Diagnostics of Models and Data Assimilation Systems

Introduction to the 25th ECMWF Seminar, 6-10 September 1999

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1 INTRODUCTION

It is a great pleasure to welcome our distinguished speakers to the 25th ECMWF Annual Seminar, whose topic this year is "Diagnostics of Models and Data Assimilation Systems". It is an even greater pleasure to welcome the student participants, who represent the future of our science in Europe.

By way of introduction I outline the ECMWF Strategy 1999-2008, as adopted by Council at its June 1999 meeting, as this sets the context for our work. I then review selected diagnostic studies which affected the direction of the Centre's developments and where I had some direct involvement.

According to the Oxford English Dictionary, the medical word "diagnosis" means the identification of a disease by means of its symptoms, from the Greek roots *dia,* with meanings < between / through / thorough>, and *gnosis* with meanings< knowing / understanding>. I therefore propose two meanings for the word diagnosis in a meteorological context

diagnosis (met): (i) Development of a thorough understanding of a meteorological phenomenon through a study of its workings,
(ii) Development of a thorough understanding of the origins of a meteorological problem from a study of its symptoms

I emphasise the need for *thorough understanding* because many so-called diagnostic studies in meteorology merely catalogue the symptoms of a problem, rather than providing a thorough understanding of the problem.

On a lighter note, the Oxford English Dictionary does not list "diabatic" but does list

adiabatic: without transference of heat

from the Greek roots a + dia + batos where *a-* means <absence / negation>; *dia* again means <between / through / thorough> and *batos* means <passable>. The next word in the dictionary is

adiabolist: one who does not believe in the existence of the devil

Those working on diabatic processes may have another view.

2 ECMWF STRATEGY 1999-2008

The background to the ECMWF strategy is that medium-range and seasonal-to-interannual weather forecasting hahave reached new levels of achievement and offer exciting prospects for further development. A new generation of operational and research satellites is coming on stream; four-dimensional variational assimilation is established as a powerful and effective method to use all observations; numerical methods continue to provide improved accuracy and substantial economies; parametrization schemes are improving steadily through new approaches which jointly exploit field experiments, large-eddy simulations and operational data assimilation; ensemble prediction systems are providing a new dimension in probabilistic forecasting; the development of simplified Kalman filters, based on singular vectors, will benefit both the assimilation systems and the ensemble prediction systems; coupled atmosphere-chemistry models offer new ways to improve the initialisation of forecast models; coupled atmosphere-ocean models have delivered successful ensemble forecasts of the 1997-98 El Nino event; and computer vendors are confident they can meet future requirements for computational power in an affordable manner. These developments will undoubtedly lead to further gains in medium-range and seasonal-to-interannual forecast skill.

The ECMWF Strategy 1999-2008, adopted by ECMWF Council in summer 1999 (ECMWF, 1999), is summarised here because it sets the framework and context in which the Centre will conduct its diagnostic work .

ECMWF's prime long-term goal is to deliver operational medium-range weather forecasts of increasingly high quality, over the range from three to ten days and beyond. A complementary long-term goal is to establish and deliver a reliable operational seasonal forecasting capability. Overall success will depend crucially on new and improved satellite observations, on improvements in the data-assimilation system, and on improvements in the forecast models. Ensemble prediction will play a major role in attaining both goals.

The new satellite data essential to achieve these goals over the next decade will be provided as a result of investments of $3B or more by Europe (EUMETSAT and ESA), $3B or more by Japan and $10B or more by the USA. By early 1999, in readiness to exploit the new satellite data, ECMWF will have implemented an advanced operational Earth-system model and data assimilation system. ECMWF's Earth-system model will comprise the following coupled modules:

Atmosphere
- an atmospheric general circulation model

Ocean circulation
- an ocean general circulation model
- ocean ice processes

Ocean surface waves
- ocean surface wave dynamics model

Land
- land biosphere module
- land surface, soil, hydrological and snow model

Ozone
- parametrized stratospheric ozone chemistry

Some modules of the model are already quite sophisticated, but others are at an early stage of development. ECMWF's advanced four-dimensional variational data assimilation system (4D-Var) has been developed specifically to optimise the use of satellite data. By the end of 2000, the operational 4D-Var system will be supported by a powerful new algorithm (a simplified Kalman filter) to provide flow-dependent forecast error structures at the start of each 4D-Var cycle.

ECMWF strategy to achieve its goals entails:

- Further development of the Earth-system assimilation capability to make best use of all available data (especially satellite data) to provide accurate analyses, together with accurate estimates of the uncertainty of the analyses;

- Further development of the integrated high-resolution Earth-system modelling facility;

- Development of the methodology of ensemble forecasting for medium-range and seasonal forecasting;

- Operational delivery of an enhanced range of meteorological and associated products;

- Maintenance and extension of the Centre's scientific and technical collaborations with scientific and technical institutes in the Member States and beyond.

The main deliverables from the strategy will be gains of order one day in medium-range forecast skill, the establishment of an operational seasonal forecast system with a thorough documentation of its capabilities, and improved services. The Centre's progress towards these goals will be contingent on its success in diagnosing the causes of forecast failures, and thus finding improved methods for the quality control and assimilation of observations, and finding improved methods for modelling. and for ensemble forecasting. Amongst the issues to be considered is the growing theoretical and experimental evidence that model resolution of order 15km is needed for accurate medium-range forecasts and that effective use of much operational satellite data requires resolution of order 15km in the assimilating model both over land and over sea.

3 SOME DIAGNOSES OF THE ECMWF FORECAST SYSTEM

In the following I instance a few examples of diagnostic studies that tried to provide a thorough understanding of the problem at hand.

3.1 Diagnosis of a Finite Difference Instability

The first experimental ECMWF model had an energy & enstrophy conserving finite difference scheme. Shallow-water and low resolution (N24) tests of the scheme were encouraging. However, diagnostics showed that the large-scale eddy- kinetic- energy was higher with dissipative processes than without dissipative processes! The first high resolution (N48) tests showed that the jets tended to collapse within a few days, and that the small scale eddy kinetic energy grew explosively in adiabatic integrations. Hollingsworth & Källberg (1979) showed analytically and numerically that the linearised equations of the finite difference scheme did not conserve momentum. This gave rise to a purely internal instability of a type not seen before, and whose growth-rate was a strong function of horizontal resolution. The practical solution was to simplify the finite difference scheme to an energy-conserving scheme whose linearised equations did conserve momentum. A more expensive solution (Hollingsworth et al 1983) would have been to modify the scheme so it conserved energy and enstrophy while the linearised equations conserved momentum.

3.2 Diagnosis of an Orographic Problem

Hollingsworth et al (1980) studied the performance of the first ECMWF forecast model, using two physics packages, the ECMWF package (Tiedtke et al 1979) and the GFDL package (Miyakoda et al 1972). Hollingsworth et al. found large systematic errors (or large climate drift) in the 10-day forecasts, and also found that the nature of the large systematic errors was quite insensitive to the differences between the physics packages; they offered no explanation for this surprising result. Operational forecasting started at ECMWF in August 1979. The first years of operational forecasts showed the same large systematic errors described by Hollingsworth et al (1980).

The origin of the large climate drift remained a puzzle until the classic study by Wallace et al (1983). These authors made considerable inroads into the problem, using an impressive range of diagnostic techniques. They first used synoptic compositing to show that the largest systematic errors in the day 1 forecast occurred over the Rocky Mountains in the area where the flow over the Rockies was strongest. The structure and synoptic variations of the day-1 errors over the Rockies suggested that the errors might be attributable to inadequate representation of orographic forcing in the model. This idea was tested analytically, and in numerical tests with a barotropic vorticity equation model. Following these successful investigations, Wallace et al. proposed a formulation for an 'envelope orography' to enhance the orographic forcing. This proved successful and was adopted for operational use in 1983. It was also used by several other modelling groups. The 'envelope orography' continued in operational use at ECMWF until 1995, when it was replaced by a sub-grid orography parametrization developed by Lott and Miller (1997) on the basis of the PYREX field observations.

The Wallace et al. study is a striking example of a diagnostic study which provided thorough understanding of a problem, and a firm basis for action.

3.3 Balance Diagnostics

Excessive zonalisation and under-forecasting of blocking frequency both contributed to the systematic errors in many models in the mid-80s. Following diagnostic work on this problem, Mc Farlane (1987), and independently Palmer et al (1986) developed a gravity wave drag to reduce the zonalisation. It is always a problem to find the correct representation of any parametrized process that is not directly measured, and this is true also of gravity wave drag.

Klinker & Sardeshmukh (1992) developed the "balance diagnostics" to estimate the correct intensity and distribution of diabatic tendencies. Their idea is that the time-mean diabatic tendencies in a long series of short -range forecasts should be in balance with the time-mean adiabatic tendencies. The time-mean adiabatic tendencies are probably much more accurately known than the diabatic tendencies. Hence a large difference between the time-mean diabatic and adiabatic tendencies probably indicates an error in the diabatic tendencies. Klinker & Sardeshmukh's balance diagnostics on gravity wave drag led to a re-profiling of the parametrization, with marked reductions in the amount of drag in the stratosphere. This together with a reduction in the vertical diffusion above the planetary boundary layer led to more realistic blocking frequencies in the ECMWF forecasts (M.Miller, pers.comm., 1988). For the last decade the balance diagnostics have been in routine use at ECMWF as a means of checking new developments in parametrization schemes.

3.4 Diagnoses of Short Range Forecast Errors

Hollingsworth/Lönnberg (1986) & Lönnberg/Hollingsworth (1986) used the North American sonde network to analyse the statistical structure of short range forecast errors. They found that the wind field errors were largely non-divergent and geostrophic; that the vertical correlations of forecast error are scale dependent; and that the vertical correlations for height and wind were quite different. The latter was at variance with the standard assumptions of the time, and Hollingsworth and Lonnberg had no explanation for the result.

Phillips (1986) completed the diagnosis. His analysis of the correlation structure of a random field of Rossby waves with energy equi-partition reproduced all the main results of Hollingsworth/Lonnberg and provided a straight-forward dynamical explanation for the unexpected aspects of their results. His analysis stimulated the development of the first operational three-dimensional variational analysis by Parrish and Derber (1992). Phillips' effective diagnosis certainly provided deeper understanding!

Hollingsworth et al (1986) used the diagnoses of short-range forecast error to demonstrate that in areas where observations are regularly available, the observations and the background fields from the assimilation have comparable accuracy, on the resolved scales. This implies that the background field of the assimilation system provides a useful transfer standard to compare and cross-validate observations. Detailed investigation of marked differences between observations and assimilation background fields have exposed many problems with observation systems such as sondes, aircraft, ships, buoys, satellites.... In the last decade a world-wide data-monitoring system, based on these ideas, has been put in place under the aegis of WMO.

As an example of this monitoring and diagnostic work, Andersson et al (1991) found large flow-dependent biases in NESDIS statistical retrievals from TOVS. Kelly et al (1991) found similarly large flow-dependent biases in newer NESDIS physical retrievals from TOVS. In both cases the biases tended to reduce atmospheric temperature variance, so that at low levels, the biases over-estimated cold temperatures and under-estimated warm temperatures. The problem occurred because the TOVS system could not get a good measurement of low-level temperature, and used an inaccurate background profile to start the retrieval. The solution eventually adopted at NESDIS was to use the temperature profile from a short-range forecast by NCEP's Aviation model to guide the choice of initial temperature profile for the library search. The short-term solution adopted by ECMWF was to use the model's lapse rate (T700-T300) to quality control the NESDIS retrievals. The long term solution adopted by ECMWF was to develop variational methods to use the NESDIS radiances. The latest steps on this path were the implementation of 4D-Var in 1997, and the use of ATOVS raw radiances in 1999.

The e-mail below

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> *Date: Thu, 2 Sep 1999 15:06:22 +0100*
> *From: Mark Leidner <stl@ecmwf.int>*
> *Subject: ERS-2 gyroscope campaign*
>
> *Global scat quality control rejected nearly all ERS-2 winds in operations for three consecutive cycles starting 1999090112. After a phone call to ESA, I learned that ERS-2 had a ''gyroscope campaign" between 08:46:40 Wed 1 Sep 1999 and 01:32:40 Thu 2 Sep 1999 which degraded the accuracy of the satellite's pointing mode. The campaign, performed annually, is part of a maintenance program for the gyroscopes.*
>
> *Operations at ESA did not believe that the campaign would have negative effect on ERS products, so we were not informed in advance. But our global scat quality control spotted the change in data quality and rejected the winds, just as it should.*
>
> ==

is an example from last week of the sensitivity and power of the data monitoring methods.

4 THE FUTURE

In the last 10-15 years we have seen a great development in the scope and power of diagnostic tools available to understand the problems of models and assimilation systems. On the model side one may instance the development of dynamical theory associated with PV thinking (Hoskins et al., 1995); operational verifications of direct model output as well as fields; verifications of model physics in field experiments and process studies (Betts et al., 1993); the use of Large Eddy simulation to understand physical processes (Gregory et al., 1997); singular value decomposition analyses of flow-dependent forecast errors (Gelaro et al., 1998); studies of climatological balances and low frequency variability in operational analyses and delayed-mode re-analyses (Corti and Palmer, 1997). On the assimilation side we have seen the powerful analyses of the sensitivity of forecast errors to initial data (Rabier et al., 1996), and development of effective methods to assess the accuracy of forward models of observations. Further development of the variational method should allow real-time estimation of assimilation and model parameters (Rabier et al., this volume). A further powerful resource is the availability of proxy observations which verify models forced by atmospheric fields; such models include Ocean Wave models, Hydrological models, Ocean Circulation models, Sea Ice models, Chemical Tracers models, and Seasonal Forecast models. ECMWF has had many direct benefits from these studies.

The papers in this volume represent a stimulating cross-section of the diagnostic methods developed in recent years. The papers in this volume also contain valuable ideas on where next to direct our thinking and efforts. On behalf of ECMWF, I thank all the speakers for their contributions.

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