FORECASTING FORECAST SKILL

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ABSTRACT

This paper is written in support of the thesis that no forecast is complete without a forecast of forecast skill. The time has come to make skill forecasting one of the central goals of predictability research. In this paper we review the state of the art of skill forecasting and we discuss predictability research in The Netherlands. The state of the art is represented by the lagged-averages method proposed by Hoffman and Kalnay. This method may not improve average forecast quality much, but it does provide a self-consistent scheme for producing skill forecasts. The way in which the difference between successive computer runs increases is representative of the most unstable atmospheric components; even with a sample size of only two a reasonably good skill forecast seems possible. Predictability research in The Netherlands concentrates on the study of the temporal and spatial variability of atmospheric instabilities. Predictability ought to be treated as a forecast variable, calculated by a subroutine much as cumulative precipitation is now. Our research on atmospheric instabilities indicates that, in principle at least, this is not an impossible task. Predictability research offers many exciting challenges, which are obviously worth pursuing in collaboration between ECMWF and Member States.

1. INTRODUCTION

The tremendous success of the forecasts produced by ECMWF tends to obscure the fact that the predictability of the atmospheric circulation will always be poor towards the end of the forecast range, no matter how much that range can be extended. Perfect forecasts valid for indefinitely long intervals are theoretically impossible. The predictability of the atmospheric circulation is limited in principle; the issue of predicting forecast skill, therefore, will not disappear by improving the average performance of numerical models. Predictability, seen as a potential forecast variable, is a legitimate object of meteorological research.

It has become customary to define the performance of numerical models of the atmospheric circulation in terms of global error climatology. No differentiation in time or geographical position is made, and no attempt is made to link the day-to-day performance to the error statistics. Obviously, it is necessary to determine the average track record of a model. But there is more to predictability than globally and seasonally averaged error growth, just as there is more to meteorology than the compilation of climate records. We feel it is inconsistent to deal with forecast skill as a climatological variable. It should be estimated on the spot, not compiled after the fact.

In this paper we are concerned with the anticipated performance of today's computer run. The daily fluctuations in predictability for any region on this planet are so large that the climatology of forecast errors often does not give a reliable indication of what we can expect from the model today. Again, in brief: forecast skill ought to be treated as one of the major forecast variables.

To a not insignificant extent, this is a question of credibility. The increasing sophistication of our professional customers makes it harder and harder to maintain our professional reputation. Our clients discover time and again that medium-range forecasts suffer significant changes from one day to the next. Everybody knows that weather forecasts are based on high technology, supported by weather satellites and the biggest number crunchers money can buy. Nevertheless, often enough a medium-range forecast is not consistent with the one issued the day before. Do we really want the public to become as cynical about weather forecasts as many of us are about economic forecasts? Can we provide the public with useful and objective information on the reliability of our products? Can we deal with the inherent limitations of predictability in a mature, sound and scientific way?

Can it be done? There is only a little bit of scientific evidence suggesting that low-cost skill forecasts of acceptable quality are possible (more about that in a moment), but there is a substantial amount of subjective synoptic experience on the subject. Many forecasters believe there is a relation between predictability and circulation type. A blocking situation, for example, is thought to allow better-than-average forecast quality. Forecasters also tend to relate model deficiencies and circulation patterns. It is not uncommon to hear a forecaster state that, with the jet in such-and-such a position, cyclogenesis in the ECMWF-model is a bit too strong, but in the Offenbach model (for example) somewhat too slow. In that way, predictability is linked to subjective assessments of systematic model errors, classified according to circulation type.

Privately, many forecasters make subjective forecasts of the skill of their predictions, and an unusually insistent customer may obtain an explicit statement on the anticipated reliability of the forecast. In most cases, however, this information is not made available to the public. A variety of reasons is given to defend this practice, ranging from the presumed risk of confusing the public to the absence of objective methods and standards in predicting forecast skill. We feel, however, that both subjective and objective information on forecast skill will be extremely useful to our customers, and that information of this type - in which we share with the public the limitations of our knowledge of atmospheric developments - will improve the credibility of our work tremendously. Indeed, television viewers in The Netherlands seem to enjoy the way in which our forecasters express their uncertainties about the vagaries of the weather.

If operational forecasters can make skill forecasts on the basis of their synoptic experience, science should be able to dig out the necessary theoretical foundations. In the next chapter, we review the lagged-averages forecasting method proposed by Hoffman and Kalnay (1983a). This method seems to form the beginning of scientific evidence in support of one kind of synoptic practice. In order to assess the probable reliability of today's computer run, forecasters tend to compare it with the computer products issued yesterday. If today's forecast for the circulation pattern four days ahead, for example, differs substantially from yesterday's forecast for what was then five days ahead, they ascribe a high probability of low skill to the current computer run. In fact this is a poor man's lagged-averages forecast, based on a sample consisting of only two members. Compared to the minimum sample size of eight suggested by Leith

(1975), this is very scanty statistical evidence indeed. As will be discussed in the next chapter, however, the research of Hoffman and Kalnay seems to support the idea that a sample consisting of two successive computer runs is sufficient to make an adequate skill forecast.

If further research were to substantiate these findings, we would have access to a powerful rule for skill forecasting, which would not require additional computer time. Such a rule might be phrased in the following terms: the effective forecast range of today's computer run ends when the difference with yesterday's run has become unacceptably large. Another version of this rule might be: in order to be reliable, the forecast issued today has to be consistent with the one issued yesterday. Rules of this type, of course, will never be infallible. We have to keep in mind that a skill forecast is unlikely to be more accurate than the forecast itself. Toward the end of the average forecast range, skill forecasts are bound to be rather poor, too.

One final issue needs to be raised. If synopticians are right in linking predictability to circulation type, it is not wise to aim at global predictions of forecast skill. If Hoffman and Kalnay are right in suggesting that the difference between two successive computer runs is a crude but effective indicator of forecast skill, it is easy to make geographically differentiated skill forecasts: one needs only look at the divergence in the region of interest. If a blocking high protects Western Europe, rapid divergence of successive forecasts over the Pacific is of no concern to European forecasters, as long as the computer continues to predict the survival of the blocking situation. Predictability is a local variable, and there is no evidence suggesting that it cannot be treated as such. On the contrary, there appears to be much promise of challenging, exciting and useful research here. A concerted effort between scientists at ECMWF and in the Member States would give us the lead in skill forecasting; we in The Netherlands hope that Europeans will rise to this occasion.

2. FORECASTING FORECAST SKILL IN PRACTICE

2.1 Introduction

Can we forecast today's forecast's skill? In this chapter we shall review the little work that has been done so far to answer this question. Our theoretical understanding of the problem increases rapidly but still at the level of fairly simple models. Therefore the answer must, for the time being, necessarily be based on synoptical and statistical studies of our present operational models. We can't provide a definite answer yet but the first results are promising. Moreover there is a lot of unexplored material, waiting for further study.

In the following we shall briefly discuss the different approaches to the problem, referring for more details and further material to the original publications. First we describe what little has been done on identifying the synoptic characteristics of variable forecast skill. Then we discuss the statistical-dynamic approach in its different forms.

2.2 The synoptics of variable forecast skill

Although operational medium range forecasting has been with us since 1979, not much is known yet about the synoptic characteristics of variable forecast skill. The only study known to us that adresses this problem is a paper by Grønaas (1982). During a two year period (1980 and 1981) he identified altogether 59 periods, ranging from 3 to 26 days, with a relatively high or a relatively low forecast quality over Europe. He then inspected these periods subjectively to find a dominant synoptic situation. He found that high day 5 and day 7 skill scores (in terms of anomaly correlation coefficients) are connected with blocking situations or persistent cut-off lows, whereas low day 5 and day 7 skill scores are characterized by a zonal mean flow in the Atlantic/European area. Grønaas attributes this to the fact that in zonal flow situations both the larger phase errors and the systematic errors of the model (negative anomalies over Europe), have a larger influence over the European area. This interpretation would mean that his results are a consequence of model errors only.

However, to us this seems only half the story. From observing system experiments (see f.e. Baede et al, 1985) we know that the middle and east Pacific may act as a source of downstream propagating and amplifying differences between forecasts, run from slightly different initial conditions. Such differences affect the European area after about five days. If the North Atlantic area is blocked however, these propagating difference waves will also be blocked. In that case the forecast skill over Europe will depend much less on the small scale initial differences over the Pacific, and much more on the atmosphere's local stability over Europe and the model's ability to maintain the block. This interpretation is supported by a result of Klinker and Hollingsworth (private communication, 1985) which suggests that in seasons characterized by zonal activity over the N.Atlantic there is a high correlation between cyclonic activity over the Pacific and forecast skill over Europe several days later. This correlation disappears in blocked seasons.

Further work along these lines is highly desirable. The work should be extended to other areas on the globe. A further, preferentially objective, stratification of the data according to circulation regime should be undertaken. The relation between the skill and the energetics of the flow, as suggested by the work of Roads (1985), should also be investigated. Special attention should be paid to identifying the geographic sources of forecasting errors, which then could perhaps be related to local stability properties of the large scale flow.

Once a better insight is obtained into the synoptic characteristics of forecast skill, an attempt could be made to develop MOS schemes to predict the forecast skill. No such attempt is known to us. Suggestions have been made however (Hollingsworth, priv. comm.; see also Lange, 1980) to use the statistical multivariate technique of canonical correlations for this purpose.

2.1 Statistical-dynamical methods

An a priori estimate of the forecast skill may in principle be obtained by solving the equations for the probability distributions of the atmospheric variables derived from the original dynamic equations. Of course the non-linearity of the problem poses a closure problem but sensible closure assumptions may be introduced. This method was developed by Epstein (1969). A review may be found in the contribution by Leith (1975) to the first ECMWF seminar. Operational application of the method, however, is hampered by the formidable computational effort required, even though computationally more efficient alternatives have been proposed (Thompson, 1985).

Viable alternatives to the stochastic dynamic approach are the ensemble forecast methods, whereby a forecast is replaced by a weighted average of an ensemble of forecasts and the skill of the forecast may be estimated from the spread of the ensemble. Leith (1974) proposed to select an ensemble of initial conditions by random perturbation of the best estimate of the state of the atmosphere, usually the result of an objective analysis scheme. This is called Monte Carlo Forecasting (MCF). He suggested that in the order of 8 ensemble members would be sufficient to obtain reliable estimates.

Apart from still being rather expensive, a problem with the method is the specification of the initial ensemble. This problem is avoided by the so-called Lagged Average Forecast (LAF) method, proposed by Hoffman and Kalnay (1983a). Again this is an ensemble method but now the N members of the ensemble are previous forecasts, based on initial conditions at $t = 0, -\tau, \ldots, -(N-1)\tau$.

These forecasts are available anyway if τ is selected properly (in the the ECMWF model τ should be taken as 24 hours). The two ways of selecting the members of the MCF and LAF ensembles are depicted in Fig. 1, which is adopted from Hoffman and Kalnay (1983a).

The paper by Hoffman and Kalnay contains an extensive intercomparison of different forecasting strategies, whereby the "nature" run is provided by a low resolution 2-layer PE f-plane spectral model, and whereby the forecasts are made by means of a quasi-geostrophic version of the model. Thus it is not an identical twin experiment. Both MCF and LAF ensembles consist of N=8 members and LAF ensemble members are selected at τ=6h intervals. They showed that ensemble forecasts at short and medium range ($t \leqslant 2$ weeks) are marginally better than ordinary dynamic forecasts. A tempered LAF strategy, whereby ensemble weighting factors are obtained by linear regression, produced the best results.

Much more interesting for our purpose however is their attempt to predict the forecast skill from the ensemble spread. Hoffman and Kalnay found that the ensemble spread S and the forecast error D are indeed related, be it

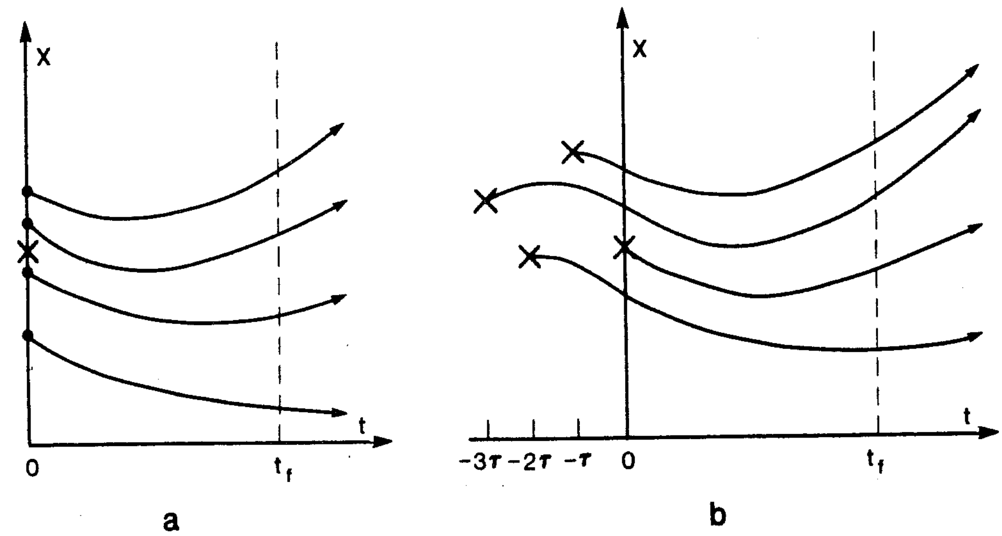


Fig. 1 Schematic time evolutions of the MCF (a) and LAF (b) ensembles. The abscissa is forecast time, t, and the ordinate is the amplitude of a model variable, x. x is observed (×) at intervals of time, τ; t_f is a particular forecast time. (Adopted from Hoffman and Kalnay, 1983a)

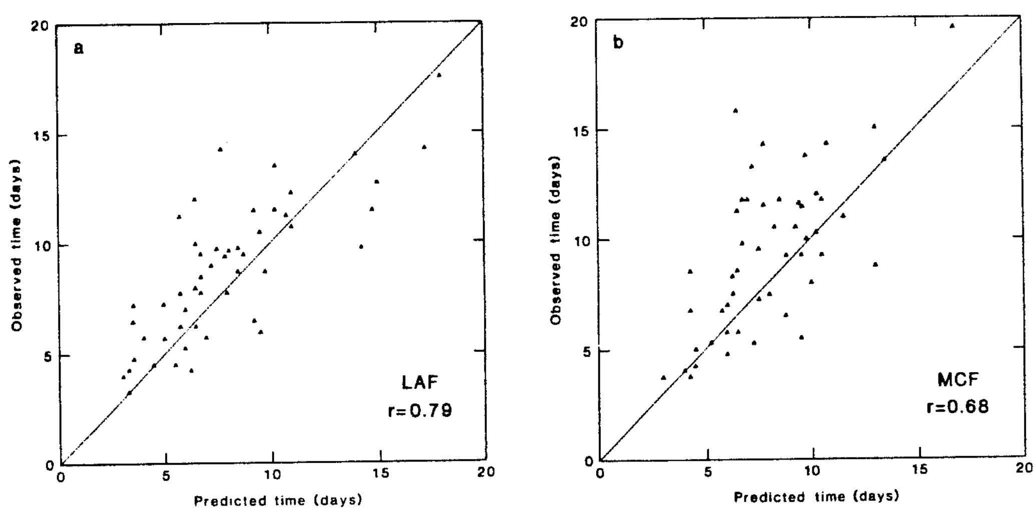


Fig. 2 Scatter plots of predicted versus observed time for the normalized forecast skill D to reach a value of 0.5 for the LAF (a) and the MCF (b) (Adopted from Hoffman and Kalnay, 1983a)

in a rather complicated manner due to the effect of model imperfections. Accounting for these imperfections by a regression analysis, they produced excellent forecast skill predictions. From Fig. 2 it is clear that LAF scores again marginally better than MCF. On an independent LAF sample the correlation coefficient was only slightly lower ($r=0.77$) whereas correlations $r=0.67$ (LAF) and $r=0.66$ (MCF) are obtained when the ensemble size is reduced to $N=4$ and the LAF interval is increased to τ = 12h. Hoffman and Kalnay claim that the marginal superiority of LAF, both in its actual forecast skill and in its ability to predict the forecast skill, is due to a better specification of the initial conditions.

This brings us to a discussion of the essential difference between MCF and LAF in specifying the initial ensemble. Adopting Lorenz' (1965) geometrical interpretation of the error growth in phase space, we assume that the initial random errors occupy an N-dimensional sphere within phase space around the point that represents the most probable initial state. During the initial linear growth of the error the spherical surface will be deformed into an ellipsoid, the semi-axes of which are determined by the eigenvalues of the matrix representing the linear error growth equations. The reliability of a forecast will depend mainly on the largest semi-axis i.e. on the elongation of the ellipsoid. The more elongated the shape, the larger the mean square distance to the centre of the ellipsoid, the less reliable the forecast. The MCF initial ensemble is selected at random and thus should be an unbiased sample of the initial spherical error distribution. On the contrary the LAF initial ensemble is biased towards a selection of those error modes that have the largest growth. This is because the model has had a time $n.\tau$ to excite the fastest growing error mode and to develop the errors according to their individual growth rates. Therefore, if the error growth properties of the atmosphere are persistent over the period from which LAF ensemble members are selected, the initial LAF ensemble will be biased towards those errors that have the largest error growth. An estimate of the ensemble spread, therefore, will be biased towards the longest semi-axes of the error ellipsoid. This suggests that LAF requires fewer ensemble members for a reliable estimate of the forecast skill. This argument does not explain however why LAF leads to better ensemble forecasts.

In a subsequent paper by Hoffman and Kalnay (1983b) they argue that an ensemble size as small as 2 would perhaps be sufficient because any error field will have some projection on the fastest growing mode, an argument consistent with this discussion. The intuition of our forecasters may not be too bad after all! At least it is worth trying, and a very simple strategy to see what the difference between two subsequent forecasts can tell us about the forecast quality of the most recent one.

An operational implementation of the LAF method is not straightforward. The regression analysis to compute the ensemble weighting factors requires the computation of many covariances from a limited sample. If no precautions are taken this could lead to unstable statistics. This problem is investigated by Hoffman, Kalnay and Dalcher in a series of subsequent papers (Hoffman and Kalnay, 1983b; Kalnay and Dalcher, 1985; Dalcher, Kalnay and Hoffman, 1985). The way they propose to circumvent this problem is to reduce the number of degrees of freedom by carefully modelling the required statistics in terms of a small number of parameters and then estimating these parameters from the data. In particular the error growth in the operational ECMWF forecasts is examined in detail (Kalnay and Dalcher, 1985) leading to a very simple model for the error variance growth which takes into account the effect of an external source of error growth representing model deficiencies.

Although the emphasis of their work is on LAF as a forecasting method, similar problems may be expected when trying to use LAF as a method to predict forecast skill.

With this solution to the degrees-of-freedom problem, Dalcher et al. (1985) apply the LAF method to the ECMWF operational forecasts. They take N=6 ensemble members with a τ = 24 h time lag between the individual members. They claim that the LAF forecasts show a marked improvement upon the operational 5-day forecasts, not just due to the pull towards climatology but because the 6-10 day forecasts do contribute independent information. Their first attempt to predict the forecast skill is less satisfactory. Fig. 3, adopted from their paper, contains a scatter plot and a regression line of the global 5-day forecast error (vertical) versus the global difference between the 5-day forecast and the LAF forecast (horizontal). This last quantity is a measure of the extent to which the 6-10 day forecasts deviate from the 5-day forecast and thus a somewhat inaccurate measure of the ensemble spread. One of the problems may be the fact that the method is applied globally. Variable forecast skill is a regional phenomenon, depending on the local stability properties of the large scale flow and on the regional properties of data density and corresponding initial errors. Geographic differentiation of the results is therefore very desirable. A better insight into the synoptic characteristics of variable forecast skill and into the geographic distribution of error sources could give clues as to how best to specify the regions.

Notwithstanding the large amount of work that remains to be done, Hoffman, Kalnay and Dalcher have shown that LAF is a promising technique for predicting forecast skill. The 24 h time lag, imposed by ECMWF's operational schedule, may be too large however. Dalcher et al. (1985) show that by far the largest contributions to the LAF forecast comes from the 5-day

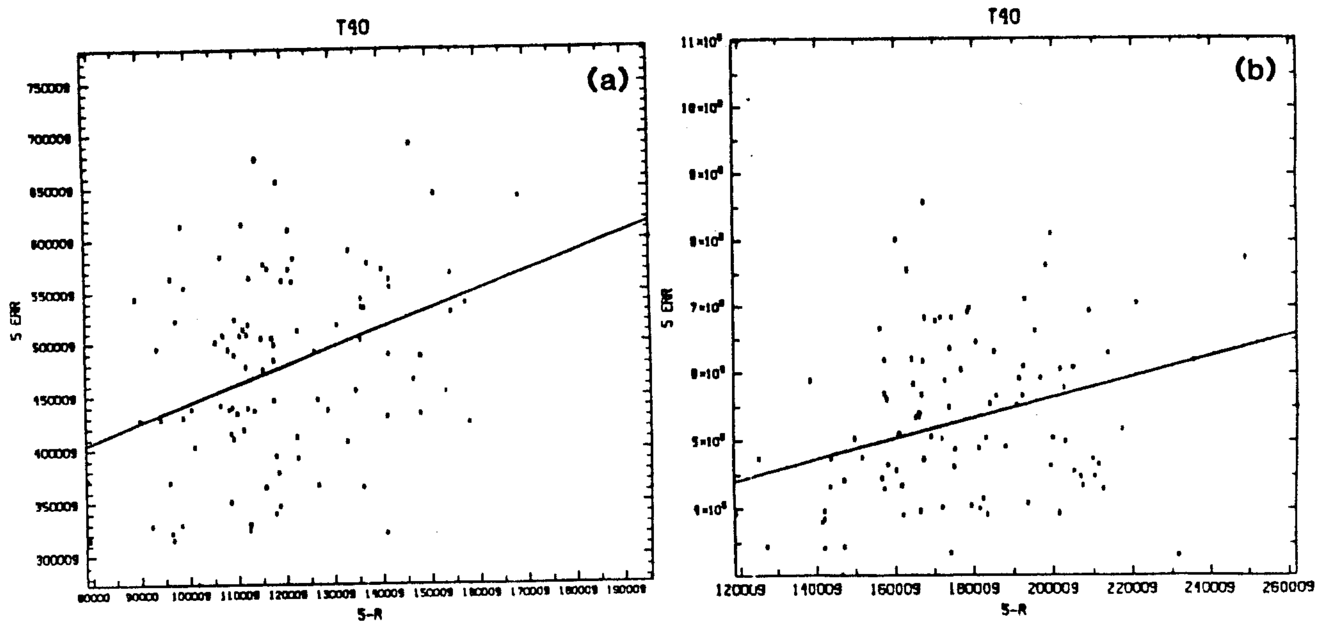


Fig. 3 Scatter plot and regression line for the 5-day dynamical forecast error of the ECMWF model (vertical) versus the difference between the 5-day forecast and the LAF (horizontal). Left: winter 1980/81. Right: summer 1981 (Adopted from Dalcher et al., 1985)

forecast alone. This could perhaps be improved upon by adopting a 12h time lag, an argument in favour of running the model twice daily merely based on medium range forecasting considerations.

Application of the method to other models is desirable in order to study the model dependence of the results. Murphy (1985) presents a preliminary report on a study at the U.K. Met. Office whereby the MCF technique was used to increase the extended range predictive skill, both under perfect model conditions ("identical twin") and against the real atmosphere. Under perfect model conditions he reports that the spread and skill of an ensemble forecast are usefully correlated up to 10 days, but the correlation disappears completely after 15 days. He also finds "that geographical variations in an ensemble distribution give a useful indication of corresponding geographical variations in ensemble-mean forecast skill".

In this chapter several suggestions have been made for further work, ranging from a simple study of the relation between forecast skill and the difference between two subsequent forecasts, to the application of sophisticated regression techniques to find relations between forecast errors and circulation regimes. All this work can be done with relatively little effort in the member states in close cooperation with ECMWF. From what we know already, most likely the results will be worth the effort. Even a coarse measure of the forecast skill is a lot more than our present complete lack of knowledge of the forecast's uncertainty. We at KNMI will certainly try to contribute to solving the problem in the next few years. We shall try to develop practical methods along the lines suggested in this chapter and moreover we shall continue our theoretical research on the predictability problem. The next chapter is concerned with our ongoing and intended effort in this area.

3. THEORETICAL PREDICTABILITY RESEARCH AT KNMI

3.1 Introduction

The chaotic character of simple deterministic nonlinear systems often resembles in a qualitative way the seemingly chaotic evolution of atmospheric flow (Lorenz 1984). In these simple models a transition from the existence of stable stationary or periodic solutions to aperiodic or chaotic behaviour often occurs in a small range of parameter values. In the chaotic regime such a system appears to evolve within an infinitely complicated plane in phase space which is called a strange attractor. The position in phase space and the topological structure of the attractor depend on the model parameters. Because the structure of the attractor is infinitely complicated, the evolution of a point in phase space is, in general, infinitely sensitive to the initial conditions. Therefore the predictability of a deterministic system with chaotic behaviour is always limited.

The statistical limit of predictability of the synoptic scales is of the order of a week. But is that all there is to say about predictability? Is it possible that atmospheric predictability depends on the parameter settings? Is it larger in certain subspaces of phase space? Is it variable in time? Is it possible to predict the reliability of a particular forecast? In order to answer each of these questions we need some direct or indirect knowledge of the topological structure of the attractor and of its dependence on the external parameters. Until recently predictability research at KNMI has mainly been concentrated on the long term predictability of planetary scale motion. Opsteegh and Van den Dool (1980) studied the importance of persistent anomalous diabatic heating in the tropics and at middle latitudes. Opsteegh and Vernekar (1982) and Kok and Opsteegh (1985) quantified the effect that transient eddies have on the time mean flow. They found this to be large compared to the direct forcing of planetary scale motion by the earth's surface. A systematic feedback of the eddies on the mean flow, leading to an adequate closure of the equations for the mean flow, has yet to be found. Nevertheless on some occasions persistent anomalies in the boundary conditions may significantly enhance the predictability range of planetary scale motion. Possible examples of periods with enhanced predictability are the frequently recurring El Niño events.

In the near future we will concentrate our research on the short term predictability of large-scale atmospheric flow. Our interest is mainly in predicting the reliability of particular forecasts. There is no way of picturing all the details of the atmospheric attractor, but we will try to uncover some of its properties which may be relevant in the context of predicting the skill of a forecast. Within this context we have three different projects which will be discussed in the next paragraphs.

3.2 Local stability and dispersion properties of planetary scale atmospheric flow

In a series of papers Frederiksen (1982, 1983a, 1983b) investigated how the structure and growth rate of the most rapidly growing perturbations depend on the stability properties of the planetary scale flow. The perturbations appear to be more or less local, their extension depending on the stability and dispersion characteristics of the planetary scale flow. Pierrehumbert (1984) has introduced the term local instability in this context. He studied the mean flow conditions that determine whether the growing perturbations have a local or global character. Detailed knowledge of the local stability and dispersion properties of the planetary scale part of the flow may be useful in distinguishing the areas that are favoured for error growth and error propagation. For short term predictions this may lead to a prediction of the reliability of the forecast as a variable in space and time. It may turn out that error growth can be connected to the growth rates of the perturbations or to their structure. For instance it is not unlikely that errors grow differently when the fastest growing mode has a dipole blocking-like character instead of a monopole structure. For a start, Haarsma and Opsteegh are studying the barotropic instability mechanism for the shallow water equations on a sphere. In contrast to Frederiksen (1983b) and Simmons et al. (1983) who studied observed time mean flows, we have confined ourselves to very simple flow configurations. The parameter governing the dynamical properties of the unforced nonviscous shallow water equations is Lamb's parameter $F = \frac{a^2\Omega^2}{gH}$, where g is gravity, a the earth's radius, H the mean fluid depth and Ω the angular velocity of the earth. For F=0 the equations reduce to the well known barotropic vorticity equation, while the limit $F \to \infty$ corresponds to the equatorial β-plane approximation. Until now studies on barotropic instability of wavy flows have been performed for F=0 only. We have investigated the stability of zonal flows, free Rossby-Haurwitz waves and forced stationary waves as a function of F. A short description of the results will appear in the proceedings of the first WMO workshop "on the diagnosis and prediction of monthly and seasonal atmospheric variations over the globe".

For unstable zonal flows, growing perturbations have phase speeds within the range of the zonal flow speed. For marginally unstable zonal flows the phase of the perturbations shows a jump across this critical line, leading to a jump in Reynolds stress ($\overline{u'v'}$) across the critical line. It is not yet clear how important critical lines or small scale critical layers are for physically relevant values of the growth rate of the perturbations and what the resolution of our models should be in order to adequately describe the physical processes in critical layers. The instability of 'wavy' flows has always been approached as a problem of resonantly interacting triads, whereby only a limited number of possible triad interactions is considered. It is not unlikely that, in order to adequately describe the stability properties of complicated flow configurations, one has to deal with processes in small scale critical layers. If this were true the results of stability calculations could be very dependent on model resolution.

In the near future we will investigate what role critical layers play in the barotropic instability problem for physically relevant values of the growth rate of the perturbations. Next we will study how the structure and growth rate of the perturbations in simple but earth-like planetary flow configurations depend on the parameters determining the character of the planetary scale flow and how these results depend on the truncation. This type of research will be repeated for the baroclinic instability problem. Finally we will try to connect error growth and error propagation in numerical models to the local instability and dispersion properties of observed planetary scale flow. The ultimate goal is to predict forecast skill as a variable in time and place.

3.3 Role of steady states in the dynamics of simple models

The second predictability research topic at KNMI will be the study of the importance of (unstable) steady states for the dynamics of simple atmospheric models and the relevance of this for the real atmosphere. Reinhold and Pierrehumbert (1982) considered a baroclinic model with 20 degrees of freedom. Their model exhibits regime like behaviour. The unstable steady states seem to play a role in the formation of these regimes, although it is not quite clear how. Legras and Ghil (1985) studied a barotropic model with 25 components. They showed that the unstable steady states remain attracting within the stable manifold. For some steady states the stable manifold absorbs a large volume in phase space and they are therefore important for the dynamics of the flow. For certain parameter settings the model exhibits recurrent hyper-predictable events during which the flow is first persistent and then becomes highly variable. They speculate that this is because the attractor becomes one-dimensional in a region close to a stationary solution. In this area the trajectories are contracted to a prescribed path, at the exit of which they are so close that they do not significantly diverge for some time. Haarsma and Opsteegh are studying the shallow water equations with forcing and dissipation. Their first results indicate that the bifurcation diagrams tend to become more complex for $F>0$. This happens because for $F>0$ resonance may occur due to selfinteraction (Boyd, 1983).

For a number of parameter settings we will investigate whether or not the unstable steady states represent preferred regimes in the model. Study of the evolution of the path in phase space close to preferred stationary solutions will hopefully uncover properties of the attractor that are relevant for the predictability of the model.

We will investigate how the model dynamics depend on the truncation, although for very large truncations it is no longer possible to numerically compute the bifurcation diagram.

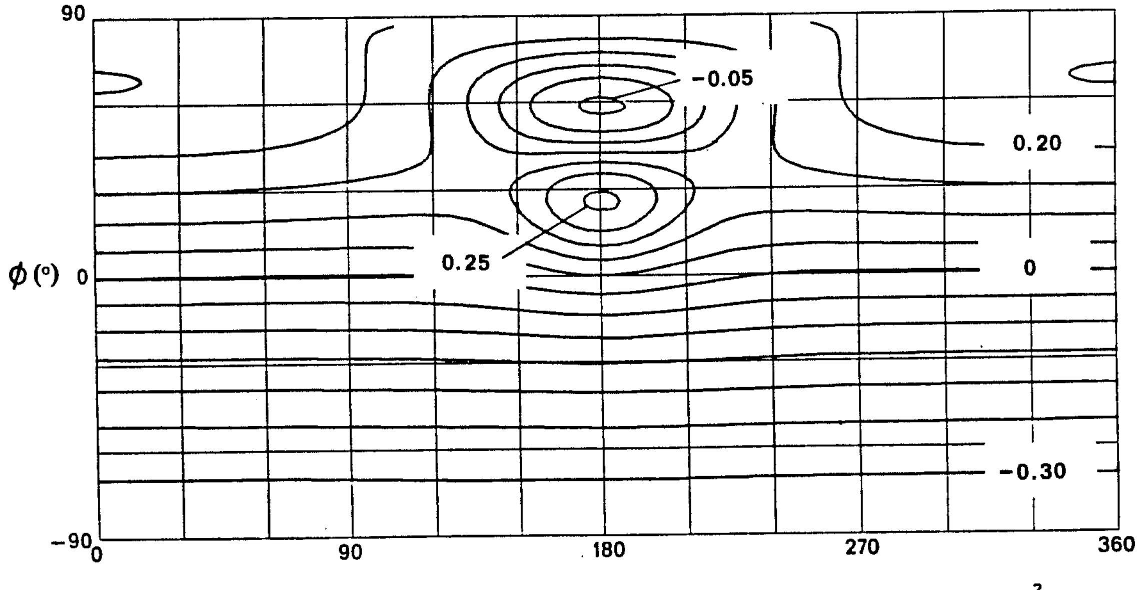
We also plan to perform this type of research with simple baroclinic models.

Instead of increasing the truncation one could also try to parameterize the effect that the unresolved modes have on the dynamics of the resolved modes. De Swart and Grasman (1986) assumed that the unresolved modes act as a stochastic forcing. They studied the dynamics of a three component spectral model of the barotropic vorticity equation forced by random perturbations. They found that the unstable steady state of the deterministic version of their model plays a role in the dynamics of the stochastically forced system because the transition from one attraction domain to the other through the separatrix is always very close to the unstable steady state. As mentioned before, Reinhold and Pierrehumbert (1982) and Legras and Ghil (1985) arrived at similar conclusions for deterministic systems. De Swart and Grasman are presently extending their work to systems with more degrees of freedom.

As a side step Haarsma and Opsteegh are presently performing a pragmatic experiment to find out whether or not the observed anomalies in the seasonal mean state of the atmosphere are somehow connected to the steady-states of a nonlinear barotropic model with orography. Apart from the orography the model is driven by a prescribed forcing, which consists of a climatological and an anomalous part. The climatological part is chosen artificially and drives the flow towards climatology. The anomalous part is taken from observations and represents anomalous diabatic heating and transient eddy forcing. The model is applied at 300 mb. The value of the damping coefficient is such that the climatological mean flow is marginally stable. With the pseudo-arclength continuation method (Keller, 1978) we will compute all possible steady states when the model is driven by normal plus observed anomalous forcing. The stability of each of the steady states is computed. This is done for a number of seasonal mean cases before, during and after the 1982/83 El Niño period. The computed steady states are compared with the observed seasonal mean circulation patterns. The degree of similarity may depend on the degree of instability of the steady state. Our thesis is that a computed steady state will only resemble the observed seasonal mean circulation if it is stable or if the stable manifold occupies a large volume in phase space. We speculate that such quasi-stable points or small areas in phase space exist and that the transient eddy forcing may in general act to drive the time mean flow towards such areas. This is analogous to the ideas of Stone (1978). He showed that the transient eddies are acting on the zonal mean flow by always keeping the temperature gradient close to a critical value.

3.4 Local coherent structures

A second approach in the study of the importance of steady-states is to look for solutions of the equations that resemble frequently recurring very persistent flow configurations in the atmosphere. We are investigating the so-called modon solutions of the barotropic vorticity equation which resemble blocked types of flow in the atmosphere. Verkley (1984) showed the existence of such solutions on a spherical domain. The phase speed of the modons is from west to east so that they can only be made stationary when superposed on an easterly zonal flow. Recently Verkley obtained modon solutions with a phase speed towards the west; these become stationary in westerly flows. He also investigated the stability properties of modons. This research was frustrated because the results were crucially dependent on the truncation. This is illustrated in Fig. 4. Fig. 4a displays the structure of the investigated modon and Fig. 4b shows the growth rate of the fastest growing mode as a function of the truncation. The fact that the results of stability calculations for local solutions depend crucially on the truncation may offer an explanation of why the maintenance or decay of blockings is not always predicted well. We are presently investigating the reason behind these peculiar results. We suspect that an inadequate description of processes in critical layers has something to do with it.



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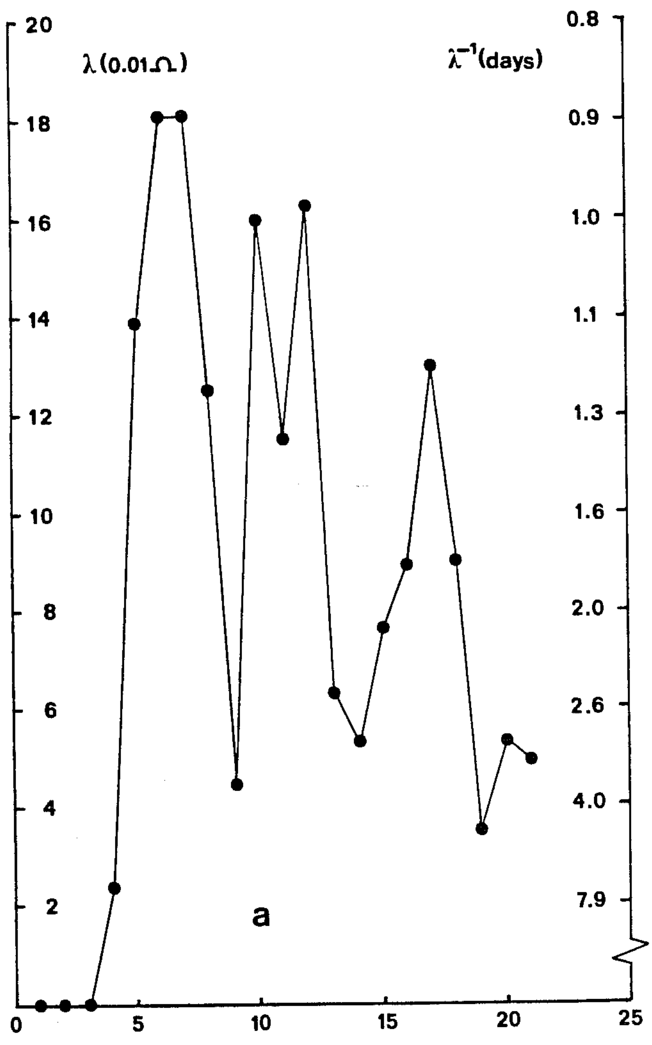

b

Fig. 4a Structure of the investigated modon

4b The growth rate of the fastest growing mode as a function of the truncation

In the near future we will try to find modon solutions in realistic shear flows both for a barotropic and a baroclinic model atmosphere. Next we will perform a series of integrations with a barotropic model with very high resolution starting from arbitrary initial conditions. This is done to investigate the possibility that modons grow by feeding themselves on the potential vorticity of neighbouring eddies. The experiment is analogous to the one performed by McWilliams (1984). For randomly chosen initial conditions on an f plane he showed that the flow ultimately evolves in a few large robust eddies. Finally, for a baroclinic model with orography and dissipation, we will investigate under what conditions persistent modon-type circulation patterns frequently recur. We will restrict ourselves to cases where the forcing is in the zonal components only.

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