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LOCAL AND GLOBAL APPLICATIONS
OF THE "3I" SYSTEM

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1. INTRODUCTION

Aiming at the three-dimensional analysis of the Earth's atmosphere structure from observations of the operational meteorological satellites of the TIROS-N/NOAA series, algorithm "3I" (Improved Initialization Inversion), since the last meeting of the International TOVS working group, has been developed and refined following five main directions:

- As a feedback to the extensive series of experiments carried out at ECMWF and aiming at measuring the impact of satellite data, processed by the 3I scheme, on middle range weather forecasting, modifications to the algorithm have been introduced and applied to several pathological NOAA-9 and NOAA-10 passes. The main improvements concern the temperature variance/covariance matrix involved in the solution estimation method, the cloud-clearing technique and the introduction of a rain detection test. Significant improvements have been obtained and are illustrated through comparisons with analyses.

- Numerous applications to special situations have been carried out, in particular over Arctic and Antarctic areas with the aim of studying polar low formation and development.

- Coming space altimetry experiments (TOPEX-POSEIDON, ERS1) have led us to pursue quantitative evaluation of TOVS vertical water vapor distribution for several study cases as well as at global scale (cooperation with ECMWF).

- Two rapidly evolving severe weather situations have been analysed and comparisons have been made with conventional data so as to evaluate their differences. Assimilation of satellite data in limited area models is studied in cooperation with KNMI (Netherlands Meteorological Institute) and DNMI (Norwegian Meteorological Institute).

- Retrieval of total ozone amount maps has been attempted from TOVS observations. Sensitivity of ozone channel to the shape of ozone vertical distribution has been quantified leading to the conclusion that particular care must be exercised in the interpretation of such maps. Details on these developments are given in the next sections and related references.
2. RECENT IMPROVEMENTS IMPLEMENTED IN THE 3I SYSTEM

2.1 Introduction

At ECMWF, an extensive series of experiments has been carried out using satellite sounding data from the NOAA satellites and the 3I (Improved Initialization Inversion) retrieval scheme developed by the ARA (Atmospheric Radiation Analysis) group at LMD. This algorithm has been run in an experimental suite to produce global data sets. More than 40,000 soundings on average have been produced for each 6 hour period from 30 January 00 UT to 14 February 12 UT, 1987. The quality of these soundings was examined and compared to the quality of operational NESDIS soundings with encouraging results: slightly better quality of 3I products on the average, in particular for the lowest layer (1000/850 hPa); very little random noise; slightly better gradients, etc... (see Flobert et al., 1989). However, problems affecting both algorithms or 3I specifically were identified that led us to either refine some of the solutions adopted in 3I or to add a few new and potentially important tests. These improvements and modifications have been described in detail in Chedin, Scott et al. (1989). They are briefly reviewed here and their quantitative impact is presented through an application to several passes (NOAA-9 and NOAA-10 ; 1 February 1987) selected according to the problems they have brought into evidence.

2.2 The temperature variance/covariance matrix

As explained in Chedin and Scott (1983) and Chedin et al. (1985), estimation of the solution to the inversion of the radiative transfer equation requires knowledge of the variance/covariance matrix of the difference between the unknown (let say: the true temperature profile) and the corresponding initial solution. The procedure to compute this matrix, from the TIGR (TOVS Initial Guess Retrieval) data set, has been refined, as explained in Chedin, Scott et al. (1989), and now exactly follows the way the initial solution is obtained in the 3I algorithm without any simplification. Moreover, the viewing angle sampling is now involved in this computation leading to 120 matrices (3 air masses; 2 surface emissivities; clear/not clear cases; 10 angles) instead of 12 in the former approach.
2.3 Cloud clearing

In the 3I approach, cloud clearing of infrared radiances is carried out through the so-called "\(\psi\)-method". Following this method, a cleared infrared brightness temperature is obtained by adding to the initial guess value of the channel considered, the difference between the observed and the initial guess values of a microwave channel, almost insensitive to clouds and peaking approximately at the same levels.

A good coincidence of the microwave and associated infrared observation is thus required to reach an acceptable level of accuracy. This is certainly the case for MSU channel 2 and both HIRS-2 channels 5 and 15. This is more questionable for HIRS-2 channels 3 and 4 and their microwave equivalent. For that reason, previous \(\psi\) simple approach was refined in the sense that these two channels are now cloud cleared using a regression of the form:

\[
\psi_{\text{3 or 4}} = a + \sum_{i=2}^{4} a_{\text{MSU}}(i) + a_{\text{HIRS}}(2)
\]

Coefficients are obtained from the TIGR data base, for each viewing angle and surface elevation and for the two types of terrain (land/sea).

2.4 Other changes

A few minor but potentially important changes have been brought to the 3I algorithm. They are described in Chedin, Scott et al. (1989) and concern:

- a new mapping of the MSU observations within the HIRS-2 spots;

- a new test for detecting low clouds over sea ice at day;

- the assimilation of the sea surface temperature from conventional analysis maps (themselves derived from AVHRR) in the water vapor retrieval;

- the capability of reading TOVS data under format level 1B or, equivalently, the Master Plus format of Centre de Météorologie Spatiale (EERM, Lannion, France);

2.5 Application to selected (pathological) cases. 
Comparison with previous results.

Improved in the way described above, the 3I algorithm has been applied to six passes corresponding to particularly bad comparisons with analyses (see Fig. 2.5.1). They are located in north and south Pacific, in north Atlantic and over Europe. Results have been presented in detail in Chedin, Scott et al. (1989) through comparisons between 3I before the modifications and 3I after the modifications on the basis of layer mean temperatures. These comparisons bring into evidence the following points:

- There is a general important improvement with the modified code over the previous one for both the biases and standard deviations.

- For two NOAA-9 passes out of four, significant negative biases for the lowest layers still persist. This is a bit surprising if one considers the proximity of NOAA-9 passes 11017 and 11016 with NOAA-10 pass 1946 (South Pacific). The negative bias is significantly decreased for the latter but not for the former two. It is most likely that the correct explanation lies in an imperfect validation of NOAA-9 synthetic computations at least for polar regions.

The next step of the quantitative assessment of the benefit brought by the modifications presented there has consisted in computing the "stability index" (defined by the difference between the temperature (virtual) of the two layers 1000/700 hPa and 500/300 hPa; see Andersson et al., 1989), and comparing it to ECMWF analyses.
Figure 2.5.1 NOAA-9 and NOAA-10 passes selected for testing the modifications introduced in 3I after the impact analysis campaign carried out at ECMWF. 1 Febr. 1987 around 12.00 UT (± 3 h).

A representative example of resulting improvements is illustrated by one NOAA-9 pass (nb. 11019 over Europe), actually the most pathological with respect to this parameter. Figures 2.5.2 (before modifications) and 2.5.3 (after modifications) illustrate the difference between 3I retrieved and ECMWF analysed stability index. Improvements are obvious particularly over and off Scandinavia and U.K. and over the Mediterranean. Previous bad comparisons are either rejected or significantly improved. Rain is suspected in part for the darker area over Greece (the rain detection test does not apply over land). A confirmation of this improvement is given by the layer mean temperature statistics presented on Fig. 2.5.4 (before) and Fig. 2.5.5 (after). Differences are 3I - ECMWF. As explained in Chedin, Scott et al. (1989), although the idea of confronting not only layer retrieved temperatures to corresponding analysed values but also quantities related to temperature
gradients in the vertical is very fruitful, it is worth thinking in detail at the definition of such a quantity when satellite products are involved. As presently defined, the stability index raises a problem related to the fact that the lowest layer extends down to 1000 hPa. If the 3I approach has proven being significantly better in the lowest layer, it is also true that the lowest 500 m or 1 km are the most difficult to manage. For that reason, we recommend to define an index better adapted to satellite observation, avoiding the lowest 500 m or 1 km and not obviously sticking to the standard levels. We have undertaken an action in this direction.

As explained in Flobert et al. (1989), several areas of relatively small sizes and characterized by much too cold retrievals in the lower troposphere, turned out to be caused by heavy rain contaminating MSU channels. The simple rain test proposed by Philips (1980) and stating that these channels are likely to be contaminated if the MSU1-MSU2 brightness temperature difference is less than twelve degrees was not included in the 3I processing due to a programming oversight. This fact resulted, on 1 February 1987, on bad "3I forecast" over North America. The origin is due to a front crossing North-East Pacific off Vancouver and observed by NOAA-9 (orbit nb. 11018). For this pass, figures on the cover display the mean cloud amount (top left) and mean cloud top pressure (top right) as determined by 3I. A zone characterized by an heavy cloudiness and relatively high tops is well identified from the west coast of the USA to the bottom left corner of the figures.

The MSU1-MSU2 difference test applied to this orbit is shown on the cover (bottom) which clearly brings into evidence a long and relatively narrow band for which difference values are much smaller than 12°C for central areas and up to 16-17°C at the edges. From this case and many others we processed at the same time, we may conclude that a good test limit is 16°C instead of the value recommended by Philips. More details are given in Chedin, Scott et al. (1989).
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3. DETERMINATION OF MESOSCALE METEOROLOGICAL PARAMETERS FOR POLAR LATITUDES

3.1 Quantitative assessment of the quality of the retrievals in temperature

In connection with the ARCTEMIZ international campaign (Marginal Ice Zone of the European Arctic), the "3I" method has been applied to 17 consecutive days of June 1986, corresponding to an extensive measurement phase of this experiment. Comparisons with radiosoundings and conventional analyses have been performed in order to assess the quality of the (NOAA-9) retrieved temperatures. Comparisons with radiosondes show biases less than 2K except for the 700-500 hPa layer where they sometimes reach 3K; this important bias being probably due to either an instrumentation problem, or an improper validation of a channel of NOAA-9 since it never appears for other satellites. Biases are mostly negative below 500 hPa and positive above.

Standard deviations are less than 2K for most of the passes and layers, except for the 1000-850 hPa layer. This exception may be explained by the great complexity of the boundary layer in this geographical area (many inversions) and by the vertical resolution of the radiometers. See Claud et al., 1989; Claud, 1989.

These conclusions appear clearly on the statistics shown on Figure 3.1.1, displaying mean bias and standard deviation for all ARCTEMIZ passes. 121 samples enter this statistics (after a "2σ" elimination).

Mean layer temperatures as determined by "3I" have then been compared to analyses provided by DNMI (Norwegian Meteorological Institute). These analyses result from a Limited Area Model, with a 150 km mesh. No satellite derived information is used in the scheme. It calculates geopotential heights and winds every 6 hours. Analyses at 12 UT have been used for the comparisons presented here.

Results are shown on Figure 3.1.2 for 4 different passes and 5 different layers (the same as for collocations with radiosoundings). They show a bias generally less than 1.5K, with values a little bit more important for the 700-500 hPa layer. Standard deviation is of about
1.5-2K except for the 1000-850 hPa layer where it may reach 3K or slightly more, a value significantly larger than the one obtained by comparing 3I to radiosondes.

3.2 Study of a polar low development over Barents Sea with the "3I" method

The "3I" method has been applied to different passes covering the life of a polar low in Barents Sea (12-14 Dec. 1982). A disturbance first appeared on the satellite AVHRR image from December 12, 0302 UT, where a cloud cluster can be seen just southwest of Svalbard (see Fig. 3.2.1). The cluster drifted slowly towards the south and then a center of rotation could be discernible. On December 12 at 1257 UT, the center of the disturbance passed 100 km west of Bear Island. This disturbance at that time could hardly be seen on the surface map, but was clearly discernible on the 500 mb map (from Rasmussen, Tellus, 37A, 407-418, 1985).

After analysis of the NOAA-7 data (Dec. 12, 1257 UT) through the "3I" system, it appears that the area of disturbance corresponds to an advection of warm air in the lowest layers (see Figs. 3.2.2.b,c: geopotential thicknesses between 1000 and 850 hPa and 1000-700 hPa). This disturbance is restricted to these lowest layers (see Fig. 3.2.2.d: geopotential thicknesses between 500 and 300 hPa).

3.3 Application of 3I over Antarctic regions: the July 3rd 1985 case

"On the 3rd July 1985, a major storm system crossed Halley resulting in continuous moderate to heavy snow and winds up to 35 kts. The pressure at Halley during the first half of the 3rd fell by just over 18 mb in 12 hours. Although the Met Office global model does show a deepening system near Halley on the 3rd it does not show the vigour of the observed system.

The development of this system is also, we believe, not well described by the meteorological office model. Looking at the satellite picture for the 1st we can see orographic cloud streaming off the Antarctic peninsula. On a manual analysis (not included) for the same day two
Frontal systems can be seen approaching the peninsula from the west. The picture for 1540z on the 2nd shows a large area of cloud formed as the leading front crosses the peninsula. We think that this represents a baroclinic zone in which the system that crosses Halley on the 3rd is formed. By the picture at 1747z on the third the system has already passed over Halley leaving only low cloud covering the ice shelf.

These comments are extracted from a document prepared for the first meeting of the European Polar Low Working Group (British Antarctic Survey, Cambridge, UK, 24-26 April 1988).

This baroclinic zone cannot be retrieved from the pass of July 1st, which does not cover the peninsula. However, cyclonic conditions can easily be detected from the determination, through 3I, of the temperature of the lower stratosphere (see Figure 3.3.1) on July 3rd. A warm area is found near Halley Bay corresponding to the system that crossed Halley. Simultaneously, a large part of the Weddel Sea which was previously cloudy, is now clear as indicated on Figure 3.3.2, displaying 3I cloud detection results. Work is in progress on this study case. Other cases are presently being studied in cooperation with Meteorological Institute, Bonn University, FRG (G. Heinemann).

Fig. 3.1.1 Layer mean temperature statistics 3I-radiosondes for 121 items. ARCTEMIZ campaign. 17 passes of NOAA-9 over Arctic in June 1986.
Fig. 3.1.2  Layer mean temperature statistics 3I-analyses (LAM/DNMI) for 4 NOAA-9 passes. ARCTEMIZ campaign, June 1986.
A Framed satellite image 1257 UT December 12, 1982. The center disturbance is seen in the middle of the picture, 100 km west of Bear Island. The southern part of Svalbard has been marked by "S", and the position of Bear Island is shown by "X". Photograph courtesy of Department of Electrical Engineering and Electronics, University of Dundee. Figure from Rasmussen, Tellus, 37A, 407-418 (1985).
Fig. 3.2.2 NOAA-7 pass on Dec. 12 at 1257 UT. a: cloud cover as detected by 31; b-d: geopotential thicknesses (dam) for the layers 1000-350, 1000-700 and 500-300 hPa respectively. Advection of warm air in the area of disturbance is clearly seen on b.
Figure 3.3.1

3I retrieved temperature of the lower stratosphere. Cyclonic conditions are clearly seen near Halley Bay. NOAA-9 pass 2868. 3 July 1985 at 1905 UT.

Figure 3.3.2

3I detected cloud cover for the same pass as Fig. 3.3.1. A large part of the Weddel Sea previously covered is now clear.
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4. RETRIEVAL OF WATER VAPOR VERTICAL DISTRIBUTION

4.1 Introduction

Retrievals of water vapor quantities (relative humidities, integrated precipitable water vapor) are made for 3 layers delimited by the levels 1000, 800, 500 and 300 mb. Following temperature profile retrieval, the brightness temperatures associated with the initial guess are corrected for the deviations between the initial temperature profile and the final solution giving rise to the initial guess for water vapor and surface temperature retrievals. The method used is based upon a simultaneous physical inversion of the water vapor amounts and of the surface temperature.

Four HIRS-2 channels are presently used: 8, 10, 11, 12 for the daytime observations and 18, 10, 11, 12 for the nighttime observations. A ridge type estimation is used: \[ \Delta \beta = (X'X + \gamma I)^{-1} X'\Delta Y, \]
where \(X'\) (transpose of \(X\)) is the matrix of the partial derivatives of the brightness temperatures with respect to relative humidities and surface temperatures and their corresponding initial values, and \(\Delta \beta\) the difference between the retrieved and the initial values of the parameters considered; \(\gamma\) is a smoothing parameter (Lagrangian parameter).

4.2 Application to NOAA-9 and NOAA-10 passes

The method briefly summarized above has been applied to nine satellite passes of both NOAA-9 and NOAA-10: five NOAA-9 passes among the ones mentioned in Section 2.5 and four passes either over Southern Europe and Africa or off western Africa coasts (5 December 1986 at 1400 UT and 1536 UT, orbits nb. 10201 and 10202; 10 December 1986 at 1443 UT and 1624 UT, orbits nb. 10272 and 10273). These observations correspond to relatively dry situations. Fig. 4.2.1 illustrates the results of comparisons with ECMWF analyses for all the retrievals associated with these 9 passes and for the total water vapor content, obtained from the determination of the relative humidities of the three layers described above.

Much better results are obtained over sea than over land which is not surprising: over sea, the surface temperature is assimilated according to paragraph 2.4; over land, surface emissivity effects,
Figure 4.2.1
Statistics of ECMWF for total water vapor content obtained for 9 passes (NOAA 9 & 10). Number of items is given in each case: global, land, sea.
mainly over deserts, were not systematically rejected (the so-called Reststrahlen effect was not accounted for). Over sea, the two dominant features are the almost zero bias and an rms value close to 0.5 precipitable centimeter. Figure 4.2.2 displays similar statistics for the NOAA-10 pass nb. 3735 over Eastern Atlantic and Europe (7 June 1987).

![Graph showing water vapor content](image)

**Fig. 4.2.2** Statistics 3I-ECMWF for total water vapor content for NOAA-10 orbit 3735 of 7 June 1987 over Eastern Atlantic and Europe. Results are splitted into three air-mass types.

### 4.3 Statistics at global scale

Comparisons between 3I-retrieved and ECMWF-analysed relative humidities have been performed at global scale at the European Center for the 15 day period selected for quantifying the impact of satellite data on middle range weather forecasting. Two representative results are shown on Fig. 4.3.1 (statistics for 30 January 1987 at 12 UT) and Fig. 4.3.2 (statistics for tropical latitudes, all longitudes, from January 30 to February 3 at 0 UT). Collocations are within ± 100 km and ± 3 h. The almost systematic bias around +10% has been voluntarily introduced by tuning the brightness temperatures of water vapor sensitive channels for a better answer of the model analysis. Standard deviations varying from 15% to 25% confirm the results presented in the preceding section. More details are given in Tahani et al. (1989) and in LMD Internal Reports (available upon request; in French).
Figure 4.3.1
Statistics 3I-radiosondes for relative humidity profiles at global scale. 30 January 1987 at 12.00 UT. Collocations : ± 100 km; ± 3 h (from ECMWF).
Figure 4.3.2

31-radiosondes statistics for relative humidity profiles at global scale. From 30 January 1987 to 3 February 1987 at 00 UT. Restricted to tropical latitudes (from ECMWF).
5. USE OF SATELLITE SOUNDINGS FOR MESOSCALE SEVERE WEATHER ANALYSIS OVER EUROPE

5.1 Introduction

For many years, question has been raised to know whether or not satellite observations (both sounding and imagery) may help the analysis of the development of mesoscale systems or may improve their forecast (e.g. Chedin et al., 1985; Prangsma et al., 1987, 1988).

Two particularly severe situations which occurred over Europe in 1987 have been examined: passage of a very active squall line over southwestern France with extremely gusty winds (June 7th, 1987) and a fast moving vigorous depression associated with severe gale and winds of October 15/16 1987 over western Europe (France, UK). In both cases, several people lost their lives, hundred of millions of francs/pounds worth of damage, and millions of trees were blown down. From that time, an enormous amount of work was devoted to study the onset of these storms (e.g. Weather, special issue, March 1988). Within this context and free from operational time constraints, we have used the available satellite and synoptic data to establish some kind of satellite guidance to these severe storms. Results concerning the 7th of June 1987, a case which was selected by the International TOVS Study Conference with the purpose of intercomparing results from various algorithms, have already been presented in Scott et al. (1988). Both situations have been studied in detail in Scott et al. (1989).

5.2 General conclusions

From the study of these two severe weather events, a few general conclusions may be drawn:

- Significant differences in the shape of geopotential thickness isosurfaces (in particular, double ridge structures or gradients orientation) are often in favor of the satellite analysis.

- Thermal wind maps may be very useful in displaying relatively complex vertical structure of a vortex centre (for example: two separate cells for the lowest layers and only one cell above).
- Thermal vorticities may show interesting structures like strong alternating vorticity gradients over short distances.

- Gradients between warm and cold air masses are often stronger on the satellite analyses than on conventional ones.

- Coupling with AVHRR imagery is highly desirable.

An obvious question could be asked whether or not such rapid developments could have been better forecasted combining robust TOVS retrieval method and suitable limited area model. This implicitly requires to make efforts:

- to have a better capacity to assimilate non-synoptic observations in fine mesh models,
- to improve satellite retrievals quality and density even in the case of heavy cloudiness.

It seems that this sophisticated approach could be realized with the present day technology and computing facilities and will highly benefit from the new microwave sounders to come

6. SENSITIVITY OF THE OZONE CHANNEL OF HIRS-2 TO THE SHAPE OF OZONE VERTICAL PROFILE

Two different approaches have been developed to determine total ozone contents from TOVS measurements. A statistical one, based on multilinear regressions, and a physical one, based on the inversion of the radiative transfer equation.

In the first case, HIRS-2 channels the most currently used are, apart from the ozone channel itself, those sensitive to stratospheric and surface temperatures. This accounts for the particular shape of the ozone channel weighting function peaking in the stratosphere and corresponding to a ground transmittance of about 0.4. In the second case,
previous knowledge of the temperature structure of the atmosphere and surface through the processing of temperature sensitive channels properly de-clouded allows for the inversion of the radiative transfer equation with respect to total ozone.

In both cases, additional unknown parameters influencing the forward radiative transfer computation may be a problem due to too restricted a number of relevant measurements in a spot. This is unfortunately the case for the shape of the ozone vertical profile which, for the same integrated ozone content may lead to either different channel 9 brightness temperatures, or to different ground transmittance, or to both.

So as to study quantitatively the impact of such a shape we first proceeded to a classification of the 1207 ozone vertical profiles archived in the TIGR data set and obtained from the work by McPetters et al., JGR, 89, 5799-5274 (1984) using NIMBUS-7/SBUV measurements. The classification algorithm is of the type ascending hierarchical. Profiles are sorted out according to the air mass type and, then, according to total ozone amount. In each of these subsets, corresponding to a maximum variation of this value of ± 20 Dobson units, the profiles (from about 10 to more than 100) are scaled to a constant total amount. Resulting profiles are finally classified. One to four classes were isolated in each subset. Figure 6.1 shows the mean profiles associated with the 4 classes of the 360 D.U. subset (mid-latitudes). Elements belonging to each class are averaged. For each profile thus obtained, channel 9 brightness temperatures and transmittances were computed through the 4A (Automated Atmospheric Absorption Atlas) forward model. Results are given in Table 6.1.

This table brings into evidence the great impact of the shape of the ozone profile on both the brightness temperature and the ground transmittance. As a consequence, relatively similar results may be obtained for two very different total ozone amounts and two different shapes (see for example shape 1 of the 320 D.U. subset and shape 1 of the 440 D.U. subset).
Table 6.1  Channel 9 brightness temperatures at nadir (col. 3) and ground transmittances (col. 4) for various total ozone amounts (col. 1 in D.U.) and various shapes of ozone vertical profiles (col. 2) obtained from a classification of 545 mid-latitude profiles.

These conclusions clearly indicate that great care must be exercised when interpreting total ozone content maps retrieved from TOVS, either through a statistical or a physical scheme. Such maps may however be of some interest in the analysis of short time (6 hours at best) big variations of ozone, in particular viewed as a dynamic tracer. We have experienced a statistical derivation of such maps using the TIGR data set and channels 1, 3, 8 and 9 as predictors. Regressions are available for each air mass type, each season (winter-spring and summer-fall), and any observing condition (10 viewing angles, 19 surface elevations, 2 surface emissivities). Figures 6.2 to 6.5 show results for two NOAA-9
passes: 10272 and 10273 on 10 December 1986 at 14.43 UT and 16.24 UT, respectively. Figures 6.2 and 6.3 are for the first orbit and illustrate the results of the 3I cloud detection scheme and the total ozone content map in D.U. It appears coherent if not obviously correct. Figs. 6.4 and 6.5 are for the second pass. The ozone field appears noisier as a result of a more extended and heavy cloudiness.

Work is continuing towards the evaluation of a physical approach and of the impact of a priori information.

![Graph showing ozone profiles](image)

**Figure 6.1** Averaged mid-latitude ozone profiles corresponding to each of the 4 classes associated with a total ozone content of 360 D.U.
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