INTRODUCTION

ECMWF has, over the years, organised and benefitted from a series of workshops covering a variety of aspects of its operational and research activities. The discussions during these workshops have had a substantial effect on the activity of ECMWF in many of the areas which have been taken as topics. This is readily apparent in even a casual comparison of workshop proceedings with forecasting system changes; the best correlation is found with a lag of three years, or thereabouts.

The topic for this workshop, high resolution analysis, was chosen because of likely developments in the area of analysis and assimilation resulting from the more powerful computers that will be available towards the end of the decade. Increased computational power will enable the exploitation of ideas that have been pipe-dreams up to now. In addition, some radically new approaches to the analysis/assimilation problem are outlined in the following pages.

Because of the time scales on which the computer developments will occur, we have considered likely developments for the analysis/assimilation problem on a wide range of spatial scales. The discussions have therefore benefitted from a wide range of viewpoints.

In these proceedings there are reports from the three working groups which considered:

- use of satellite data
- short term developments
- development of new techniques

The first two working groups made specific recommendations about how to improve the use of satellite data and analysis techniques in the short term, whereas the third group concentrated on giving an overview of the new analysis techniques being developed which will bear fruit in the long term. The proceedings also contain all the papers presented at the workshop.

As always, we are indebted to our visitors for contributing so generously of their time and energy to both the formal and informal sessions of the workshop. We hope that they may have profited from a lively and stimulating meeting.

USE OF SATELLITE DATA

1. CURRENT USE OF OPERATIONAL NESDIS SOUNDINGS

The current SATEMS from NESDIS provide thickness data between a reference level (usually 1000 mb) and other standard levels; in addition precipitable water content (PWC) is available in 3 layers (usually 1000/700, 700/500, 500/300). A variety of methods are used in different meteorological centres to make use of thickness data, but PWC is almost unused operationally. A comparison between the error statistics used in different centres (WMO questionnaire) shows large differences in the assigned observation errors.

At ECMWF, adjacent thin layers are used in the optimum interpolation (OI) scheme, but studies are underway to review the specification of the satellite thickness boundaries. Further statistics are needed for thickness increments, and these have been rederived recently at ECMWF [Kelly, those proceedings].

Up to now the 250 km SATEMS have shown only a very small impact on the ECMWF analysis system, compared to the 500 km SATEMS. This may be due to there being a mismatch between the horizontal resolution in satellite data, the vertical resolution and the shape of the structure functions used in the analysis. All these aspects must be examined carefully.

2. USE OF RADIANCE DATA

2.1 Comparison of various statistics of physical retrievals

Research into physical retrieval methods is being conducted at a number of centres. For example, ECMWF, the UK Met Office, GLAS and Wisconsin are investigating the use of a model forecast as background to the retrieval process, whilst LMD is developing a scheme which selects a first guess by pattern recognition of the cloud-cleared radiances.

It is desirable that there is a statistical evaluation of the impact of each of these retrieval systems on ECMWF's analysis/forecast system, using tools developed at the Centre. This should be done in 3 stages:

(i) a comparison of the retrieval data with an analysis made without using the data;

(ii) a comparison of analyses made with and without using the data;

(iii) a comparison of forecasts generated from analyses made with and without the data.

This study would require the above centres to provide the retrieval data in a common (FGGE IIb) format as well as information on the horizontal and vertical structure of the retrieval errors.

2.2 <u>Comparison of radiance statistics</u>

If satellite radiances are used directly in an analysis scheme or are used by a physical retrieval method, then an accurate knowledge of radiance observational errors is required. These quantities may have to be determined regionally and seasonally. In order to monitor this, the TOVS study group has recommended to WMO that a special baseline network of radiosonde stations be set up and that radiosondes be launched at the time of the satellite overpass.

The French Peridot fine mesh system (30 km grid) uses satellite radiance observations for its multivariate optimum interpolation analysis. The system should provide information concerning the horizontal scale of the satellite radiances and how this varies with the channel. This is an important consideration in the design of the new ECMWF analysis system.

So far the Peridot system has produced about 50 cases of analyses and forecasts with and without radiances. These sets of fields could provide experimental statistics about the structure of radiance, temperature, geopotential, humidity and wind. The results could be directly compared with the previously computed statistics.

2.3 Real time availability of special data

ECMWF should investigate the availability of high resolution SATEM data. Such data could be used as partial back up for the global data provided by NESDIS, especially if an early cut-off time is required, and VAS data could provide additional information for the Centre's analysis system, particularly over the Pacific Ocean.

3. USE OF OTHER SATELLITE DATA

3.1 Cloud and moisture data

A statistical evaluation of the quality of the humidity analysis at ECMWF has shown that humidity data, such as radiosonde data and TIROS-N PWC data, are of roughly comparable quality and that the variance of the difference is very close to the climatological variance [Illari]. This points to the importance of measuring and closely analysing a quantity such as moisture which is highly variable in space and time. ECMWF should try to use the moisture data from measured radiances as well as the large variety of other information available, and assess the impact of each type of data in its operational system. In particular, humidity bogus observations from satellite cloud imagery, such as those produced at NESDIS and JMA, could prove to be very useful. The use of Meteosat moisture data, which are currently provided, should also be investigated.

Cloud imagery can provide a variety of information which could be used as input to the physical processes represented in a model, such as cloud cover (which could be used for the analysis of clouds), albedo, and convective activity (e.g. GMS convective index).

3.2 Cloud winds

If cloud winds could be produced with a 3 or 6 hourly cycle using automated quality control, the data could provide additional information to the ECMWF assimilation system.

4. RECOMMENDATIONS

(a) Action is required to obtain high resolution satellite data, and to modify the current ECMWF system to provide monitoring statistics. ECMWF should assist WMO in monitoring the baseline satellite radiosonde network which will provide radiosonde flights at asynoptic times.

(b) There is a need for producers of satellite soundings to provide statistics on the correlated error in their retrieval if the data are to be used correctly in an OI system. Since satellite radiance data are used either directly or in a physical inversion method, the profile producer must provide software for both synthetic radiance calculations and for estimates of the error structure of both the measurements and the synthetic calculations.

(c) Further work is required with the current ECMWF operational system to determine whether the 250 km TOVS improve the current system compared with the previous 500 km resolution.

(d) If radiances are used directly or if a physical inversion method is used in the ECMWF operational system, then improved estimates (i.e. analyses) of surface parameters are required. There are further problems in calculating radiances due to the lack of vertical resolution. More vertical resolution is required in both the analysis and forecast in order to improve the quality of the retrieved data.

(e) Collaboration with other groups using satellite data is important in determining the horizontal structure of the errors of the satellite data.

(f) Further investigation is required to study other satellite products such as water vapour profiles obtained by cloud imagery, and also both cloud and albedo data.

SHORT TERM DEVELOPMENTS

1. OBSERVATIONS AND THEIR REPRESENTATIVENESS

Global data assimilation systems have generally been regarded as efficient filters of instrumental noise and small scale atmospheric features. As we increase the resolution of our analysis, we reduce the redundancy in the observations and run the risk of aliasing noise onto the local analysis fields. This problem can be approached in different ways; small scale motion can be removed from the observations, or the background field may be improved by general developments of the parameterisation schemes as well as by local diagnosis of sub-grid scale processes at the observation sites.

1.1 Observation representativeness

The usefulness of an observation depends not only on the measurement accuracy but also on the context within which it is used. Therefore an investigation of the four-dimensional representativeness of different observation types in the current and envisaged future assimilation systems is required. In particular, there is a need to study the following aspects:

- representativeness of single level observations (such as surface and aircraft winds), and certain surface observations (such as current weather and clouds);

- potential benefits from using the background field valid at the time of the observation;

- impact of using radiosonde information in their proper 4-dimensional position;

- errors arising from the mismatch between model orography and reality;

- the relative usefulness of wind and mass data for meso-α scale assimilation (grid resolution 100 km).

1.2 Observation filtering

Different techniques are available to estimate the large scale motion from surface or near-surface observations. One and two-dimensional physical models of varying sophistication as well as statistical models ("inverted" MOS) can be used to derive the synoptic scale flow. For example, a technique to increase the representativeness of 10 m wind observations is being developed at KNMI. For some parameters such as humidity it is probably sufficient to average observations in order to filter local features [DiMego].

1.3 Improved background field

Ideally, the background field should represent the same small-scale structures as the observations. Under such conditions, the difference between observation and background could be regarded as a real signal to be analysed and need not be filtered or modified. There are different ways to achieve this:

- improved physical parameterisation of sub-grid scale processes in the forecast model;

- modification of model fields by dynamical or statistical schemes to model small-scale features, e.g. by the use of sub-grid scale terrain;

- improved initial state, in particular a better moisture field and a more realistic description of surface and boundary layer parameters to reduce spin-up time and errors in radiance calculations.

2. TECHNIQUES FOR HIGH RESOLUTION ANALYSIS

Although the accuracy of the short-range forecast of mass and wind in data rich regions is similar to the observation accuracy, there are still gains to be made from fully exploiting recent work on the theoretical aspects of statistical interpolation. Consequently it is foreseen that statistical interpolation will, at least for the next 4-5 years, produce analyses which are of similar or higher accuracy than those from the successive correction method, Kalman filtering or generalised splines.

The short terms efforts in refining techniques for high resolution analysis should concentrate on the aspects outlined in Sections 2.1 to 2.6.

2.1 Improved representation of forecast error covariances

It has been shown that there is significant local variability in the forecast errors which is important for high resolution analysis [Gustafsson]. Consequently efforts need to be devoted to investigating the following aspects of forecast error statistics:

- data density, region and terrain dependence;
- flow dependence with respect to amplitude, scale length, and unstable modes;
- scale dependence of height-stremfunction coupling;
- anisotropy and tilt.

2.2 Analysis of divergent wind

The planetary-scale divergent wind field is reasonably well analysed by the current assimilation system. However, it is felt that considerable improvements are possible, in particular in the representation of detailed divergent motion in the tropics. The following studies would therefore be of benefit:

- to test the sensitivity to divergent structure functions of the OI scheme;
- to determine the spectrum of the error in the divergent wind for tropical regions;
- to study the impact on the initialisation of divergent structure functions;
- to define an algorithm to estimate the divergence field from cloud information and devise a technique to use it either in a statistical interpolation scheme or in between OI and initialisation.

2.3 Humidity analysis

As the assimilation system moves to the lower end of the meso-α scales the initial humidity field becomes more important. Efforts need to be made to explore more fully the use of satellite moisture observations, to document regionally and seasonally varying regression coefficients between cloud or weather information and relative humidity, and to examine flow and stability dependent humidity structure functions.

2.4 Vertical coordinates and resolution

It has been recognised that isentropic coordinates would improve the representation of inversions, fronts and the tropopause [Reimer]. However, its applicability for tropical analysis still needs to be investigated. Since the usefulness of isentropic coordinates for extratropical humidity has been demonstrated, thought needs to be given to its use in humidity analysis schemes.

An increased vertical resolution of the assimilation system, in particular near the tropopause, is expected to improve the accuracy of short-range forecasts. It would also reduce the errors in the radiance calculations, which in turn may improve the horizontal resolution of satellite radiance information.

2.5 Quality control algorithms

A vital component of a high resolution analysis system is an efficient quality control scheme. The standard OI data checking has been recognised as a powerful method of identifying observations with random, normally distributed observation errors. The ECMWF Workshop on the Use and Quality Control of Meteorological Observations, 6-9 November 1984, made relevant recommendations. The knowledge of data quality should be exploited in full, for example with Bayesian type data checking.

2.6 Data assimilation frequency

Further work needs to be carried out to determine the optimal data assimilation frequency as a function of analysis resolution.

3. RECOMMENDATIONS

(a) The four-dimensional representativeness of different observation types in data assimulation systems should be studied.

(b) Further investigations of ways to estimate synoptic-scale motion from surface or near-surface observations are required.

(c) In the context of optimum interpolation the following topics require investigation:

- representation of forecast error covariances
- analysis of the divergent wind
- analysis of humidity
- improved vertical resolution and the use of isentropic co-ordinates
- quality control algorithms
- data assimilation frequency

DEVELOPMENT OF NEW TECHNIQUES

1. OBJECTIVES AND TIME-SCALES FOR HIGH RESOLUTION (80-100km) ANALYSIS

It is envisaged that within the next 10 years it will be possible to run operational global models with equivalent grid-point resolution of 80-100km. The main objective of the work on analysis is to provide initial states which will lead to the best possible forecasts with these models.

Within the next year ECMWF will implement a re-coded flexible analysis system which will be able to exploit high resolution data where it is available, and to optimise the use of all available data. The full exploitation of these developments will take several years, but return for the effort invested is almost guaranteed.

2. AREAS FOR FUTURE RESEARCH

To initialise high resolution models using observations of lower spatial resolution, it will be necessary to use knowledge of coherent structures (e.g. fronts) which might occur. Predictability studies have shown that high resolution models can generate the smaller scale details of such features from external and larger scale forcing. The analysis needs to use this ability (which is essentially non-linear), by using these models as an integral part of the assimilation process. This also enables the lack of spatial observational resolution to be compensated by the higher temporal resolution of many satellite observing systems. The ability to correct a wrong forecast while preserving non-linear coherent structures would be most useful.

A second area of research concerns the analysis of the planetary scales. Current methods correct a possible error on these scales only where data are available, but revert to the first guess in data voids. However, if the errors are large scale they need to be corrected globally, including the data sparse areas. The extension of the analysis methods to four dimensions might offer a way to exploit the time history in order to get a correct analysis of the planetary scales.

A further area where research is underway, but where the likely outcome is unclear, is in the spin-up problem. This is partly a problem of the parameterisation scheme and partly a problem of the assimilation system. Present plans call for improvements in the physics, and for the exploitation of currently unused satellite data to improve the initial specification of convection and radiation.

3. VARIATIONAL ANALYSIS METHODS

Bayesian, minimum variance, and variational approaches all result in similar analysis equations, which can be solved using methods known in various fields as universal kriging, generalised spline, optimum interpolation, Kalman-Bucy filtering, and variational analysis.

The establishment of these links may mean that results established in one area can be generalised to others. A question of considerable interest concerns the accuracy with which the OI statistics need to be known. There are results from Matheron's work in geostatistics which suggest that, within reasonable bounds, the statistics used in universal kriging are not too important, as long as the method is correctly formulated. We suspect that multivariate OI may be more stringent in its requirements. Attempts to clarify these questions are clearly needed.

4. ADJOINT METHODS AND 4-D ANALYSIS

All variational methods require the definition of a distance function or cost function, and also a practical method of determining the first order variation of the distance function. The use of adjoints of the relevant operator can be extremely useful in this respect. These aspects were demonstrated in the work on satellite temperature retrievals for a one-dimensional problem, and particularly for the four-dimensional problems considered by Talagrand and Courtier. Their work has implications which extend far beyond the data assimilation problem, but this is the only application discussed here.

Talagrand and Courtier provide a theoretical framework in which the initial state of a forecast model can be adjusted so that the differences between the forecast evolution and the observations is minimised over some arbitrary period such as 24 or 48 hours. In a way this is the culmination of long standing efforts to find an effective mathematical representation of the ideas underlying forward-backward assimilation.

The area they have opened up is so extensive that a great deal of exploratory work needs to be done. Linear aspects of the theory need to be examined, and related to Kalman-Bucy filters. The sensitivity to errors in observations, to errors in model formulation and to flow instabilities also needs study. The possibility of including non-differentiable processes such as moist processes into the method still needs to be explored. Economical approximate versions of the method may be possible, and this area too needs exploration.

The methods these authors have developed may be of value in treating the problems discussed above, as well as many others. The exploitation of the time history in an explicit way may offer a means of propagating features backwards into data sparse areas, and exploiting asynoptic data in an optimal way. At this point it is not clear if serious aliasing problems can arise due to observational or model deficiencies.

The method may be of value in reducing the spin-up problem. It will also provide a more rigorous method of diagnosing those aspects of the initial state which contributed to a particular forecast problem as originally envisaged by Marchuk.

5. DIAGNOSTIC WORK ON ANALYSES AND FORECASTS

Much research needs to be done to further clarify the short-comings of existing analysis systems. Statistical study of the observation minus analysis differences offers a useful technique for doing just that in three dimensions. It has already been useful in documenting problems in the analysis of the tropical large-scale wind field, and in synoptic scale analysis in mid-latitudes. Future applications include detailed study of the mass-wind balance of the analyses. Methods need to be developed to study the four-dimensional accuracy and continuity of the analyses. Present methods essentially use the forecast fields to measure the time-continuity of the analyses. It may be worthwhile to examine the statistical structure of the observation minus forecast fields for longer ranges than 6-hours to study the changes in internal balance of the analyses and forecasts.