1. INTRODUCTION

The organization of symposia and workshops is a part of ECMWF's research activities. The following publication contains the proceedings of a workshop on Stochastic Dynamic Forecasting which was held at ECMWF, Shinfield Park, Reading from 17 to 19 October 1979. The first part of this publication gives a summary of the discussions held at the workshop while the second part contains most of the lectures which were given. The lecture given by A. Wiin-Nielsen "On the Asymptotic Behaviour of a Simple Stochastic-Dynamic System" can be found in Geophysical and Astrophysical Fluid Dynamics, 1979, 12, 295-311.

Preliminary estimates of the accuracy of the Centre's operational forecasts indicate that they give a directly applicable forecast for up to 3 or 4 days ahead, and useful guidance for up to 6 or 7 days. Beyond this time the forecasts do not, on the average, give obviously useful information. The forecast of the larger scales of motion appears generally to be of some significance for one or two days longer than that of the shorter, baroclinically-unstable waves.

This workshop has provided an opportunity to discuss research projects aimed at extending by statistical methods the provision of useful forecast information beyond the current average 6 - 7 day limit of deterministic forecasting. Three main approaches have been identified:

(i) Deterministic forecasts of the larger scale (or period) motion using a statistical representation of shorter scale (or period) phenomena.

(ii) Evaluation on a daily basis of confidence limits for the current, deterministic, operational forecasts.

(iii) Statistical correction of the model or forecast.

These are discussed more fully below.

2. FORECAST MODELS FOR LARGE-SCALE OR LONG-PERIOD MOTION

This approach requires the development of simpler forecast models containing only those components of the atmospheric state vector which are thought to be deterministically predictable over an extended period, the interactions with the remaining components then being suitably parameterized. Various such models, in particular for blocking situations, have already been proposed. The advantage of simpler models is that one can more easily generate the extended data base needed for model construction and statistically significant verification.

In particular a sufficiently simplified model could be tested against the already existing 12 - 14 years of continuous northern-hemispheric analysed data, and one would be able to establish with some confidence (within the framework of the model) the predictable components of the atmosphere and the statistical structure of the forcing function errors, and develop methods of improved parameterization.

A particular model which could be developed at the Centre would be one in which the largest scales of motion are explicitly forecast, but shorter scales are parameterized. The deterministic long-wave model may use a vertical resolution more suited to larger scales of motion, in particular an improved stratospheric representation to resolve the upward energy transport associated with long waves.

Such an approach has already received some attention from climate modellers. The prime research problem is to determine how to parameterize the interaction with the shorter scales. In addition to the data-based method outlined above, a second method is to design a physically-based model of short-wave behaviour. This approach is particularly suited to studies of climatic change, since the short-wave statistics may then change from those currently observed, but for the purpose of medium-range long-wave forecasting the data-based approach is perhaps more straightforward and more immediately useful.

A related technique is to filter the shorter time scales from the forecast model. Successful results have been reported based on filtering the barotropic Rossby modes in a two-level quasi-geostrophic atmospheric model coupled to a simple ocean model. Some parameterization of shorter period motion may be required in this case.

3. CONFIDENCE LIMITS FOR DETERMINISTIC FORECASTS

The Centre's present forecasts would be of more use to the operational forecaster if confidence limits on individual forecasts could be presented. This would enable the forecaster to utilize, on occasions, information at times close to the average limit of forecast skill. Several approaches have been considered.

The first is use of stochastic-dynamic forecast equations in order to forecast the variance as well as the mean. This, however, requires a major computational effort for even a relatively simple model, and appears practically impossible for a forecast model capable of providing useful synoptic information for the period of interest.

The second is use of a Monte Carlo procedure. Such procedures have been applied to data primarily to study the sensitivity and stability of forecasts with respect to variations in the initial conditions. The results of some of these experiments suggest that in fact the errors in the forcing functions (e.g. physical parameterizations) may represent a larger source of prediction uncertainty than errors in the initial state. It would, therefore, be useful to determine empirically the statistical space-time structure of these forcing function errors (from the time series of the difference between observed and predicted rates of change of the atmospheric state vector) in order to run a sequence of Monte Carlo simulations in which these errors were simulated, with the correct statistical structure, as additional forcing terms. In a sense this problem is easier to handle than the case of initial value errors as the statistical structure of the forcing function errors can be determined empirically without additional assumptions.

In order to obtain a confidence limit within 10% of the true limit about 100 samples would be required for a Monte Carlo simulation. To make this realisable operationally a particularly fast model (or smaller sample) would be needed, but as an initial research project a model intermediate in timing between an ideally fast model and the current deterministic model could be used. This model would have a reduced horizontal and vertical resolution, for example spectral triangular 30 truncation and five vertical levels. An efficient parameterization scheme appropriate to this resolution would have to be developed. This would be a major project since in addition a large number of forecasts would need to be performed in order to determine forecast error statistics prior to commencement of Monte Carlo forecasting. An alternative, perhaps more efficient, vertical representation for the fast model would be an expansion in empirical orthogonal functions, but this would require further model development. As a by-product, the resulting fast model could also be useful for a number of other investigations, such as response studies to variations in ice and sea-surface temperatures.

It may also be possible to make use of the internal error growth mechanism in making assessments of the relative confidence of model predictions on a regional basis. This can be investigated by carrying out a forecast with a high resolution model, followed by a sample of forecasts with the fast model. The variance of this forecast sample could be calculated in physical space and normalized by its maximum values. There would result a map of relative forecast uncertainty.

Experience with such an approach would permit the comparison of relative forecast uncertainty with the actual forecast error. A correlation between these two quantities, if it were found to exist, could be utilised in refining future estimates of forecast uncertainty. There is no guarantee that such an approach would be useful, but it is at least worth exploring.

Further work is needed on the generation of the sample of initial states so that the meteorological modes are perturbed in a self-consistent fashion, and the perturbations are not rejected by the initialization procedure. Perturbing the vorticity field, then deriving the corresponding height field, should achieve the desired result of maintaining the structure of the vorticity field while ensuring that the perturbations were entered primarily in the meteorological modes. This might do less violence than other methods to the correlation structure of the atmosphere through perturbing a highly differentiated quantity.

A different way of using Monte Carlo methods would be to make several high-resolution forecasts for 6 or 12 hours, then choosing by some methods (perhaps comparing with observations) the best of these forecasts and continue this one for 10 days. This would be useful only if it could be shown that the best forecast in the beginning stays the best for the whole period of 7 or 10 days. This method could be used also in an analysis cycle.

Finally, two much cheaper approaches (a poor man's Monte Carlo) merit attention. The first method would be to try to exploit the many successive forecasts issued by the Centre. For example if we consider the weather 5 days hence then we have six different forecasts verifying on that day, namely the 5 day, 6 day....10 day forecasts. Experience shows that the forecasts for a particular day may be very consistent with each other or very different. The spread of forecasts and the available verified skill for each forecast can then be used as an index of confidence and is indeed used already in a subjective way by the synopticians.

The second way to explit readily available data is to compare forecasts from different institutes. If the forecast/analysis systems in use at the different Centres have comparable performance then calculations of the mean and variance of these forecasts should be of considerable interest. Each Centre has, after all, made its best attempt at the analysis and forecast. This comparison is done subjectively at most Forecast Centres. Data from many Centres is being collected this year at the Finnish Meteorological Institute. An investigation along these lines would seem to be worthwhile

4. STATISTICAL CORRECTION OF FORECASTS

A systematic analysis of model errors is needed in order to suggest areas for model improvement. There should also be developed a systematic procedure for testing the statistical significance of any apparent benefit from modifications to the physics or numerics of a model. Such a procedure will require knowledge of the space/ time statistical properties of the error field. Some of this information is also needed for the improvement of the statistics used in the analysis suite. Such work is already in progress.

The above studies may also be used to correct statistically the quality of the forecasts by

(i) Modifying the model-produced forecast by the mean error of a large sample of forecasts

(ii) Modifying the model by a stochastic forcing dependent on the error structure of individual forecasts.

The first approach would lead to a reduction of RMS errors, but whether or not this procedure would lead to improvement of model result usage remains to be investigated. The record would make it difficult to learn more about model deficiencies.

For practical application the use of MOS regression is recommended as the best approach in this context. It should predict not intermediate information such as the height field, but rather the final "weather" variables such as minimum temperature or probability of precipitation. Information is lost in two step regression with an intermediate variable.

5. EXTENDED RANGE PREDICTION

For extended range prediction the response of the atmosphere to changes in the boundary conditions (sea-surface temperature, ice and snow extent) is a key question. Traditional treatments have involved running extended period response experiments with high resolution GCM's. However, most investigations of this nature have faced serious signal-to-noise problems because of the inherent natural variability of the model atmosphere.

A satisfactory treatment of the signal-to-noise problem requires

a) a knowledge of the space/time covariance structure of the natural model variability and

b) a first guess of the expected response, as provided, for example, by a model of a quite different (probably simple) type.

Both of these requirements could be readily met using models and model statistics which were developed independently for stochastic modelling investigations in the framework of medium range weather prediction.

6. CONCLUSIONS

The value of Monte Carlo methods for estimating forecast reliability requires that the rate of internal error growth be close to the rate of forecast error growth. To achieve this the major effort must continue to be directed towards the improvement of deterministic forecasts. Monte Carlo forecasts are unlikely to be useful until this is achieved.

The continuing accumulation of statistics of forecasts errors and of short/long-wave interactions is clearly potentially useful for the studies discussed in preceding sections. New studies which may usefully be started in the near future are

(i) Development of the simpler, fast model.

(ii) Evaluation of this fast model's capability of distinguishing initial states for which the deterministic operational model gives particularly good or bad forecasts.

(iii) Evaluation of the reliability of the 12 hour operational forecast as an indicator of a good or bad medium-range forecast.