NUMERICAL WEATHER PREDICTION: PARADIGMS AND PRINCIPLES

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According to *Chambers Dictionary* a paradigm is (i) a pattern or example, or (ii) a conceptual framework within which scientific theories are constructed; we use the term in the latter sense.

This paper summarises key paradigms and principles guiding current development of Numerical Weather Prediction. High-resolution models and assimilation systems are needed to exploit fully the forthcoming generation of advanced instruments. For Numerical Weather Prediction (NWP) in mid-latitudes, the Dynamics and Assimilation paradigm may be summarised as: *The worst forecast errors arise in localised sensitive areas which are highly baroclinic and which can be identified a-priori (cf. FASTEX).* Satellite and in-situ observations, with high vertical and horizontal resolution, are needed in the sensitive areas. The corresponding Parametrization and Assimilation principle may be summarised as: *Medium-range and seasonal forecasting requires comprehensive and accurate Earth system models, and the assimilation systems and observations to initialise the physical processes.* Progress has been good on the dynamical side, but we must accelerate the development of methods to model and assimilate the comprehensive new observations coming on-stream in the next few years.

Observations related to the diverse model variables represent the major cost element of the weather forecast. Satellite observing systems provide regular global coverage but are amongst the most expensive of observing systems. It behoves us not only to use the satellite data well, but also to prove that we are using the data well. Repeated data impact studies show that ECMWF has delivered substantial forecast benefits from existing satellite data.

Experience shows that a comprehensive model of the Earth-system is needed for medium range and seasonal forecasts. Such models predict, and therefore need data on, the following variables:

- pressure, wind, temperature, humidity, rain, cloud and ozone;
- boundary conditions, such as ocean surface waves, sea ice, and land properties such as soil moisture and snow cover;
- the ocean circulation, esp. SST, Temp profiles, sea-level.

The ECMWF Earth-System Model comprises the following elements

Atmosphere	40km (TL511) 60-level AGCM with top at 65km
Ocean	Hamburg (HOPE) OGCM with simplified ocean ice processes
Ocean Waves	WAM ocean surface wave dynamics model
Land	Tiled land biosphere, hydrology and snow model
Ozone	Parametrized ozone chemistry (Cariolle and Deque)

ECMWF's four-dimensional assimilation, 4D-Var, exploits the model dynamics and physics to find a trajectory of the model which fits the time-evolution of the observations. In practice, 4D-Var iteratively runs the model in a forward and adjoint sense to adjust the model state over a period of 12 hours. On the forward step of an iteration, the algorithm measures the mis-match between observation and latest model trajectory. On the backward step the algorithm calculates the sensitivity of the observation-minus-model mis-match to the starting point and generates a new trajectory. A good trajectory fits the data in time, and gives a good forecast.

The sensitivity of forecast error to initial data error may be calculated by advecting forecast error backwards in time, using the adjoint of the tangent linear model. Rabier et al's (1996) perturbation experiments used the sensitivity calculation to generate remarkable forecast improvements . Rabier et al also show a close relationship between the sensitivity calculations and the singular vectors defined as follows

> *Let R be the resolvent of the tangent model, linearised about the forecast trajectory for a time T (e.g. 2 days), and R* its adjoint. R*.R is a symmetric positive definite operator*
>
> *The singular-vectors (SVs,) of R*.R are a complete and useful description of the evolution of the flow and / or the forecast errors in (0,T)*
>
> *The eigenvalues of R*R give the amplification factors of each SV in (0, T).*

Most SV structures are either mildly amplifying, or nearly neutral, or decaying in (0, T). The dynamical paradigm of numerical weather prediction is that *errors in a small subset of SVs with large amplifications (~10), and which are well-localised, will grow fast, and may trigger large forecast errors.* The capability to observe these key structures, together with the capability to assimilate the information effectively, will substantially reduce the frequency of bad forecasts.

A important aspect of this paradigm guides the development of the ensemble forecast system. The SVs provide an effective method for generating initial perturbations which

- model the amplitude of initial uncertainties
- grow at the same rate as observed forecast errors

Current work is focussed on developing diabatic SVs, and SVs targeted on tropical cyclones.

A third aspect of this paradigm is related to the identification and observation of sensitive regions. Recent experiments such as FASTEX and NORPEX have demonstrated the ability to identify and observe sensitive regions with targeted observations from aircraft, dropsondes and ships. Competing targeting methodologies are available, based in one way or another on the SVs. These experiments have also demonstrated that the assimilation of observations from sensitive areas has a beneficial effect on forecast skill.

A further aspect of this paradigm is that it is essential that the space observing system have the horizontal and vertical resolution needed to document the sensitive structures in the vertical and in the horizontal. Prunet et al. (1998) have shown that TOVS is largely blind to the key temperature structures while the AIRS and IASI instruments will have the resolution necessary to satisfy the temperature observational requirements (Prunet et al.) in clear sky. It remains to be proven that the temperature observing capability, unsupported by wind observing capability, will be adequate to deliver a marked improvement in forecast skill. There is a good level of confidence that a multivariate assimilation system such as 4D-Var can exploit all types of data to good effect.

Effective assimilation of observations of sensitive regions will require that the assimilation system be particularly responsive to data on the sensitive structures. In fact 4D-Var responds best to observations of the most unstable structures. 4D-Var currently begins each cycle by assuming that the error in the background field is to a large extent quasi-geostrophic, isotropic and barotropic. Each 4D-Var cycle then implicitly calculates flow-dependent structure functions based on the location and structure of the sensitive regions. The Reduced Rank Kalman Filter (RRKF) is designed to calculate explicitly the location and structure of the sensitive regions, for the next cycle of 4D-Var. The RRKF needs a large and affordable set of suitable basis functions. Current experiments use small sets (and several flavours) of SVs. Efforts are underway to enlarge the basis sets in an affordable way.

In passing, one may remark that a marked improvement in forecast skill will require a marked reduction in the number of poor forecasts. We also note that the improved capability of AIRS and IASI will be available only in clear sky conditions. In cloudy regions we shall continue to depend on the all-weather microwave capabilities of AMSU, SSM/I and of scatterometry.

ECMWF currently uses the following categories of passive Satellite Measurements

- Ultra-violet (SBUV backscatter to measure ozone)
- Visible and Near Infra-red Imagery (vegetation, TV pictures of cloud motion)
- Thermal Infra-red sounding data (profiles of temperature, water vapour and ozone)
- Microwave sounding and imagery (sea-ice, ocean wind speed, land characteristics, cloud, rain rate, ice scattering from dense cold cirrus)

ECMWF also uses the following categories of active Satellite Measurements

- C-band and Ku-band Scatterometers measuring ocean surface wind speed and direction
- Radar Altimeters, measuring dynamic anomalies in the ocean surface height, as well as ocean surface waves and surface wind speed
- Synthetic aperture radars measuring, inter alia, ocean surface wave spectra and land surface properties.

The new satellite instruments coming on stream in the next 5-10 years will pose many scientific challenges including

- Will radiance assimilation continue to out-perform retrievals?
- How to optimise the trade-offs between RRKF and 4D-Var?
- How to analyse / assimilate rain-rate, clouds, land-surface.
- How to use the coming El Dorado of satellite data to improve model physics?
- How to improve the physics-dynamics interface?
- What are the prospects for automatic adjoints of big non-differentiable codes?

In considering the magnitude of the challenge, one should recognise that we also have considerable scientific resources to meet the challenges. To meet operational needs, NWP's Earth-system models and Earth-system assimilation systems provide accurate forward models of every observation used. The accurate meteorological context for each observation helps one to separate *what is understood* from *what is not understood* in the observation, and helps one's understanding to grow. Real-time NWP analyses are thus a key resource for, and a major beneficiary from, a wide range of scientific investigations. Furthermore, periodic reanalyses of the observational record, with the most advanced NWP systems, deliver the most comprehensive synthesis of the satellite and in-situ instrumental record.

In discussing the challenges this week, we are particularly pleased to have with us this week a galaxy of experts who will provide road-maps to solutions, if not complete solutions. ECMWF is grateful to them and to you.

REFERENCES

F Rabier, E Klinker, P Courtier and A Hollingsworth (1996) Sensitivity of forecast errors to initial conditions. *Quarterly Journal of the Royal Meteorological Society* 122, pp 121-150

P Prunet, J-N Thepaut and V Casse (1998) The information content of clear sky IASI radiances and their potential for numerical weather prediction. *Quarterly Journal of the Royal Meteorological Society* 124, pp 211- 242