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ESTIMATION OF SATELLITE DERIVED TEMPERATURE AND MOISTURE FIELDS OVER EUROPE FROM TOVS DATA USING "3I" AND "ITPP" ALGORITHMS

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The results of two TOVS retrieval algorithms in determining the three-dimensional temperature and water vapor fields from NOAA polar orbiting satellite data are presented. Derived products, specifically the 500 to 1000 mb thickness field and the integrated tropospheric water vapor (precipitable water) field are derived for the northwestern European area on 13 August 1990. Comparisons with the in-situ radiosonde measurements and numerical weather analysis products are made. Overall the fields agree well with the German Weather Service synoptic products and additionally mesoscale features associated with cloud clusters are contained in the satellite derived fields.

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ACRONYM LIST

4A - Automated Atmospheric Absorption Atlas

3I - Improved Initialization Inversion

AFB - Air Force Base

AIMS - Air Force Interactive Meteorological System

ARA - Atmospheric Radiation Analysis Group

CIMSS - Cooperative Institute for Meteorological Satellite Studies

CIRCE - Centre Inter Regional de Calcul Electronique

GMGO - German Military Geophysical Office

GPAS - Satellite Meteorology Branch of Phillips Laboratory

HIRS - High Resolution Infrared Sounder

HRPT - High Resolution Picture Transmission

IBM - International Business Machine

ITPP - International TOVS Processing Package

LMD - Laboratoire de Meteorologie Dynamique

MAP - Maximum a Posterior

MSU - Microwave Sounder Unit

NESDIS - National Environmental Satellite, Data, and Information Service

NOAA - National Oceanic and Atmospheric Administration

SSM/T - Special Sensor Microwave, Temperature

SSM/I - Special Sensor Microwave, Imager

SSU - Stratospheric Sounding Unit

TIGR - TOVS Initial Guess Retrieval

TIP - TIROS Information Processor

TIROS - Television and Infrared Operational Satellite

TOVS - TIROS Operational Vertical Sounder

UTC - Coordinated Universal Time

VAX - Virtual Address Extension

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Chapter 1

Introduction

In the past the lack of conventional meteorological observations, especially in the less accessible regions of the world (like the oceans and sparsely populated regions), hindered a lot of the study of weather systems in the mentioned areas. Routine analyses and forecasts had to rely on small amounts of observational data.

The analysis and forecast of meteorological (especially mesoscale) phenomena was also hindered at intervals between the synoptic observation times due to the non-availability of conventional data. Conventional data means the data of ground-based meteorological observation instruments such as thermometers, and upper-air balloons, or radiosondes. Nevertheless the availability of observations in between main synoptic observation times is critical for the forecasting of meteorological hazards in many fields, such as aviation. Knowledge early in time of hazardous events like squall lines or severe storms can provide significant warning potential and thus may save lives.

With the availability of polar orbiting satellites like the NOAA/TIROS-N (Television and Infrared Operational Satellite) the quantitative analysis of the three-dimensional state of the atmosphere is possible at times between synoptic observations over all regions of the globe. Due to the orbit characteristics (sun-synchronous, orbit period 102 min.) the whole globe is covered two times a day by each satellite. With a swath width of about 2500 km there is a more frequent area overlap at higher latitudes.

It is possible to gain information on mesoscale phenomena at the resolution of the satellite instruments. The TIROS Operational Vertical Sounder (TOVS) instrument provides data that make it possible to determine the three-dimensional structure of the atmosphere at a scale of about 100 km and larger in horizontal space as well as 1-3 hours in time, which is the definition of the Meso-β scale (after Orlanski, 1975). Quantitative information on atmospheric temperature fields can be obtained with considerable accuracy (LeMarshall, 1988). Recently, there have been efforts to estimate the atmospheric humidity with TOVS-derived data (Husson et al., 1991). Up to now there are not many examples available on the study of mesoscale water vapor structure in the atmosphere using only satellite information.

Several studies of mesoscale phenomena have been carried out in the past, covering the Antarctic (Heinemann, 1990) the arctic region, and polar lows (Claud et al., 1990, Prangsma, 1989) as well as mid-latitude cloud clusters (Klaes, 1991).

The purpose of this research is to demonstrate the capabilities of two TOVS retrieval algorithms. The algorithms used here are the Improved Initialization Inversion (3I) (Chedin et al., 1985) as well as the International TOVS Retrieval Package (ITPP) methods (Smith et al., 1985). In this report the application of the TOVS retrieval algorithms "3I" and ITPP is demonstrated with the example of a thunderstorm situation in summer over central Europe. It occurred on 12-13 August 1990. One significant event is the development of a large mesoscale cloud cluster over eastern France and Southwest Germany.

In Section 2, there is an overview of the TOVS instruments, including the HIRS/2 High Resolution Infrared Sounder and the Microwave Sounding Unit (MSU), both of which are used by the retrieval algorithms. The two retrieval algorithms will be discussed in Chapter 3. Chapter 4 describes the synoptic situation over central Europe on 12-13 August. Chapter 5 shows some retrieval results obtained by the two algorithms for the case study. Finally, Chapter 6 gives a summary of the possible comparisons with other data sources including the conventional meteorological data.

Chapter 2

The TOVS Sensors

The TOVS-instrument aboard the NOAA satellites is comprised of three passive sounding instruments (Smith et al., 1979). The HIRS/2 is a radiometer with 20 channels, the MSU is a passive microwave radiometer with four channels, finally the Stratospheric Sounding Unit (SSU) is an infrared radiometer with three channels, based on the principle of pressure modulation. The TOVS instrument characteristics are contained in Planet (1988). Therein is given detailed information on the calibration characteristics and the data formats. The following subsections list the radiative sensing characteristics of each unit.

2.1 High Resolution Infrared Radiation Sounder, Model 2 (HIRS/2)

The HIRS/2 is a further developed version of the HIRS/1 which flew on the NIMBUS-6 satellite. It measures upwelling radiation in 19 regions of the infrared spectrum and one region of the visible spectrum. The ground resolution, i.e. the footprint of the HIRS/2 is 17.4 km in diameter at nadir. There are 56 scanning steps in one scan-line, one scan takes 100 milliseconds, and the complete scan-line is scanned in 6.4 seconds. The scan covers an angle of ± 49.5 deg, or ± 1125 km left and right from the subsatellite point for a swath-width of 2250 km. Due to the curvature of the earth the footprint at the edge of scan is different from the one at nadir: 58.5 km cross-track by 29.9 km along track. That means that there is an elliptical pattern of the HIRS/2 spots off the subsatellite track. Figure 1 shows the ground pattern of the HIRS/2 instrument.

After every 40 HIRS/2 scan lines there is an in-flight calibration of the instrument, during which there are no retrieval data available. This means a gap of three lines for each calibration cycle.

Table 1 shows the characteristics of the HIRS/2 channels. There are seven channels (1-7) in the 15 μm region, mainly used for temperature sounding. Channel 8 at 11.10 μm is a window channel and serves for cloud detection and surface temperature estimation. Channel 9 at 9.7 μm is the ozone channel. Total ozone concentration may be obtained by using its data. Channels 10-12 are used for water vapor retrieval. They are positioned from 8.3 μm to 6.7 μm. Further information on the temperature profile of the atmosphere is retrieved by using the information of HIRS/2-channels 13-17, which are positioned around 4.3 μm. They provide a better sensitivity to warmer regions of the atmosphere than do the 15 μm channels. They are also less sensitive to clouds than the 15 μm channels. There are two more window channels with central wavelengths at 4.0 and 3.7 μm. They too can be used to estimate the surface temperature and to detect cloud presence. Finally, there is a channel in the visible part of the spectrum. Channel 20 at 0.7 μm is used during daytime for cloud detection and thus to help define clear fields-of view.

Figure 2 shows the weighting functions for the HIRS/2 channels. Each peak represents the region of the atmosphere from which a channel receives its major energy contribution.

2.2 Microwave Sounding Unit (MSU)

The MSU is a passive microwave Dicke radiometer (see e.g. Vowinkel, 1988). Its four channels are positioned in the 50 GHz region of the electromagnetic spectrum (the 5.5 mm oxygen band).

The horizontal scan pattern is 109.3 km at nadir. There are 11 scans at a scan time of 25.6 seconds per scan. As shown in Figure 1, the cross-track scan angle is ± 47.35 deg, which means a swath of 2 x 1173 km, or 2346 km. The field-of-view pattern at the end of a scan is 323.1 km cross-track and 178.8 km along track.

Channels 2-4 are used for temperature sounding through clouds. Channel 1 at 50.31 GHz is a window channel and is used to determine cloud attenuation and surface emissivity parameters. Table 2 displays the characteristics of the MSU channels. Figure 3 shows the weighting functions of the MSU channels.

2.3 Stratospheric Sounding Unit (SSU)

The SSU measures the absorption of radiation by carbon dioxide contained within its sensors. The pressure of the carbon dioxide in the gas cell determines the altitude of the weighting function peaks in the atmosphere. Table 3 gives the characteristics of the SSU instrument channels. The SSU will not be presented further, because it is not used for the retrievals discussed in this study.

Chapter 3

Retrieval Algorithms

It is well known that the three-dimensional structure of the atmosphere may be deduced in terms of temperature and moisture from measurements of the earth's and clouds' radiance, measured by satellite or aircraft-based multichannel passive sounding instruments. This is done by a so-called "inversion" procedure, which in the present case means the inversion of the radiative transfer equation.

There are several problems involved in the inversion procedure. One is the underdetermination of the problem, making it necessary to obtain additional information from some other source. Another is the non-uniqueness of the inversion of the radiative transfer equation - that means given a state of the atmosphere in terms of temperature and moisture profiles, and information on the important gaseous constituents of the atmosphere, then a unique solution for the vertical distribution of radiances may be obtained. On the other hand, inverting the radiative transfer equation by having as input a vertical profile of radiances yields a multiplicity of solutions for the three-dimensional state of the atmosphere in terms of temperature and moisture, depending on the respective situation. To solve the problem, a so-called "first guess" is necessary to start the solution process. The solution is very strongly dependent on the choice of the initial guess, especially in regions (like in cloud areas) where less information is obtainable (Susskind and Rosenberg, 1980). A detailed discussion of the inversion problem is given by Twomey (1977).

Different software packages are available to derive atmospheric parameters from TOVs data. These packages make use in varying degrees of two basic types of retrieval methods: 1) Statistical retrievals begin with the measured radiances and apply regression schemes on them to obtain the desired atmospheric parameters such as temperature or water vapor; statistical retrievals are fast, making them for a long time the only candidates for operational application. The disadvantages are the large amount of reference situations needed to estimate the regression coefficients, and following from this there are misleading results in atmospheric situations deviating from standard situations. 2) Physical retrievals solve the radiative transfer equation using an iteration process until a sufficient good solution matching the actual observations is reached. Physical retrievals require the computation of transmittances and radiances at each iteration. They also need a "first guess" which is the more important factor, since when it is badly chosen it influences the result in a negative sense.

A physical scheme is presently used operationally by NOAA/NESDIS (Fleming et al., 1986). It has replaced a statistical scheme (Reale et al., 1986). One other widely used scheme is the "International TOVS Processing (ITPP) Package," developed and maintained at the University of Wisconsin, Madison (Smith and Woolf, 1976; Smith et al., 1979; Smith et al., 1985). ITPP is a physical scheme that allows the simultaneous retrieval of surface temperature, the vertical temperature profile, and the vertical moisture profile.

The Improved Initialization Inversion ("3I") algorithm (Chedin and Scott, 1984; Chedin et al., 1985; Chedin and Scott, 1985), developed and maintained at Laboratoire de Meteorologie Dynamique (LMD) at Palaiseau, France, is a physico-statistical method. It relies upon *a priori* knowledge of the atmospheric structure and a brightness temperature (BT) for each channel used of the TOVS-instrument.

One other method is the differential retrieval, a direct method which has not been applied to operational data yet (King, 1990; Ou et al., 1990).

For the presented study, the VAX-Versions of "3I" - and the ITPP-algorithm were used (Klaes et al., 1991; Woolf, 1990). "3I" comparisons were made with LMD's IBM-Versions. For display the LMD-display software was used (Husson et al., 1991).

3.1 The "3I" Retrieval Algorithm

The "3I" algorithm (Chedin et al., 1984; Chedin and Scott, 1985; Chedin et al., 1985) is a direct physico-statistical method. For the retrieval the data of the HIRS/2 and MSU instruments of the TOVS instrument package are used, thus representing an infrared and a microwave contribution.

3.1.1 Theory

The philosophy of the "3I"-method is threefold:

- The method must be physical, thus taking into account all information of the environment and the observing conditions such as viewing angle, surface properties like emissivities, land/sea distinction, surface elevation, solar zenith angle, etc.;

- The algorithm has to be fast because of the large amount of data to be handled, thus the number of iterations necessary should be minimized;

- The first guess must be the nearest possible to the actual situation, thus containing as much *a priori* information as possible.

This is resolved by obtaining the first guess solution from the observations themselves. The procedure used for this is *a pattern recognition* algorithm, which uses the TOVS Initial Guess Retrieval (TIGR) dataset. The TIGR dataset is composed of computed sets of brightness temperatures for selected atmospheric conditions at 40 levels for (presently) five air mass types, 10 viewing angles and different ground properties. Since summer 1991 a considerably improved TIGR-2 dataset has been in use consisting of 1761 atmospheric situations, selected out of more than 150,000 radiosonde observations.

Transmissions, radiances and weighting functions for all of the channels of the instruments used in the “3I”-algorithm and for the different satellites (at present NOAA-8 to NOAA-11) are calculated by using the Automated Atmospheric Absorption Atlas (4A) line-by-line radiance model (Scott and Chedin, 1981). For each profile, cloud-free conditions are assumed. There are 10 viewing angles between 0 and 60 deg. (nadir and maximum scanning angle for the used instruments, respectively), two types of earth surfaces - land and sea, and ten surface pressure values. The simulated radiances are available on the 40 “4A” levels (Table 4).

In the proximity recognition algorithm a comparison is made of the measured radiances (by the satellite instruments) with the archived TIGR radiances. The distance d in the phase space of the TIGR-dataset between the observed brightness temperatures T_0 and the brightness temperatures T_j for the jth TIGR set ($j = 1,...,1761$), is given for a selected number of TOVS-channels n as

$$d_0^2 = \frac{1}{n}\sum_{k=1}^{n}\frac{\left[T_0(k) - T_j(k)\right]^2}{\left(s_k^{\,2}\right)}, \tag{3.1}$$

where s_k is the variance of $T_j(k)$ over “n” TIGR datasets. The TIGR profile with the smallest d or a mean of a number of profiles around the most proximate situation is taken as the initial guess for the retrieval.

Since the TIGR-dataset is composed of cloud-free conditions, and on the other hand, many of the HIRS/2 (infrared) radiances are contaminated by clouds, the cloud influence has to be eliminated before the retrieval is carried out.

To detect possible cloud contamination, tests are carried out at HIRS/2 sensor resolution. These tests are based on the method of McMillin et al. (1982), which has been considerably modified (Wahiche et al., 1986 and Chedin, 1989).

The cloud "clearing" is done by the so-called Ψ-method (Chedin et al., 1985 and Chedin, 1989). The Ψ-method computes a clear radiance for a HIRS/2-channel from the difference between the observed and the TIGR-2 values of an MSU channel which has the peak of its energy contribution near the one of the HIRS/2-channel under consideration. If the microwave radiances are not contaminated by heavy rainfall, the integration of the energy contribution over approximately the same part of the atmosphere yields a difference, which describes the major part of the initial value and the equivalent clear value of the HIRS/2 channel. See Appendix A for details of the Ψ-method.

Having obtained the first guess solution the temperature retrieval is carried out. The method of temperature retrieval is based on a Bayesian approach (Chedin et al., 1985). In principle the basis is the equation of radiative transfer in the form

$$TB(\nu_i) = \int \Phi^*(\nu_i,\zeta)T(\zeta)d\zeta \tag{3.2}$$

where $TB(\nu)$ denote the satellite measured brightness temperatures, T the atmospheric temperatures to be retrieved, Φ^* is the kernel, which includes the atmospheric transmittances, ζ is the altitude variable (arbitrary, generally the atmospheric pressure), and the ν_i denote the various observation conditions (instrument channels, viewing angle, surface characteristics, etc.).

Linearizing Equation 3.2 by quadrature we arrive at

$$TB = \Phi^* T + \varepsilon \tag{3.3}$$

where ε indicates non systematic error. For the errors several assumptions are made: they should have a mean of zero, should be normal distributed in terms of their probability and their error covariance matrix S_ε should be known; the temperatures T are assumed to be described by a multivariate normal distribution with mean T_0 and covariance matrix S_T.

Applying Bayes' conditional probability rule

$$P(T/TB) = \frac{P(TB/T)P(T)}{P(TB)} \tag{3.4}$$

we find a probability density function of the atmospheric state T under the assumption that the observations are given. Finding the profile (atmospheric state) with the maximum probability we obtain an estimator - *maximum a posterior (MAP)* - as

$$\delta T = \left[\Phi^{*T} S_{\varepsilon}^{-1} \Phi + S_T^{-1}\right]^{-1} [\Phi^*]^T S_{\varepsilon}^{-1} \delta TB \qquad (3$$

where $\delta T = T_{MAP} - T_0$; $\delta TB = TB_{\varepsilon} - TB_0$, with T_0 and TB_0 the expectation values respectively. The initial guess retrieval procedure has no bias (Chedin et al., 1985), thus the means of $T^* = T_{MAP} - T_{IG}$ and $TB^* = TB_{\varepsilon} - TB_{IG}$ are zero. $[X]^{-1}$ denotes the inverse and $[X]^T$ the transpose of a matrix X. It follows

$$\delta T^* = \left[\Phi^{*T} S_{\varepsilon}^{-1} \Phi^* + S_{T^*}^{-1}\right]^{-1} [\Phi^*]^T S_{\varepsilon}^{-1} \delta TB \qquad (3.6)$$

The matrix Φ^* contains the Jacobians $\frac{dTB_i}{dT_j}$, i and j are the levels.

3.1.2 Application

The retrieval is carried out on so-called "boxes" of 100 km x 100 km, containing four to six HIRS-2 spots which are merged into the MSU spots (see Figure 4), taking into account the different ground resolution of the TOVS instruments used for the retrieval.

After having completed the temperature retrieval, cloud parameters are estimated by the *"method of coherence of effective cloud amounts"* (Wahiche et al., 1985), a complex procedure yielding cloud top pressure, cloud top temperature and effective cloud amount (cloud cover times cloud emissivity).

The extraction of water vapor information out of the TOVS observations is done after the temperature profiles have been estimated. The inversion of water vapor parameters is done for the three atmospheric layers 300-500 hPa, 500-800 hPa and 800-1000 hPa. The parameters retrieved include water vapor contents for the three layers, total precipitable water and surface temperature.

The method used here is a ridge-type approximation for a simultaneous retrieval of the above mentioned parameters. Assuming that $S_T = \sigma_T^2 I$ for the HIRS/2 channels 8, 10, 11 and 12, and further $S_{\varepsilon} = \sigma_{\varepsilon}^2 I$, where I is the unity matrix we arrive at a ridge-type estimator (Chedin et al., 1985)

$$\delta q_i^* = \left[\Phi^{*T} \Phi^* + \gamma I\right]^{-1} [\Phi^*]^T \delta TB^* \qquad (3.7)$$

for $q_i^* = U_i, i = 1,...,3$ for the three layers, U_i is the relative humidity, $q_4^* = T_s$. The δ denote the deviation from the first guess.

After all these operations have been carried out further derived geophysical parameters can be estimated, e.g. geopotential thicknesses or thermal winds, by using the retrieved temperatures and humidity parameters to derive the virtual temperatures for chosen layers and apply the results to the respective equations.

The "3I" algorithm can be improved by providing additional information in the form of forecast fields for the refinement of the initial guess. The final retrieval is carried out with the thus specified initial guess.

3.2 The ITPP Retrieval Algorithm

The "International TOVS Processing Package" (ITPP), also known as the "TOVS Export Package", has been developed at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin, Madison, Wisconsin (Smith et al., 1985). The first physical approach consisted of the iterative scheme developed by Smith (1968). The current version permits the *simultaneous retrieval of surface* temperature, temperature and moisture profiles (Smith et al., 1985). The physical character makes it possible to consider the influence of surface parameters (elevation, emissivity, etc.) and of clouds.

The essential retrieval method is the simultaneous temperature and water vapor retrieval (Smith and Woolf, 1984). The basis again is as in (3.2), the equation of radiative transfer in the form

$$TB_i = \int \Phi(v_i, p) T(p) dp \qquad (3.8)$$

where the pressure p replaced the vertical coordinate ζ of (3.2), TB_i are the radiance expressed as brightness temperatures as observed by the satellite, $\Phi(v_i, p)$ is the kernel and contains a pressure dependency of the profiles to retrieve, $T(p)$ is the atmospheric temperature profile to be retrieved.

Integrating the radiative transfer equation by parts and developing a small perturbation of the brightness temperature we obtain

$$\delta TB = \int_0^{p_s} \delta m_{ppw} \frac{\partial T}{\partial p} \frac{\partial \tau}{\partial m_{ppw}} \frac{\left(\frac{\partial B}{\partial T}\right)}{\left(\frac{\partial B}{\partial TB}\right)} dp - \int_0^{p_s} \delta\tau \frac{\left(\frac{\partial B}{\partial T}\right)}{\left(\frac{\partial B}{\partial TB}\right)} dp + \delta T_s \frac{\left(\frac{\partial B_\varepsilon}{\partial T_s}\right)}{\left(\frac{\partial B}{\partial TB}\right)} dp \quad (3.9)$$

where $\delta x = x\text{-}x_0$, and x_0 is an *a priori* mean of first guess of the variable x.

Each perturbation is assumed as dependent on a pressure function $\Phi(p)$ thus that

$$\delta q(p) = g\sum_{i=1}^{N} a_i q_0(p)\Phi_i(p) \quad (3.10)$$

and

$$\delta T(p) = -\sum_{i=N+1}^{M} a_i \Phi_i(p) \quad (3.11)$$

with $q(p)$ being the water vapor mixing ratio and g the gravity acceleration. With the hydrostatic equation and the gas law Equation 3.10 becomes

$$\delta U(p) = \sum_{i=1}^{N} a_i \int_0^{p_0} q_0(p)\Phi_i(p)dp. \quad (3.12)$$

Setting $a_0 = \delta T_s$ and substituting Equations 3.11 and 3.12 into 3.9 yields the following matrix equation

$$\delta TB_j^* = \sum_{i=0}^{M} a_i \Phi_{i,j},\ j = 1, \ldots, K \quad (3.13)$$

where K denotes the number of sounding channels used for the retrieval. Thus,

$$\delta TB_j^* = \Phi a. \quad (3.14)$$

If the number of channels K is greater or equal to the number of variables plus one $(M+1)$, then least square methods transform 3.14 into

$$a = \left[\Phi^T \Phi\right]^{-1} \Phi^T \delta TB\, * \quad (3.15)$$

which can be approximately written as

$$a = \left[\Phi^T \Phi + \gamma I\right]^{-1} \Phi^T \delta TB * \qquad (3.16)$$

The term with the Lagrange parameter γ (nominally 0.1) (Smith et al., 1985) is introduced to stabilize the matrix inversion. Again, I denotes the unity matrix, $[A]^{-1}$ the inverse and $[A]^T$ the transpose of matrix A.

The choice of the pressure functions $\Phi(p)$ is arbitrary; however, in the ITPP the profile weighting functions $\frac{d\tau}{d\ln p}$ of the equation of radiative transfer are used. One other possibility was the use of eigenvectors of the temperature and water vapor covariance matrices.

The initial profile in the processing of the TOVS retrieval may be obtained from climatology or a regression based on synthetic radiances or on radiances obtained by matching radiosonde observations. Both possibilities are part of the ITPP. A third possibility is the introduction of the first guess profiles from analysis or forecast information - this information has to be provided by the user - from outside.

The HIRS/2 and MSU radiances are used on a 3 x 3 field of HIRS/2 field-of-views (FOV), which is about 75 km resolution (Smith et al., 1985). The cloud contamination is treated by the N^* method.

3.3 Pre-Processing

For both retrieval packages the ITPP pre-processing (Woolf, 1990) was applied. This includes 1) the treatment of the direct ingested raw data of the HRPT (High Resolution Picture Transmission) data stream, 2) the extraction of the TIP (TIROS Information Processor) data, which include the TOVS data, 3) the extraction of the TOVS data, 4) the calibration and earth-location of the HIRS/2 and MSU data (see e.g. Planet, 1988 for more details on the data format), and 5) the limb-correction, depending on whether "3I" or ITPP is used. Thus, both packages use the same raw data. (This is also an advantage for the operational application of both packages.)

Chapter 4

Weather Situation

For the application of the two retrieval schemes the weather situation for 13 August 1990 over Europe was chosen. On one hand there has been the mesoscale phenomenon which has to be investigated, a cloud cluster over eastern France and western Germany in the synoptic surroundings of a decreasing high pressure situation. On the other hand there has been the direct ingested HRPT data available, received directly at the German Military Geophysical Office (GMGO) at Traben-Trarbach, Germany (Klaes, 1990). The TIP-data were extracted out of the HRPT-data and preprocessed to be ready as "3I" as well as ITPP input data.

The synoptic situation for 13 August 1990 over Europe is characterized by hot subtropical air over Southern and Central Europe. Frequently the maximum temperatures over the continent reached more than 30 deg C. The synoptic surface pressure field was characterized by high pressure over the Karpates and southern France/Italy (Figure 5). Combined with this surface field there was an upper ridge over Central Europe which extended at 00 UTC from the western Baltic Sea to Southern France (Figure 6).

Two weak upper troughs were analyzed over The Netherlands and over the Gulf of Biscay; the latter being the stronger one. The eastward movement of the upper ridge as well as the strong heating during the day caused a weakening of the high pressure influence over Europe. There was, according to the upper trough and the heating of the surface, a flat low pressure system over The Netherlands, with a frontal system along the North Sea coast and over the Gulf of Biscay, mainly recognizable at upper levels.

A mature low pressure system is nearly stationary west of Iceland, its already occluded frontal system extending from the North Atlantic over Northern Scandinavia, the North Sea and the British Isles. The fronts are already weak.

Thus, the mesoscale situation is not the ideal case - ideal case meaning that the mesoscale phenomenon is situated in a homogeneous synoptic environment - a situation which will be found very rarely over Central Europe. The present situation is characterized by unstable, subtropical air over Central Europe, being further destabilized by strong heating as well as an approaching upper-air trough.

The satellite picture (Figure 7) is an AVHRR Channel 4 (10.5 μm) composite of the three orbits 9704, 9705 and 9706 of NOAA-11 over central Europe, projected on a polar stereographic projection by the Free University of Berlin (1990). The structures discussed above can be easily detected. Since the time of the displayed orbits is about 12 hours later than the synoptic maps shown, there are a lot of thunderstorm cells developed along the frontal zone. Two structures are most interesting: the big cloud cluster over eastern France/south western Germany, which has a horizontal extension of about 300 x 100 km^2 and a circular structure over the Gulf of Biscay, also a well developed structure of about 100 x 100 km^2.

The two retrieval algorithms discussed in Chapter 2 were applied to direct readout satellite data for all the cases discussed above. In the following chapter some of the results will be shown and some aspects of the results will be discussed in the light of the qualitative comparison with "conventional" meteorological data and analyses discussed above.

Chapter 5

Retrieval Results

In the following, results of the two retrieval procedures "3I-2" and ITPP V4.1 will be shown. Both versions were available and used as VAX versions (Klaes et al., 1991a, Woolf, 1990). "3I" was also used in the original IBM version at the C.I.R.C.E. (Centre Inter Regional de Calcul Electronique du C.N.R.S.) at Orsay, France.

The VAX versions were installed on the AIMS (Air Force Interactive Meteorological System) computer system of the Geophysics Directorate, Satellite Meteorology Branch, Hanscom Air Force Base, Massachusetts, U.S.A. (Klaes, 1991). Comparisons of the "3I" VAX version have been done with the original version of "3I" at Palaiseau. The results were found identical (Klaes et al., 1991a).

Comparisons have been done between "3I-2" and "3I-1" for the case investigated here, the results have been discussed elsewhere (Klaes et al., 1991b).

The results displayed in this chapter are geophysical fields of both retrieval packages. There are examples of the Geopotential Thicknesses 500/1000 hPa as a measure of the average temperature of the lower half of the atmosphere as well as the quantity total precipitable water as a measure of the water vapor contents of the atmosphere. There are some comparisons of vertical profiles of temperature, they are compared with radiosonde measurements of selected places. The data used are the NOAA-11 orbits of 13 August 1990, 1233 UTC and 1403 UTC. The geophysical fields retrieved from them are displayed together and therefore are referred to as 1315 UTC.

5.1 "3I" Results

Figure 8 shows the Clear/Not Clear Flags of the two combined orbits of 1315 UTC, 13 August 1990. The results are displayed for the "3I" "boxes" (cf. Figure 4). The green spots denote cloud-free boxes over land, the blue spots denote cloud-free boxes over sea, the yellowish boxes denote cloud contaminated boxes. The two cloud cluster areas are clearly represented, the one over the Gulf of Biscay more clearly because of its isolated nature. The one over central Europe is embedded in the other clouds of the frontal zone. Note that even the area of low cumulus clouds over Eastern Europe is recognized as cloudy (compare also the AVHRR image Figure 7). Looking at the cloud top pressures obtained after the temperature retrieval (Figure 9) it can be seen that the regions of the cloud clusters are detected as regions with high reaching clouds - cloud top pressures of 350-200 hPa. Nevertheless, this is indicated by black spots, a number of boxes is rejected because of too large cloud amounts, thus no estimation of cloud altitude possible. Also apparent is that the frontal area over the British Isles is composed of lower clouds.

Figure 10 shows the geopotential thicknesses 500/1000 hPa as point plots for the 1315 UTC date. It can be seen that the frontal zone over the North Sea/British Isles is represented as a strong gradient in the thickness field. The mature low west of Iceland is represented as a center of cold air (low thicknesses).

The area of the mesoscale cloud cluster over Eastern Europe, southwestern Germany is represented as a cyclonic deformation (trough) in the thickness field exactly over the area (compare the AVHRR image Figure 7). The warm subtropical air approaching western Europe from north Africa can be seen as a tongue of warm air from Maroc. The results are confirmed if the field is displayed as an isoline field (Figure 11). Results have to be looked at first in terms of boxes before they are displayed as isoline fields to preclude spurious contouring errors.

The moisture field in terms of total water vapor content (total precipitable water) is displayed in Figures 12 and 13. There is a well expressed moist maximum in the zone of the frontal area over Scandinavia and the British Isles, the moisture field confirms that the front is weak in its middle part over the North Sea. The dry zone over Central Europe denotes very significantly the area of dry air which brought the longest period of drought over central Europe since the dry summer of 1976 (Deutscher Wetterdienst, 1990). It can also be seen that the subtropical air approaching from the southwest is carrying more moisture with it.

5.2 "ITPP" Results

Displaying the geopotential thicknesses 500/1000 hPa of 13.15 UTC of the 13 August 1991 as point plots of the ITPP V4.1 (Figure 14) we see that the structures of the temperature field are retrieved in a similar way - the cloud cluster area over eastern France and southwestern Germany is also represented as a deformation in the thickness gradient which may be easily seen in the isoline display (Figure 15).

The moisture field in terms of total precipitable water (Figures 16 and 17, point plots and isoline displays respectively) shows the frontal structure as an increase of moisture. The dry area over central Europe is smaller. Generally the amounts of ITPP retrieved moisture are higher than with "3I".

Statistical results of the comparison as well as comparisons with radiosondes are contained in Table 5.

5.3 Vertical Profiles

Figure 18 shows an example of a vertical profile of temperature obtained by the two retrieval algorithms "3I" and ITPP as well as by a radiosonde observation. The vertical sounding of box 8 of HIRS line 68 is chosen, being situated nearest to the radiosonde 10338 Hannover in Germany. Displayed are the results of "3I-2" (solid thick), ITPP V4 (dashed) and the radiosonde (thin solid). It can be seen that in the region between 900 hPa and 300 hPa the vertical stability of the atmosphere is simulated similar to the radiosonde from both retrieval algorithms. This can be shown for all the retrievals near radiosonde stations. It can, therefore, be concluded that the thermal stability of the troposphere is well retrieved by either algorithm.

There is a difficulty in the treatment of the surface. This is explainable as: 1) one of the major difficulties in retrieval; 2) the fact that the day under investigation was a very hot day in terms of surface temperature - in most parts of Germany the temperatures reached or exceeded 303 K; 3) that there is a difference in the terrain elevation of the radiosonde station and the mean terrain altitude of the box or the retrieval area respectively (composed of 4-6 HIRS/2 spots). Thus, there may be a major difference in surface temperatures. If the temperatures at the same levels are compared, we obtain a difference of approximately 3 K at the surface.

Note that the character of the retrieved profiles and radiosoundings are essentially different. The radiosoundings are taken over a time of about 100 minutes for an area up to 400 km in diameter, depending on the wind drift of the sonde, whereas retrievals are the results of instantaneous measurements, representative for one moment, the moment of the radiance measurement of the satellite instrument, valid for the area of the resolution of the ground spot - in case of more than one instrument the area of the coarsest resolution instrument.

The radiosonde is making a point measurement, at the position in space where the sonde is during the ascent. Retrieved profiles represent volume averages, the volume being defined horizontally by the size of the footprint of the respective instrument and in the vertical by the width of the respective contribution (weighting) function.

Thus, radiosonde measurements and retrievals must not be compared without taking into consideration the different character of both measurements. The comparison of radiosonde measurements with retrieval results of 13 August 1990 is based on four overpasses of NOAA-10 and NOAA-11 spacecraft. The collocation criteria were the following: 1) the collocated retrieval profiles must be located within 100 km diameter around the radiosonde observation; and 2) the time difference must be less than 3 hours. Given these conditions, 534 collocated retrievals could be found to compare the thicknesses 500/1000. Based on the mean of 5535.17 gpm the bias was found to be -34.65 gpm ("3I" retrieval minus radiosonde measurement), corresponding to -1.71 K. The standard deviation is 20.39 gpm (corresponding to 1.01 K).

Total water content was found to be biased by -0.22 cm with a standard deviation of 0.57 cm, based on the radiosonde average of 2.16 cm. The comparison results are summarized in Table 5.

The temperature measurements in terms of thicknesses can be considered to be of comparable range to each other, the retrieval being colder than the collocated radiosonde profiles. The humidity in terms of total water vapor contents is underestimated by the satellite retrieval, with an error of about 26%. The majority of this difference is due to the underestimation of the humidity in the lowest retrieval level, where the highest amount of humidity occurs, which cannot be resolved by the HIRS instrument channel 10.

It can be stated in general that the retrieved profiles are in acceptable agreement with the in situ measurements.

Chapter 6

Conclusions

The purpose of this reserach is to demonstrate the ability and capability of two TOVS retrieval algorithms, "3I" and the ITPP.

It is demonstrated how the two retrieval algorithms treat the temperature retrieval of TOVS instrument soundings as well as the deduction of water vapor quantities. It is shown that the retrieval algorithms are able to produce geophysical fields over a specified area, according to the satellite passes. Meteorological features like mesoscale cloud clusters, down to a resolution of the meso-β scale are resolved. It must be emphasized that for this study TOVS data alone were used for the retrievals. No forecasts were used as additional information.

It is demonstrated from Figures 19 and 20 that the derived fields fit well the results obtained by "conventional" analysis. Figure 19 shows the geopotential thicknesses 500/1000 hPa, analyzed by the German Weather Service for 00UTC, 13 August 1990. The analysis is based on all available observations, including satellite data. Figure 20 shows again the result of "3I" for 1315 UTC of the same day. Considering that there is more than 12 hours difference between the two fields, it can be concluded that there is considerable agreement between the two. Again, it is emphasized that the mesoscale cloud cluster as a deformation in the thickness field is recognized properly by the retrieval.

Additionally it can be stated that the cold air regions in the area of the mature low pressure system west of Iceland as well as those over Sweden/Finland and western Russia are well simulated. It is concluded that the retrieval algorithms are a good instrument to derive geophysical fields from satellite data alone, especially in between synoptic observation times and/or in regions where "conventional" observations are sparse. This is supported by the good simulation of the vertical stability of the troposphere in the layer 900 to 300 hPa.

The humidity retrievals are not that well defined; it is not possible from this study alone to state accuracies (as well we do not know the "*truth*"). Comparisons need to be made with radiosonde data as well as with data from different satellite sensors such as the SSM/I and SSM/T-2 (microwave) derived moisture fields.

To make statistical statements additional research is required with more data - especially radiosonde and passive microwave satellite data.

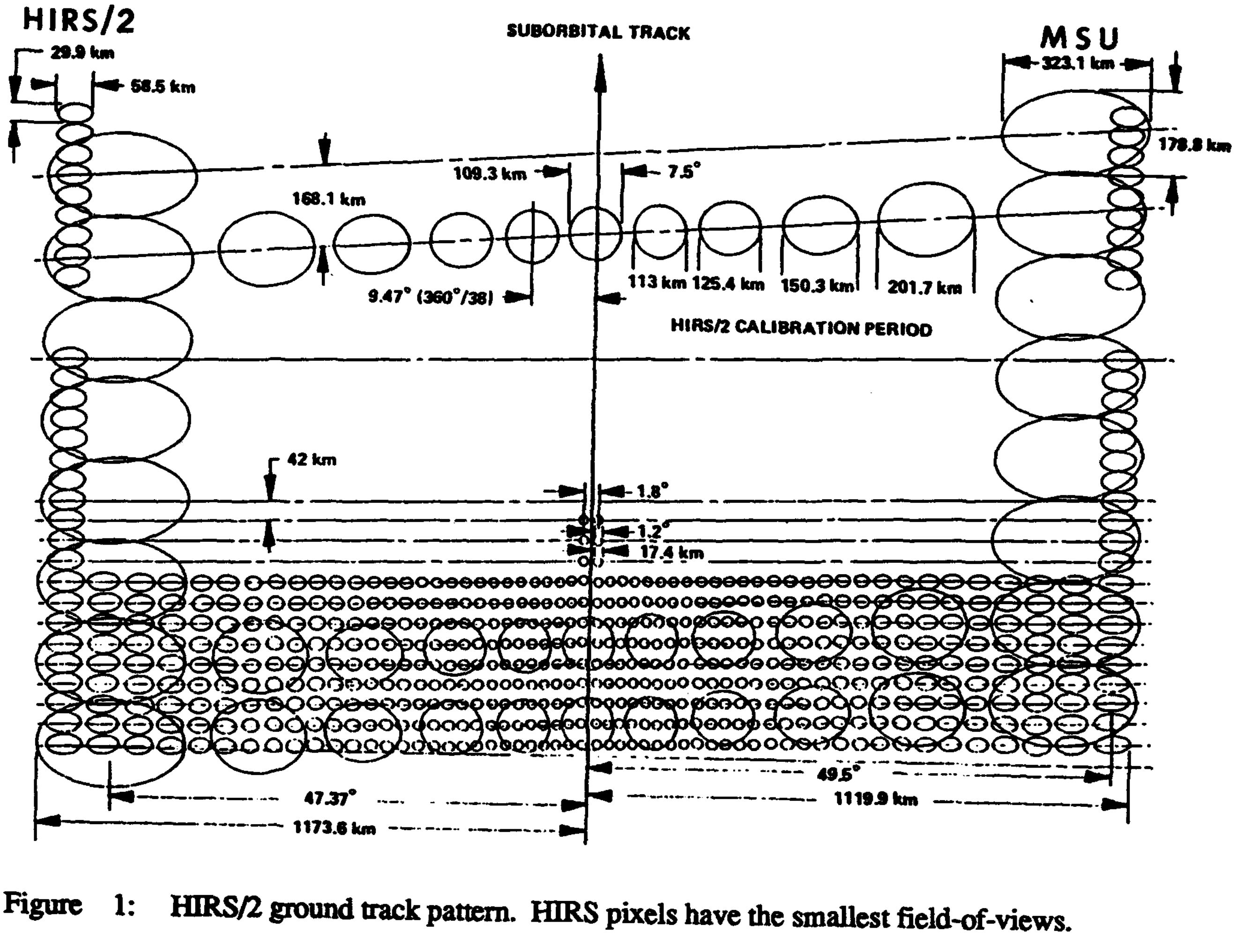

Figure 1: HIRS/2 ground track pattern. HIRS pixels have the smallest field-of-views.

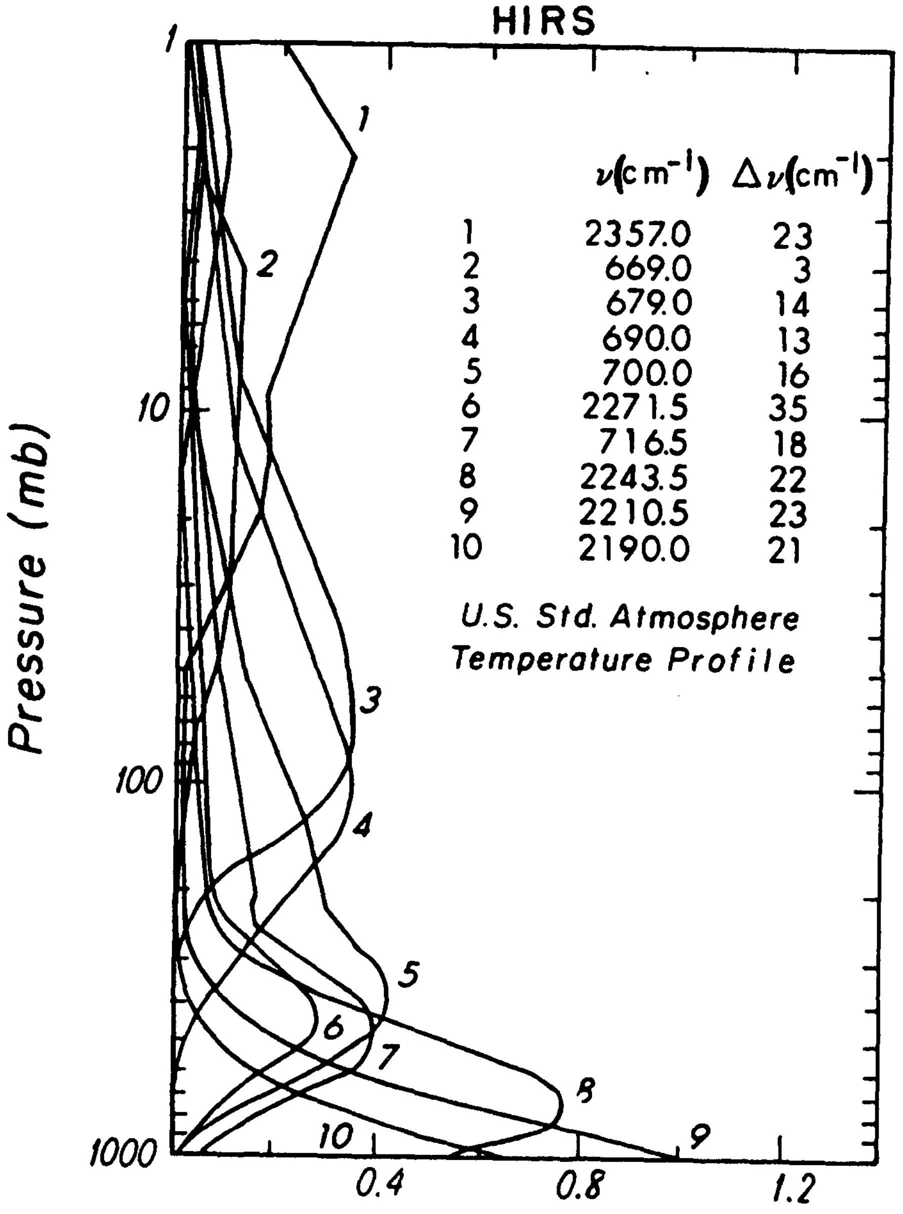

Figure 2: Energy contribution functions of HIRS/2 channels.

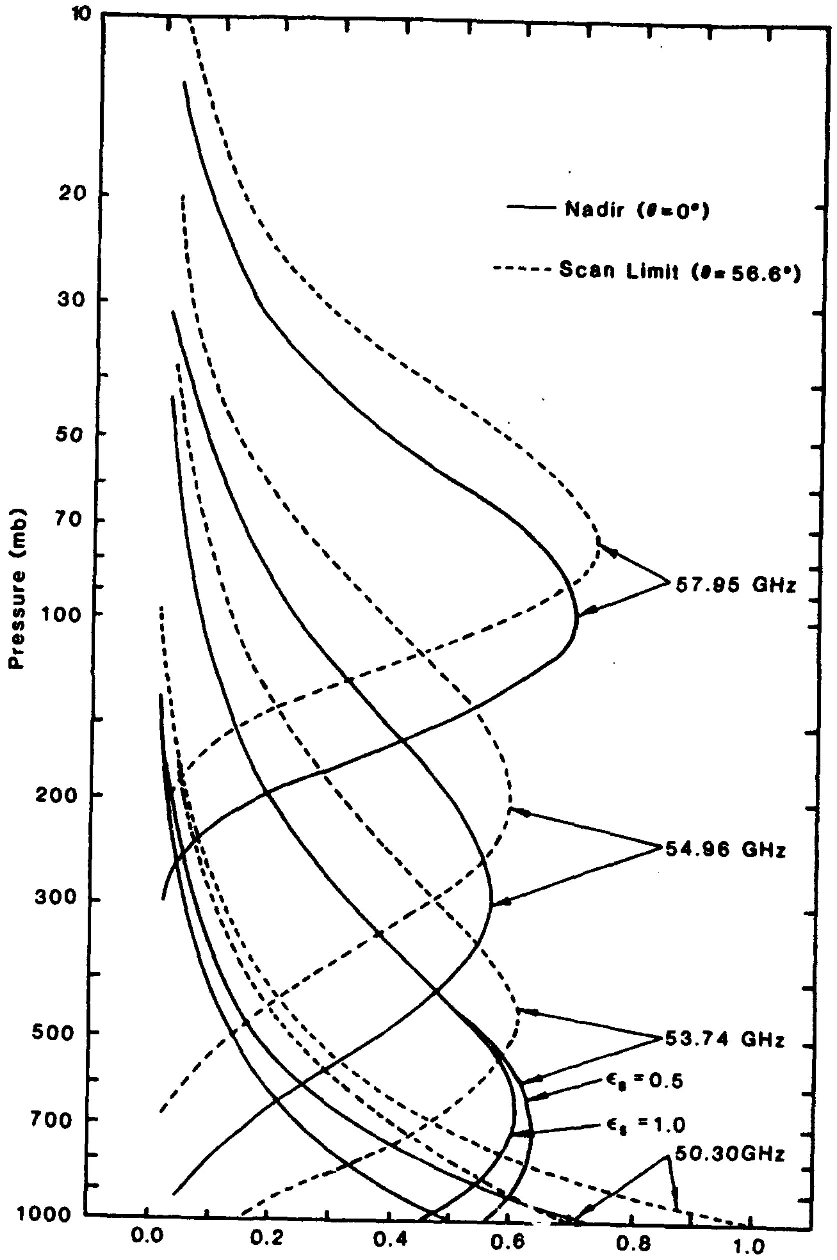

Figure 3: Energy contribution functions of MSU channels.

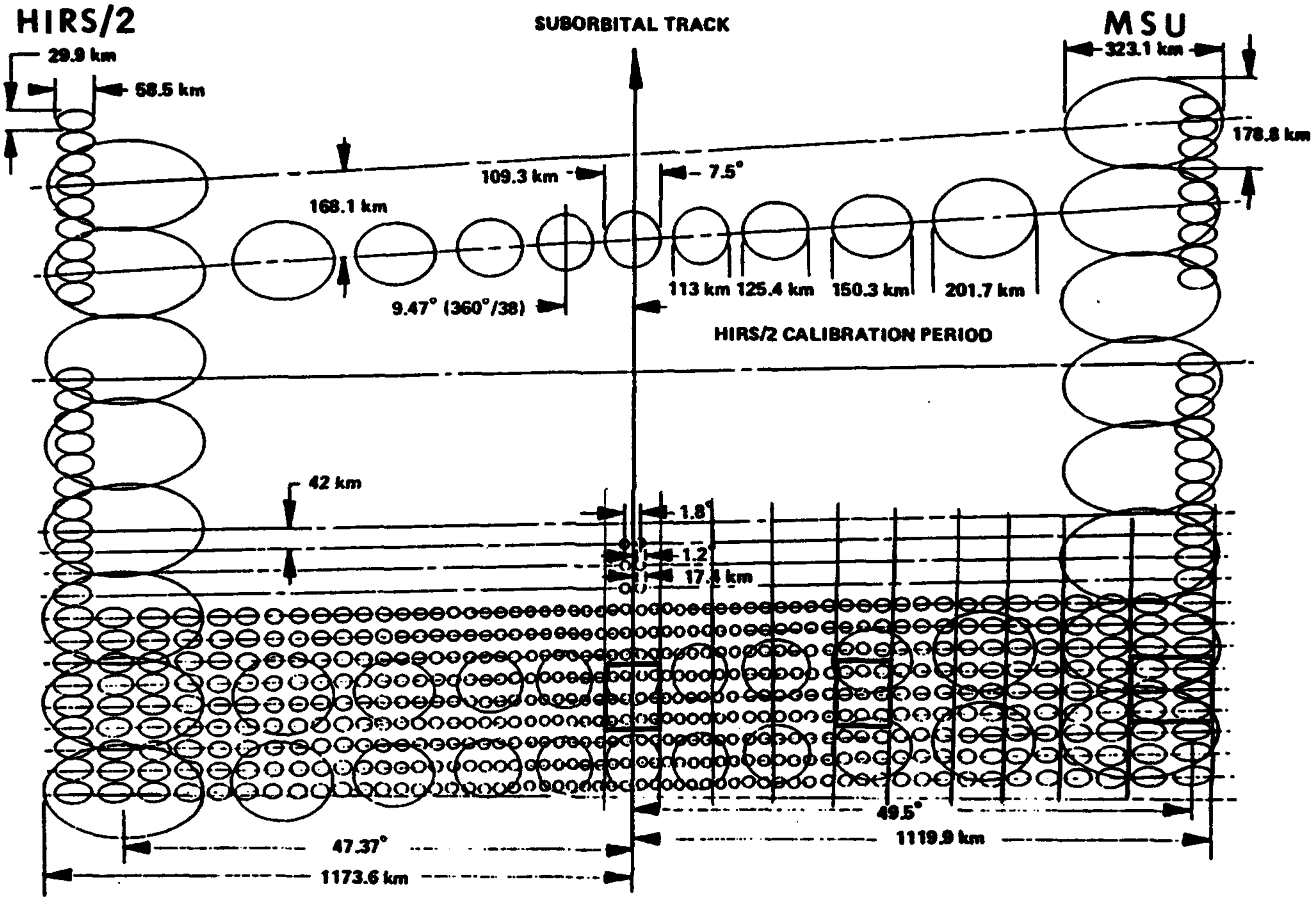

Figure 4: "3I" BOXES: HIRS/2 spots merged into MSU spots.

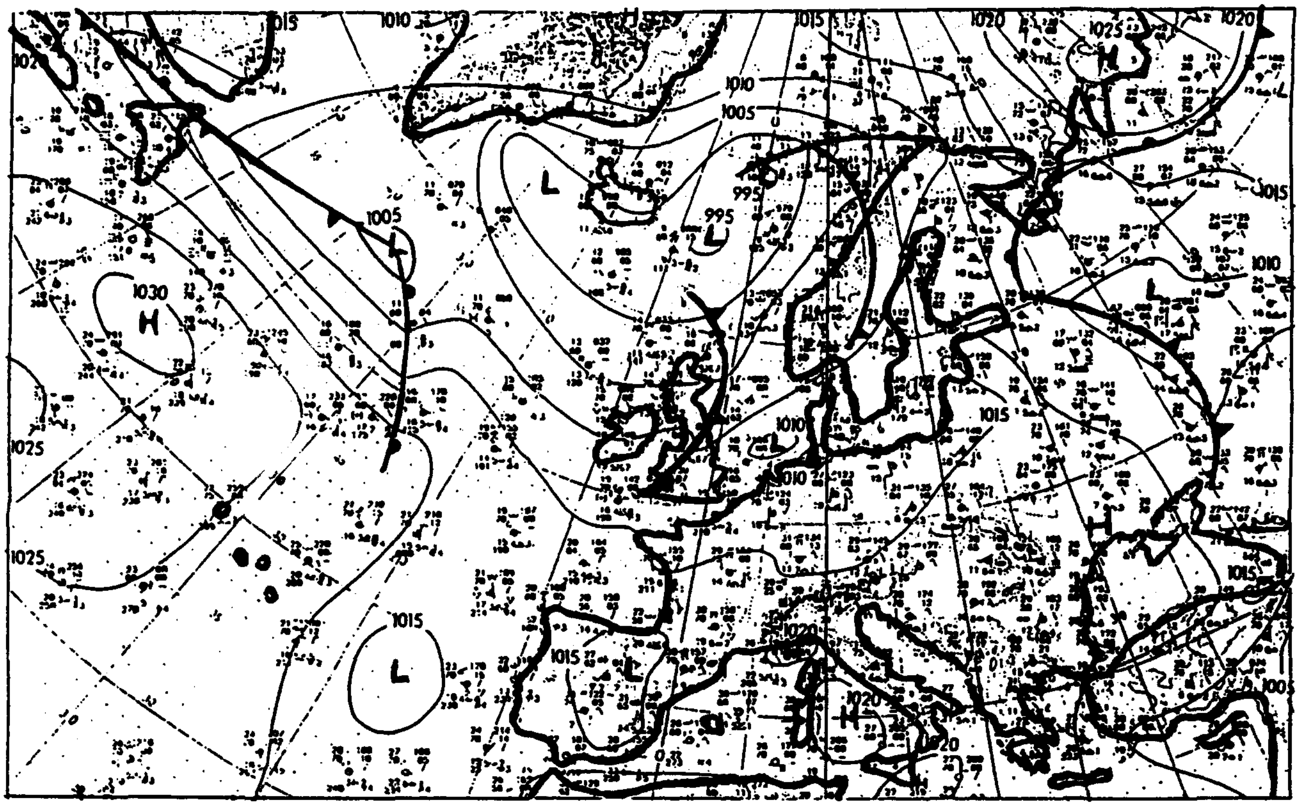

Figure 5: Surface pressure, analyzed by Deutscher Wetterdienst for 13 August 1990, 00 UTC.

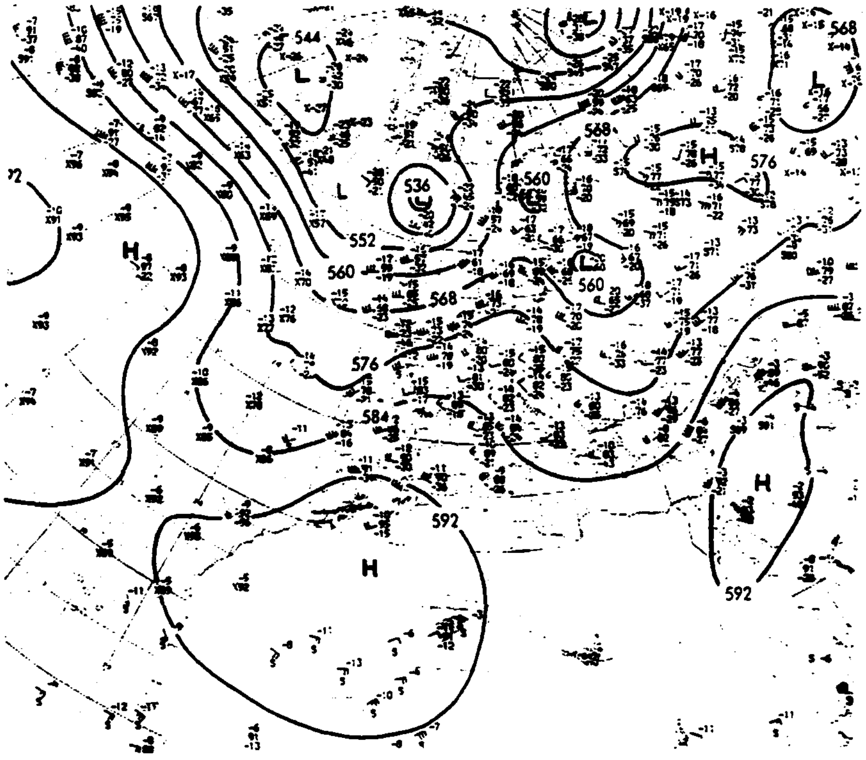

Figure 6: Geopotential height 500 hPa, analyzed by Deutscher Wetterdienst for 13 August 1990, 00 UTC.

Figure 7: AVHRR channel 4 (10.5µm)composite image of NOAA-11 orbits 9704, 9705 and 9706 for 13 August 1990 (central time 13.15 UTC), processed by the Free University of Berlin (1990).

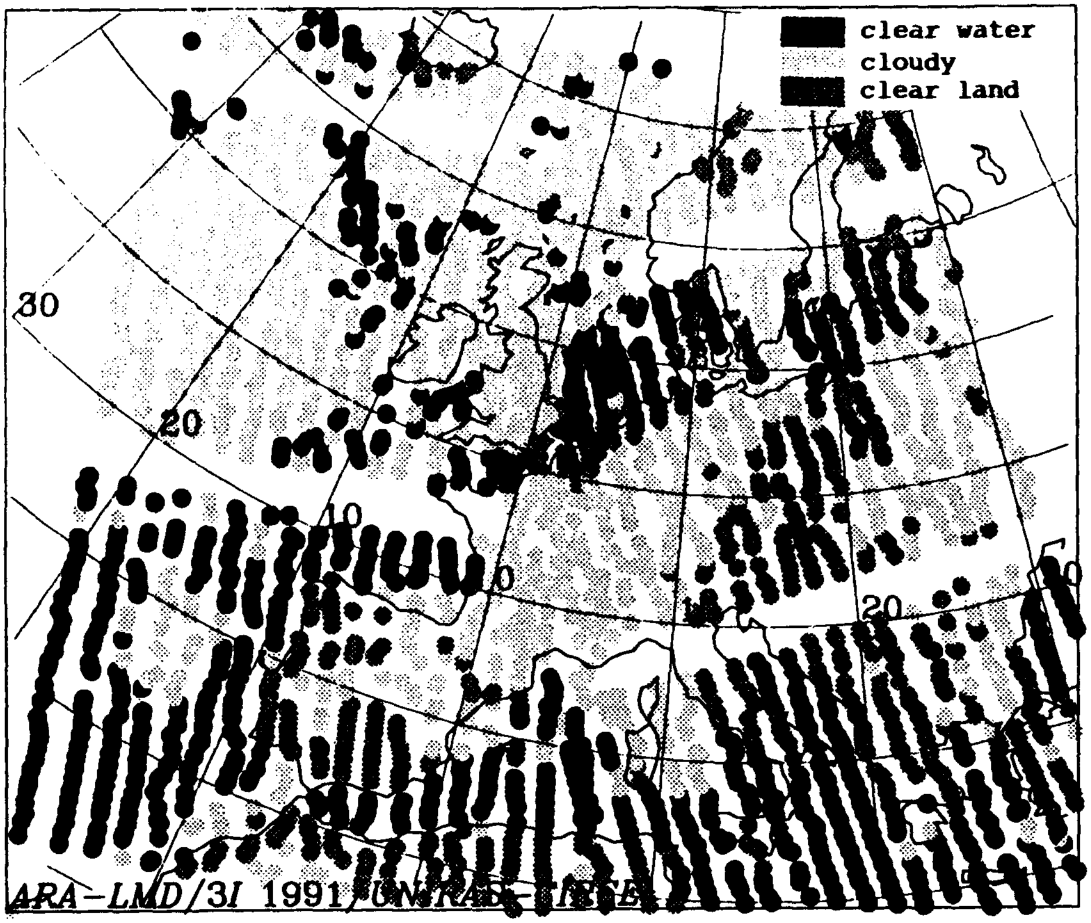

Figure 8: Clear/not clear flag, processed by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706.

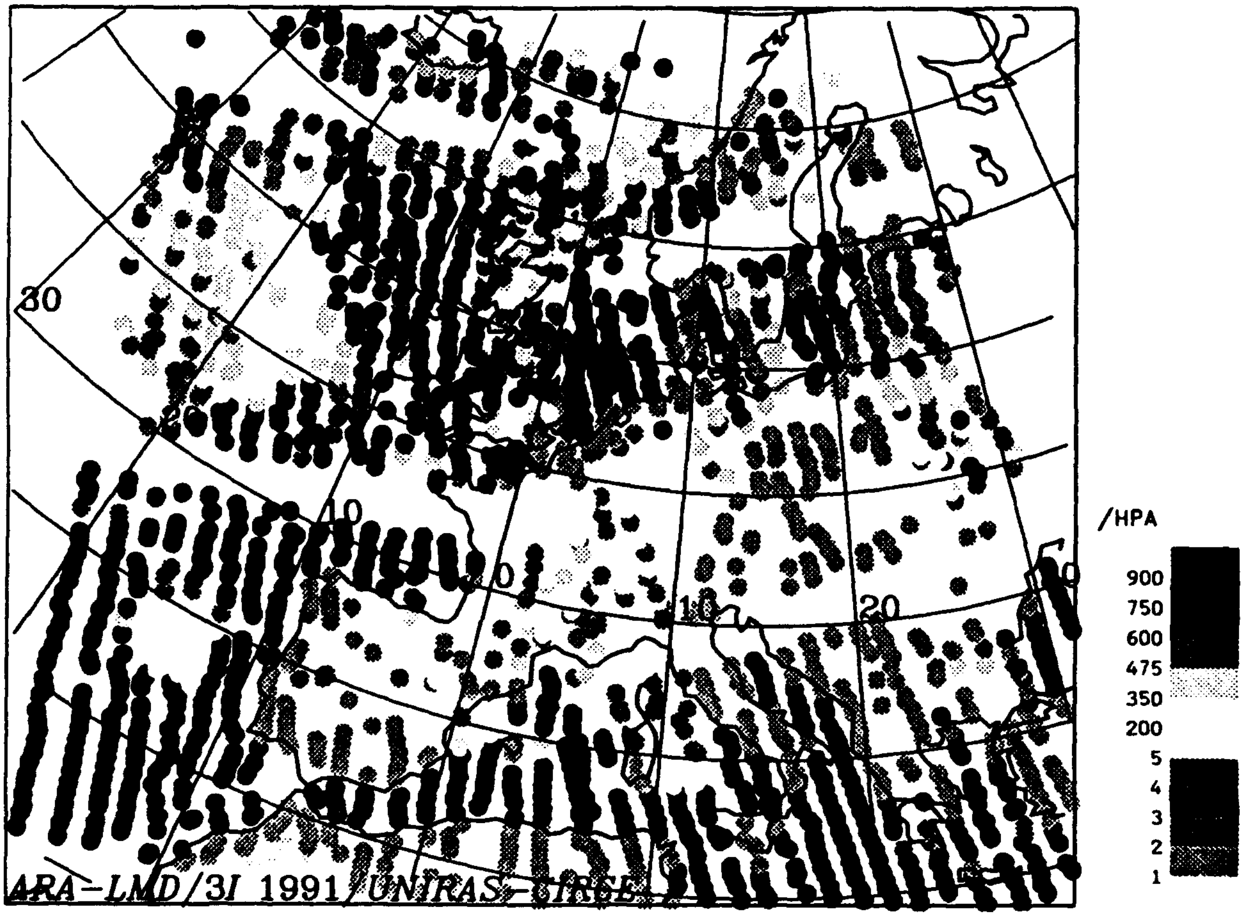

Figure 9: Cloud top pressure/hPa, retrieved by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706.

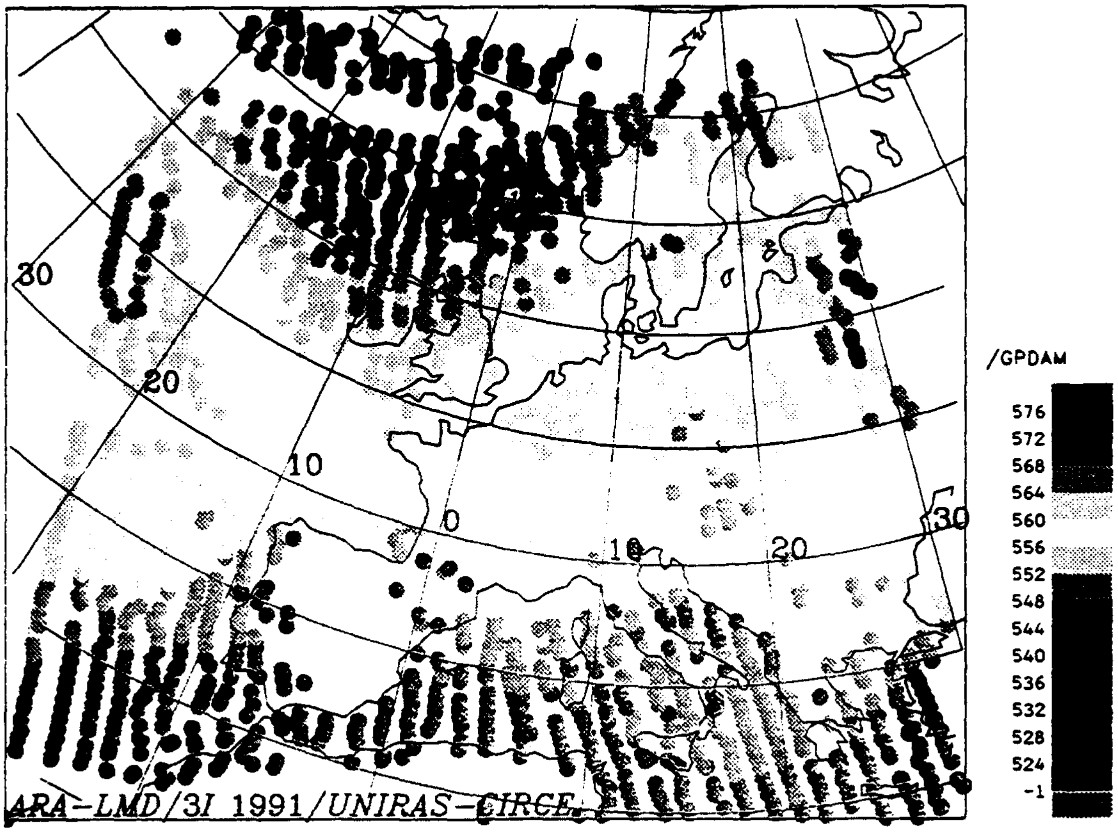

Figure 10: Geopotential thicknesses 500/1000 hPa /gpdam, retrieved by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results of "boxes".

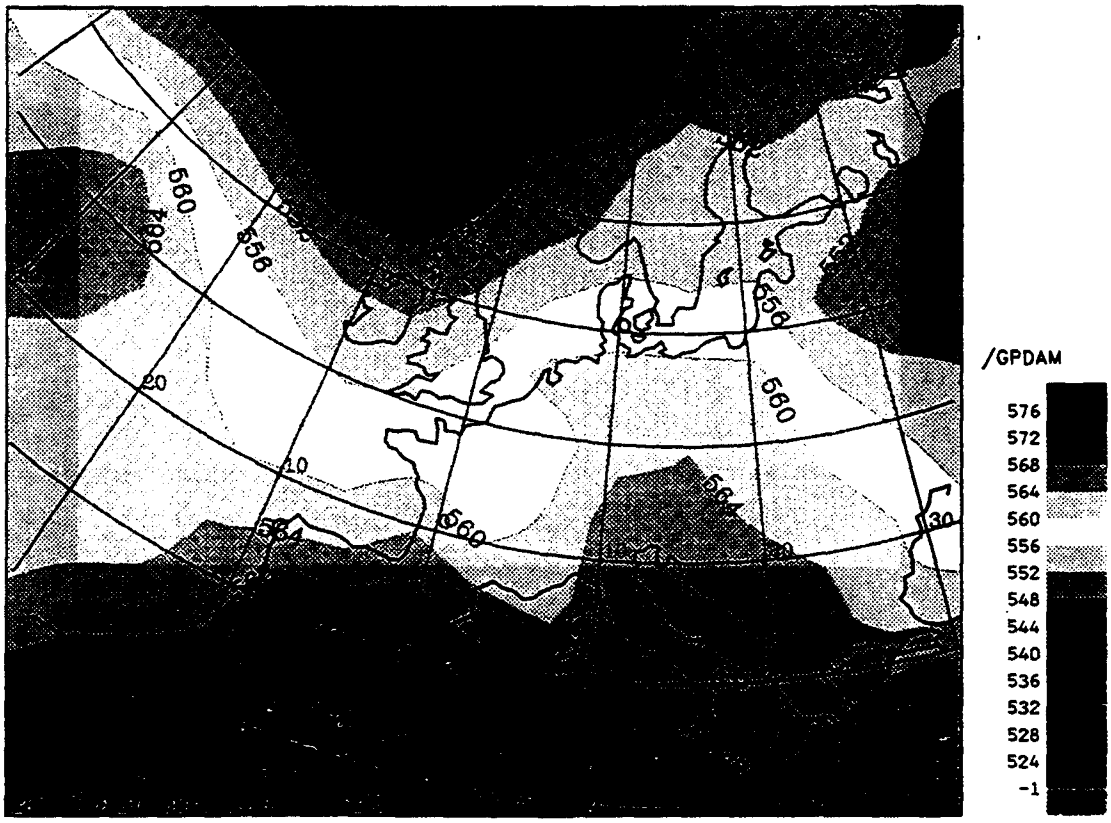

Figure 11: Geopotential thicknesses 500/1000 hPa /gpdam, retrieved by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results as before but as isolines.

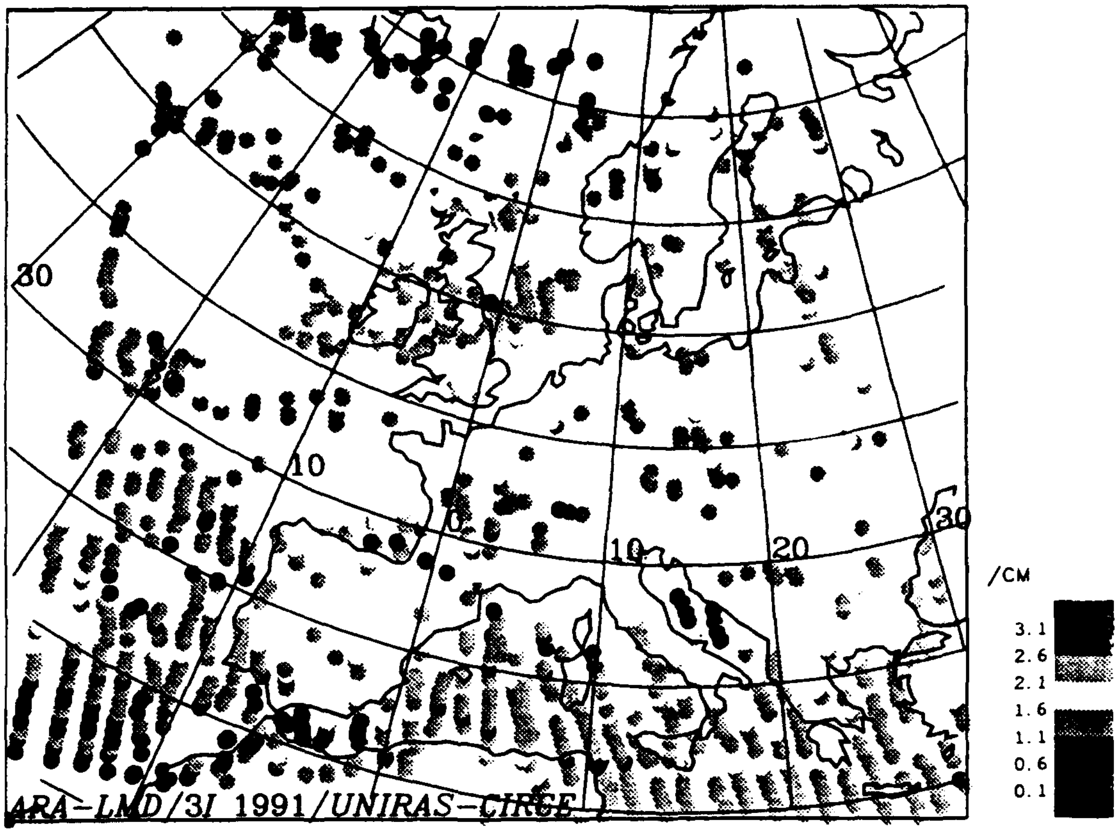

Figure 12: Total water vapor contents as PPW TOT /cm, retrieved by "3I-2" for 13 August 1190 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results of "boxes".

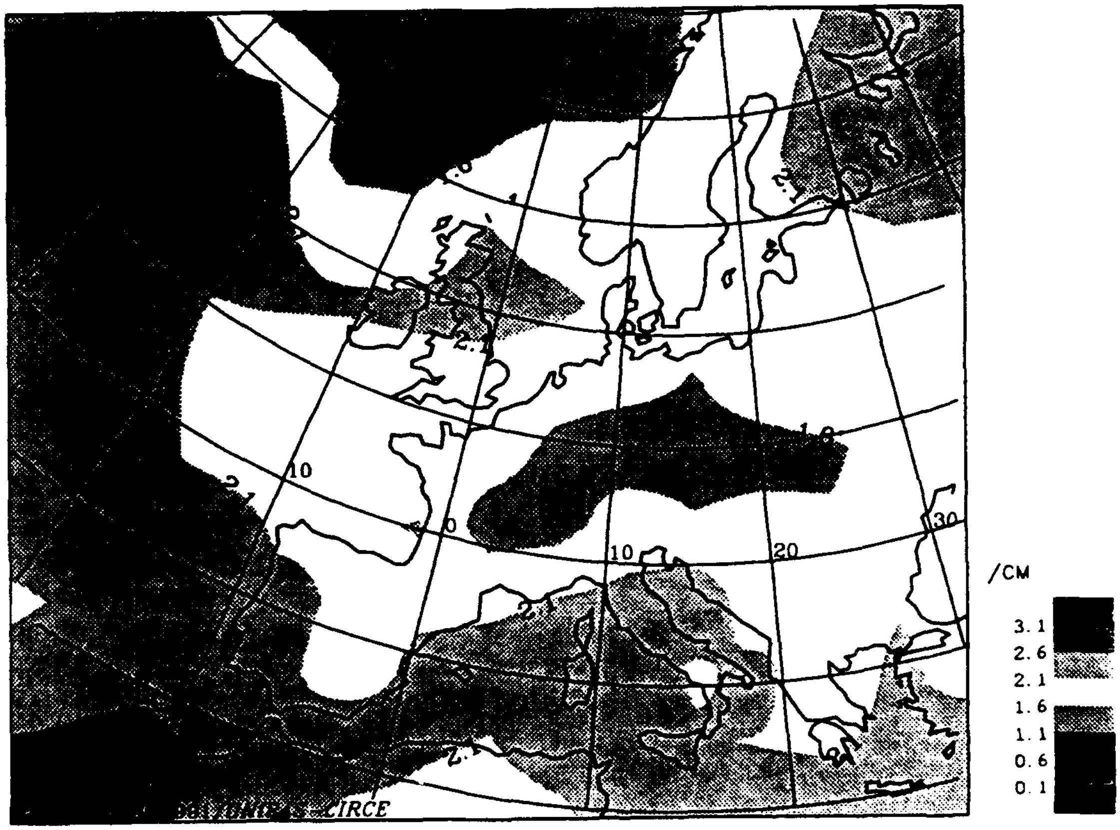

Figure 13: Total water contents as PPW TOT /cm, retrieved by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results as for Figure 12 but as isolines.

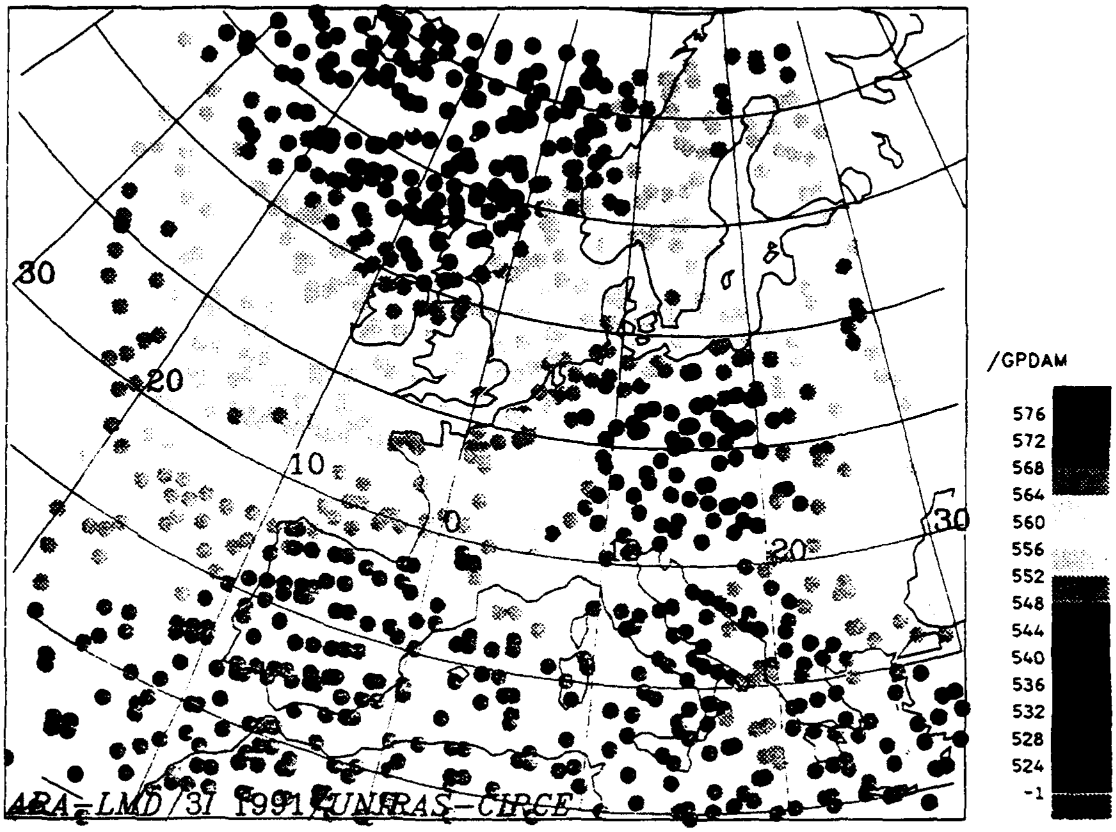

Figure 14: Geopotential thicknesses 500/1000 hPa /gpdam, retrieved by "ITPP 4" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results of 75 km areas.

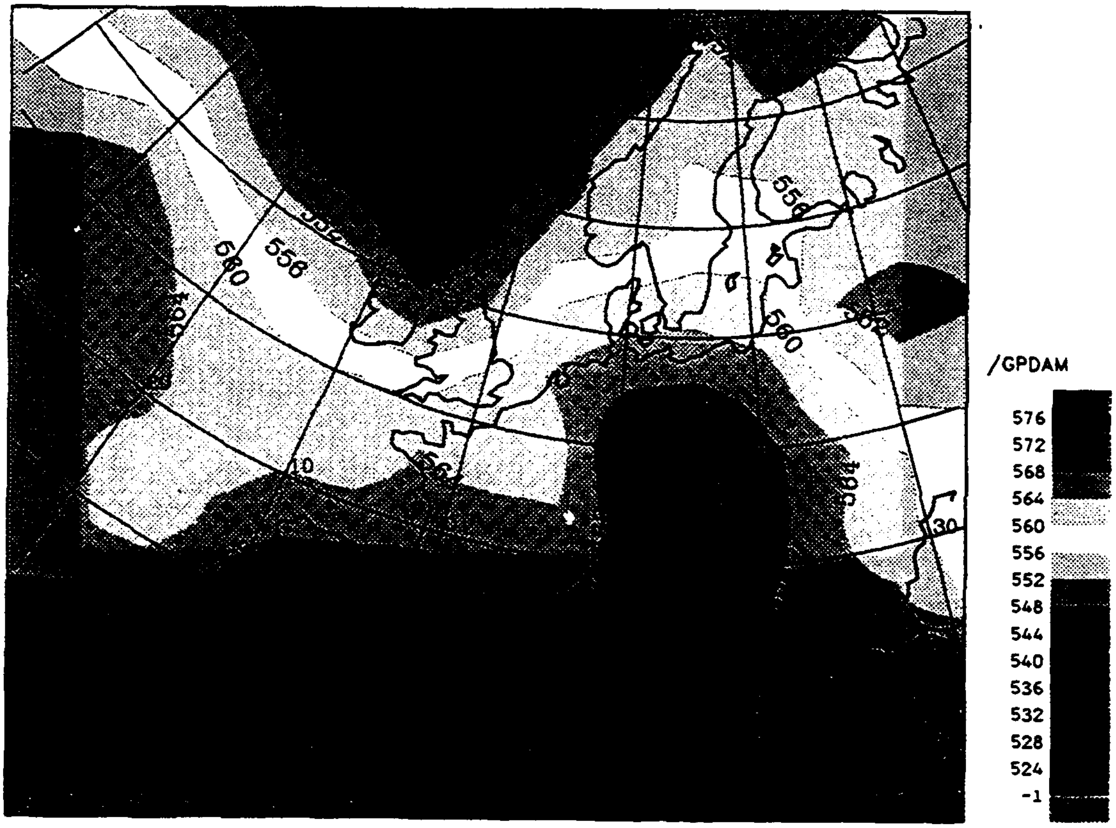

Figure 15: Geopotential thicknesses 500/1000 hPa /gpdam, retrieved by "ITPP 4" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results as for Figure 14 but as isolines.

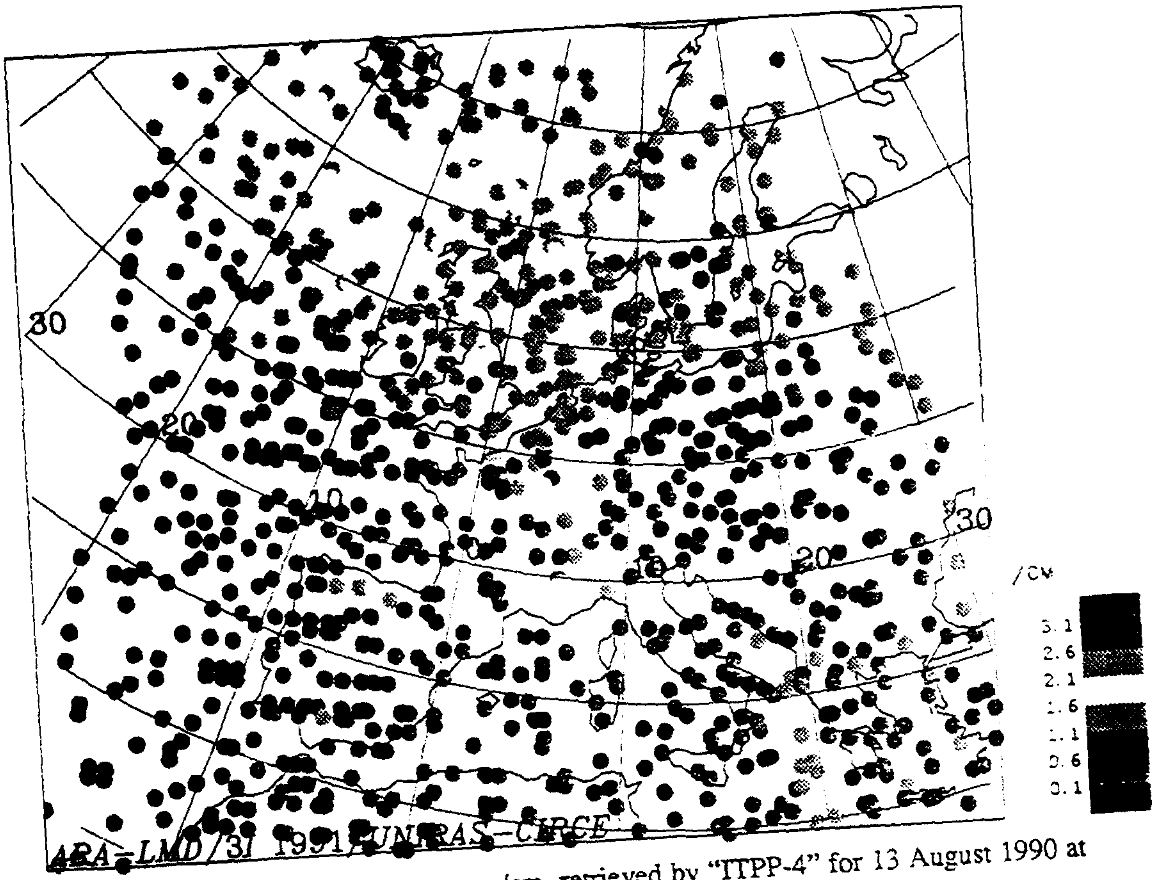

Figure 16: Total precipitable water /cm, retrieved by "ITPP-4" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results of 75 km areas.

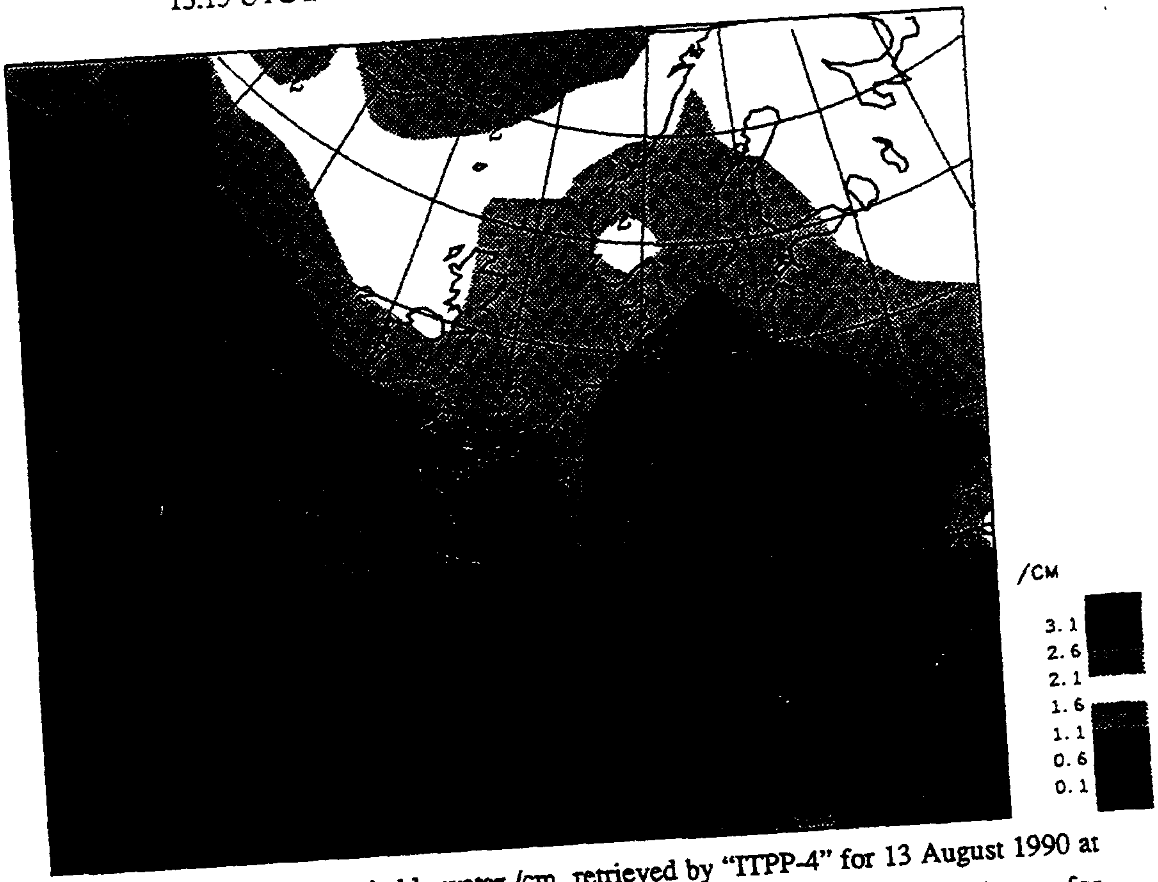

Figure 17: Total precipitable water /cm, retrieved by "ITPP-4" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706. Results as for Figure 16 but as isolines.

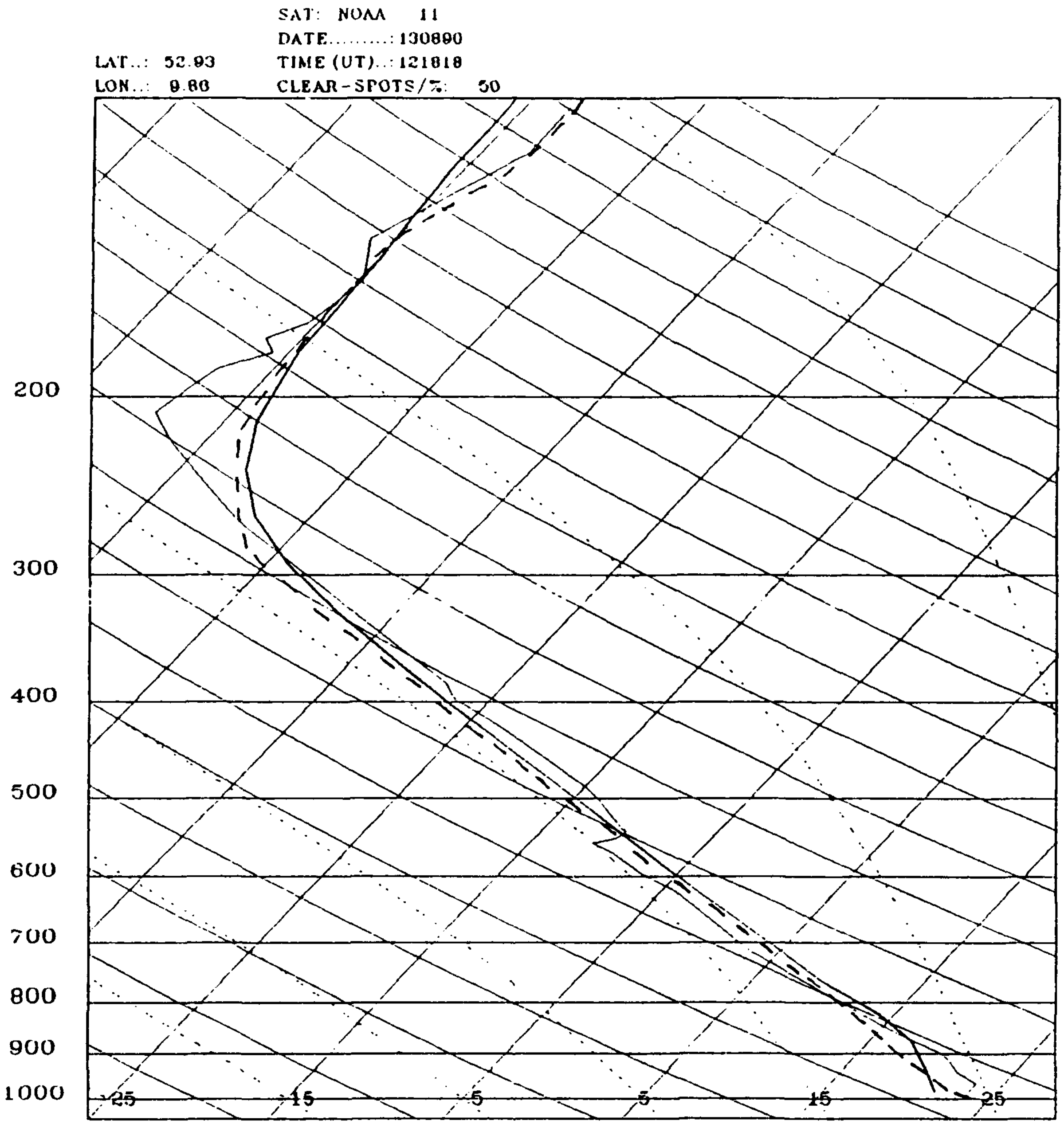

Figure 18: Vertical profiles of atmospheric temperature, obtained by "3I" (thick solid line), ITPP (dashed line) for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706 and obtained from the radiosonde observation at Hannover (10338) on 13 August 1990, 1200 UTC.

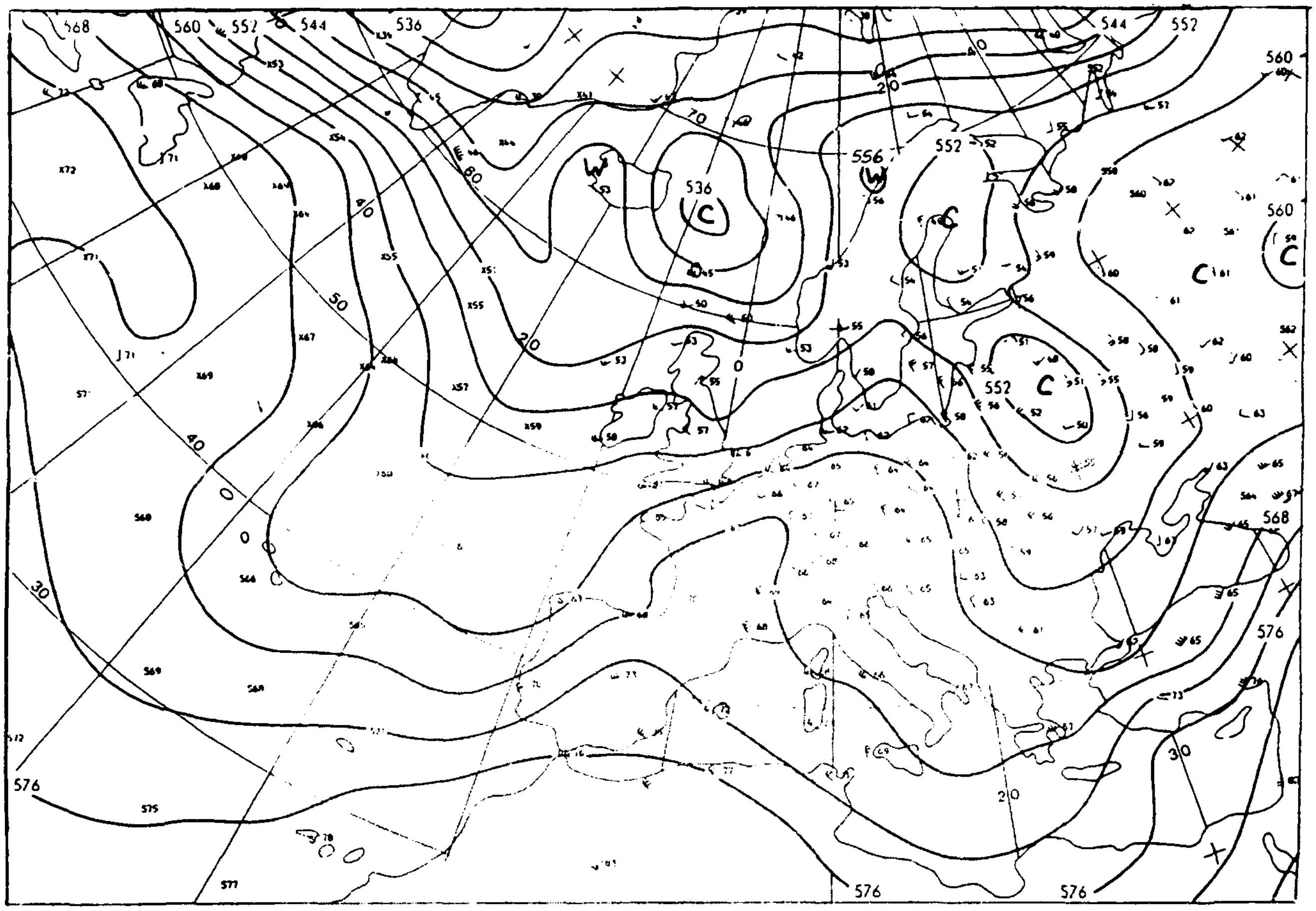

Figure 19: Geopotential thicknesses 500/1000 hPa, analyzed by Deutscher Wetterdienst for 13 August 1990, 00 UTC.

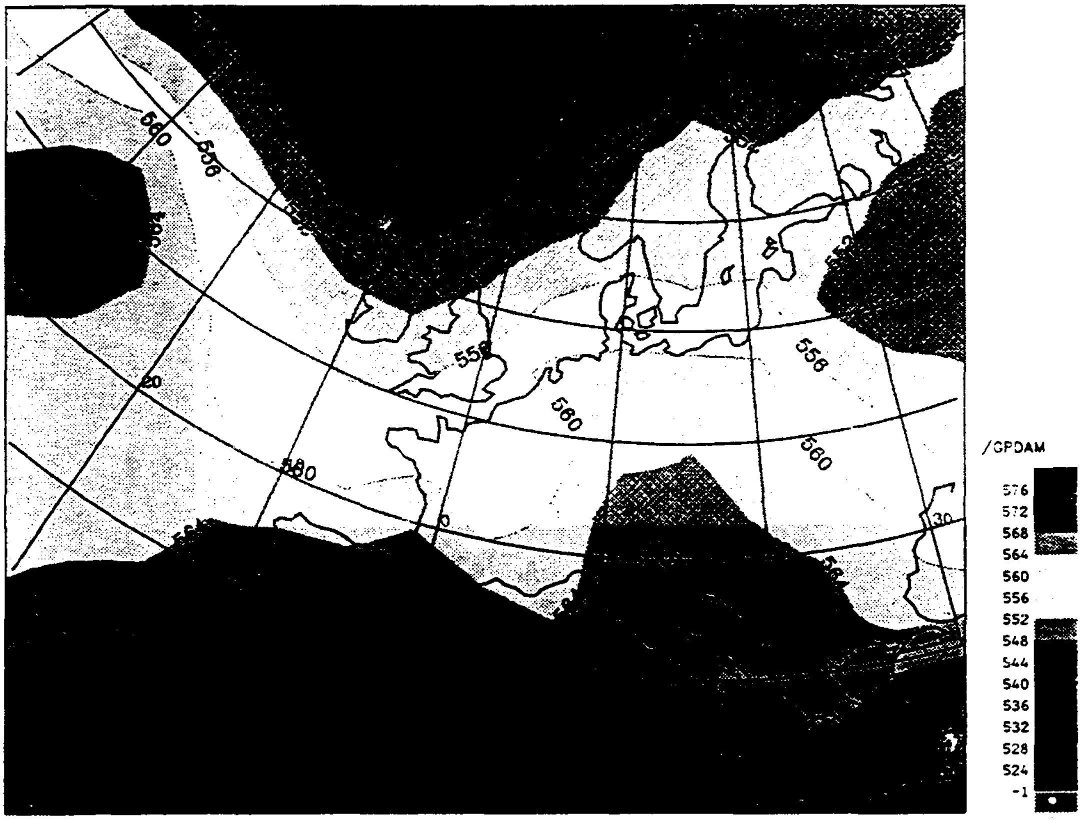

Figure 20: Geopotential thicknesses 500/1000 hPa /gpdam, retrieved by "3I-2" for 13 August 1990 at 13.15 UTC from NOAA-11 orbits 9705 and 9706.

Table 1: Characteristics of the HIRS/2 sounding channels.

HIRS/2 CHARACTERISTICS				
HIRS/2 Channel Number	Channel Central Wavenumber	Central Wavelength /μm	Principal Absorbing Constituents	Level of Peak Energy Contribution/hPa
1	668	15.00	CO_2	30
2	679	14.70	CO_2	60
3	691	14.50	CO_2	100
4	704	14.20	CO_2	400
5	716	14.00	CO_2	600
6	732	13.70	CO_2/H_2O	800
7	748	13.40	CO_2/H_2O	900
8	898	11.10	Window	surface
9	1028	9.70	O_2	20
10	1217	8.30	H_2O	900
11	1364	7.30	H_2O	700
12	1484	6.70	H_2O	500
13	2190	4.57	N_2O	1000
14	2213	4.52	N_2O	950
15	2240	4.46	CO_2/N_2O	700
16	2276	4.40	CO_2/N_2O	400
17	2361	4.24	CO_2	5
18	2512	4.00	Window	surface
19	2671	3.70	Window	surface
20	14367	0.70	Window	surface

Table 2: Characteristics of the MSU sounding channels.

MSU CHARACTERISTICS			
MSU Channel Number	Frequency /GHz	Principal Absorbing Constituents	Level of Peak Energy Contribution/hPa
1	55.73	Window	Surface
2	53.73	CO_2	700
3	54.96	O_2	300
4	57.95	O_2	90

Table 3: Characteristics of the SSU sounding channels.

SSU CHARACTERISTICS			
SSU Channel Number	Wavelength /μm	Principal Absorbing Constituents	Level of Peak Energy Contribution/hPa
1	15.00	CO_2	15.00
2	15.00	CO_2	4.00
3	15.00	CO_2	1.50

Table 4 : "4A" pressure levels.

"4A" PRESSURE LEVELS	
Level Number	Level / hPa
1	0.05
2	0.09
3	0.17
4	0.30
5	0.55
6	1.00
7	1.50
8	2.23
9	3.33
10	4.98
11	7.43
12	11.11
13	16.60
14	24.79
15	37.04
16	45.73
17	56.46
18	69.71
19	86.07
20	106.27
21	131.20
22	161.99
23	200.00
24	222.65
25	247.90
26	275.95
27	307.20
28	341.99
29	380.73
30	423.85
31	471.86
32	525.00
33	584.80
34	651.04
35	724.78
36	800.00
37	848.69
38	900.33
39	955.12
40	1013.00

Table 5: Statistics (4 orbits) "3I Std" compared with values derived from radiosondes, 13 August 1990.

Thicknesses	Mean Radiosondes (gpm)	Bias (gpm) or (K)	STDV (gpm) or (K)	# Items
500/1000	5535.17	-34.65	20.39	534
		-1.71	1.01	
Total water	(cm)	(cm)	(cm)	# items
q_{tot}	2.16	-0.22	0.57	437

References

F , Freie Universitaet, 1990: Berliner Wetterkarte. Amtsblatt des Instituts fuer Meteorologie, 13. August 1990.

Chedin, A. and N.A. Scott, 1984: Improved Initialization Inversion Procedure ("3I"). Proc. First Int. TOVS Study Confl., Igls, Austria, P. Menzel, Ed., Cooperative Institute for Meteorological Satellite Studies, 14-79.

Chedin, A. and N.A. Scott, 1985: Initialization of the Radiative Transfer Equation Inversion Problem from a Pattern Recognition Type Approach: Application to the Satellites of the TIROS-N Series. Advances in Remote Sensing Retrieval Method. A. Deepak, H.E. Fleming and M.T. Chahine (Eds.), A. Deepak Publishing, 495-515.

Chedin, A., N.A. Scott and Y. Tahani, 1990: Observation of water vapor from space and ground-based sensors for climate studies. Complementary of NOAA (TOVS) and DMSP (SSM/I) data. NASA Workshop on the Role of Water Vapor in Climate Processes. October 29-31, 1990.

Chedin, A., N.A. Scott, C. Wahiche and P. Moulinier, 1985: The Improved Initialization Inversion Method: A High Resolution Physical Method for Temperature Retrievals from Satellites of the TIROS-N Series. J. of Climate and Applied Meteorology, Vol. 24, No. 2, 128-143.

Chedin, A., N.A. Scott, C. Wahiche, P. Moulinier, N. Husson, and P. Sitbon, 1986: The "3I" Procedure Applied to the Retrieval of Meteorological and Climate Parameters from NOAA-7. Ocean-Air Interactions, Vol. 1, 29-42.

Chedin, A., N.A. Scott, J. Flobert, N. Husson, C. Levy, G. Rochard, J. Quere, B. Bellec, and J. Simeon, 1987: Analysis of Thickness Fields Retrieved from NOAA-7 Observations Through the "3I" Inversion Method. Interest for Weather Forecasting. Proc. Symp. Mesoscale Analysis and Forecasting, Vancouver, Canada, 17-19 August 1987, ESA SP-282, 97-101.

Chedin, A., N.A. Scott, and V. Achard, 1990: Pattern recognition and assimilation of satellite data in numerical weather forecasting. Proceedings of the International symposium on Assimilation of Observations in Meteorology and Oceanography, Clermont-Ferrand, France, 7 pp.

Chedin, A., 1989: The 3-I Retrieval Method. Recent local and global applications. ECMWF Seminar Proceedings, Data Assimilation and the Use of Satellite Data, 5-9 September, 1988, ECMWF, Reading, UK, 181-214.

Claud, C., N.A. Scott and A. Chedin, 1990: Mesoscale meteorology in polar regions from a coupling of NOAA (TOVS) and DMSP (SSM/I) data. Fifth Conference on Satellite Meteorology and Oceanography, September 3-7, 1990, London, England. American Meteorological Society, 386-391.

Deutscher Wetterdienst, 1990: Europaeischer Wetterbericht. 13, August 1990.

Fleming, H.E., M.D. Goldberg, and D.S. Crosby, 1986: Minimum variance simultaneous retrieval of temperature and water vapor from satellite radiance measurements. Second Conference on Satellite Meteorology - Remote Sensing Applications. Williamsburg, Amer. Met. Soc., 20-29.

Heinemann, G., 1990: On the use of TOVS data for studies of mesoscale vortices in the Wedell Sea (Antarctica). Tech. Proc. Fifth International TOVS Study Conference, Toulouse, France. A report of the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Ed., W.P. Menzel, 184-200.

Husson, N., B. Bonnet, Y. Tahani, C. Claud, N.A. Scott, A. Chedin, 1991: The "3I" (Improved Initialization Inversion) Interactive 3D Software to process, analyze and display NOAA/TOVS data. Seventh International Conference on Interactive Information and Processing Systems for Meteorology. Hydrology and Oceanography, January 14-18, New Orleans, LA, 137-143.

King, J.I.F., 1990: Differential solutions of the remote sounding problem for spline function transmittances. Fifth Conference on Satellite Meteorology and Oceanography, September 3-7, 1990, London, England, American Meteorological Society, 73-77.

Klaes, K.D., 1990: A system for operational realtime satellite data processing. Fifth conference on satellite meteorology and oceanography, September 3-7, 1990, London, England, American Meteorological Society, 414-415.

Klaes, K.D., 1991: The environment of meso-beta phenomena with TOVS. Tech. Proc. 6th International TOVS Study Conference, 1-6 May, 1991, Airlie, VA, USA. A Report of the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Ed. W.P. Menzel.

Klaes, K.D., J. Escobar, B. Bonnet, 1991a: A 3I-VAX Version. A system to process TOVS data from the antenna to the end-product. Laboratoire de Meteorologie Dynamique, Internal Note No. 164, 50 pp.

Klaes, K.D., A. Chedin, N.A. Scott, N. Husson, B. Bonnet, J. Escobar, V. Achard, 1991b: First results of a comparison between the old and the new 3I-version. Tech. Proc. 6th International TOVS Study Conference, 1-6 May, 1991, Airlie, VA, USA. A Report of the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Ed. W.P. Menzel.

LeMarshall, J.F., 1988: An intercomparison of temperature and moisture fields derived from the TIROS operational vertical sounder data by different retrieval techniques. Part I: Basic Statistics. J. Appl. Met., 27, 1282-1293.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. Bull. Amer. Met. Soc., 56, 527-530.

Ou, S.C., K.N. Liou and J.I.F. King, 1990: Remote sounding of temperatures in cloudy atmospheres using the differential inversion method. Fifth Conference on Satellite Meteorology and Oceanography, September 3-7, 1990, London, England, American Meteorological Society, 60-63.

Planet, W.G. (Editor), 1988: Data Extraction and Calibration of TIROS-N/NOAA Radiometers, NOAA Technical Memorandum NESS 107, Rev. 1, U.S. Department of Commerce, Washington, D.C., November 1979, Revised October 1988, 58 pp. + App.

Prangsma, G.J., 1989: A squall line over southwestern France: 7 June 1987. Description of the synoptic situation preceding the afternoon event. The ITOVS Northern Hemisphere Case Study. Tech. Proc. Fifth International TOVS Study Conference, Toulouse, France. A report of the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Ed., W.P. Menzel, 303-312.

Reale, A.L., D.G. Gray, M.W. Chalfront, A. Waroop, A. Nappi, 1986: Higher resolution operational satellite retrieval. Proc. of the Second Conference on Satellite Meteorology-Remote Sensing and Application, Williamsburg, Amer. Met. Soc., 596 pp.

Scott, N.A. and A. Chedin, 1981: A fast line-by-line method for atmospheric absorption computations: The automatized atmospheric absorption atlas. J. Appl. Met., 21, 1005-1014.

Smith, W.L., 1968: An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements. Mon. Wea. Rev., Vol. 96, No. 6, 387-396.

Smith, W.L. and H.M. Woolf, 1976: The use of eigenvectors of statistical covariance matrices for interpreting satellite sounding radiometer observations. J. Atmos. Sci., Vol. 33, No. 7, 1127-1140.

Smith, W.L., H.M. Woolf, C.M. Hayden, D.Q. Wark and L.M. McMillin, 1979: The TIROS-N operational vertical sounder. Bull. Amer. Meteor. Soc., 60, 1177-1187.

Smith, W.L., 1983: The retrieval of atmospheric profiles from VAS geostationary radiance observations. J. Atmos. Sci., 40, 2025-2035.

Smith, W.L., H.M. Woolf, C.M. Hayden, A.J. Schreiner and J.M. LeMarshall, 1985: The physical retrieval TOVS export package. First International TOVS Study Conference, Tech. Proc.

Smith, W.L., H.M. Woolf, C.M. Hayden and A.J. Schreiner, 1986: The simultaneous retrieval export package. Second International TOVS Study Conference, Tech. Proc., 224-253.

Tahani, Y., N.A. Scott, and A. Chedin, 1990: Evaluation of TOVS water vapor retrievals from the improved version of the "3I" system. XXVII COSPAR, 1990. The Hague, The Netherlands.

Tahani, Y., 1991: Restitution de va vapeur d'eau atmospherique a partir des observations de satellite meteorologiques. Interet pour l'altimetrie spatiale. These presentee a l'universite Pierre et Marie Curie (Paris VI), Paris, 132 pp.

Twomey, S., 1977: Introduction to the mathematics of inversion in remote sensing and indirect measurements. Elsevier Scientific Publishing Company, Amsterdam, Oxford, New York, 243 pp.

Vowinkel, B., 1988: Passive Microwellenradiometrie. Friedrich Vieweg und Sohn, Braunschweig, Wiesbaden, 326 p.

Wahiche, C., N.A. Scott, A. Chedin, 1986: Cloud detection and cloud parameters retrieval from the satellites of the TIROS-N series. Annales Geophysicae, Vol. 4, B, No. 2, 207-222.

Woolf. H.M., 1990: International TOVS processing package (ITPP) software description and installation guide. Version 4.0, January 1990. A Report from the Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, 21 pp.

Appendix A

The Ψ-Method in "3I"

The Ψ-Method uses the non sensitivity of the MSU channels to clouds (provided there is not too much rain contamination) and tries to create "cleared" HIRS/2 channel radiances by comparing MSU brightness temperatures with HIRS brightness temperatures for channels, whose energy contribution functions peaks at the same level.

Thus Ψ-radiances are created as

$$\Psi^{HIRS}(i) = T^{HIRS}_{CLOSEST} + \left[T^{MSU}_{obs}(j) - T^{MSU}_{CLOSEST}(j)\right] \tag{A.1}$$

where i = 4, 5, 6, 15 while j= 3, 2, 2, 2, respectively, and

$$\Psi^{HIRS}(14) = b_0 + \sum_i b_i T^{HIRS}(i) + \sum_j c_j T^{MSU}(j) \tag{A.2}$$

where i = 1,...,6 and 15; for j = 2,3.