TECHNICAL MEMORANDUM

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The new analysis system

P. Lönnberg, J Pailleux
and A. Hollingsworth

Research Department

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European Centre for Medium-Range Weather Forecasts
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1. BACKGROUND

The Centre's first analysis system has had an operational lifetime of seven years and was used to produce the MAIN and FINAL FGGE IIIb analyses. During the design and development phase (1975-79) computer architectures imposed many constraints on the structure of the system. On the Cray-1A, I/O was very expensive compared to "number crunching" and needed to be minimized. This problem was solved by grouping observations from an area with approximate size of 660 km square into a block. Such a block formed the smallest data unit in the analysis. Vectorization capabilities favoured solving a few large systems of equations instead of many small systems. These two features of the Cray-1A lead to the implementation of the volume analysis technique in which a large number of points are analysed using the same (extensive) data set. The meteorological implications were not fully understood at that time, but it is now widely recognised that the volume technique is superior to the point technique since it widens the spectral window for synoptic scale waves. In addition, the great power of the quality control features made possible by this aspect of the design were not fully appreciated at the outset.

Improvements in the analysis response were, however, inhibited by the rigid structure of analysis volumes and the N48 grid of the old system. In regions of high data density, a special algorithm to select representative observations was designed. Critical observations which were regarded as less representative might not have been used by the analysis. Increases in vertical resolution were difficult as data from at most 15 standard pressure levels could be used. Furthermore, central memory limitations on the Cray-1A forced a partitioning of the analysis into several steps which communicated through extensive file handling.

In the stratosphere, an algorithm using persistence and climatology above the top model level was applied to keep the assimilation stable. Because of the use of persistence it was difficult to remove incorrect structures from the analysis once they had been inserted as the result of using bad data. In addition, the vertical coherence of the first-guess was disturbed, resulting in large stratospheric initialisation changes. Furthermore, tidal signals were mishandled.

All these limitations gave ample justification for the redesign and re-programming of the analysis system.

The upgrading of the ECMWF assimilation system is being carried out in two phases. In the first phase (Phase I) the 19-level model and the new analysis code are to be implemented. The second phase (Phase II), to take place in 1987-88, will evaluate and subsequently implement major meteorological enhancements such as high resolution divergent non-separable structure functions. The aim of phase I was to keep the meteorological changes to a minimum. However, significant impact followed both from the operational introduction of the 19-level model and in the pre-operational experiments with the new analysis system.

The technical changes introduced in the new analysis are briefly described in Section 2. Section 3 deals with the meteorological modifications to the assimilation system. In Section 4 the results of these modifications are presented and Section 5 outlines the programme for the continuing development of the new analysis system over the next two years. Finally, Section 6 summarizes the impact of the operational introduction of the 19-level model and the new analysis system.

2. TECHNICAL DEVELOPMENTS

The old analysis system was designed to run efficiently on the Cray-1A. Central memory limitations forced the system to be built as a sequence of modules communicating with each other through files. Observations had to be kept on an I/O device. The acquisition of the CRAY X-MP/48 made it possible to integrate the analysis codes into a single system. Furthermore, the old system could not have run without a major coding effort on any other resolution than N48. The new system uses a memory manager facility to control the use of central memory and employs the same resolution as the forecast model in the data assimilation.

The analysis process is ideal for multi-tasking. It consists of a large number (10^3 - 10^4) of independent problems which can be solved in any order. A tree structure is set up to control the computations in the data quality control and in the evaluation of analysis increments at the analysis points. The tree contains information on every analysis volume, such as volume boundaries, minimum and maximum extent of data selection and number of observations in the volume. The tree is, in contrast to the old system, fully dynamic as the size of the analysis volumes can be varied according to observation density. Pointers define a unique path through the tree to facilitate the control of the computation. When a volume has been processed a tree search for the next unprocessed volume is initiated and when found it is allocated to a free processor. The synchronization of the processes takes place at the end of the tree traversal and thus creates little multi-tasking overhead.

The availability of central memory has made it possible to keep all observations in core. This simplifies data selection considerably and makes future development of data selection algorithms for special situations relatively simple.

3. METEOROLOGICAL DEVELOPMENTS IN PHASE I

Although the meteorological changes have been minimized in Phase I, some of those that have been made are important and should have a significant impact on the quality of the analysis and of the subsequent forecasts.

3.1 Use of data at the reported level

In the old analysis system, for each item of data, the increment "Observation-First guess" is moved to the closest standard level before entering the O/I equations. There are 15 standard levels between 1000 and 10 hPA. This implies that all the AIREPs reporting, for example at 263 hPa or 239 hPa, are moved to 250 hPa before being used and also that boundary layer detail in the data is not retained since data are used at 1000 and 850 hPa only.

In the new system, the increments are evaluated and used in the 3-D analysis directly at the reported level; that is the 3-D optimum interpolation is fully three dimensional. This feature will be important near the surface (the different surface SYNOPs give reports at many different levels), in the boundary layer (since some information from part B of radiosondes ascents is now used), and also near the tropopause where many AIREPs and SATOBs (cloud drift winds) are normally available for the analysis.

The consequence of such a modification is an increase in the actual vertical resolution of the analysis; in the old system the analysis vertical resolution is controlled by the use of data at 15 standard levels.

3.2 Fewer interpolations leading to reduced errors.

A general principle of the design of the new analysis is to minimize the total number of field interpolations occurring in the whole assimilation process (vertical and/or horizontal interpolations applied to the first-guess, the increments or the analysis itself). Consequently, in the vertical, the first-guess is interpolated directly from the model levels to the reported levels in the observations (avoiding an interpolation of the first guess to the standard levels, and then to the observation levels).

In the horizontal the analysis increments are evaluated directly on the model's Gaussian grid (T106 at present - a resolution of 120 km) and the model levels rather than on the N48 (1.875° x 1.875°) grid used in the old system.

3.3 Analysis box structure and data selection

Another important feature of the new analysis is the development of a flexible box structure. In phase I the full flexibility of the box structure algorithm is not being used; however, the box structures are somewhat different in the new system. In the old system all the boxes are about 660 km x 660 km. In the new system sub-division of boxes of this size occurs in data dense areas (Europe, China, North-America, for example).

In the vertical each analysis box was analysed either in one slab or in three slabs in the old system, depending on the total number of data available; the three slabs being 1000-700, 700-200, 200-10 hPa. In the new system the analysis is always carried out in two slabs: 1000-100 hPa (tropospheric slab) and 200-10 hPa (stratospheric slab).

3.4 Super-obbing preceded by the appropriate O/I check

When some observations are too close to each other, they are merged into one single "super-observation"; the "super-obbing" technique being based on O/I theory. In the old system the super-obbing is applied before the data-checking algorithm, so that when a super-observation is rejected it is difficult to trace the problem back to an individual faulty observation. Firstly, in the new system, super-obbing is applied to a lesser extent - only to observations of the same type (while in the old system a SYNOP observation was often super-obbed with a radiosonde observation, for example). Secondly, the quality control is performed before the super-obbing by applying an O/I check to each piece of data which has to be super-obbed, as a consequence the super-observation itself is never rejected. Although this is only a minor change, it must however lead to a better use of data in data-dense areas.

3.5 3-D statistical interpolation of relative humidity

The analysis of humidity is the part which will probably be most affected by change to the new system. The old humidity analysis scheme used a 2-D correction scheme performed in one pass on standard layers. In this scheme horizontal interpolation is crude, and additional vertical interpolations are required to produce a three dimensional humidity analysis for the model.

The new humidity analysis is similar to the mass/wind analysis in that it is a 3-D optimum interpolation scheme performed directly on the model levels; appropriate structure functions have been derived by verifying the six hour forecast against North American radiosondes. This should lead to a better procedure for combining the information in different observation types: SYNOPs, TEMPs and SATEMs.

In addition, the many improvements which have been introduced in the old operational scheme in March 1986 are also included (see ECMWF/SAC(86)5 for a documentation of these changes).

3.6 19-level forecast model

An important step made in May 1986 before the evaluation of the new analysis system, was the increase of the vertical resolution of the operational model from 16 to 19 levels. The three additional levels were added to the stratosphere (as illustrated in Fig.1a). Prior to this modification, the old data assimilation suffered severely from the mismatch between model and analysis resolution in the stratosphere. Above 100 hPa there were only 2 model levels to generate first guess information at 5 analysis levels. This required extra information from persistence and climatology and this had serious drawbacks. Because of the use of persistence it was difficult to remove incorrect structures from the analysis, secondly the vertical coherence of the first guess was disturbed, resulting in large stratospheric initialisation changes and finally the tidal signals were mishandled.

The new analysis system uses the 6 hour forecast as first guess at all levels (19 levels up to 10 hPa), without any special use of persistence or climatology.

This development will have an important bearing on the Centre's projects to use satellite radiance data in the analysis. Physical (temperature and humidity) retrieval procedures require a good first guess both in the troposphere and in the stratosphere; the stratospheric 16-level first guess was too poor to use with a physical retrieval scheme (see paper ECMWF/SAC(86)5).

3.7 Orography in analysis

When near-surface observations are used in the analysis, several tests are performed; these tests depending on the model's orography (e.g. surface observations are not used when the station height differs significantly from that of the model orography). In the old system, the analysis is performed on the N48 grid, using an orography which is interpolated from the T106 orography. In the new system since the analysis is carried out directly on the model's Gaussian grid consequently it uses the model's orography which is closer to reality. The outcome should be a better use of the data near the surface, particularly in the areas where the orography is very steep.

4. RESULTS FROM PHASE I

This section describes the impact the 19-level model and new analysis system has on the quality of the analyses and on the skill of the subsequent forecasts.

4.1 19-level model

The improved vertical resolution of the forecast model efficiently removes spurious vortices in the stratosphere that are excited by bad data. The improved balance between mass and wind fields reduced the stratospheric short-range forecast error substantially (Fig.2) and as a result fewer observations are rejected.

The most striking impact is obtained for the tropical wind field but the short-range forecast of height also improved. As a result of the closer agreement between data and first-guess, less contamination of the upper tropospheric analysis occurs. From time to time 16 level analysis produced a number of small scale vortices in the tropics at 50 hPA. By contrast, the 19 level analysis produces a more uniform easterly flow which agrees well with observations.

Parallel forecasts for both T63 and T106 horizontal resolution have been run. 9 pairs of 16 level forecasts from 16 level assimilations and 19 level forecast from 19 level assimilations have been run. Fig. 3 shows the mean anomaly correlation for Northern hemisphere height field averaged between 1000 and 200 hPa, for zonal wavenumbers 1-3 and for total field.

The 19 level system scores better in the medium range from day 6 onwards. Taken at the 50% level, the scores improve by about 1 day in the mean. This improvement is mainly due to a better handling of the long waves. Of these 9 cases, only one 19 level forecast was slightly worse. Southern hemisphere scores show a similar result, and improvements in tropical wind scores appear early on in the forecasts. Running 16 level forecasts from 19 level initial data showed that improvements are largely due to the better defined initial state, and improvements in the latter parts of the 10 day forecasts showed up clearly in the Atlantic jet, jet-splitting and the downstream ridges and troughs (see Fig.4).

4.2 Results from new analysis system

The results presented in this section are based on two 19-level data assimilation experiments with 19 level forecasts. The first, a T63 experiment from February 1985, consisting of 11 days of data assimilation and 10 T63 forecasts, has been completed. A second experiment starting on 1 June 1986 with a T106 resolution system was still running at the time of writing. Results from 4 T106 forecasts are available. Some tentative explanations for the analysis and forecast differences are offered in the following.

(a) Differences in analyses

The mass and wind analyses of the old and new system are very similar in the Northern Hemisphere. Occasionally, the quality control (QC) algorithms treat dubious data differently causing local variations in the analyses. These disturbances seem to be of little importance for the ensuing forecasts.

In clear contrast to the Northern Hemisphere, the analysis in the Southern Hemisphere depends strongly on which scheme - old or new - is used. In nearly every analysis cycle, the QC algorithms of the old and new systems disagree on decisions concerning the correctness of some surface data. These decisions have a considerable impact on the analyses, but only by inspection of the subsequent forecasts is it possible to verify these QC judgements; this is be discussed below.

The Southern Hemisphere tropospheric temperature fields are clearly different in the two systems. A good measure of the accuracy of the analysis is the verification of the six hour forecast against observations. A clear advantage for the new analysis system is evident in the forecast verification against satellite thicknesses (Fig.5).

Two features, in particular, of the new system are likely to produce different analyses. Firstly, the troposphere is always analysed in one slab supplying a proper reference level to tropospheric satellite thickness data. The single slab troposphere technique produces more coherent analyses than the old system in which the boundary layer was analysed separately from the rest of the troposphere. The other important difference is the wider data selection. This should improve the analysis response to large scale features such as meridional temperature gradient. Extensive data selection is thought to be particularly important in areas which are observed by homogeneous observing system such as satellites.

Perhaps the largest change resulting from the use of the new analysis is found in the moisture fields. Globally, the new system is drier (approximately 2%) and much more faithful to observations than the old system. A close agreement between satellite moisture data and the short-range forecast is found in the new analysis.

(b) Impact on forecasts

The results are again discussed separately for the two hemispheres. In the T63 experiments, differences in forecast scores are quite weak in the Northern Hemisphere as measured by anomaly correlation or rms-error. Even individual forecasts show little sensitivity to the new analysis procedures. The forecasts start to diverge in the latter part of the medium range but the differences are difficult to trace back to the initial states.

A stronger sensitivity to the analyses is found in the T106 experiments than in the T63 experiments. The forecasts begin to evolve differently at around day 4 or 5 and some predictions show little similarity in the flow over Europe and North Atlantic at day 6. Two possible explanations can be put forward; the T106 analysis resolution preserves the small scale features of the high resolution assimilation and /or the new humidity analysis has led to different treatment of secondary cyclone developments during the summer season.

The strongest differences between the results from the two assimilations are again found in the Southern Hemisphere. Clear differences in the initial states amplify in the forecasts from the new analyses and move downstream. Significant improvements in structure and phase of the meteorological systems are found already in the early part of several forecasts. This is also verified by objective scores. Fig.6 shows the anomaly correlation for 500 hPa height of the T63 experiments. It is therefore safe to conclude that the QC decisions are more often correct in the new system.

An intriguing systematic difference between forecasts from new and old analyses appears in the latter part of the 10 day predictions. The circulation type is frequently quite different with the forecasts from the new system being the most accurate.

Objective verification of tropical fields are very sensitive to the verifying analyses. However, the upper tropospheric wind forecasts from the new analyses show higher skill than those from the old system as verified against operational analyses of February 1985 (Fig.7).

4.3 Summary of the forecast results

Some of the features of the new analysis system should invariably have a positive impact analyses and forecasts. These are

- T106 analysis projection grid
- Fewer vertical interpolations

Other aspects of the new system are in general regarded as beneficial but may alter the QC decisions or increase the sensitivity to systematic observation deficiencies. These modifications are the following:

- 2 slab analysis providing proper reference level for satellite data
- Extensive data selection with comprehensive QC
- 3-D statistical interpolation of relative humidity

5. PLANNED DEVELOPMENTS FOR PHASE II

It will take several years to exploit fully the capabilities which have been built into the new analysis system. The priority given to each development will depend on the results of diagnostic examination of operational performance, and on experimental work with special high resolution datasets such as GATE, ALPEX, GALE, AMEX.

The main goal over the next few years is to use the flexibility provided by the new system to upgrade the resolution and sophistication of the analysis to match the model's resolution. To attain this goal will require more sophisticated diagnosis of analysis and forecast errors and more elaborate analysis technique. Our earlier work provided us with a comprehensive spectral description of the variances and covariances for the 2-point correlations describing the isotropic components of the forecast error. These formulations imply, for example, that the constraint of non-divergence may be made scale-dependent, or that the constraint of near-geostrophy may also be made scale dependent. Both features are likely to be of importance in high-resolution analysis and in tropical analysis. We need to generate a set of experimental results using high-resolution data in order to determine what the scale dependencies should be.

Our current separable representation in the vertical is known to be unsatisfactory, based on i) empirical statistical results on forecast errors which clearly imply non-separability, ii) theoretical results which show that the analysis of the thermal wind is inadequate and iii) experimental results which show that it is very difficult to get a really satisfactory thermal wind analysis near strong fronts with our current system. We shall therefore experiment with non-separable structure functions in order to improve the thermal wind analysis.

The very flexible box structure in the new system will provide an invaluable experimental tool to understanding the effect of scale dependent constraints, by enabling us to restrict their operation to very localised regions, or to extend them over much larger regions. We have developed some theory and intuition about the importance of analysing small scales and large scales simultaneously. These need to be sharpened with experimental results. The results will be important in developing a good strategy to make the analysis parameters (selection radius, structure function scales) dependent on the data density.

In parallel with this work we shall extend the current work on structure functions for the North Atlantic to all other major oceans. In due course we expect to introduce a solidly based regional variation for the structure functions.

Some preliminary experiments have been made on the value of increasing the analysis frequency, so as to approach a continuous assimilation system in the frequency of data insertion. Preliminary analysis suggests that the introduction of isolated single level data may cause problems, and that it may be better to introduce data in as extensive and three-dimensional a manner as possible. In the old system we "batch" together data which may have been observed six hours apart. Much of the error inherent in this can be reduced if we work with the differences between the data and the first guess valid at the observation time. In the new system it will be relatively easy to evaluate the observation minus guess differences with an hourly frequency, and carry out the analysis calculations every six hours. This approach to a more continuous assimilation will be explored.

Planned activities in the area of satellite retrievals will require extensions of the surface analysis to provide additional fields such as surface temperature and surface humidity. The surface analysis will be rewritten in the near future and upgraded to provide the necessary additional fields.

6. SUMMARY

Phase I of the implementation of the high resolution analysis system has been completed. Although this phase was planned as a technical transition to the new analysis code, it brought with it substantial meteorological improvements. The use of a 19-level model not only improved the stratospheric analyses but also gave a significant increase in the skill of medium range forecasts. The new analysis system had an unexpectedly strong impact on the Southern Hemisphere forecasts. In particular, it demonstrated the significance of the accuracy of the initial state for predictions of the Southern Hemisphere flow. The revised humidity analysis is a plausible cause for Northern Hemisphere forecast sensitivity obtained in summer experiments. Finally, the new analysis should provide a basis to upgrade the resolution and sophistication of the analysis in the near future.

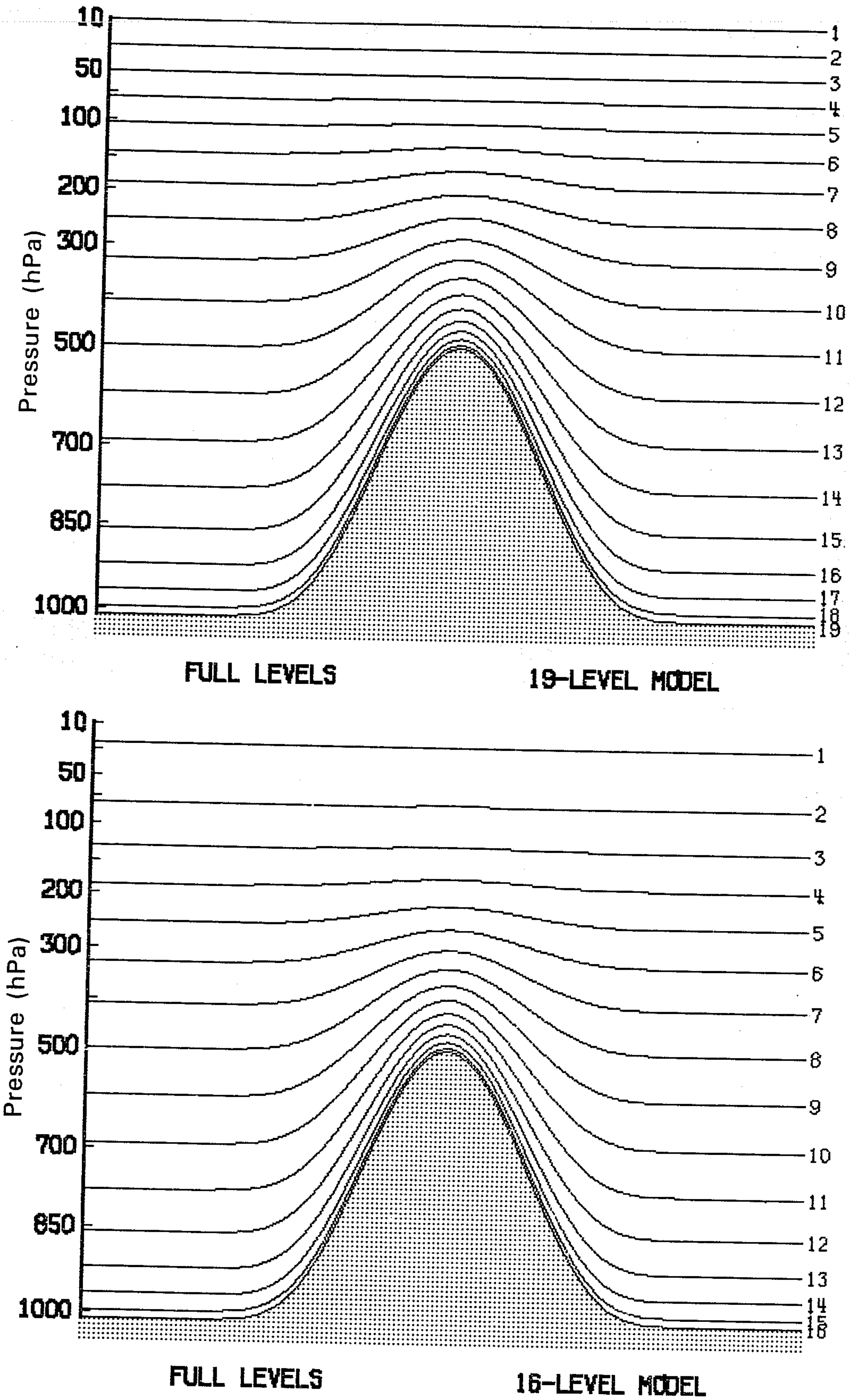

Fig. 1 Vertical distribution of full model levels for 16 level model (operational until May 86) and 19 level model.

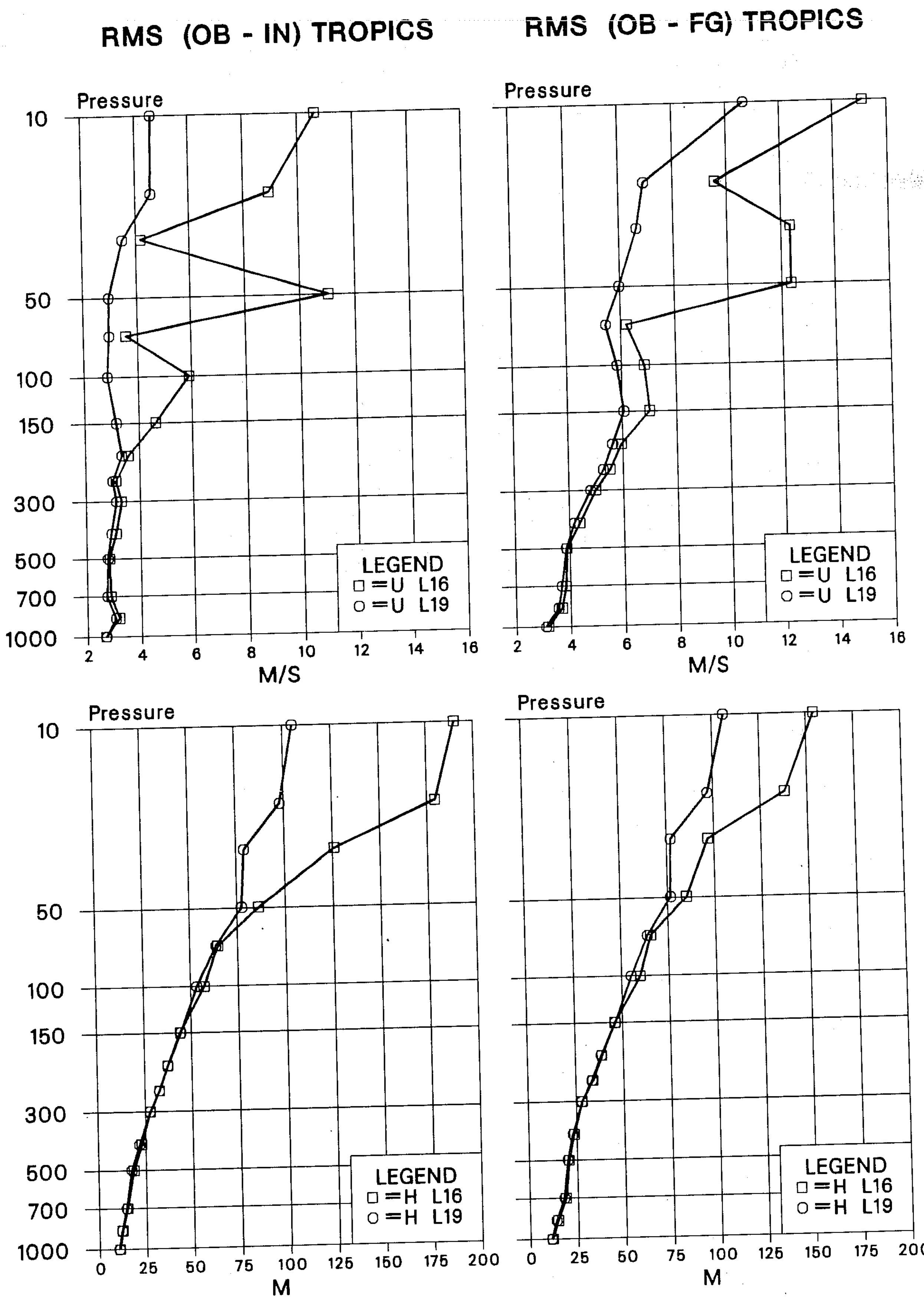

Fig. 2 Time mean (16.2.85 - 26.2.85 00Z) RMS fit of initialised analysis (left) and first guess (right) to tropical radiosonde data. Top panels show fit of zonal wind component, bottom for height field. Line with circles is for 19 level model, squares for 16 level run.

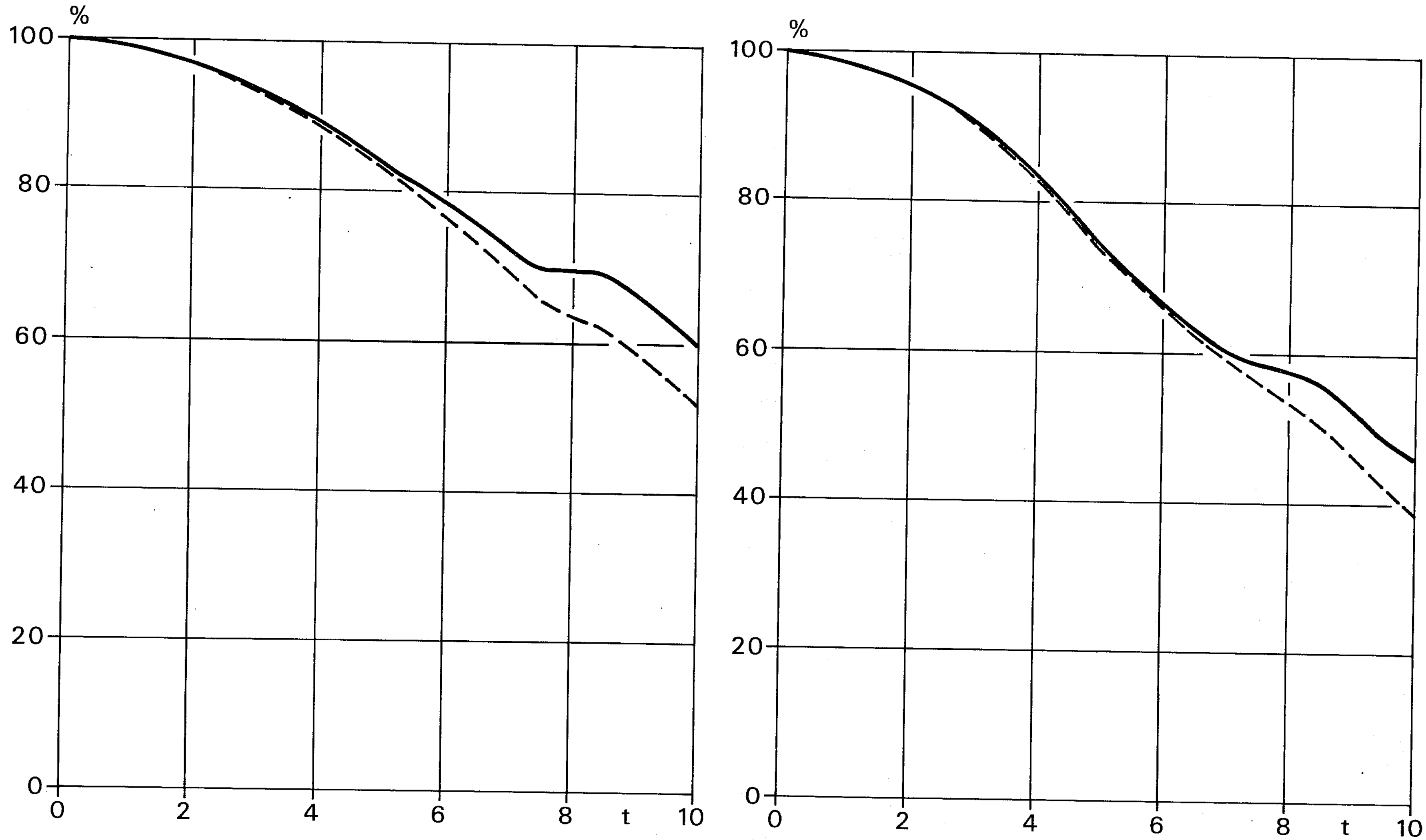

Fig. 3 Anomaly correlation of northern hemisphere height, averaged from 1000 to 200 hPa. Mean over 9 cases. Left for zonal wavenumber 1 to 3, right for total field. Solid lines denote 19 level results and dashed lines those for 16 levels.

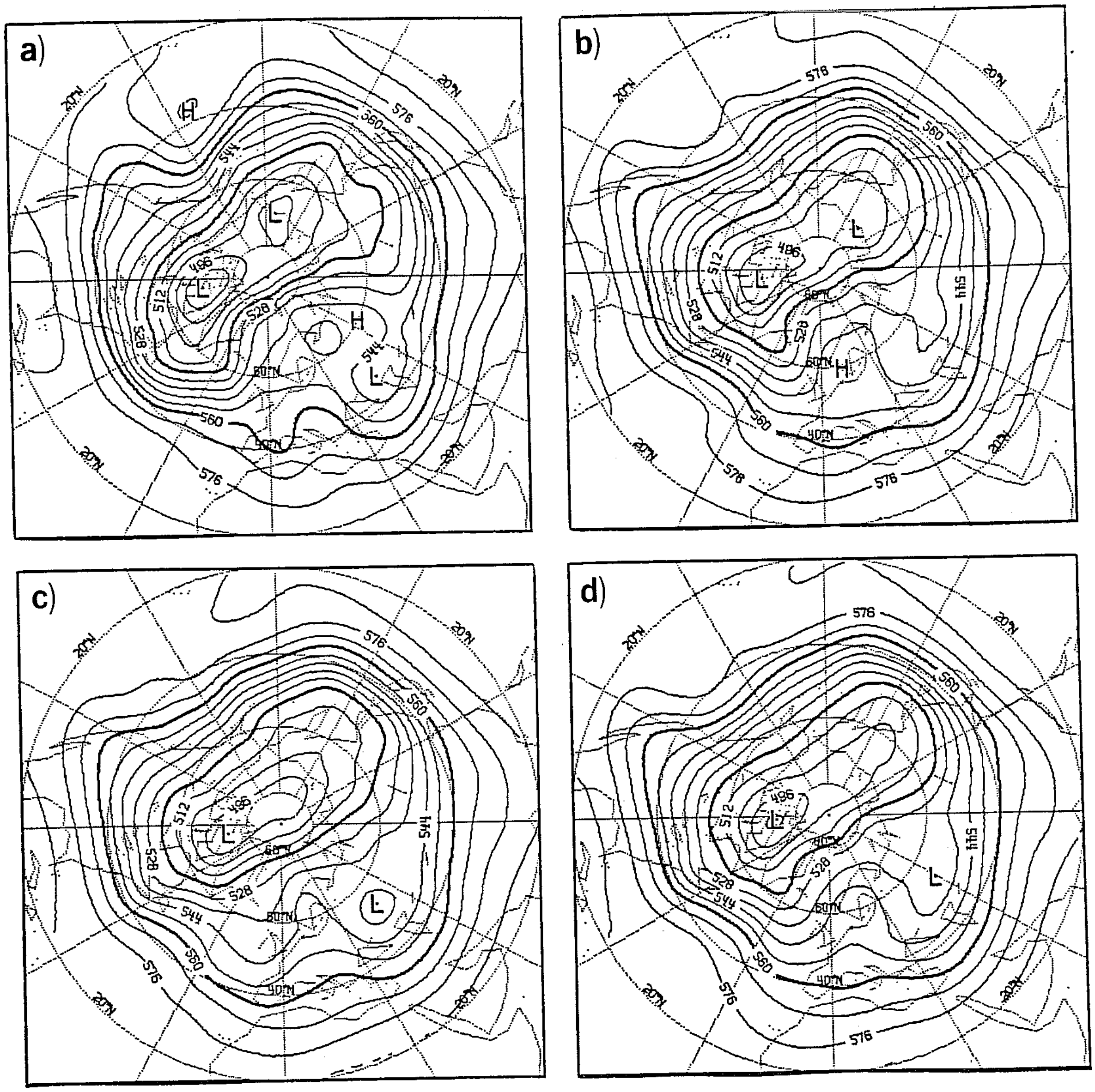

Fig. 4 Ensemble-mean 500 hPa heights for a) verifying analyses, b) 19 level D+10 forecasts from the 19 level assimilation, c) 16 level forecasts from the 16 level assimilation, d) 16 level forecasts from the 19 level assimilation.

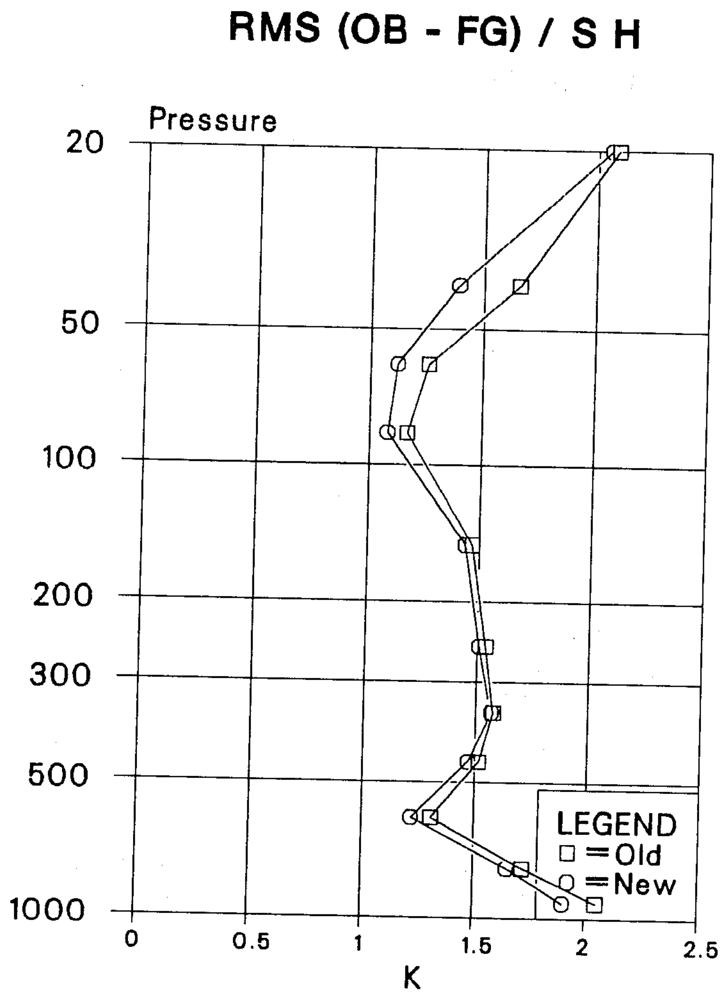

Fig. 5 Time mean (3.6.86 - 9.6.86 12 GMT) RMS fit of first guess to southern hemisphere satellite thickness data. Line with circles is for new analysis system, squares for old analysis. Unit: K.

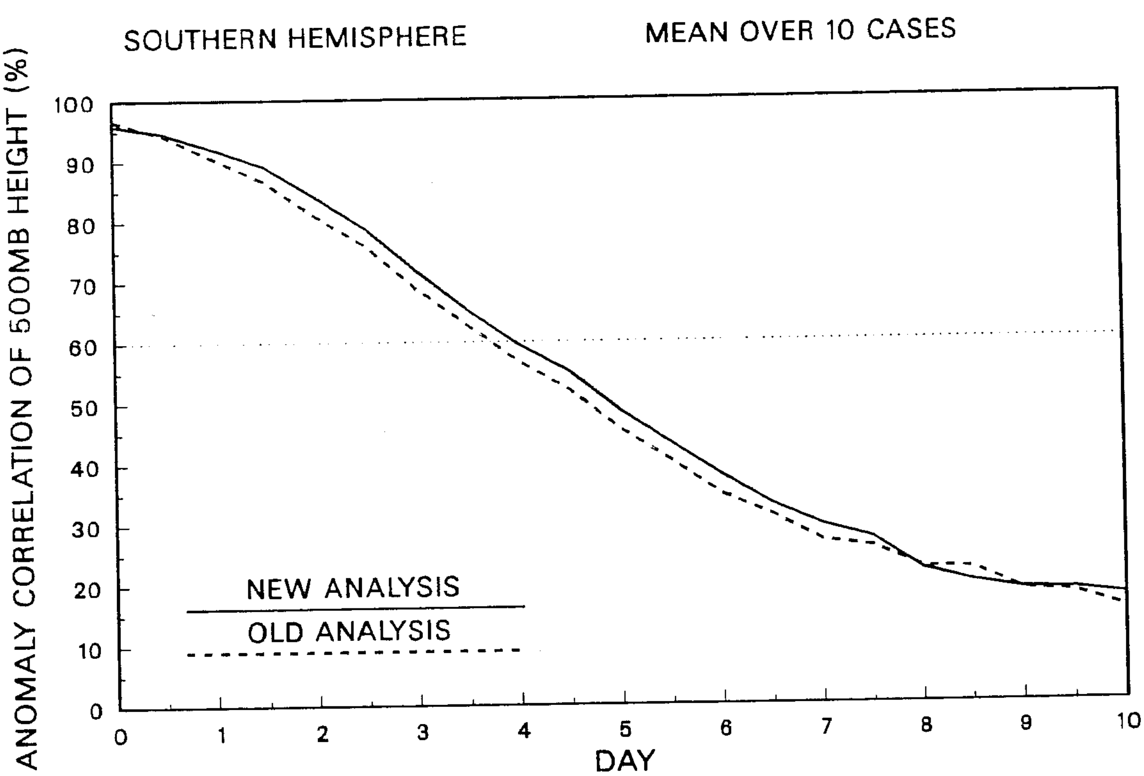

Fig. 6 Anomaly correlation of southern hemisphere 500 hPa height. Mean over 10 T63 cases. Solid line denotes results from new analysis system, dashed line from old analysis.

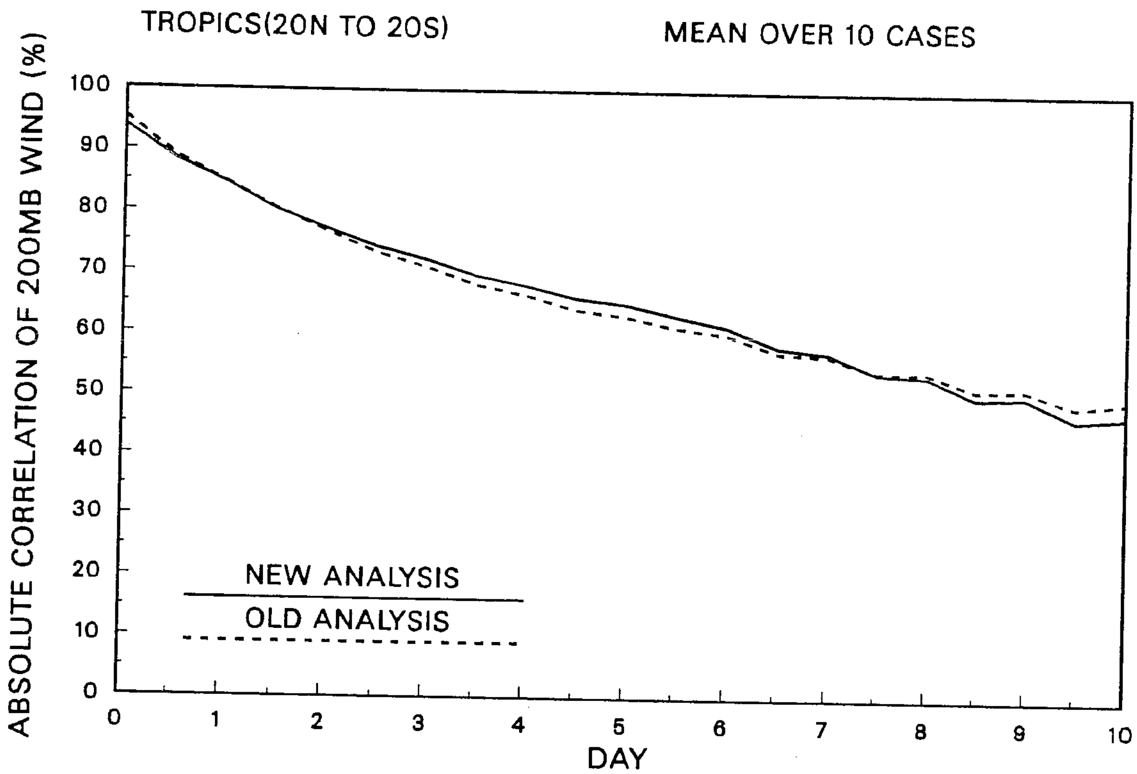

Fig. 7 Absolute correlation of tropical 200 hPa wind. Mean over 10 T63 cases. Solid line denotes results from new analysis, dashed line from old system.