameters, the solution is computationally efficient. Finally, ancillary observations of temperature and/or moisture from surface sensors or aircraft, for example, can be readily incorporated in the solution.

Logistics

The processing of the TOVS data begins with the specification of an initial profile and surface observations, if available. The initial profile can be specified either from climatology or through the use of regression coefficients, based either on synthetic radiances or on real radiances matched to radiosonde observations. The climatological and regression generated initial profile algorithms are internal to the Export Package. A third option exists whereby an analysis or forecast generated grid field of temperature and water vapor profiles can be used to create initial profiles. In this case the grid fields are external to the Export Package as are the surface data grid fields.

Once a guess profile is generated, MSU and HIRS radiances are obtained for a particular 3 x 3 array of HIRS FOV's, as described in the earlier report (Smith et al., 1983), the MSU data having been interpolated to each HIRS FOV. As described in the next section, a search through the nine FOV's is performed to arrive at a set of "clearest" radiances for the sounding retrieval.

The stratospheric HIRS brightness temperatures (channels 1-3), the MSU brightness temperatures (MSU 1-4), and the middle and upper tropospheric HIRS water vapor channels (HIRS 11 and 12) are used to derive a first estimate of the temperature and moisture profile for the sounding location. Because of the channels used, this estimate should be relatively free of error due to cloud attenuation. The weighting functions for HIRS-1 and MSU 2-4 are utilized as the basis functions for temperature and the HIRS 7 and

12 weighting functions are used as the basis functionas for water vapor in the initial retrieval. Once the first estimate of the temperature and water vapor profile is achieved, the height and amount of any cloud affecting the infrared observations is determined by the method described in the next section. After this is accomplished all channels (except HIRS channels 13-19 in the cloudy case) are used to calculate the final surface temperature and the temperature and water vapor profiles. For the achievement of the final profile estimates the weighting functions for HIRS 1, 3, 7 and MSU 2-4 are used as the temperature profile basis functions and those for HIRS 7, 11, and 12 are used as the water vapor profile basis functions. Since as many as nineteen different spectral radiance observations are used for the surface temperature and profile retrievals, the system of equations to be inverted is heavily overdetermined, thereby stabilizing the solution. (It should be noted that ozone and geopotential height are determined in the same manner as described for the iterative solution Export Package.)

<u>Handling the Influence of Clouds</u>

In the TOVS data processing, soundings are derived from a 3 x 3 matrix of HIRS fields of view (FOV), the Microwave Sounding Unit (MSU) data being spatially interpolated to the location of the HIRS spots. From the array, the observations for the "clearest" FOV's, defined as those whose 11 µm radiance values are within 2°K of the maximum, are averaged for the sounding determination. The magnitude of the visible channel reflectance and the 3.7 µm, 4.0 µm, and 11 µm window channel brightness temperatures are used in conjunction with surface temperature observations, if available, to specify whether the "clearest" radiances are contaminated by clouds. If the radiances are determined to be affected by clouds then their pressure height and fractional coverage are specified on the basis of certain CO_2 channel infrared radiances and the microwave radiance specified temperature profile. The cloud height is calculated using the CO_2 slicing technique (Smith and Platt, 1977, Menzel et al., 1983) from the relation

$$\frac{I(\nu_1) - \hat{I}_c(\nu_1)}{I(\nu_2) - \hat{I}_c(\nu_2)} = \frac{\int_{P_c}^{P_o} \tau(\nu_1,p) \frac{\partial B(\nu_1,\hat{T})}{\partial p} dp}{\int_{P_c}^{P_o} \tau(\nu_2,p) \frac{\partial B(\nu_2,\hat{T})}{\partial p} dp}$$

where $\hat{I}_c(2)$ is the clear-column radiance calculated from the microwave specified temperature profile, $\hat{T}$, and ν_1 and ν_2 refer to HIRS channels 5 and 7 respectively. The cloud pressure P_c is obtained by trial and error. The cloud fraction, N, is then obtained from the relation

$$N = \frac{I(\nu_1) - \hat{I}_c(\nu_1)}{I(\nu_2) - \hat{I}_c(\nu_2)}$$

where $\hat{I}_{cd}(\nu_1)$ is the radiance calculated for an opoque cloud overcast condition.

Given P_c and N, the guess mixing ratio profile is adjusted by assuming that the mixing ratio at the cloud level is given by

$$W(p_c) = NW_{sat}\,[\hat{T}(p_c)] + (1 - N)\hat{W}(p_c) \qquad (9)$$

where W_{sat} is the saturation mixing ratio corresponding to the microwave specified temperature at the cloud pressure P_c and W is the original guess value of mixing ratio. Below the cloud a new guess mixing profile is achieved by interpolation using the original surface mixing ratio value.

Once the cloud parameters and the guess mixing ratio is established then the brightness temperature discrepancies from the guess conditions, δT^*, can be calculated, including the effects of cloud within the field of view of the HIRS instrument. Also, for the infrared channels the effects of cloud and the transmittance function, τ, employed in equation (4) can be properly included by assuming that

$$\tau = (1 - N)\ \tau^{orig}$$

for pressures greater than the cloud pressure. This latter transmittance function modification is important to reduce the influence of the infrared observations on the solution below the cloud in proportion to the cloud obscuration. Once this step is employed, the simultaneous solution proceeds in exactly the same manner as in the clear sky condition.

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