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G.J. Cats

A scheme for mass and wind analysis on a limited area using multivariate threedimensional optimum interpolation:scientific documentation and first evaluation

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Koninklijk Nederlands Meteorologisch Instituut,
Dynamisch Meteorologisch Onderzoek,
Postbus 201,
3730 AE De Bilt,
Nederland.

U.D.C.: 551.509.38

Abstract

A scheme for height (or pressure) and wind analysis is documented. It is based on multivariate, threedimensional interpolation. The scheme is applicable for varying purposes. It includes sophisticated data quality control procedures. An example of a sequence of analyses on an (approx) 35 km grid is discussed.

1. Introduction

This paper aims at documenting a series of programs, that have recently been developed at the Royal Netherlands Meteorological Institute (KNMI), as a framework to produce analyses for a variety of purposes. In particular, it is applicable to provide initial conditions for a limited area model on a, say, 100 km grid; and it has been applied to boundary layer analysis. A description of the latter application is included in this document (Section 9).

The analysis scheme is in essence a mixture of two analysis methods that have proven to behave very satisfactorily in an operational environment. These are the ECMWF's (Lorenc et al. 1977; Lorenc, 1981; Björheim et al., 1981) and the SMHI's (Swedish) (Gustafsson, 1980; Van der Tol, 1982).

As ECMWF's the present scheme is based on a multivariate threedimensional optimum interpolation of mass and wind fields. (Analysis of other parameters, such as humidity, has not been implemented yet). Mass, i.e. pressure at height-levels, or height of pressure-levels, wind and temperature data can be assimilated. The last have to be presented in the form of thickness (or mass) between two adjacent analysis levels. The data quality control procedure, which is of paramount importance to the quality of the scheme, has been copied almost exactly from ECMWF. The division of the analysis area into volumes, that overlap both horizontally and vertically, resembles the ECMWF formulation.

The ECMWF scheme has been designed for global analyses, to be produced on a fast computer. Limitations of both the analysis area and the available computer resources require that the present scheme deviates in several critical aspects from ECMWF's. In particular, a number of physical and computational parameters were taken from the SMHI scheme. The distribution of gridpoints (either regular lat/lon, or regular lat/lon with the gridpole at 30°N on the dateline) is similar to SMHI's. The selection of observations from the squares surrounding the gridpoints was coded with extremely beneficial reference to the SMHI procedure.

The multivariate and threedimensional version of optimum interpolation has been chosen for its inherent horizontal and vertical and inter-variable analysis consistency. The main drawback is its impound on computer resources. The use of optimisation techniques, developed at ECMWF, enabled a reduction of this to acceptable limits, although some computational constants had to be adjusted. Especially, the maximum number of selected data had to be chosen low in comparison to ECMWF, but it could be kept at an acceptable value, as is indicated by the fact that the present value was also used in NMC's (USA) multivariate threedimensional scheme (Bergman, 1979; Hollingsworth et al., 1983).

The structure of the present scheme into separate programs is also a blend of the ECMWF and SMHI systems. The suite consists of an initial program to construct a control file with parameters such as area, observations to be used, etc. It is followed by a data extraction program (described in section 3). Subsequently a preanalysis (section 4) to preanalyse the observational data, the optimum interpolation (section 5) and a postanalysis (section 6) to convert the optimum interpolation output to standard file formats are run. Two programs have been included to prepare for the next analysis in a sequence of analyses: One to forecast the first-guess and one to forecast the errors of the first-guess. The first-guess forecast was included solely to be able to test the scheme in an analysis sequence, not because it is an integral part of the suite. It is described in section 7. The description of the first-guess errors and their correlations, and the model to forecast them for the next analysis, is given in section 8. Some general information on the present implementation has been collected in section 2.

Throughout this paper, the word "observation" is used to denote a meteorological report, and a "datum" (pl. data) is one observed parameter at one level from the report. "Observation error", however, is used with the same meaning as "datum error". Most physical or computational constants that are quoted in the text are default values, they may be overridden for individual analyses or to carry out experiments with the scheme.

2. General remarks

2.1. Coordinate system and analysis variables

The analysis is performed on a regular latitude/longitude grid, which optionally may have the grid north pole shifted to 30°N on the dateline. The analysis area is limited, but otherwise free. Also the choice of longitudinal and latitudinal gridspacings and the list of vertical levels is left open. The vertical coordinate is either height or pressure.

The analysed variables are pressure (if height is the vertical coordinate) or height (in the other case) and the two windcomponents: u from west to east (as defined by the grid) and v from south to north.

The analysis scheme scans through the area from the northwest to the southeast corner, proceeding along latitude lines. The in- and output files contain one record per latitude line as defined by the "KNMI lineformat" (internal KNMI document). In each gridpoint, the optimum interpolation (OI) is performed to obtain an analysis of all analysis variables at all levels at once, unless the number of nearby data is big, in which case the atmosphere gets partitioned in the vertical.

The analysis area and a band of ½ grid-distance width around it, is partitioned into "squares" (usually actually rectangles on a regular lat/lon projection), with each square centred around a gridpoint. The squares have been numbered from 1 in the NW corner, in the order of scanning.

2.2. The concept of "errors"

In OI, a model of statistical properties of the first-guess and the observations must be provided. The desired result of the analysis will be called the "truth". The error of the analysis, first-guess or observations is the difference between analysis, first-guess or observations (resp.) and the truth. Variances and correlations of the first-guess and the observation errors over an ensemble of atmospheres are required as input, and OI produces an estimate of the analysis error variances. In this document, the word "error" will in general be used to denote the square root of the error variance (e.g. "analysis error" means the OI estimate of the square root of the analysis error variance).

The specification of the error statistics is crucial to the present implementation of OI: It controls the relative weights of data and first-guess and, in particular, it controls the data quality control. Also, via the prescription of error statistics, constraints as the hydrostatic or geostrophic relation are imposed.

The truth as defined here, is not necessarily the real state of the atmosphere. Specifically, subgrid scale waves are present in the atmosphere, but one would not want these to alias onto the analysis in the gridpoints. Consequently, the error statistics, and especially the observation errors and their correlations, should include the contributions of the subgrid scale processes. Therefore the observation errors depend on the analysis gridspacing. Two sets of observation errors are standard provided, one valid for a grid mesh in the order of 150 km (obtained from the Swedish analysis scheme, Gustafsson, 1980), and one for a mesh of around 25 km. The latter set has only been chosen preliminarily and fairly ad hoc. For practical reasons, the choice between the two sets is controlled by the vertical coordinate, the former set being chosen if the vertical coordinate is pressure, and the latter if it is height. Up to now, only extremely limited provisions have been made to describe the observation error correlation and the observation/first-guess error cross correlation; instead it is usually assumed zero.

2.3. Data quality control flags and events

The data are quality controlled at several stages:

1) At the extraction stage for report mutilations, fatal coding errors, etc.
2) Against climatology
3) Against the first-guess, which is in effect a time-continuity check
4) Against a preliminary analysis, which is in effect a check against neighbouring data, if available, with full exploitation of statistical relations, such as geostrophy.

With each datum a set of flags is carried to record the history of the checking of the datum. The "quality flag", or simply "flag" takes the values as shown in Table 2.3.1. A datum flagged 0 or 1 is used for the analysis and also to check other data against it. If a datum is flagged 2 or 3 it is used for neither; if the flag is 2, the datum will be rechecked by subsequent checking stages, but if the flag is 3, the datum will not be considered anymore. During the scanning of the gridpoints by the proper OI program, the data that are in the square being treated, are said to receive their "final" flag by stage 4 above. Data that have received their final flag are never rechecked, and therefore, if that flag is 2, treated as if the flag were 3.

Table 2.3.1. also gives the values taken by the "where set" flag. This flag describes the history of the datum through the data checking stages 1 till 4. Only data that have this flag set to 3 are considered acceptable for the ultimate analysis.

The data checking history is further recorded by a series of messages, the so-called "events". These events describe where and why data flags were changed. They also record the construction of "bogus" data, a number of analysis parameters, etc. At the end of a run of the analysis program suite, a summary of the events is produced. This summary is an essential tool in the manual diagnosis of the automatic data quality control procedures.

3. Observation preparation

3.1. Introduction

Before the start of the analysis, observational data are extracted from the telecommunication channels. After this extraction, the observed data are subjected to several checks, if required converted and brought into the format of data that is acceptable to the analysis. Also information about the data quality is added, in the form of data flags and of observation error statistics.

At present, only limited data extraction facilities exist at KNMI. The following observation systems were available for testing of the described program:

a) SYNOP and SHIP reports

b) TEMP and PILOT reports

c) RIV wind and long-wave radiation measurements
   There are about 40 RIV (National Institute of Public Health) wind stations, distributed fairly homogeneously over the Netherlands; some of these are on television masts at heights up to 300 m.

d) "Cabauw" data. In Cabauw, near the geographical centre of the Netherlands, wind and temperature are continuously measured along a mast at heights of 10, 20, 40, 80, 120, 160 and 200 m.

None of these, however, could at present be extracted on an operational basis in the format required by the programs.

In this section a subsection will be devoted to each of these observation systems. Only mass (pressure or height) and wind data are extracted. In the near future, extensive alterations to the data extraction are foreseen. The inclusion of this section at this stage is merely to serve completeness of this report.

3.2. SYNOP and SHIP reports

3.2.1. Mass datum

The extracted datum is surface pressure, reduced to mean sea level (mslp). If it is not within the climatological limits of 940 mb and 1080 mb it will not be extracted. If the vertical coordinate is pressure, mslp is converted to 1000 mb height, assuming an air temperature of 280 K. The RMS observation error is 15 m or 0.4 mb for a SYNOP, and 17.5 m or 0.6 mb for a SHIP or an automatic station, where the two figures refer to the case that the vertical coordinate is pressure or height respectively. The mass datum is flagged 0 ("not checked", Table 2.3.1.).

3.2.2. Wind data

The wind speed (ff) and direction (dd) are extracted simultaneously. No extraction occurs if one of the following coding or climatological errors is detected:

a) ff and/or dd missing or negative
b) either ($ff = 0$ and $dd \neq 0$) or ($ff \neq 0$ and $dd = 0$)
c) $dd > 36$ unless $dd = 99$
d) $dd = 99$ ("weak variable") and $ff > 2$ m/s
e) $ff > 120$ m/s

If dd equals 99, wind speed is set to 0.

Extraction is only achieved in either of the two following cases:

a) The lowest analysis level is 1000 mb. In this case, only data from weatherships (C7R, C7L, C7M or C7C) or from the land stations 06320 and 03496 are extracted. The wind is applied at 1000 mb, after veering over 20° and increasing wind speed by 50%, to model surface friction. The observation error is set to 3 m/s in the u and v components separately.

b) The lowest analysis level is 10 m. Now a distinction is made between stations for which an objective exposure correction is available (Wieringa, 1976), and the other stations. If the objective correction exists (this includes most synoptic stations in the Netherlands, Belgium, West-Germany, North France and East England), the wind speed is corrected to one that would have been observed over open terrain (surface roughness $z_0 = 3$ cm), under otherwise unchanged circumstances. This corrected wind speed is called "potential wind speed". For the other stations, a matching wind speed correction is attempted using local surface roughness from a subjective terrain classification (Van Dop, 1983). In spite of the fact that these two correction methods are not fully compatible, a great reduction of spatial wind variability is achieved; in particular the wind jump along the coast is substantially reduced. Due to this procedure, the analysed 10 m wind is also to be considered as "potential". The real 10 m wind speed is obtainable from the potential one by applying the inverse procedure. (There is an option to switch off the correction methods; then the wind speeds are simply increased by 20%). The u and v observation errors are set to 1 m/s.

If the lowest analysis level is 10 m, and the second lowest is below 81 m, an attempt is made to construct bogus wind data at the second lowest level from the 10 m wind, surface roughness and a stability model. (Holtslag, 1983). The attempt will fail if the 10 m wind could not be extracted, if the uncorrected 10 m wind speed was less than 2 m/s, if the station was not a land synop, or if cloud cover was not observed, or reported unobservable. The employed stability model requires the 1.5 m temperature. If this was not available in the report, default values of 280 K during night and 288 K during daytime were substituted. Also surface roughness is required. For this, the same value as used for the 10 m wind speed correction was used. The wind direction at the second lowest level is assumed equal to that at 10 m. The observation error of the bogus wind is obtained from

$$e_2 = (f_2/f_1 + 1)\ e_1 \qquad (3.2.2.1.)$$

In here e stands for the observation error, f for wind speed, and indices 1 and 2 refer to the lowest and the second lowest level respectively. Eq. 3.2.2.1. tries to account for the inherent increase of the error due to increase of wind speed (term $(f_2/f_1)e_1$) and for the additional error introduced by Holtslag's model (term e_1). Obviously, the two errors are strongly correlated. At present, however, no previsions exist in the code to model that correlation.

All extracted winds are flagged 0 ("unchecked" Table 2.3.1.).

3.3. TEMP and PILOT reports

Only if the vertical analysis coordinate is pressure, an attempt will be made to extract TEMP or PILOT data. Only standard pressure height or wind are considered, and only in as far as the levels coincide with analysis levels. For each analysis level, the report is searched for reported data on that level. After identification of the level in the report, extraction proceeds as follows:

3.3.1. Mass data

Standard pressure level height is extracted and flagged 0 ("unchecked", Table 2.3.1.). There is a hydrostatic consistency check, the results of which are however not used yet. The observation error is set according to Table

3.3.1.

3.3.2. Wind data

If coding errors on wind speed (ff) or on wind direction (dd) are detected, extraction of wind data is avoided. The detectable coding errors are similar to those listed in the SYNOP 10 m wind section. However, TEMP and PILOT winds are not allowed to exceed 150 m/s. The 1000 mb wind is treated similarly to the 1000 mb SYNOP/SHIP wind, i.e. only at selected stations is it used, and it is corrected for surface friction by veering it over 20% and increasing wind speed by 50%. Table 3.3.1. lists the ascribed observation errors. All extracted data are flagged 0 ("unchecked", Table 2.3.1.).

3.4 RIV reports

Only wind data are decoded from RIV reports, and only if the vertical analysis coordinate is height. The checks on the wind speed and direction are identical to those for SYNOP winds.

Many RIV reported winds are not on an analysis level. The analysis level at which the report is then applied is the one nearest (in absolute height) to the observation level. If the observation is below the second lowest analysis level, the observed wind speed is adjusted with a logprofile, based on Van Dop's (1983) surface roughness. Because cloud cover is not observed, no attempt is made to correct the logprofile for stability. If, on the other hand, the observation is above the second lowest analysis level, a parameter is set according to

$$w = \frac{Z_{OB}-Z_{AN}}{\| Z_{AO}-Z_{AN} \|} \qquad (3.4.1.)$$

In (3.4.1.); Z_{OB} = observation height
Z_{AN} = height of analysis level nearest Z_{OB}
Z_{AO} = height of analysis level nearest Z_{OB}, above Z_{OB} if $Z_{OB} > Z_{AN}$, else below.

But if Z_{AO} would be below the lowest or above the highest analysis level, w is set to 0, which is equivalent to assuming the observation height to coincide with the nearest analysis level.

The observation error is set to 1.5 m/s and the extracted data are flagged 0 ("unchecked", Table 2.3.1.).

3.5. Cabauw reports

At present, the Cabauw observations are available as one report per level. More desirable would be that they were collected into one report. The present extraction for each one-level report proceeds identically to that of the RIV reports (subsection 3.4.). The observation errors, however, are those listed in Table 3.5.1.

4. Preanalysis

4.1. Introduction

A preanalysis step preceeds the proper optimum interpolation (OI) program. In the preanalysis the increments of the observed data with respect to the first-guess are calculated; those increments and the observation errors are normalised by the first-guess errors; finally both increments and errors are checked.

Usually, the first-guess is constructed on the basis of a previous analysis. Then the check on the increments is in fact a time-consistency check on the data. The check on the observation error prevents useless observations from entering the OI step: Not only would they be useless because of the low weight they would receive by OI, but even they would be harmful for two reasons: They would reduce the effectiveness of data selection, and they would increase the risk of the correlation matrix becoming ill-conditioned (Cats and Robertson, 1980).

4.2. Calculation and normalisation of increments and observation errors

In order to calculate and normalise the observed increments, the first-guess and the first-guess errors are interpolated to the observation position and level. This is done for every observed variable (mass, u, v or thickness). The horizontal interpolation in the x-direction (W to E) is quadratic, unless the variable to be interpolated is staggered in the x-direction. In that case, the interpolation is linear. For points near the west or east boundary of the field, the field is thought extended by duplication of the boundary values. The horizontal interpolation in y direction proceeds analogously.

Data that are not on an analysis level (which the program recognises by $w \neq 0$ (Eq. 3.4.1.)), are shifted towards the nearest analysis level, with adjustments of the increments and the observation errors as follows:

The increment is adjusted using the vertical first-guess gradient; the observation error is increased by a factor of $1 + 4w^2$.

The normalised increment σ and the normalised observation error ε now follow straightforwardly:

$$\sigma = (O-F)/E(F) \qquad (4.2.1.)$$

$$\varepsilon = E(O)/E(F) \qquad (4.2.2.)$$

where O and F are the values of observed datum and the first-guess resp., and E(O) and E(F) their ascribed errors resp., with F and E(F) interpolated to the observation position, and O and E(O) to the analysis level.

If the observed datum is thickness, F is calculated as the difference of the mass field on two adjacent levels and E(F) is obtained from the first-guess errors on those levels and their correlation.

4.3. Data checking

The normalised observed increment σ and observation error ε are used to check the data against the first-guess. If the first-guess error and the observation error are not correlated, the expectation value of σ^2 is $(1+\varepsilon^2)$. The quality control flag is set depending on the value of ε and of $d^2 = \sigma^2/(1+\varepsilon^2)$, according to Table 4.3.1.

The chosen limits on d are fairly liberal: If d would have a normal probability distribution, less than 1 in a million data would be flagged 2 or 3. There is, however, a substantial tail in the distribution of d, due to e.g. coding errors. In practice a few data per 1000 are flagged 2 or 3. The limits on d have not been set tighter because this data checking is purely univariate, and no attempt is made to have doubtful data confirmed by nearby observations or other data within the same observation.

After completion of the checks, the flags on the u of v components of the wind are coordinated by taking the higher flag for both. If a datum flag increased in the first-guess check, the "where set flag" is changed to 2.

4.4. Epilogue

The normalised increments and observation errors are communicated to the OI program via a file that is of the same format as the file that was input to the preanalysis. The observations, however, have been ordered according to the number of the square that they are in. A second output file is produced, which contains ordered observations, but with the original, (not normalised) observed data and observation errors. In the second file, the flags are those as obtained from the check against the first-guess. This second file is used to verify the fit of the first-guess and the analysis to the observations.

5. Optimum interpolation

5.1. Introduction

The core of the analysis suite is the optimum interpolation (OI) program. It performs the following tasks:

a) Selection of "analysis centres". An "analysis centre" is a gridpoint for which the data selection task (see b) is performed.

b) For each analysis centre, selection of data that are useful for the analysis. The data selection is done in two stages: First a number of observations with potentially useful data are selected; subsequently, from the selected observations the data to be used are selected. If the selected observations contain enough data, the analysis levels are grouped into several slabs in the vertical. The data selection and subsequent steps are then carried out for each slab separately.

c) Quality control of the selected data.

d) Production of the analysis in every gridpoint, at each level and for each analysis variable, and estimation of the analysis error. In this task, the use of data that failed the quality control check (task c) is of course avoided.

A subsection will be devoted to each task separately.

5.2. Selection of analysis centres

An analysis could be obtained in every gridpoint by going through the tasks of data selection, quality control and analysis for each gridpoint separately. One would, however, require the data selection task to achieve a substantial overlap between the selected data for neighbouring gridpoints, because the selected data should be fairly evenly distributed around the gridpoint. The overlap in selected data leads to a lot of repetition in the subsequent calculations. This repetition can be substantially reduced by exploiting an option in the OI program to skip gridpoints for the data selection and control tasks. The gridpoints that are not skipped for these tasks are called analysis centres.

With each analysis centre, an analysis volume is defined. It covers a rectangular area, up to the next analysis centre, but not including the gridpoints on the boundaries. The mutual positions of gridpoints, analysis centres and analysis volumes is illustrated in Fig. 5.2.1.

The analysis in all gridpoints within an analysis volume is calculated from the same data that were selected for the analysis centre. For a number of gridpoints more than one analysis will be produced. These analyses will later be averaged with weights w_a:

$$w_a = (|x_p - x_c|/x_{cc'})\ (|y_p - y_c|/y_{cc''}) \qquad (5.2.1.)$$

where x_p, y_p	are the coordinates of the gridpoint
x_c, y_c	are the coordinates of the analysis centre
$x_{cc'}$ $y_{cc''}$	are the x-and y distances respectively between the analysis centres

This procedure may alternatively be viewed at as a way of achieving a data selection that does not change abruptly from one gridpoint to the next one. It adds therefore to horizontal consistency of the analysis (in addition to substantial time savings).

The estimation of analysis errors is performed at the analysis centres only. The errors in the other gridpoints are obtained as weighted averages of the surrounding central values, with weights as in (5.2.1). This procedure smooths the analysis error field, which is desirable theoretically for separability assumptions (Lorenc, 1981). It also saves considerably on computer time, as the analysis error estimation is relatively expensive.

The calculations for each analysis centre start with the formation of a list of gridpoints within the analysis volume. At present, an analysis volume contains at most 9 gridpoints (perhaps fewer near the east or south boundary, depending on whether the number of gridpoints in either direction is odd or even), i.e. every second gridpoint in either direction is selected as an analysis centre, as in Fig. 5.2.1. (The program code supports also the option to select all gridpoints as analysis centres).

5.3. Data selection

5.3.1. Observation selection

The observations are selected from analysis squares surrounding the analysis centre (Fig. 5.2.1.). The first square to be scanned for observations is the central square, i.e. the square that contains the analysis centre. Subsequently the squares are scanned in the order as illustrated in Fig. 5.3.1.

The squares to the east/north of the central square are scanned before equally distant squares in the other quadrants. This preponderance has been introduced because some analysis variables may be staggered into the east or north direction. The square scanning stops after completion of the scan of square 68 (Fig. 5.3.1.). Optionally, the scanning may be discontinued after completion of square 8, 20 or 44.

For the observations within the scanned area, a quantity, called "posteriority" is formed. Observations with lower "posteriority" are selected with preference over those with higher "posteriority". The algorithm to calculate the posteriority is designed to achieve a fairly even distribution of selected observations around the analysis centre, with preference for nearby observations, and with strong preference for more important observations.

Two classes of importance have been defined for observations. Important are those, that have more than 8 useful data, the other observations are "less important". A useful datum is a datum that has not been definitely rejected, i.e. that has not been flagged 3, or 2 by the final data checking stage. For the purpose of determining the importance of an observation, a useful mass datum is counted as 2 data, and u, v and thickness each as 1.

To aid in achieving an even observation distribution, the squares of Fig. 5.3.1. have been grouped into clusters. Each of squares 9 through 60 governs a cluster of squares. The squares in such a cluster are said to be masked by its governing square. Table 5.3.1. lists which squares mask which. The contents of that table are stored as bit patterns in the computer. The code was implemented on a 48 bit machine, therefore masked squares do not appear with rank numbers in excess of 48. Instead, squares 61 and higher are considered to be masked by all lower ranked squares.

The posteriority algorithm is highly empirical. It is described in Appendix 5.3.1. After calculation of the posteriority for each observation, the 4 lowest posteriority observations in the central square are selected. Subsequently, the following steps are taken:

a) A limit of the number of selected observations is calculated. $N_{o,x}$, at present 30; this value is reduced near the area boundaries.

b) From squares 1 through 8, the lowest posteriority observations are taken; if more than 0.7 $N_{o,x}$ observations have in total been found, selection stops. At most $N_{o,x}$ observations are then selected.

c) The limit of 0.7 $N_{o,x}$ is also checked after completion of the scan of squares 20, 44 and 68. If it is reached, at most the 0.7 $N_{o,x}$ observations with lowest posteriority are selected, else all are taken.

The selected observations are grouped:

i) those in the central square
ii) those in squares 1 through 20
iii) those in squares 21 through 44
iv) those in squares 45 through 68.

Within each group the observations are ordered to increasing posteriority.

For computational reasons, not more than 100 observations are considered for selection. Observations without useful data are never considered, and do therefore not count towards any limit.

Observations in the inner analysis volume (Fig. 5.2.1.) get a flag that their data are eligible for final data quality control, if they were selected; if they were not, they are prevented from being selected at any later stage, to reduce the risk of using unchecked data.

5.3.2. Definition of subvolumes

If the selected observations contain more than $N_{d,x} = 20$ data on the lower levels, the analysis computations are done for two slabs separately. The analysis volume (Fig. 5.2.1.) is then split vertically into "subvolumes". The separation is immediately below the highest level below which there are fewer than $N_{d,x}$ data. The lowest slab will encompass at least 1 and not more than half the number of levels.

5.3.3. Data selection

From the selected observations, data are selected for each subvolume separately. The selected observations are scanned in the order of their selection. For each observation the order of selection is: Data on the lowest level within the subvolume, on the highest level and then on the inner levels.

Selection stops upon reaching the limit of $N_{d,x}$ data (section 5.3.2.). If this limit is not reached with data from levels within the subvolume, the level below the subvolume is scanned, followed by the level above. In order to achieve a reasonable distribution of selected data over levels and variables, not more than 4 mass data, 3 u, 3 v and 3 thickness data are allowed from any level. Thickness data are not allowed from levels outside the subvolume.

Data within the subvolume are eligible for final quality control, unless they were checked so already. A flag is set to carry this information.

5.4. Data quality control

(The data quality control procedure is a fairly true copy of the one in current use at ECMWF).

A quality control check is performed on each datum that was selected for the analysis of the current subvolume, unless it has already been subjected to final checking or it has been flagged 3 ("wrong", Table 2.3.1.). For each datum to be checked, a preliminary analysis a_p is formed at the position and level of the datum. This analysis is obtained with the full OI technique, but avoiding the use of the datum being checked and of data that are flagged 2 or 3. The difference between the datum value, σ, and a_p is compared to the estimated expectation value of $(\sigma-a_p)^2$ by the quantity q:

$$q^2 = (\sigma-a_p)^2/(E^2(a_p) + E^2(\sigma) + E^2(m)) \qquad (5.4.1.)$$

In (5.4.1.) E stands for estimated error: $E(a_p)$ of the preliminary analysis a_p, $E(\sigma)$ of the datum σ, E(m) of the interpolation method (at present $E^2(m) = 0.1$; all quantities in (5.4.1.) are normalised with the first-guess error).

If $q \leq 3$ the datum is flagged 0, and if $q \leq 4$ it is flagged 1. If there is a datum with $q > 4$, the datum with the highest value of q is rejected (flag 2 if $q \leq 5$, else 3). If a datum is rejected, all other data with $q > 4$ are rechecked as above, also excluding the newly rejected datum.

Upon completion of the checks, the flags on the two wind components are coordinated by taking the worse flag for both. The "where set flag" (Table 2.3.1.) is set to 3, to identify that the datum has been checked. Data that are eligible for final checking (section 5.3.3.) have these flags also recorded for use by the analysis of subsequent subvolumes.

5.5. Analysis and analysis errors

The analysis and analysis errors in a subvolume are calculated with OI from the selected data that have a flag less than 2. The flag may have been set either preliminary by the data quality control for the subvolume, or definitely by the data quality control for this or an earlier subvolume. Therefore, no unchecked data are used, although some data flags may be preliminary, their final value being only obtainable from the quality checks for subsequent subvolumes. The use of checked data, and the possible use of data with a preliminary flag is analoguous to that in the ECMWF scheme if run with the "QUICKDC" option (Lorenc, 1980).

If the subvolume does not contain all analysis levels, the lowest level above the subvolume will be analysed as well. That level will also be analysed by the next higher subvolume. After completion of the analysis for all levels, those two analyses for the same level are averaged. Thus a vertical overlap of subvolumes is obtained, similar to the horizontal overlap (Fig. 5.2.1.). This vertical overlap, however, is not applied in the calculation of analysis errors.

Some variables to be analysed may be staggered with respect to the grid. It would have been meteorologically attractive, and programmaticly fairly simple, to calculate the analysis for those variables on a staggered grid. Yet, this was not implemented because of the excessive increase of computation time required by such code. Instead, the analysis is unstaggered.

5.6. Epilogue

The results of OI are communicated to the next program in the analysis suite in the form of normalised analysis increments and normalised analysis error variances. They are in the order in which they have been produced, that is, grouped according to analysis volume sequence numbers.

6. Postanalysis

After the OI step, normalised analysed increments and normalised analysis error variances are available for each gridpoint, and, perhaps, for some gridpoints there is more than one analysis available. Furthermore, the analysis results are not in the correct order. After OI, a postanalysis is run, to reorder the results into standard file format, and to perform the following tasks with physical implications:

a) If more analyses are encountered at a gridpoint, they are averaged with the weights of Eq. 5.2.1.

b) The analysis is denormalised by multiplication with the first-guess error. This step is suppressed when the program is applied to the analysis error variances. (There is an option to override the use or suppression of this step).

c) Analysis error variances may be converted to analysis errors (normally suppressed).

d) If the first-guess of an analysed variable was staggered, the analysed increment will be staggered, by linear interpolation of the analyses (on the area boundary, the area is thought extended by duplication of the boundary values).

e) The denormalised and staggered analysis increment is output; also it is added to the first-guess to get the full analysis. (By option, the output of either can be suppressed).

7. The first-guess for the next analysis

No extensive provisions have been made yet to produce a guess field for an analysis from the previous analysis, although it is realised that the guess field is of paramount importance to the quality of the analysis.

Provisionally, the first-guess for an analysis cycle is the previous analysis, shifted over an integer number of gridpoints in both x and y directions. The number of gridpoints is specified externally in the form of an "advection velocity" and the time interval between the two analyses.

If the analysis is run hourly, on a small scale grid, this "advection model" may turn out to produce a reasonable first-guess, in spite of physical shortcomings, such as violation of vorticity conservation or the advection of topography-locked phenomena. But if the analysis is less frequent, presumably a more sophisticated model should be invoked.

The advection velocity may be obtained from a large scale model (Forbes, 1983).

8. First-guess error covariances

8.1. Introduction

The specification of the first-guess error covariances is one of the most important building stones of an implementation of the optimum interpolation (OI) method. Those covariances set the severity with which physical constraints such as geostrophic or hydrostatic balance are imposed on the analysis increments. The ratio of first-guess to observation error determines the relative weights of those sources of information. The first-guess error is a crucial quantity in the data quality control procedures.

The specification of first-guess error covariances in the present OI implementation follows closely that of ECMWF (Lorenc, 1981). It is based on a separate specification of the correlations (section 8.2) and the errors (8.3).

8.2. First-guess error correlations

The first-guess error correlation is assumed to be separable in the horizontal and the vertical. The horizontal correlation is specified identically for height-height and for streamfunction-streamfunction:

$$c = \exp\left(-\tfrac{1}{2}\, r^2/b^2\right) \qquad (8.2.1.)$$

The height-streamfunction cross correlation is the same, but reduced by a constant $\mu(=0.9)$. Because the calculation of the gaussian is expensive, it is pretabulated. This pretabulation decreases occasionally the condition of the correlation matrix (Julian and Thiebaux, 1975). Although up to now no decrease to fatal levels has been observed, a safeguard has been implemented in the code to avoid problems in the analysis (Cats and Robertson, 1980).

The analysis scheme chooses from two values of b; one value being taken for the analysis of the highest subvolume, and the other for the analysis of the lowest, unless the lowest extends through the whole depth of the atmosphere. With this construction, the scheme is able to analyse small-scale features near the surface, if the data density is sufficiently high. But in data sparse areas, or aloft in data dense areas, the analysis will be smoother. The present values of b are shown in Table 8.2.1.

The vertical correlation is given as an $n_1 x n_1$ matrix where n_1 is the number of analysis levels. This matrix is derived following Andersen and Cats (1982). To save computer time, the vertical height-thickness and thickness-thickness correlation matrices are precalculated from the vertical height-height correlation and the first-guess height errors. In the vertical, wind is treated identically to height.

With this specification of the first-guess correlations, (and provided that the first-guess errors are specified following some rules) the analysis increments are consistent in the vertical (i.e. if thickness would be analysed separately, it would be equal to the difference of the height/mass at the two adjacent levels), and almost geostrophic. The extent to which geostrophy is imposed is controlled by the parameter μ. If $\mu < 1$ in the presence of many height and wind data, the data will be drawn to; even if this violates geostrophy.

8.3. First-guess error

In a series of analyses, the first-guess error for an analysis is assumed to depend on the quality of the previous analysis. This dependence has been modelled as follows (see also Fig. 8.3.1):

The first-guess error $E_{l,v}(F)$ for variable v on level l is calculated from

$$E_{l,v}(F) = p\, E_{l,v}(F_A) \qquad (8.3.1.)$$

where $E_{l,v}(F_A)$ is the first-guess error that was used for the previous analysis. The factor p is chosen such that the first-guess error variance, averaged over all levels and variables, grows linearly with time between two successive analyses, from its initial value (the error of the previous analysis) to a limit (the error of a random state):

$$p^2 = \begin{cases} \dfrac{1}{n_l n_v} \displaystyle\sum_{l=1}^{n_l} \sum_{v=1}^{n_v} \dfrac{E^2_{l,v}(A)}{E^2_{l,v}(F_A)} \left(1-\dfrac{\Delta}{T_R}\right) + \dfrac{E^2_{l,v}(C)}{E^2_{l,v}(F_A)} \left(2\,\dfrac{\Delta}{T_R}\right) & \text{if } \Delta < T_R \\[2ex] \dfrac{2}{n_l n_v} \displaystyle\sum_{l=1}^{n_l} \sum_{v=1}^{n_v} \dfrac{E^2_{l,v}(C)}{E^2_{l,v}(F_A)} & \text{if } \Delta \geq T_R \end{cases} \qquad (8.3.2.)$$

where: Δ is the time lapse between the two analyses.

T_R is the time after which the forecast model, used to make the first-guess, produces a field that is not of better quality than any random state.

$E^2_{l,v}(C)$ is the standard deviation of the field v on level l (or alternatively, the error if climatology is used as first-guess).

$E^2_{1,v}(A)$ is the error of the previous analysis.

n_1, n_v are the numbers of levels and variables resp.

By virtue of Eq. 8.3.1., the ratio of the first-guess errors for different variables or levels is not changed by the model. This is required because

a) if geostrophy is desired, the ratio of first-guess wind to height errors should follow from

$$E_{1,v=u\text{ or }v}(F) = \frac{g}{bf} E_{1,v=h}(F) \qquad (8.3.3.)$$

(where g = acceleration by gravity, f = coriolis-parameter, b as in Eq. 8.2.1.).

b) the ratio of height errors at different levels has been used in the pretabulation of the height-thickness vertical correlation (section 8.2).

Eq. 8.3.2. describes how the first-guess error, while being constrained by a) and b), grows from the analysis error $E_{1,v}(A)$ to the error of a random state $\sqrt{2}\, E_{1,v}(C)$.

Eq. 8.3.1. will only produce results in agreement with a) (the geostrophic relation) and b) (height-thickness relation) if the previous first-guess error satisfied those conditions. A separate program has been provided to calculate all errors $E_{1,v}(F_F)$ in agreement with a) and b) from those for mass at one level, where F_F is the very first first-guess in a series of analyses. In (8.3.3.) b is taken equal to the values of Table 8.2.1. at the highest subvolume. In this program, an option is available to in/decrease the height and wind errors separately, thus relaxing on (8.3.3.). This option is useful, for example, to decrease the lower level wind errors if there is reason to believe that those errors are subgeostrophic.

9. An example of a series of analysis

9.1. Introduction

With the scheme that has been described in the previous sections, a series of analyses has been run. The area, date and time and the meteorological situation are discussed in section 9.2. Section 9.3. provides some additional information on the scheme, including how the initial first-guess was obtained and which parameters had their default values overridden. In section 9.4. the results are presented, and a discussion follows in section 9.5.

9.2. Area, date, time

The analysis area was taken from 49°N to 55°N and from 2°W to 10°E, with 21 gridpoints in both directions, regularly spaced in latitude or longitude. The analysis levels were chosen at 10 m, 70 m and 200 m. With this grid, a mesoscale boundary layer analysis of mass and wind was attempted. There are no strong orographic features in the area, but some land-sea transitions exist, which will especially influence the lower level winds. Because of the low orography it was felt justified to consider pressure at 10 m identical to mean sea level pressure, the difference between the two not having dynamical consequences.

The example analyses were hourly from 0 GMT to 13 GMT on 12 May 1983. In this time interval a severe storm moved through the area. The storm had mesoscale dimensions: The diameter of the outermost closed isobar of the associated cyclone was about 120 km. At the initial time of the selected period the storm was still well outside the analysis area.

The timings on a Burroughs B6800 computer of an analysis over the selected area are summarised in Table 9.2.1.

9.3. Additions and changes with respect to the described scheme

The first-guess for the first analysis was obtained by a linear interpolation of the pressure and wind field at 10 m. Their values at the 4 area corners were manually read from a low detail weather chart. The wind field at the higher levels was taken identical to the 10 m wind, and the pressure at those levels was obtained by reducing the 10 m pressure as if the atmosphere had a homogeneous temperature. This method is extremely crude. The resulting first-guess was good enough to make most data pass the data checking procedures, but it was worse than (presumably any) objective method would produce.

The initial first-guess errors were set at 30% of a set of climatological errors $E_{1,v}(C)$ (8.3.2.) that were available of old. The errors $E_{1,v}(C)$ are fairly homogeneous, for pressure around 4 mb at 10 m, reduced by factors 0.95 and 0.90 at the higher levels. The wind errors, as derived geostrophically (8.3.3.) had been decreased by factors 0.70, 0.80 and 0.90 on the three levels respectively, to simulate subgeostrophic wind errors.

The first-guess for later analysis cycles was taken to be the last analysis, shifted over 2 griddistances (67 km) to the north, and 1 (around 40 km) to the east. This corresponds to the advection velocity that was suggested for the selected period and area by Forbes (1983). It was assumed that this type of first-guess would loose all information after 6 hours, i.e., $T_R = 6$ h in Eq. 8.3.2.

For a number of parameters, the default values as mentioned in the text were overridden:

In Eq. 8.2.1. (or Table 8.2.1.), the horizontal decay length b was taken 150 km, or 75 km at the lower subvolume if there were 2 subvolumes. Because the first-guess wind errors were 70% to 90% (dependent on level) of the values that follow from (8.3.3.) using the higher value of b, the winds were treated as if the first-guess errors were 70% to 90% of their geostrophic values in data sparse areas or aloft, and still smaller by a factor of 2 in data dense areas near the surface. In the analysis area the data distribution was such that the scheme went into a two-subvolumes analysis mainly over land, and then the lower subvolume contained one level. Consequently, the wind errors were in general 35% of the geostrophic value over land at 10 m, and in general 70% over sea at 10 m; at the two higher levels these percentages were 80% resp. 90% everywhere.

The wind observation errors of synop/ship reports were set at 2 m/s, those for RIV reports at 3 m/s and those for Cabauw at 1.5 m/s on every level. These numbers apply to each wind component separately. They were estimated from a preliminary analysis experiment by comparing the fit of the analysis to those observations with the limits for that fit, that follow from OI theory.

9.4. The results

The first 6 analyses, namely those at 0 till 5 GMT, are considered as a "warming up" to obtain reasonable first-guess and first-guess error fields. They will not be discussed further. Fig. 9.4.1. till 9.4.8. show the 10 m wind and pressure analyses from 6 GMT onwards.

At 6 GMT there is a tiny pressure indication of the approaching cyclone in the southwest corner of the area. There is no clear connected structure in the wind field. Presumably the cyclone is inconsistently analysed because of the vicinity of the area boundaries.

At later times, the storm becomes more evident. At 7 GMT clearly a strong wind field is seen to follow the cyclone centre. At this stage it is brought into the reader's recollection that the wind speed observations have been exposure corrected. As a consequence, the shown 10 m wind speeds are "potential", i.e. those that would be found over open terrain (surface roughness = 3 cm) in otherwise unchanged dynamical conditions. The real 10 m wind speed will in general be lower over land (usually by some 10 to 20%), and higher over sea (by approx. 10%) than the plotted wind speeds. This effect is illustrated by Fig. 9.4.9. in comparison to Fig. 9.4.5.: At 10 GMT there is a 28 m/s (55 kts) potential wind speed in North France. The model surface roughness is there 1.1 m. The actual wind speed turns out just over 17.5 m/s. On the other hand, the maximum potential wind speed over the Channel is 18 m/s (35 kts) whereas the actual maximum is 20 m/s.

9.5. Discussion of the results

The sequence of analyses of the example will be discussed in terms of several verification methods.

For the first method, the analyses were subjectively compared with hand analyses (available from 9 GMT, G. Forbes, private communication). As a typical example, the 12 GMT hand analysis is shown in Fig. 9.5.1. The centre of low pressure, and the trough SE of the centre coincide almost exactly. In the manual analysis, the centre pressure is lower by 1 mb. The W-E elongation of the system near its centre is present in both analyses. The objective analysis shows also a N-S elongation, to the extent that there is in fact a double structure. This structure is not present in the hand analyses, but the objective analysis is supported by other information (e.g. 6 hour forecasts with a two-parameter filtered model produced the double low (L. Heijboer, private communication)). The objective analysis is a good deal noisier than the manual one. The noise has a typical wavelength of a few griddistances, and an amplitude of less than 0.5 mb. Whether or not the analyses should have been smoother can only be assessed by balancing the required amount of detail, the tolerable noise and the presence of the noise in reality. The required and tolerable amount depend on the analysis purpose. Because the purpose was left open, this factor was not considered further. Also the real presence of the noise could not be verified lacking sufficient observational information. Overall, this first verification method showed good agreement for the pressure field at 10 m.

At 10 m, manual analyses of u and v components were available from 9 GMT onwards, on the area covered by Fig. 9.5.1. (110 gridpoints), in addition to the pressure analyses. For the second verification, these were read at gridpoints and statistically compared to the objective analyses. The rms difference between the two analyses varied with analysis time, between 0.73 and 0.85 mb for pressure, and between 2.3 and 2.9 m/s for wind speed; the correlation varied between 96.8% and 98.9% for pressure and between 77% and 92% for the two wind components.

Thirdly, the objective analyses were compared to the observations. Subjectively, a good agreement is found. E.g., in Fig. 9.4.7. and 9.5.1.: The 45 kts SW wind south of the low pressure centre; the extent of the area with high wind speeds; the weak winds preceding the cyclone. Fig. 9.5.2. shows the fit of the 10 m pressure analysis to the observations in more detail. Some objective verification numbers are given in Table 9.5.1. The period covered by this Table, 9 GMT till 12 GMT was chosen because it covers the most active stage of the storm. Because of that activity, the fit of the analysis is in general somewhat worse than at the other hours. The shown numbers indicate that the analysis fits the observations much better than the first-guess, as it should. The analysis error is small, with the exception of the v component of the wind at 70 m and 200 m. The root mean square difference between analysis and observations is slightly more than the assumed observation error.

From OI theory it follows that the analysis rms difference should not exceed the rms observation error, provided that there is a correspondence between the assumed observation- and first-guess error statistics on the one hand, and the actual errors on the other. In this storm situation, however, it may be expected that the actual observation errors exceed their rms values (where the "m" stands for "mean over a number of realisations of atmospheric boundary layers"). Indeed, at the earliest hours, the ratio analysis rms difference to observation errors was smaller, although not always smaller than 1.

The wind at higher levels is badly fitted. This is due to, on the one hand, the fairly big observation error for most observing systems, and, on the other hand, the fact that the Cabauw data were not considered important (because the data were presented as one report per level). It is concluded that the results of this verification method show an overall viability of the scheme, but it also highlights some shortcomings in the presently used statistics and data extraction.

The analyses were further verified by looking at the internal consistency. Presumably it is best studied with objective methods, e.g. using an initialisation method to assess the acceptability of the analyses as initial conditions for a forecast model. But such methods were not available yet. Instead, the analysis increments were subjectively checked on e.g. the degree to which geostrophy is effectuated. Fig. 9.5.3. has been added as an illustration of this verification. It shows the analysis increments (i.e. difference of analysis and first-guess) at 12 GMT. Near the north boundary of the area, over the North Sea, there is a pressure increment of 4.5 mb. In this area of low data density, the wind around it is fairly geostrophic. But over the Channel much bigger gradients in the pressure increments occur, yet the wind increments are far from geostrophic. Clearly, in this data dense area, the fact that $\mu < 1$ (section 8.2) allows effective suppression of the geostrophic requirement.

The increments, shown in Fig. 9.5.3. take exceptionally high values. (This particular example was chosen because of its illustrative power, rather than its representativity). The increments could become so high, because the first-guess was based on the previous analysis, that is the 11 GMT analysis. At that time, however, hardly any ship reports were available, and no synop reports from North France were received. As a consequence, the first-guess was bad, but also, the first-guess errors, being based on the previous analysis error, reflect the low first-guess quality over the sea and North France. The observations at 12 GMT received therefore substantial weight. The effect of the previous data density on the first-guess error is demonstrated in Fig. 9.5.4., which shows the first-guess errors for four consecutive analyses. The presence of North France synop reports at 9 GMT and 12 GMT is clearly reflected in the first-guess errors at 10 and 13 GMT. The shown time sequence of first-guess errors corresponds to that in Fig. 8.3.1.

The analysis scheme has been tested on its sensitivity to some parameters. The main sensitivity that was observed was via changed data quality control, conform earlier findings (e.g. Cats, 1984). As an example Fig. 9.5.5. has been added. It shows the 12 GMT analysis in a sequence that was obtained with the same scheme, but with a different (less consistent) formulation of the first-guess error growth model. Conspicuous differences with Fig. 9.4.7. occur, for example in the shape of the cyclone.

10. Conclusions

The example of a sequence of analyses shows that the implemented version of optimum interpolation produces a realistic low level analysis. The resulting fields corresponds well to manual analyses and fit the data to a high degree, especially so near the surface. There are, however, a number of qualifications that invite to further work on the scheme. The following list is not meant to be exhaustive or indicative of priorities.

The use of surface roughness data and exposure corrections to anemometer readings is beneficial for the analysis. Yet, a higher conceptual consistency can be obtained by a careful revision of the applied methods. The construction of 70 m bogus wind data should be extended to ship reports, where the air-sea temperature difference provides a stability measure. This would require a sea temperature analysis.

The advection model that was used to forecast a guess-field for the next analysis has several physical inconsistencies. The procedure does not conserve vorticity; topographic phenomena, such as the land-sea transition, are totally ignored (The last problem does perhaps not show conspicuously in the analysis example because the advection velocity is more or less parallel to the coast). A more sophisticated model should be used.

Substantial improvements and extensions should be made in the data extraction. Cabauw data should be collected into one observation, so as to make that observation "important" and become selected. Other observation types (e.g. metars in North France) and other data types (e.g. temperature data) should be extracted.

In a mixed boundary layer the driving force for the wind is rather the mixed-layer average pressure gradient than the on-level gradient. Temperature data are perhaps useful to define a thermal wind field, which then gives an indication of the vertical variation of the pressure gradient. It is not clear yet if the resulting reduction of on-level geostrophy is also seen in the first-guess errors, or, if so, how it should be incorporated into the correlation model.

A further deficiency of the present implementation is the assumption of zero observation error correlation. In the shown example it is certainly wrong for the correlation between 10 and 70 m winds at the same synop station, leading to an underestimation of the accuracy of the vertical wind shear (Gustafsson, 1980).

Still further outlooks of development on the scheme include the use of non-conventional data sources. Winds, derived from successive radarsoundings, should provide smaller scale information aloft; rainfall rates may contribute to a divergence analysis, which perhaps could be incorporated into the multivariate scheme.

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Appendix 5.3.1.

The algorithm to calculate the selection priority of observations.

In this appendix, the algorithm for the "posteriority" of observations in the selection is given. Observations with lower posteriority are preferred over those with higher. The concepts of "important observation" and "masking" are explained in the main text.

The posteriority is preset at an initial value, that is incremented by a small amount for each subsequent observation, in order to maintain the order in which the observations appear in the extraction file. In the central square the posteriority is incremented by 1 for less important observations. For the other squares, the posteriority is augmented by:

a) The square number, to maintain the order as shown in Fig. 5.3.1.

b) An approximate distance to the analysis centre, if the observation is in square 1 through 8. Together with rule a, this leads to preference for nearer observations.

c) 50, if the observation is in square 1 through 8, but not within the inner volume as shown in Fig. 5.2.1.; and 100 if the observation is not within squares 1 through 8. This increases the probability that all data will be selected for final data checking, even if not all gridpoints are used as analysis centres (cf. Fig. 5.2.1.).

d) 20, unless the observation is the first in the square. This reduces the probability that 2 observations are selected from the same square.

e) 400, unless the observation is important. This gives strong preference to important observations.

f) 800, if there is an important observation in a masking square. This prohibits almost entirely the selection of an observation, if there was already an important one in the same cluster of squares.

g) 200, if the observation is less important and there is a less important observation in a masking square (see f).

h) 20, if the observation is in squares 1 through 8, and there is an important observation in those squares, unless it is the first important one (this rule applies square by square).

i) 800, if there is an important observation in the same square, unless it is the first such one. This rule extends f to cover also observations within the same square.

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Table 2.3.1.

Meaning of the data flags.

Quality flag:	Significance:
0	datum not checked or correct
1	datum presumably correct
2	datum presumably wrong
3	datum wrong

Where set flag:	Significance:
0	quality flag not set yet
1	not used
2	quality flag was raised by check against first guess
3	quality flag set in final step

Table 3.3.1.

Root-mean-square observation errors at standard pressure levels

Level (mb) datum	1000	850	700	500	400	300	250	200	150	100
Temp-height (m)	12	15	15	20	15	30	35	40	50	60
Temp-wind (m/s)	2	2	2.5	2.5	3	3	4	5	5	5

Table 3.5.1.

Root-mean-square observation errors at height levels

level (m) datum	10	20	40	70	120	200	300	500	700	900	1200	1500
Cabauw wind (m/s)	1.5	1.5	1.5	1.5	1.5	1.5						
Temp pressure (mb)	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	2.0	2.5	3.0
Temp wind (m/s)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.5	3.0

Table 4.3.1.

Flagging limits. The table lists the conditions on the normalised observation error ε and the normalised observation increment σ that will lead to the listed values of the quality control flag f_q.

Conditions on ε or on $d = [\sigma^2/(1+\varepsilon^2)]^{\frac{1}{2}}$	Flag f_q
$\varepsilon > 16$	3
$d \leq 4$	0
$4 < d \leq 5$	1
$5 < d \leq 6$	2
$6 < d$	3

Table 5.3.1. Listing of which squares are masked by which.

Square:	is masked by					
9	1	5	8			
10	2	5	6			
11	3	6	7			
12	4	7	8			
13	5	9				
14	5	10				
15	6	10				
16	6	11				
17	7	11				
18	7	12				
19	8	12				
20	8	9				
21	9	13	20			
22	10	14	15			
23	11	16	17			
24	12	18	19			
25	5	13	14			
26	6	15	16			
27	7	17	18			
28	8	19	20			
29	9	13	21	25		
30	10	14	22	25		
31	10	15	22	26		
32	11	16	23	26		
33	11	17	23	27		
34	12	18	24	27		
35	12	19	24	28		
36	9	20	21	28		
37	13	25	29			
38	14	25	30			
39	15	26	31			
40	16	26	32			
41	17	27	33			
42	18	27	34			
43	19	28	35			
44	20	28	36			
45	9	13	20	21	29	36
46	10	14	15	22	30	31
47	11	16	17	23	32	33
48	12	18	19	24	34	35
49	13	14	25	37	38	
50	15	16	26	39	40	
51	17	18	27	41	42	
52	19	20	28	43	44	
53	13	21	29	37	45	
54	14	22	30	38	46	
55	15	22	31	39	46	
56	16	23	32	40	47	
57	17	23	33	41	47	
58	18	24	34	42	43	
59	19	24	35	43	48	
60	20	21	36	44	45	

Table 8.2.1. Values of b (Eq. 8.2.1.) in km

	Vertical coordinate:	
	pressure	height
Higher subvolumes:	415	415
Lowest subvolume, unless coïncident with highest one:	527	527

Tale 9.2.1. Timings of an analysis on a Burroughs B6800 computer.

Times are in seconds, and refer to the 8 GMT analysis of the example.

Program:	CP:	I-O [1]:	Elapsed[2]:
Observation preparation	11		46
Preanalysis	14		93
Optimum interpolation	71		150
Postanalysis [3]	4		9
(Total between observations and analysis)	(100)		(298)
First-guess for next cycle	2		7
First-guess errors for next cycle	5		12
Summary of events	8		24
Fit to observations [4]	6		15
Statistical checks [5]	3		5
(Total diagnostics)	(31)		(79)
Administration [6]	64	67	143
Total for one analysis cycle	216	162	587

[1] I-O time is only available for the total cycle and for administration due to the computer configuration. The I-O time of the other programs could be reduced with a different file handling, which would, however, also reduce portability of the fortran code. The preanalysis reads the observation file in random order, and it is therefore the most I-O expensive program.

[2] Elapsed time was influenced unfavourably by the fact that the machine was shared with other users.

[3] Postanalysis is run twice. For analysis and for analysis errors.

[4] The fit to observations program is run twice. For first-guess and for analysis.

[5] Statistical checks are prints of maximum, minimum, average, standard deviation. This program is run for 5 files separately.

[6] Administration includes the construction of the job control cards for the next analysis, for some plot jobs and the submission of those jobs.

Table 9.5.1. Fit of the first-guess and the analysis to some observing systems. Shown are the average observation error for the observing system, the bias and the RMS of the difference between the field and the observations, and the number of data used. All quantities have been averaged over the 4 analyses 9 GMT through 12 GMT. All extracted data have been used, with the exception of data flagged 3 in the check against the first-guess to exclude flagrantly wrong data.

System	Datum		level(m)	Average	First-guess		Analysis		N
		Units		obs. error	bias	RMS	bias	RMS	
SYNOP	PRES.	mb	10	0.40	-0.31	1.31	-0.05	0.73	124
	u	m/s	10	2.00	-0.06	3.35	-0.13	1.75	126 1)
	u	m/s	70	4.86	-0.21	5.06	-0.32	3.74	115 1)
SHIP/	PRES.	mb	10	0.60	-1.02	2.40	-0.16	1.42	18 2)
ASHIP	u	m/s	10	2.00	-1.55	6.51	0.68	4.12	18 1)2)
ALL	PRES.	mb	10	0.41	-0.32	1.41	-0.06	0.83	134
	u	m/s	10	2.23	0.12	3.72	0.10	2.30	182
	v	m/s	10	2.23	-0.48	3.39	-0.25	2.15	182
	u	m/s	70	4.76	-0.23	5.18	-0.33	3.66	119
	v	m/s	70	4.76	-3.39	6.10	-3.19	5.14	119
	u	m/s	200	2.57	1.04	4.87	1.35	4.28	7
	v	m/s	200	2.57	-5.43	6.13	-4.82	4.74	7

1) Statistics for the v component are of similar magnitude.

2) At 10 and 11 GMT only 3 data were available. These were not included in the shown statistics.

Figure captions.

Fig. 5.2.1. The distribution of gridpoints, analysis squares, analysis centres, analysis volumes and internal analysis volumes, in the case that every second gridpoint in the x- and y-direction is selected as an analysis centre.

Fig. 5.3.1. Order in which the analysis squares are scanned for observations. After the central square, the first square to be scanned is to the east of the central square (number 1 in the Figure), then the one to the north (number 2) etc.

Fig. 8.3.1. The time sequence of analysis and first-guess errors in a typical series of hourly analyses. The dependent variable E^2 is the mean square of the errors, averaged over all levels and variables. At the times 0, 3, 6 etc. GMT the analysis error E(A) is smaller than at the intermediate hours because of the better data coverage.

E(F): Error of the first-guess

E(C): Standard deviation (i.e. $\sqrt{2}$ E(C) is the error of a random field).

In the figure, $\Delta = 1$ hr, $T_R = 3$ hrs (see Eq. 8.3.1). For clarity, the first-guess error has been plotted slightly before the analysis time.

Fig. 9.4.1. through 9.4.8.

Wind and pressure analysis at 10 m, from 6 till 13 GMT on 12 May 1983. The contour interval is 1 mb, winds have conventionally been plotted (1 fleche is 10 kts). The winds are potential, i.e. valid if surface roughness were 3 cm.

Fig. 9.4.9. Analysed wind speeds at 10 m, 10 GMT. The shown speeds have been derived from the potential wind speeds, using a realistic surface roughness. The isotach interval is 2.5 m/s (contours at non-integer speeds have been labelled by the lower integer value).

Fig. 9.5.1. Manual analysis at 12 GMT. Observations have been conventionally plotted. (Mean sea level pressure data in the storm area are shown in Fig. 9.5.2.). The contour interval is 1 mb, and the labelling is with deletion of hundreds of mb.

Fig. 9.5.2. The 10 m pressure analysis over the south east North Sea, and the synop and ship observed wind and pressure. The isobar contour interval is 0.5 mb, non-integer valued contours have been labelled with the lower integer. The wind is plotted as a line from the station into the direction into which the wind is blowing, with wind speed in m/s as a number at the end of the line. The pressure observation at PGVW of 995 mb has been rejected by the final data checking; it has been marked to this effect.

Fig. 9.5.3. Analysis increments of 10 m wind and pressure at 12 GMT. The winds have been plotted conventionally. The isobar contour interval is 0.4 mb. Non-integer valued isobars have been labelled without the fractional part.

Fig. 9.5.4. The first-guess errors for the analyses at 10, 11, 12 and 13 GMT. Thick contours are for pressure at 10 m, (interval 0,25 mb) and thin for the 4 component of wind (interval 0.5 m/s). Non-integer contours have been labelled with the lower integer value.

Fig. 9.5.5. As Fig. 9.4.7. with a slightly different formulation of the model to forecast the first-guess error for the next analysis.

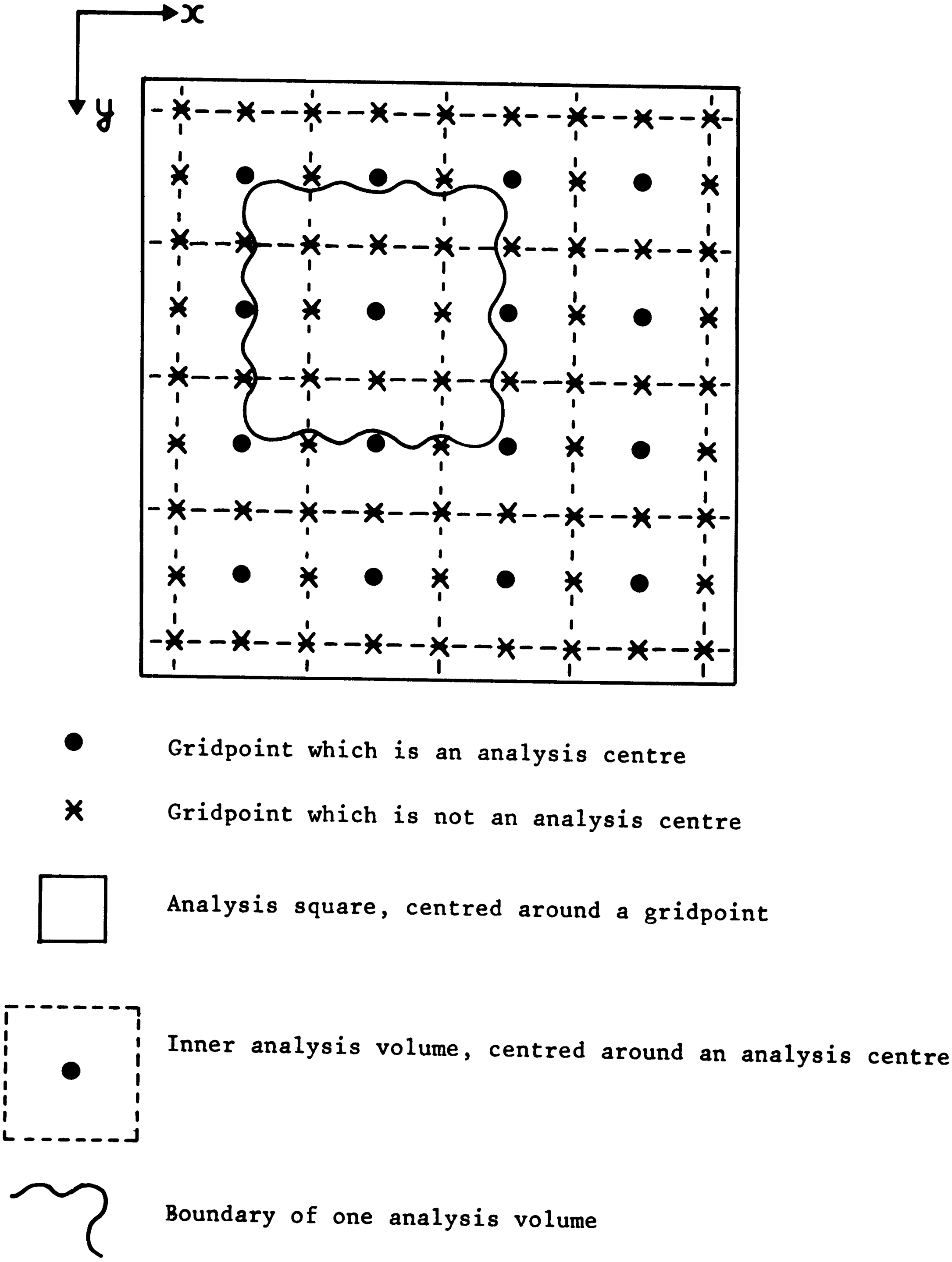

x
y
Gridpoint which is an analysis centre
Gridpoint which is not an analysis centre
Analysis square, centred around a gridpoint
Inner analysis volume, centred around an analysis centre
Boundary of one analysis volume

Fig 5.2.1

		63	55	46	54	62		
	50	39	31	22	30	38	49	
64	40	26	15	10	14	25	37	61
56	32	16	6	2	5	13	29	53
47	23	11	3		1	9	21	45
57	33	17	7	4	8	20	36	60
65	41	27	18	12	19	28	44	68
	51	42	34	24	35	43	52	
		66	58	48	59	67		

Fig 5.3.1

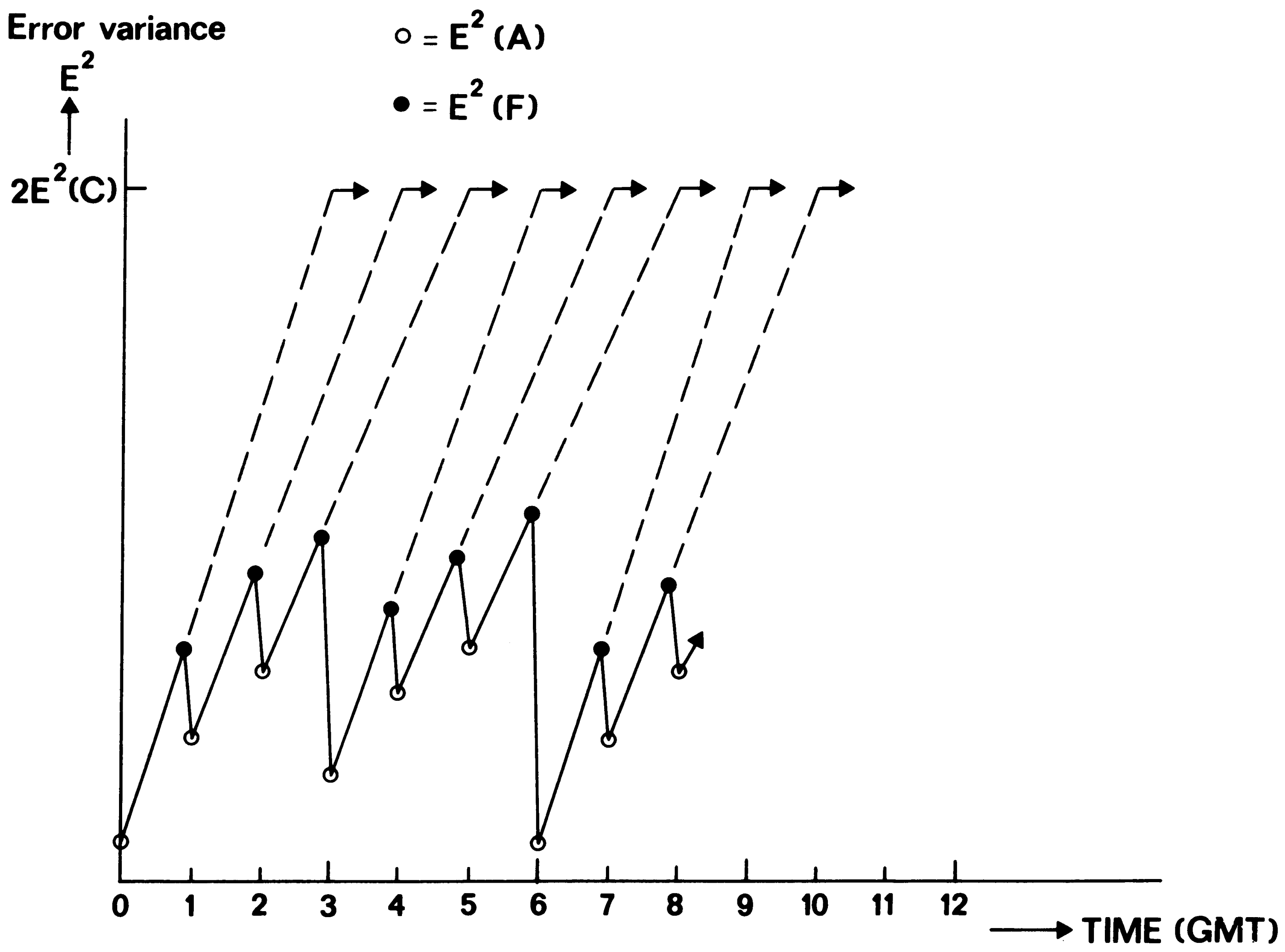
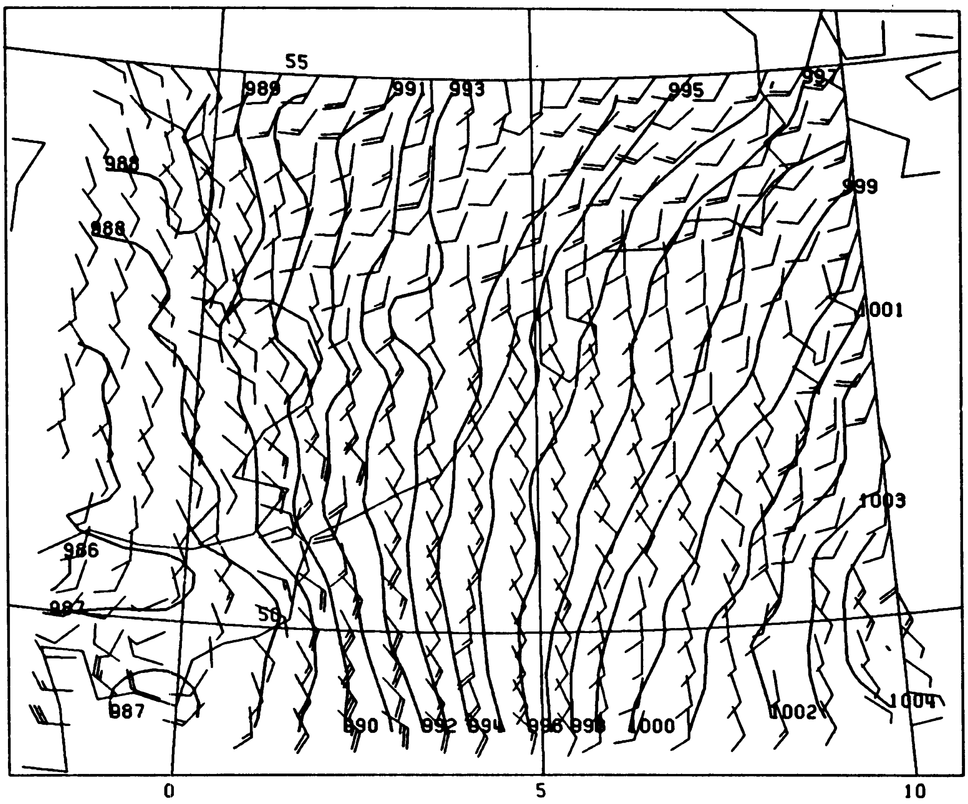


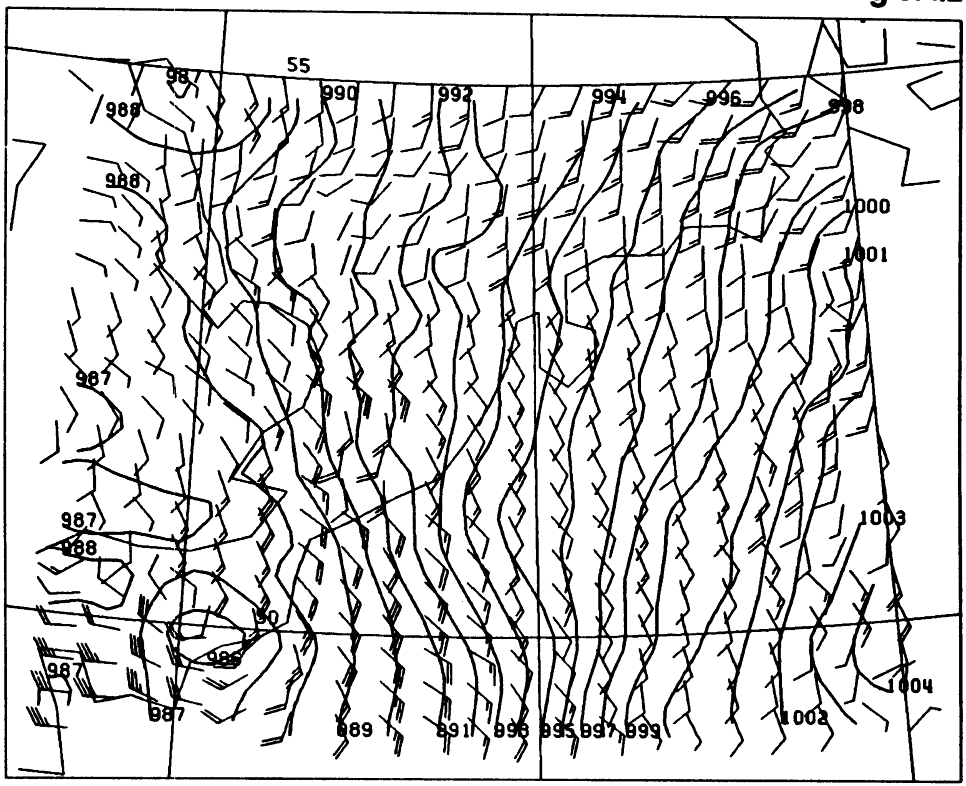
Fig 8.3.1

Fig 9.4.1



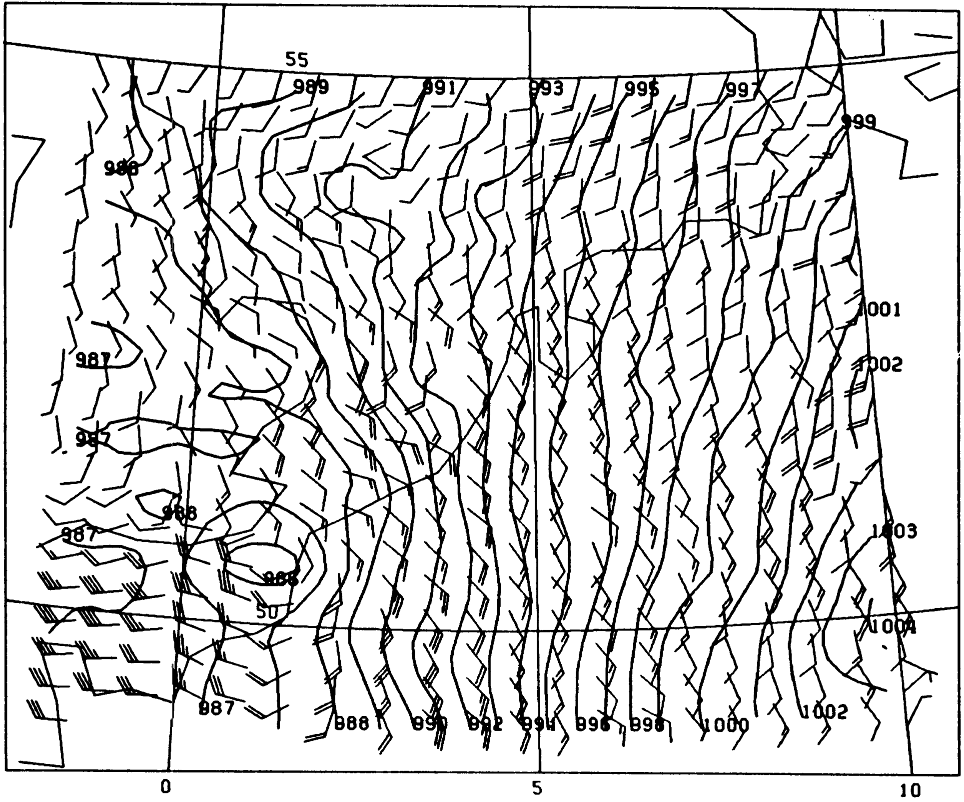
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051206)

Fig 9.4.2



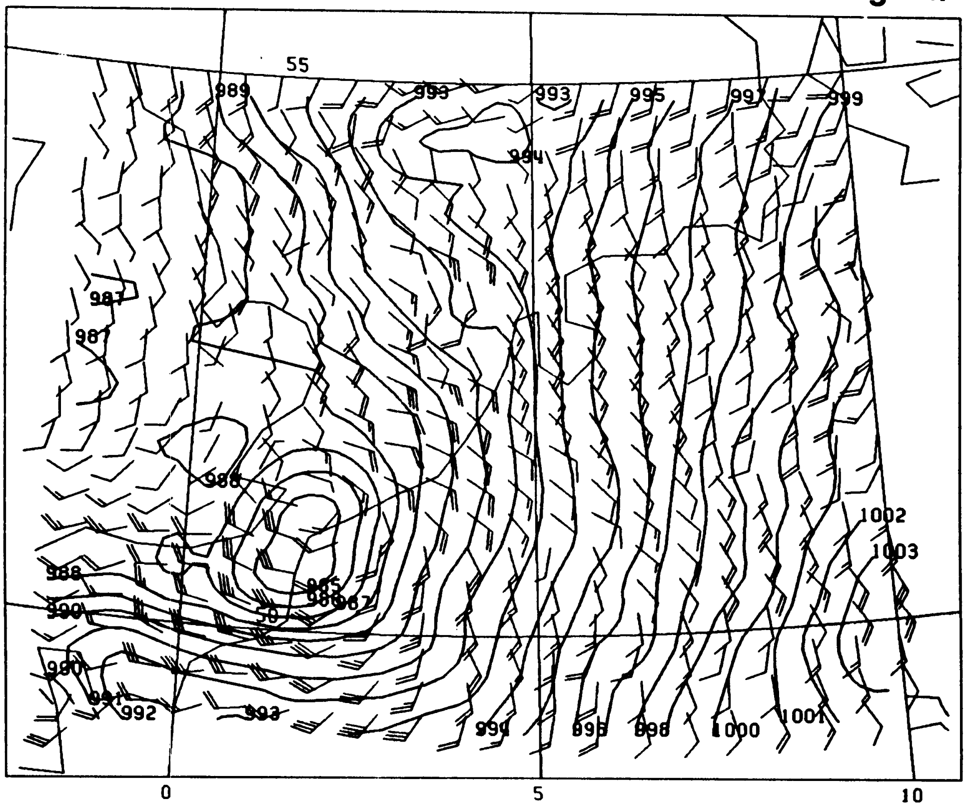
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051207)

Fig 9.4.3



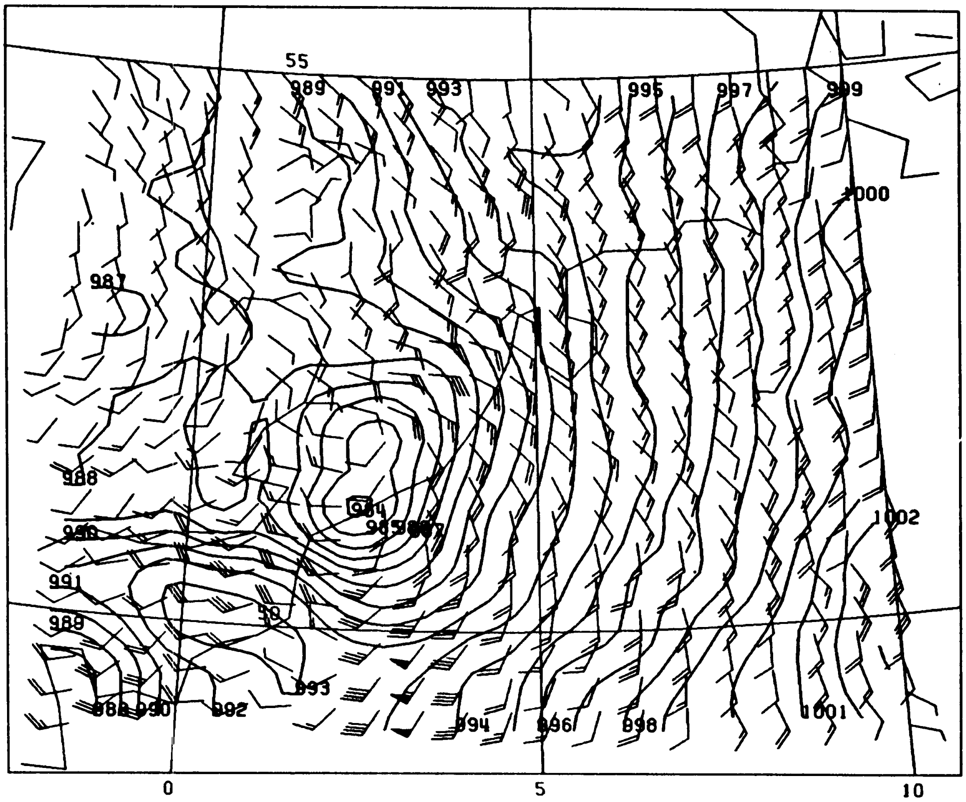
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051208)

Fig 9.4.4



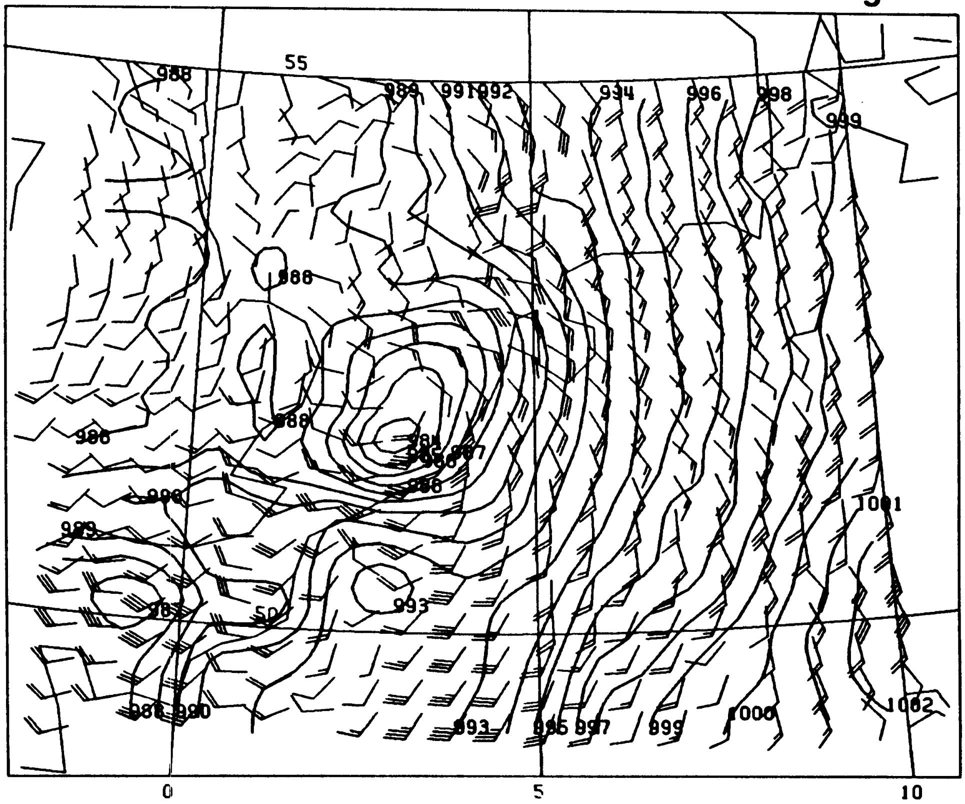
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051209)

Fig 9.4.5



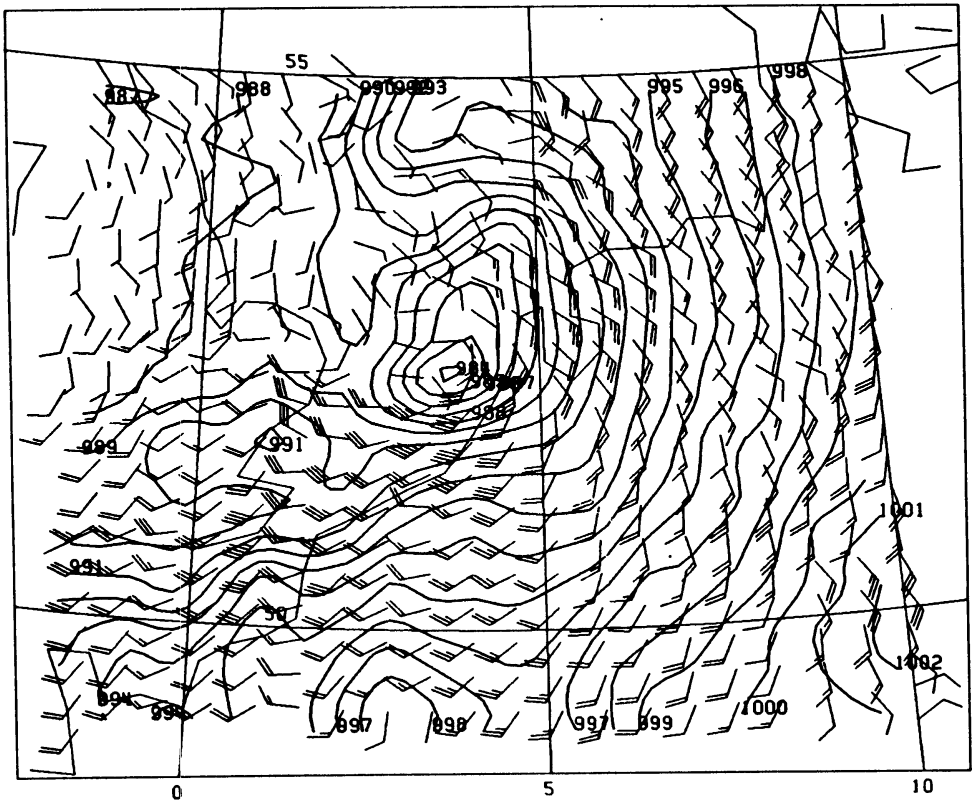
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051210)

Fig 9.4.6



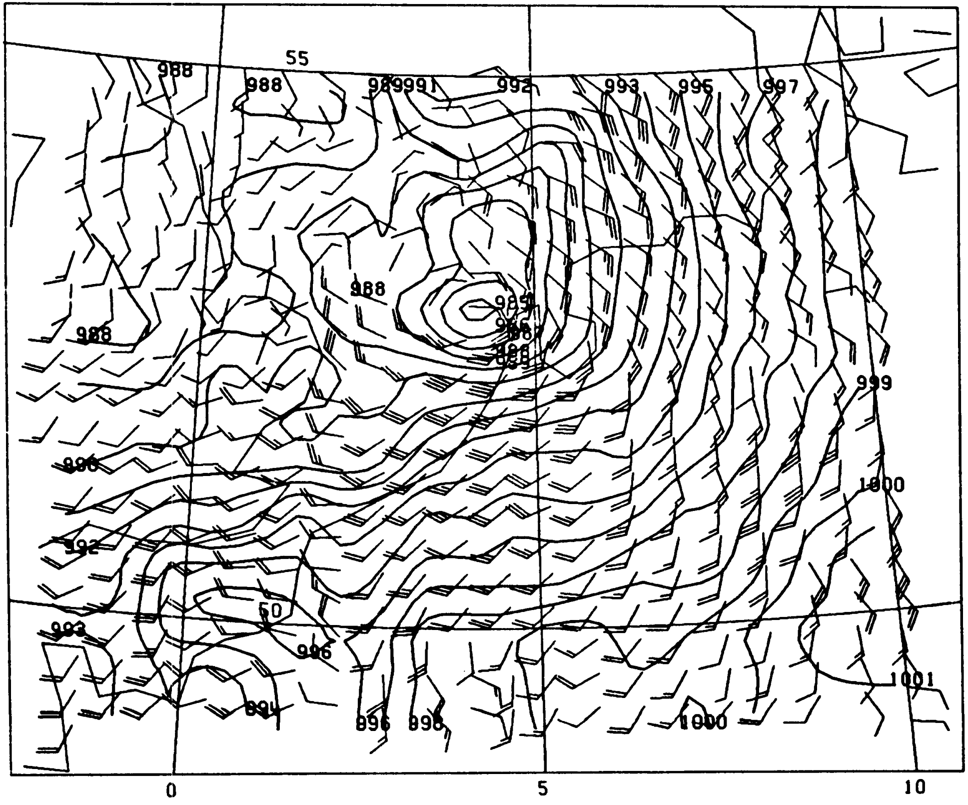
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051211)

Fig 9.4.7



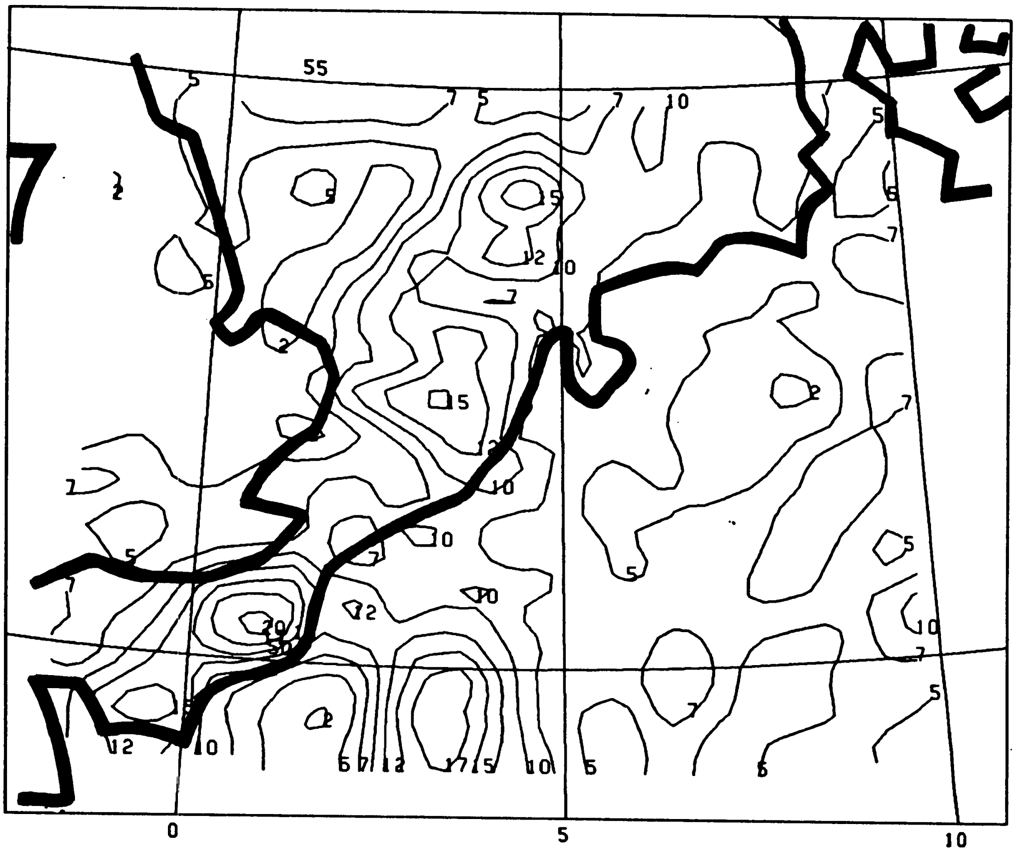
WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051212)

Fig 9.4.8



WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051213)

Fig 9.4.9



ACTUAL ANALYSED 10M-WIND SPEED (M/S) (ANALYSIS TIME 83051210)

Fig 9.5.1

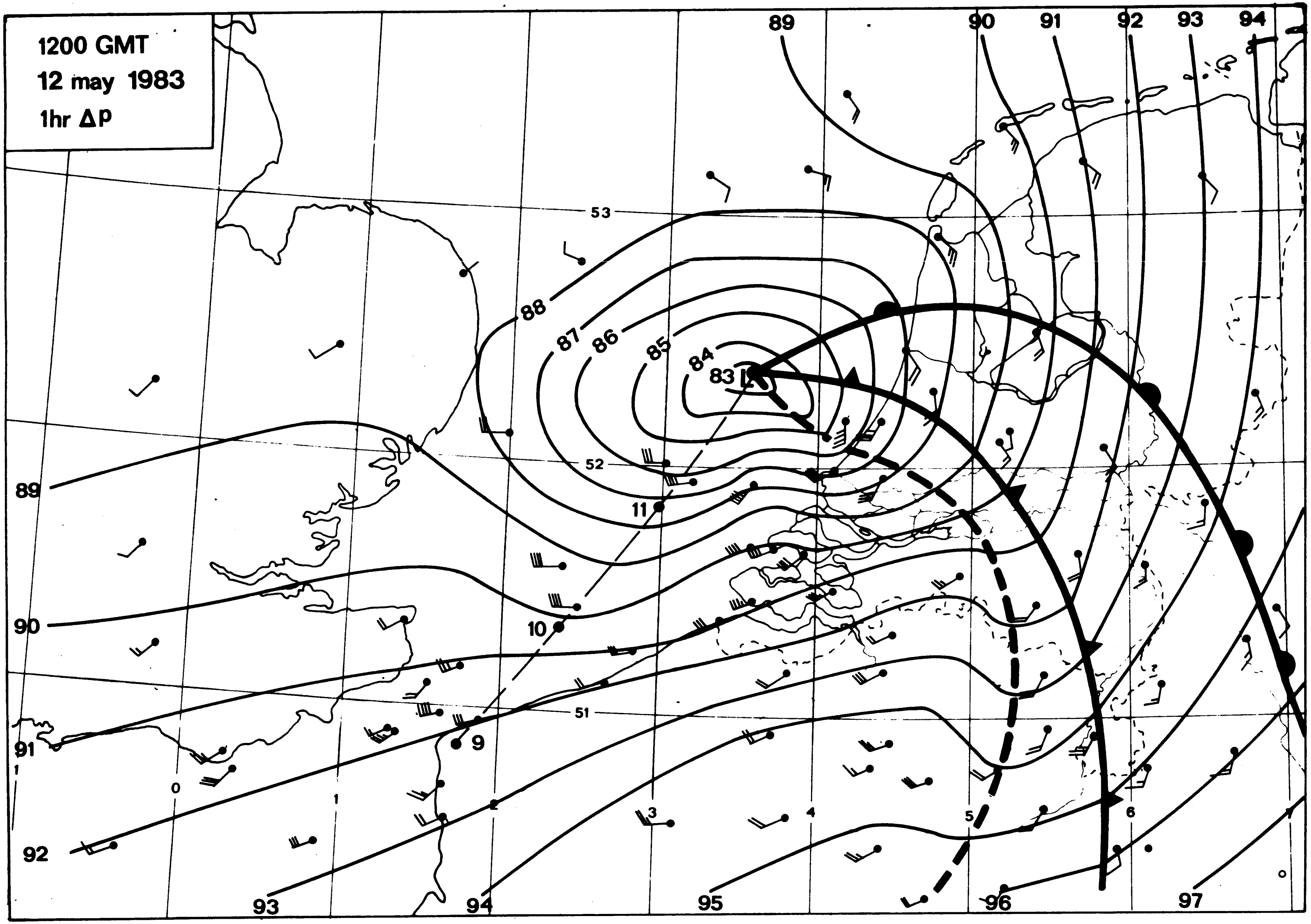
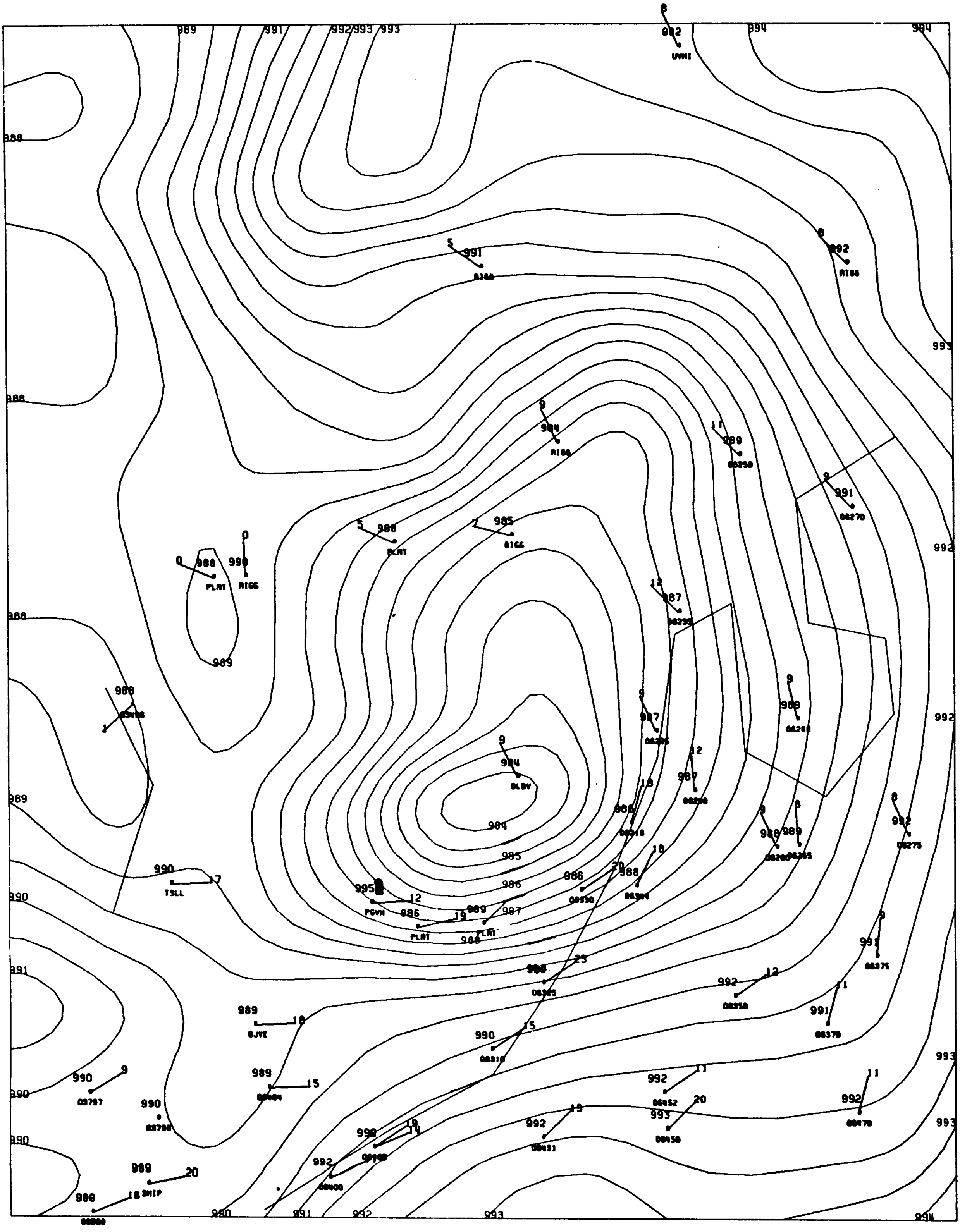

1200 GMT
12 may 1983
1hr Δp
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
53
52
51
11
10
9
0
1
2
3
4
5
6

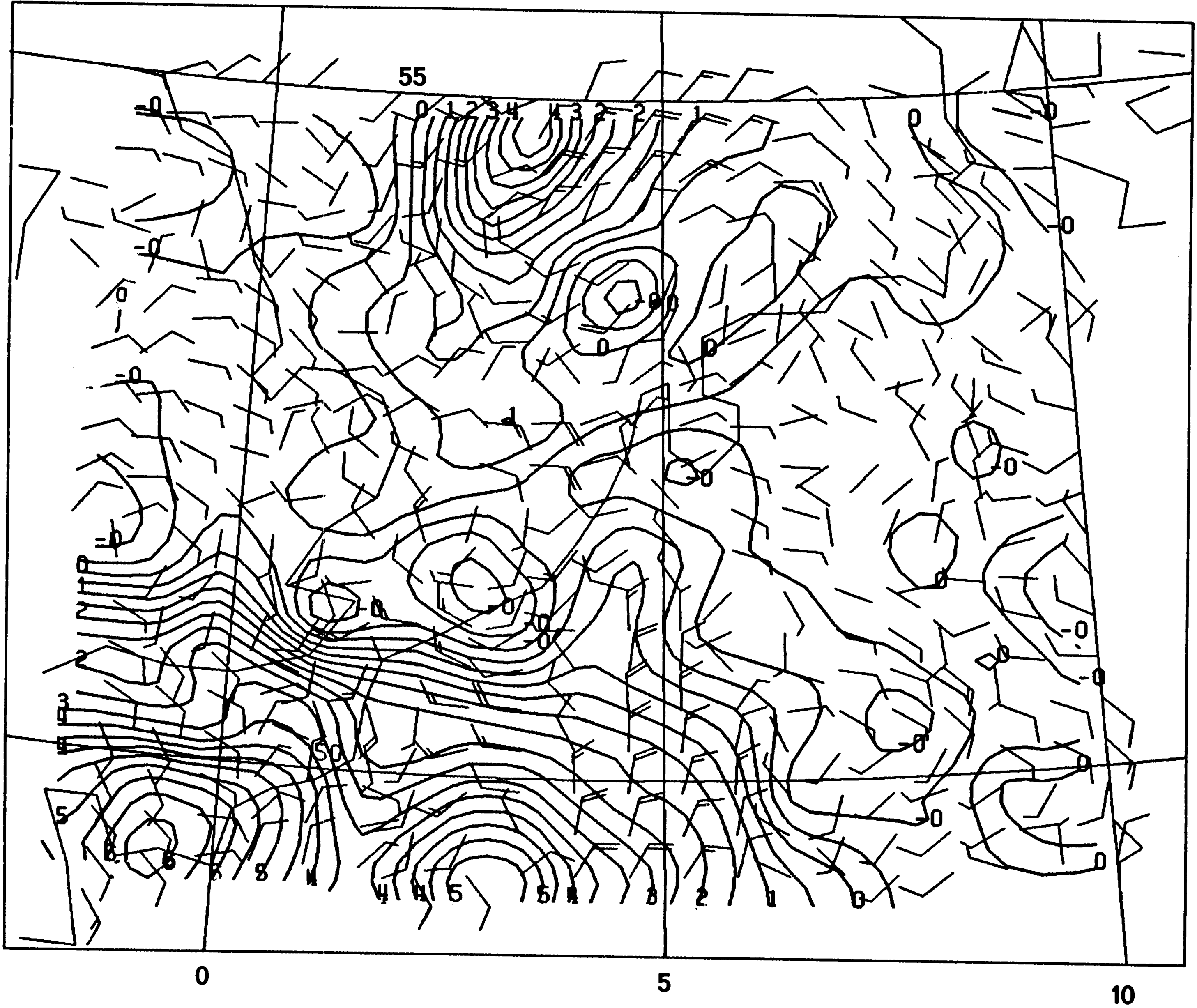
Fig 9.5.2



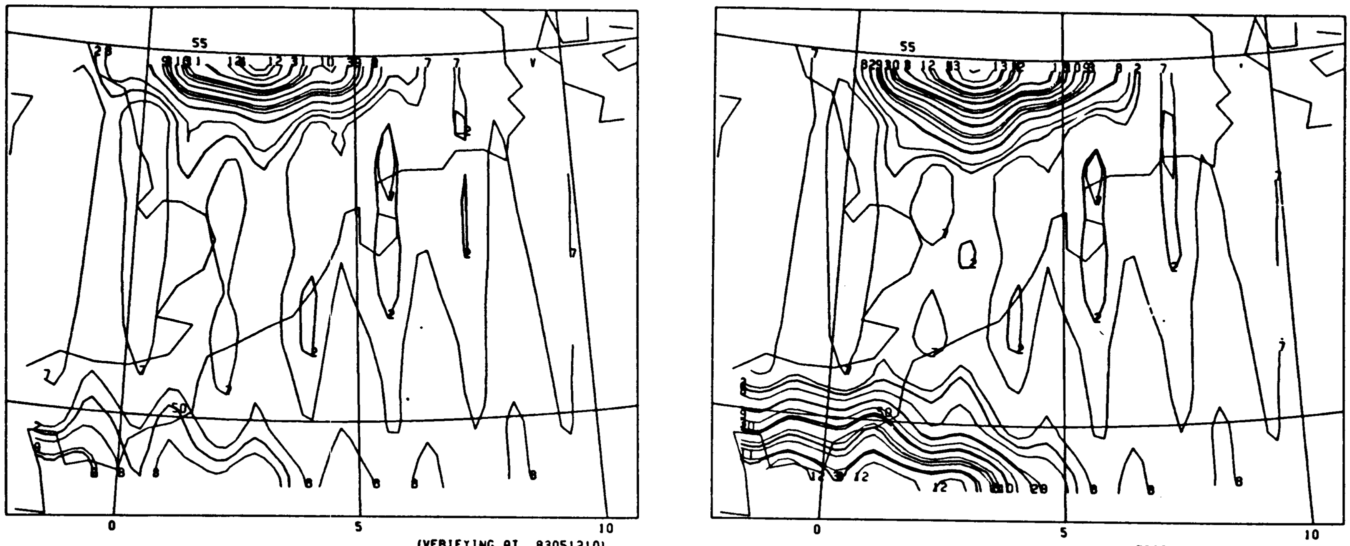
OBSERVATIONS AND PRESSURE ANALYSIS AT 10 M

83051212 10 30
(ANALYSIS AT 83051212)

Fig. 9.5.3



WIND AND PRESSURE ANALYSED INCRMTS AT 10 M (ANALYSIS TIME 83051212)



U-WIND AND PRESSURE FG-ERRORS AT 10 M (VERIFYING AT 83051210) (FORECAST FROM 83051209)

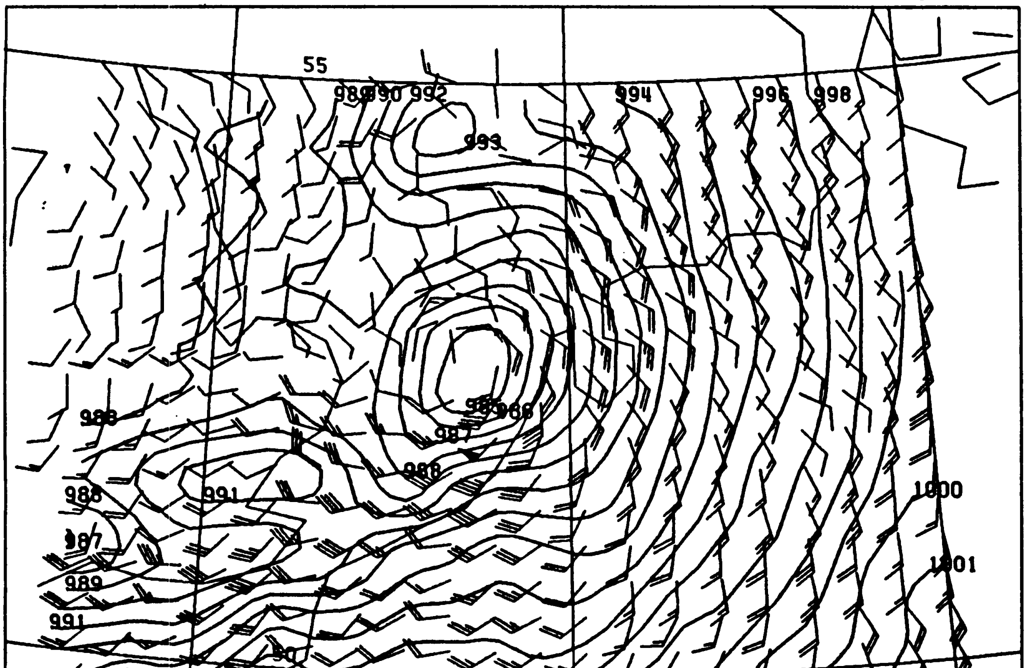
U-WIND AND PRESSURE FG-ERRORS AT 10 M (VERIFYING AT 83051212) (FORECAST FROM 83051211)

U-WIND AND PRESSURE FG-ERRORS AT 10 M (VERIFYING AT 83051211) (FORECAST FROM 83051210)

U-WIND AND PRESSURE FG-ERRORS AT 10 M (VERIFYING AT 83051213) (FORECAST FROM 83051212)

Fig.9.5.4

Fig 9.5.5



WIND AND PRESSURE ANALYSIS AT 10 M (ANALYSIS TIME 83051212)