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The ECMWF Newsletter is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States. The ECMWF Newsletter is not peer-reviewed.

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Front cover
The weather roulette.

Editorial

A strategy for ECMWF

At its 64th session on 7 December 2005, the Council of ECMWF unanimously adopted the strategy for 2006–2015. This was the completion of a process which started in June 2004 when the Centre presented to Council a review of the then current strategy (1999–2008). This review included an assessment of the achievements of ECMWF, analysis of the evolution of the context within which it operates, and proposals for the main elements of a new strategy. As a result the Council tasked ECMWF to prepare a new strategy for the period 2006–2015.

During last winter, task teams were set up in ECMWF to elaborate on the scientific and technical opportunities in several domains. Based on the input from these teams an initial framework of the proposed strategy was prepared and discussed at the Council in June 2005. The strategy, incorporating the feedback from the Council, was written during the following summer, discussed with the Committees in the autumn, and finalized by the Council after an in-depth discussion.

The strategy is a 30-page document which will be published and distributed amongst the international community. At this stage it is worth emphasizing a few major points.

◆ The vision guiding this strategy is that European citizens should continue to receive the very best meteorological forecasting services at all ranges, particularly regarding severe weather. This involves the whole of the European Meteorological Infrastructure in which ECMWF will play a leading and co-ordinating role for global Numerical Weather Prediction.

◆ The principal goal of ECMWF in the coming ten years will be to maintain the current, rapid rate of improvement of its global, medium-range weather forecasting products, with particular emphasis on early warnings of severe weather. ECMWF will devote the main part (80 to 85%) of its resources to this goal.

◆ Important complementary goals are:
- To improve the quality and scope of monthly and seasonal-to-interannual forecasts;
- To enhance the support to Member States' national forecasting activities by providing suitable boundary conditions for limited-area models;
- To deliver real-time analyses and forecasts of atmospheric composition;
- To carry out climate monitoring through regular re-analyses of the Earth-system;
- To contribute towards the optimization of the Global Observing System.

The whole strategy relies upon complementarity with our Member States and calls for even more cooperation with the Member States as well as with many institutions, in particular WMO and EUMETSAT, and with the research community at large. It identifies the need to further develop co-operation with the European Commission.

The strategy fixes specific targets in term of forecast skill improvement and development of performance measures for early warnings of severe weather and for seasonal forecasts. It recognizes the need for a significant increase in the funding of the supercomputing facilities. The level of achievement of this increase will now determine the speed of implementation of the strategy.

Dominique Marbouty

Changes to the operational forecasting system

David Richardson

Changes made on 8 September, 9 November and 30 November 2005

- AMSU-A radiances from the new NOAA-18 satellite were included in the operational assimilation from 8 September.
- Warmest (rather than central) field of view AIRS data included in the operational assimilation from 9 November.
- MHS humidity data from NOAA-18 and humidity data from dropsondes were included in the operational assimilation from 30 November.

Changes made on 1 February 2006

A new model cycle including a major resolution upgrade was introduced on 1 February 2006. The changes are:

- Increase in horizontal resolution to T799 for the deterministic forecast and the outer loops of 4D-Var.
- Increase in vertical resolution to 91 levels; model top raised to 0.01 hPa.
- Increase in horizontal resolution to T255 for the second inner loop of 4D-Var.
- Increase in horizontal resolution to T399 and in vertical resolution to 62 levels (model top ~5 hPa) for the EPS.
- Increase in horizontal resolution to 0.36 degrees for the global ocean wave model.
- Increase in wave spectral resolution to 24 directions and 30 frequencies (from 12 and 25 respectively) for the EPS ocean wave model.
- Use of grid-point humidity and ozone in 4D-Var.
- Revised coefficients (version 2.3) for the linearised ozone chemistry scheme, supplied by Daniel Cariolle, CERFACS.
- Use of Jason altimeter wave height data and ENVISAT ASAR spectra in the wave model data assimilation. The ERS-2 SAR spectra are no longer assimilated.

Despite the longer run times of the higher-resolution system, the dissemination time of many products, in particular the EPS, will be significantly earlier than the previous system. This is achieved by a much tighter internal production process. Detailed information about the schedule for all dissemination streams can be found in the Dissemination Manual on our web site at:

www.ecmwf.int/services/dissemination/3.1/

With the longer runtimes of the high-resolution system and the much tighter production process, the de facto differences between dissemination, MARS and web-based products access will become very small.

ECMWF's plans for 2006

Dominique Marbouty

At its 64th session in December the ECMWF Council unanimously adopted both the strategy for 2006–2015 and the four-year programme of activities for 2006–2009. The associated documents are available on the Centre's website at www.ecmwf.int/about/programmatic. The plans for 2006 flow directly from these documents.

Here only the main activities and targets for 2006 will be presented, focusing on the users' point of view. It is worth remembering that most planned developments need to be properly validated before implementation. If not proven beneficial, the implementation would be delayed.

The high-resolution upgrade was a good example of effective validation. Initially the change was scheduled for autumn 2005 but testing indicated that there were some instability problems. Further work solved the problems and the major model upgrade was implemented on 1 February. Details are given in the usual review of changes to the operational forecast system which can be found on page 2.

The next change should be the implementation of the Variable Ensemble Prediction System (VAREPS): this will allow the forecasts to be extended from day 10 to day 15 at a lower resolution. Compared to the initial plans, the change of resolution has been moved from day 7 to day 10 in order to accommodate difficulties foreseen by some Member States with their existing applications.

Other changes expected this year will include several improvements to the physics (e.g. cloud scheme, orographic drag) and to the assimilation (e.g. variational satellite bias correction, 4D-Var third inner loop). As usual a special effort will be made to ensure full usage of satellite data which should culminate with the new instruments from METOP, whose launch is scheduled this summer.

The interim reanalysis will start this year and is expected to be completed in 2007. It will cover the period from 1989 to present and will continue in near-real-time. The aim is to improve significantly on, and correct the main deficiencies identified in, ERA-40. Use will be made of a 12 hour/4D-Var analysis, run at a higher resolution than ERA-40 (T255 outer loop, 91 levels) and based on the most recent cycle (probably Cy30r2), thus incorporating all the model changes from the last five years.

Significant developments are expected as part of the

GEMS project. The assimilation system for reactive gases, greenhouse gases and aerosols will be developed, and the representation in the IFS of greenhouse gases and aerosols will be refined. The specific GEMS reanalyses will be started for greenhouse gases and aerosols, concentrating on the period 2003–2004. Discussions about preparing for the operational follow-up of GEMS will start at the European level within the various bodies associated with the EU's initiative on "Global Monitoring for Environment and Security".

Concerning seasonal forecasting, a new system (system 3) will start this year and will be run in parallel with the current system for several months. In addition there will be further development of the multi-model system (EUROSIP, built in cooperation with the Met Office and Météo-France). The work will start for the preparation of the next system (system 4 expected by 2009) which will incorporate a new ocean model and data assimilation system (OPA/OPA-VAR).

Research into longer-term improvements in the forecasting system will continue in all areas. One can specifically mention the development of Ensemble Data Assimilation, the work on weak-constraint long-window 4D-Var (taking into account the fact that the model used in the assimilation is not perfect), and the evaluation of a non-hydrostatic version of the IFS in order to decide whether the development of a new dynamical core is necessary.

On the computing side, the main event of this year is the move to phase 4 of the IBM supercomputer. The entire process will span most of the year. There will then be a sustained performance increase from the current 2.5 teraflops to 4.5. Another major development will be the installation of new drives on the data handling system allowing the storage of 500 gigabytes per tape.

A new model-climate suite (re-forecasts) will be set up with the introduction of the high-resolution forecasting system. This will initially support the calibration of the Extreme Forecasts Index (EFI) and later in the year it will be extended to support the calibration of VAREPS up to day 15 and the monthly forecasting system. The output of the model climate suite will be available to Member States and will also be used within ECMWF for the development of guidance about severe weather.

An important milestone will be the development of the TIGGE (THORPEX Interactive Grand Global Ensemble) database, in co-operation with NCAR and the Chinese Meteorological Administration (CMA). This includes in particular specific developments in MARS and GRIB2. A dedicated archive server will be set up.

Finally this year will see the completion of the building developments started in 2004: the move into the new office building is expected this summer. Terrapin Towers, a temporary building which will have been occupied for eight years, will be removed in the autumn.

New items on the ECMWF web site

Andy Brady

Second HALO workshop

The second HALO workshop was held at ECMWF on 12–13. December 2005. The first aim of the workshop was to finalise the document prepared by HALO specifying in detail the exchanges of data and information- products between the interacting parts of the GEMS, MERSEA, and GEOLAND Integrated Projects (IPs), and the Candidate Solutions for these exchanges. The second aim was to identify the scope and content of a review (to be prepared by the HALO partners in 2006) of the likely scientific and technical upgrade paths of the interacting parts of the three IPs in the first few years after the transitions to operational status.

www.ecmwf.int/research/EU_projects/HALO/workshops.html

ECMWF training courses

ECMWF has an extensive education and training programme to assist Member States and Co-operating States in the training of scientists in numerical weather forecasting, and in making use of the ECMWF computer facilities. The training courses consist of modules which can be attended separately. A student may decide to attend different modules in different years.

www.ecmwf.int/newsevents/training/2006/

ECMWF Convention

ECMWF Convention and the Amended Convention are now available in all official languages of ECMWF (Dutch, English, French, German, Italian).

www.ecmwf.int/about/basic/volume-1/convention_and_protocol/

IFS cycle sources and documentation

The IFS cycle sources and documentation has been updated with the addition of cycles 30r1, 29r2 and 29r1. (Note: requires login).

www.ecmwf.int/services/prepifs/source/

Historical documents about ECMWF

In preparing the book *Medium-Range Weather Prediction – The European Approach* many archive documents were consulted, including those of COST (Brussels), Deutscher Wetterdienst (Offenbach) and the Meteorological Office of the United Kingdom, in addition to the documents held in the Centre's archives. Copies of many of these documents are now archived at the Centre and a selection is available on the ECMWF web site at:

www.ecmwf.int/about/history/

This website includes some photographs and audio recordings from the first Council session.

64th Council session on 6–7 December 2005

Manfred Kloeppel

Chaired by Anton Eliassen from Norway, the ECMWF Council held its 64th session in Reading on 6–7 December 2005. Besides several decisions on financial matters, such as the adoption of the scale of Member States' contributions for the years 2006–2008, and staff matters, such as approval of Reports from the Co-ordinating Committee on Remuneration (CCR), the main results of this session were as follows.

- **Strategy**. The Council unanimously adopted the ECMWF strategy for the period 2006–2015 (see the Editorial).
- **Four-year Programme of Activities**. The Council unanimously adopted the updated "Four-Year Programme of Activities" for the period 2006–2009. For further information see
  www.ecmwf.int/about/programmatic/index.html
- **Co-operation Agreements**. The Director was authorised to negotiate an agreement for co-operation with the Republic of Bulgaria for eventual accession to the Convention, when the amended Convention comes into force.
- **Budget 2006**. The Council adopted the Budget for 2006 with a 2% increase in Member States contributions compared to the 2005 Budget. The Council agreed to give the Director full flexibility to execute the Budget.
- **Boundary Conditions – Optional Project**. The Council adopted revised guidelines for the optional project "Boundary Conditions for Limited Area Modelling" which will improve the quality and facilitate the use of the boundary conditions provided by ECMWF to the Member States participating in this optional project.
- **Products of the Centre**. The Council agreed on an enhancement of the ECMWF data distribution (in GRIB) for the African Centre of Meteorological Application for Development (ACMAD) and product dissemination (in GRIB) for WMO RA VI members, both via EUMETCAST which is the EUMETSAT broadcast system for environmental data.
- **Staff Contracts**. The Council approved the appointment of Mrs Ute Dahremöller from Germany as Head of Administration for a four-year period, from 1 May 2006, and appointed Dr Philippe Bougeault, Head of the Research Department, as Deputy Director for the period 1 May 2006 until 6 July 2007.
- **Scientific Advisory Committee**. The Council appointed Prof Julia Slingo (United Kingdom) and Prof Michael Tjernström (Sweden) to the SAC for a first term of office and Dr Huang (Denmark) for a second term.
- **Auditor**. The Council appointed Mr Uwe Barth as Auditor and Ms Petra Jasper as Deputy Auditor, both from Germany, for the financial years 2006–2009. The accounts for the 2005 financial year will be audited by the current auditors, Mr Seppo Akselinmäki from Finland and Mr Gerhard Steininger from Austria, whose term of office expires with the closure of the accounts for the 2005 financial year.

ECMWF/NWP–SAF workshop on bias estimation and correction in data assimilation

Jean-Nöel Thépaut

The workshop on bias estimation and correction in data assimilation was co-sponsored by the EUMETSAT NWP SAF (Satellite Application Facility) and ECMWF, and organised by ECMWF. It was held on 8–11 November 2005 with more than fifty people attending. This workshop had a slightly different nature than usual. Indeed, the goal of this event was twofold:

- To provide an educational background to scientists about bias estimation and correction in data assimilation.
- To gather scientific experts to provide an extensive review of the different sources of biases involved in data assimilation (model, radiative transfer, instruments etc.), review the state-of-the-art bias correction strategies adopted in NWP centres, and propose a set of recommendations to the Centre on possible new avenues for progress for consideration in an operational, reanalysis or environmental monitoring context.

The workshop had the usual format of invited lectures, covering both tutorials and state-of-the-art scientific issues, followed by discussion in working groups and a plenary session. A number of issues to be discussed were presented to three working groups; they considered the following subjects.

- Environmental monitoring and reanalysis aspects
- Sources of systematic errors and independent validation datasets
- Operational implementation of bias correction including regional applications

The recommendations of the working groups have been posted on the ECMWF website at:
www.ecmwf.int/publications/

In summary, the workshop participants emphasised the importance of identifying the different sources of systematic errors involved in data assimilation (sensor calibration, forward modelling, pre-processing, NWP biases, etc.). The crucial value of a reference observational network (in situ or spacedbased) to independently monitor and cross-calibrate the behaviour of bias correction schemes applied operationally or in a reanalysis context was stressed by the three working groups. These groups also recommended a continuous dialogue between data providers, operational centres and the research community as regards field campaigns, instrument calibration, data reprocessing, etc., noting that NWP provides a privileged framework for calibration/validation excercises. Last but not least, it was noted that while most of the current operational bias correction schemes are based on static and off-line approaches, adaptive techniques were emerging and providing promising results, especially in the context of reanalysis applications. However, the groups stressed the need to explore a common strategy when handling observational bias and model error adaptively. The weak constraint approach followed by ECMWF was recognised as a promising way to harmonise these two aspects.

In conclusion, ECMWF would like to thank the NWP SAF and all the participants for contributing to a successful and stimulating workshop, and providing guidance to research and development in such a crucial area of data assimilation.

Meeting of the COST Committee of Senior Officials

Manfred Kloeppel

To mark the 30th anniversary of ECMWF, the COST Committee of Senior Officials (CSO) held its 163rd meeting at the premises of the ECMWF on 23–24 November 2005. This committee is the main decision-making body of COST. The meeting was chaired by Prof Francesco Fedi, President of CSO. The Director of ECMWF, Dominique Marbouty, gave a presentation on "The European Centre for Medium-Range Weather Forecasts in the 21st Century – Result of a COST Action". He introduced the major achievements in numerical weather forecasting at ECMWF as well as planned future developments.

Established in 1971, COST is the oldest and widest European intergovernmental network for cooperation in research. COST Actions cover basic and pre-competitive research as well as activities of public utility. One of the early COST Actions resulted in the establishment of ECMWF. At present there are 14 COST Actions dealing with a wide range of meteorological topics.

COST has developed into one of the largest frameworks for research co-operation in Europe and is a valuable mechanism for co-ordinating national research activities in Europe. It has almost 200 Actions and involves nearly 30,000 scientists from 34 European member countries and more than 80 participating institutions. More information about COST can be found at www.cost.esf.org.

Tenth ECMWF workshop on meteorological operational systems

Horst Böttger

This biennial workshop on Meteorological Operational Systems was held at ECMWF, 14–18 November 2005. It was the tenth workshop in the series. As on previous occasions the workshop reviewed the state of the art meteorological systems, looking at trends and developments in the use of medium- and extended-range forecast products (session 1), operational data management systems (session 2) and applications in meteorological visualisation (session 3). The workshop proved to be very popular with over 100 participants from ECMWF Member States, Co-operating Sates, from other parts of Europe and beyond.

In session 1 major forecasting centres presented their operational predictive systems and discussed the use and interpretation of medium-range and extended-range forecast guidance. Several presentations from academia and industry were addressing the use of the forecasts in weather risk management: the use of probabilistic forecast information was discussed as was the prediction of severe weather.

In session 2 a wide range of data management systems were presented, focussing on access to distributed data sets through user-friendly application portals and data distribution systems. Such applications will soon be required to support data exchange and access in global scale research activities, such as THORPEX/TIGGE, as well as the emerging future operations information systems of the WMO.

A variety of mature data visualisation systems are now in operational use at several centres. New applications and updates to existing ones were presented in session 3. Several visualisation systems were demonstrated during the exhibition which was arranged for one afternoon.

During the week the workshop split into three working groups to meet twice and to discuss issues relevant to the session topics. The findings of the working groups were presented and discussed in a final plenary session which concluded an informative and successful workshop.

Working group 1 discussed:

- ◆ User requirements for forecast information
- ◆ Value of forecasts

Forecasters find the ECMWF verification results on the web very useful in their work. Further training on how to use and interpret such verification, in particular the scoring of probabilistic forecasts, would be welcome. ECMWF plans to introduce 15-day forecasts with a variable resolution EPS were discussed. It was noted that the operational post-processing procedures in Member States will require re-forecasts at these variable resolutions for calibration purposes. While it was acknowledged that users will have requirements for deterministic forecasts to help them in their decision-making processes, the workshop recommended ECMWF to be more proactive in explaining forecast uncertainties and the use of probability information as decision support.

ECMWF was encouraged to work with Member Sates and Co-operating States on forecast evaluation techniques which are closely related to the value and the societal benefit of the products.

Working group 2 on data management systems discussed issues related to:

- ◆ Interoperability between centres and disciplines
- ◆ Data catalogues
- ◆ Discovery mechanisms
- ◆ Metadata standards

Systems under development in the research and operational environments aim at implementing standards for accessing data, which would simplify the task of the user but also allows reinforcement of existing data policies. Data discovery will be facilitated through the appropriate use of metadata and related standards.

Working group 3 considered visualisation applications and looked at:

- ◆ Output formats for meteorological plots
- ◆ Formats suitable for interfacing with Geographical Information Systems (GIS)
- ◆ Use of XML to describe a visualisation task

For printing and documents, Postscript and PDF are still dominant, but Encapsulated Postscript (EPS) is now popular in the research community. Interactive graphics formats were discussed in detail. Panning, zooming and toggling of layers, together with the possibility of retrieving geographical co-ordinates at user selected points and load supporting data on demand are the main features required by users.

The workshop programme, and the presentations and the summaries of the working groups presented at the final plenary can be found on the web at:

www.ecmwf.int/newsevents/meetings/workshops/2005/MOS_10/index.html

ECMWF workshops and scientific meetings in 2006

Bob Riddaway

Workshop on Preparation for a New Generation of Atmospheric Reanalyses (19 to 22 June 2006)

A workshop on reanalysis will review:

- ◆ Experience and plans of producers of global atmospheric reanalyses in Europe, Japan and North America.
- ◆ Successes and failures of past reanalyses and the requirements of future reanalyses from a user perspective.
- ◆ Recent developments in data assimilation especially relevant to reanalysis, with special attention paid to accounting for bias in observations and the assimilating model.
- ◆ The conclusion from recent workshops covering observational aspects.
- ◆ Some specific topics such as sea-surface-temperature and sea-ice datasets and the homogenization of radiosonde and radiance data.

Discussion sessions will identify the further work needed to prepare for the new generation of multi-decadal global reanalyses to succeed ERA-40, JRA-25 and the NCEP reanalyses, and consider the needs and opportunities for both collaborative European efforts and wider international coordination and collaboration.

Participation in the workshop is by invitation. Further information will be available at:

www.ecmwf.int/newsevents/meetings/workshops/2006/Reanalysis

ECMWF 2006 Annual Seminar: Polar Meteorology (4 to 8 September 2006)

In the context of the impending International Polar Year (IPY, 2007–9, www.ipy.org), this Seminar will provide a pedagogical review of the recent advances in our knowledge and understanding of polar atmospheric science, and of some of the key issues to be addressed in IPY. Subjects to be covered will include data assimilation, modelling and predictability challenges unique to such high latitudes including those associated with the land, ocean and cryosphere. Some attention will be focussed on the performance of NWP and climate-modelling systems in these regions and the nature and causes of identified deficiencies.

A registration form and further information is available from:

www.ecmwf.int/newsevents/meetings/annual_seminar/2006

Workshop on High Performance Computing in Meteorology (30 October to 3 November 2006)

Every second year the European Centre for Medium-Range Weather Forecasts hosts a workshop on the use of high performance computing in meteorology. The emphasis of this workshop will be on achieving sustained teraflops performance in a production environment, and on developing a vision for getting towards Petaflops computing. Our aim is to provide a venue where:

- Users from ECMWF's Member States and around the world can report on their experience and achievements in the field of high performance computing during the last two years; plans for the future and requirements for computing power will also be presented.
- Vendors of supercomputers will have the opportunity to talk to managers and end users of meteorological computer centres about their current and future products.
- Meteorological scientists can present their achievements in the development of parallel computing techniques and algorithms, and can exchange ideas on the use of supercomputers in future research.
- Computer scientists can give an update on their efforts in providing tools which will help users to exploit the power of supercomputers in the field of meteorology.
- The challenges of creating a computer centre infrastructure for High Performance Computing can be discussed.

Attendance at the workshop is by invitation and will be limited to around 100 persons. If you are interested, please contact the workshop organizers at:

hpcworkshop@ecmwf.int

Workshop on Parametrization of Clouds in Large-scale Models (8 to 10 November 2006)

The representation of clouds in large-scale models is still a challenging problem and the further development of the cloud scheme is central to ECMWF's plans. The purpose of the workshop is to review the most recent developments in this area of research and to explore new ideas. Aspects that will be addressed are:

- Cloud microphysics with consideration of more processes and prognostic variables than currently in the IFS.
- Statistical nature of cloud schemes.
- Interaction of clouds with radiation.
- Numerical methods for fast cloud processes in the NWP context.
- Verification using ground based and satellite observations with particular emphasis on ice clouds.

Further information about this workshop will be available on the ECMWF website:

www.ecmwf.int/newsevents/meetings/workshops/2006/Clouds

ECMWF turns 30: an opportunity to look back

Manfred Kloeppel

On 1 November 2005 ECMWF reached its 30th anniversary. The ECMWF Convention came into force on 1 November 1975, thus formally establishing ECMWF on that date.

The opportunity has been taken to record the foundation and establishment of ECMWF, and to review its work during its first three decades, in a book entitled *"Medium-Range Weather Prediction – The European Approach"*. The author of the book is Austin Woods, a former staff member.

The book starts with a Foreword by Prof. Anton Eliassen, President of the ECMWF Council, which includes the following.

Meteorologists have long recognised the need for greater co-operation between the different European states. Eventually, in 1967, following initiatives from the Council of the Commission of the European Communities, at the time a community of only six countries, a group of visionaries drew up a list of scientific and technical challenges in which "the possibility of international co-operation could be discussed". By the end of that year, a proposal had been made for the establishment of a "European Meteorological Computing Centre". This far-sighted initiative led to the setting up of the European Centre for Medium-Range Weather Forecasts (ECMWF), which on 1 November 2005 reaches its 30th anniversary.

The book recounts the tortuous path by which the visionary concepts were turned into reality, and how ECMWF developed into a world leader in the field of numerical weather prediction. The result is an institution which runs the world's most sophisticated medium-range prediction model of the global atmosphere and oceans, and holds in its archive the world's largest collection of numerical weather prediction data.

For further information about the book, including the table of contents, see:

www.springeronline.com/sgw/cda/frontpage/0,11855,4-40109-22-61703749-0,00.html

Co-operation Agreement with Estonia

Manfred Kloeppel

A Co-operation Agreement was signed between ECMWF and Estonia on 7 November 2005 in Tallin, Estonia.

Dominique Marbouty, Director of ECMWF, said: "The worldwide leadership of the ECMWF in the field of Numerical Weather Prediction is based on close collaboration with the European meteorological community. All nations now recognise the necessity of improving the quality and accuracy of advance warning of floods, gales and other severe weather events. I am looking forward to closer collaboration with the Estonian Meteorological and Hydrological Institute in extending the use of our medium-range and seasonal weather forecasts for the benefit of the people of Estonia."

Villu Reiljan, Minister of Environment of the Republic of Estonia, stated: "The European Centre for Medium-Range Weather Forecasts is the world leader in its area of scientific and technical expertise. The European Centre's products will greatly assist the Estonian Meteorological and Hydrological Institute to fulfil its mission including the protection of life and property. I am confident that both the ECMWF and the Estonian Meteorological and Hydrological Institute will benefit from their close co-operation in meteorology."

Dominique Marbouty (Director of ECMWF) and Villu Reiljan (Minister of Environment of the Republic of Estonia) signing the Co-operation Agreement between ECMWF and Estonia on 7 November 2005 in Tallin, Estonia.

Jaan Saar, Director General of the Estonian Meteorological and Hydrological Institute, said: "This Co-operation Agreement is a significant milestone for meteorology in Estonia. The data from the ECMWF supercomputer system will be vital for improving the overall quality of our forecasting, and for our warning services in advising of the likelihood of extreme weather events. Our meteorological staff will benefit from extending their contacts with their colleagues at the ECMWF. We will be using the Centre's products to extend both the range and the validity of our forecasts to the benefit of the people of Estonia. We very much welcome this Agreement."

When a Co-operation Agreement has been established, the Co-operating State:

- Has exactly the same access to ECMWF products as a Member State (dissemination, MARS, software, etc).
- Has access to servers (ECGATE) but does not have a supercomputer allocation.
- Makes a contribution to the ECMWF budget which is half what it would pay as a Member State.

To date, Co-operation Agreements have been concluded with Croatia, Czech Republic, Estonia, Iceland, Hungary, Romania, Serbia and Montenegro, and Slovenia.

Michèle Vesperini

Michèle Vesperini

Jean-Nöel Thépaut, Tony Mcnally

Michèle Vesperini, a French national, born in 1965, joined ECMWF as a Eumetsat funded Consultant in the Satellite Data Section of ECMWF between 1993 and 1994, before becoming an Associate-Professor in Physics at the University of Lille, where, as an expert in remote sensing (especially POLDER and SSM/I), she maintained many scientific contacts with the Centre.

While at the Centre, Michèle pioneered the use of well calibrated independent satellite data to understand deficiencies in NWP assimilation/forecasting systems. By comparing estimates of total column water vapour (TCWV) retrieved from the DMSP SSM/I microwave instrument with values computed from the ECMWF analysis/forecast fields, she was able to identify and quantify substantial systematic errors in our description of the hydrological cycle. She also demonstrated deficiencies in the then operational ECMWF model sea ice.

It is a testament to the exhaustive scientific rigour that backed up her findings and a particular skill in handling the delicate egos of her colleagues, that her results were so readily accepted and instigated immediate action to improve the handling of water vapour. She was centrally involved in this action, and challenged the then wisdom that NWP models were insensitive to humidity initial conditions. Again using the SSM/I as a validation standard, she found that many of the problems she had discovered with the humidity analysis could be substantially improved through the assimilation of infrared radiances. Possibly more significantly, she clearly demonstrated that this improvement was retained by the forecast model well in to the medium-range.

These were ground breaking results which provided a huge impetus to the satellite data assimilation community. She showed that satellite data could improve NWP systems both through diagnosis and active assimilation. The techniques she initiated with the SSM/I in the early 1990s have become an established practice today for model development and assessing the impact of observations upon the assimilation system.

During the time she spent at ECMWF, Michèle was an extremely pleasant person to work with. She was always full of energy and enthusiasm. She seemed able to smile all the time and was the best "deliverer of bad news" (about the model) that could ever be met. Long after she had left the Centre, she stayed in close contact with her colleagues in the Research Department at ECMWF, always generating active discussions and new collaborations on the use of satellite data, and this despite suffering from serious ill health.

Michèle died on 31 October 2005, after a long fight against her illness. Her scientific abilities and personality will be missed forever by her former colleagues and friends from ECMWF.

Honorary degree for David Burridge

Dominique Marbouty

On 8 July 2005, David Burridge, former Director of ECMWF, was awarded an honorary degree of Doctor of Science by the University of Reading. The picture shows him wearing the traditional attire for such occasions.

At the award ceremony Prof Brian Hoskins delivered the speech outlining the contribution David had made to the world of meteorology, with particular emphasis on the crucial role he has played in the development of ECMWF. It was noted that for many years ECMWF has led the world in the development of global weather forecasting systems and in producing the most accurate medium-range weather forecasts. Also ECMWF has taken the lead in ensemble weather prediction. Prof Hoskins emphasized the strong relationship which has developed over years between ECMWF and the Department of Meteorology at the University of Reading. As well as praising David for his scientific and leadership abilities, Prof Hoskins drew attention to David's characteristics of informality and friendliness.

The full text of the speech delivered by Prof Hoskins is available at:
www.rdg.ac.uk/graduation/speeches/

David Burridge

Ensemble prediction: A pedagogical perspective

Tim Palmer, Roberto Buizza, Renate Hagedorn, Andy Lawrence, Martin Leutbecher, Lenny Smith

The ECMWF Ensemble Prediction System (EPS) has featured extensively in the ECMWF Newsletter, including articles assessing the performance of the EPS, plans for EPS development, and applications to which the EPS has been used. For example, in ECMWF Newsletter No. 104, trends in EPS probability skill scores since 1994 were reviewed by Roberto Buizza. In this issue, the skill of the EPS in forecasting rainfall and potential vorticity is discussed by Mark Rodwell.

Despite the fact that the EPS brings additional value to ECWMF's dissemination products through its ability to assess flow-dependent weather risk, the EPS is a less straightforward tool to use than the more traditional deterministic forecast. Not surprisingly, therefore, conceptual questions are sometimes asked about the EPS. Here are some examples. What is the relationship between the spread and skill within the EPS? If the northern hemisphere RMS error of a typical ensemble member is routinely larger than that of the corresponding deterministic forecast, does this imply that this ensemble member is simply a degradation of the deterministic forecast? Should we be striving to reduce the RMS error of ensemble members relative to the deterministic forecast? Does it make a difference if we ask how many ensemble members are better than the deterministic forecast locally, compared with hemispherically? Are the baroclinically-tilted structures often seen in the EPS initial perturbations consistent with our knowledge of analysis error? Perhaps most important of all

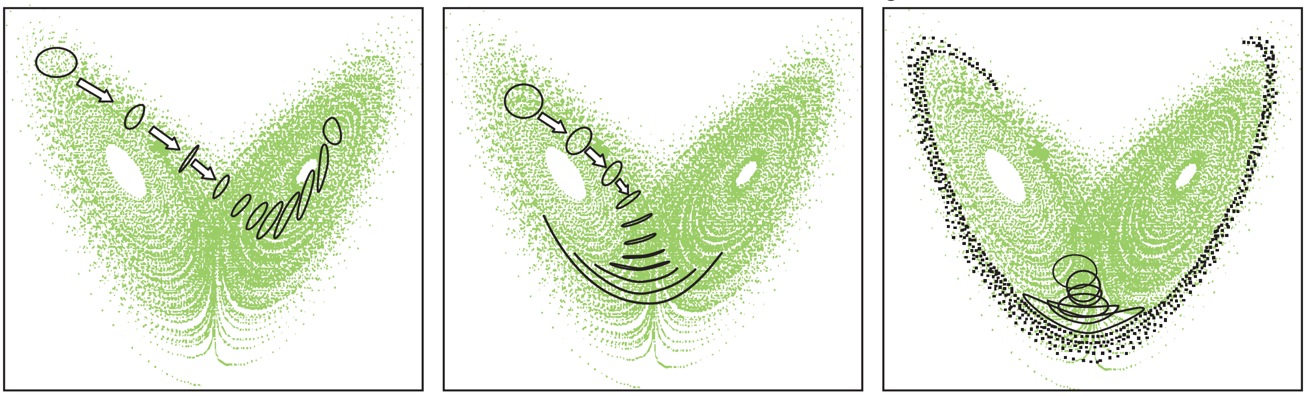

Figure 1 Scientific basis for ensemble forecasting. In a nonlinear system the growth of initial uncertainty is flow dependent – here illustrated with the Lorenz (1963) model. The set of initial conditions (black circle) is located in different regions of the attractor in (a), (b) and (c).

is this question: Is it really worth running the EPS when ECMWF has such a high-quality deterministic forecast?

We try to answer these and other related questions in this article, which, therefore has a more pedagogical flavour to others on the EPS which have appeared in the ECMWF Newsletter.

Properties of a perfect Ensemble Prediction System

The scientific basis for ensemble forecasting is encapsulated in Figure 1. In a nonlinear system, here the Lorenz (1963) model, but the principle applies to the real atmosphere too, the growth of initial uncertainties during a given forecast period is flow dependent. From some initial states the forecast evolution can be highly predictable, from other initial states it can be highly unpredictable. The ensemble allows us to forecast this flow-dependent predictability.

The illustration in Figure 1 has been formed by integrating the Lorenz equations many times from an ensemble of initial states which form a small circle in the nonlinear system's state space. It is to be imagined that the radius of the circle is some measure of the expected amplitude of initial error.

More generally, the data from which the initial state (at time t_0) is constructed (e.g. atmospheric observations), do not determine this state precisely, but rather determine some probability density function $\rho(X,t_0)$. Essentially $\rho(X,t_0)\ dV$ denotes the probability at time t_0 that the true value X_T of the variable X (for example, 2-metre temperature at London's Heathrow airport) lies in the small volume dV in state space. The objective of an EPS is to estimate the corresponding forecast probability density function $\rho(X,t)$ at forecast time $t > t_0$. In theory, $\rho(X,t)$ can be obtained from $\rho(X,t_0)$ by integrating an equation called the Liouville equation, or its generalisation, the Fokker-Planck equation. In practice, these equations are difficult to solve, even for simple dynamical systems. Instead, and consistent with the methodology applied to obtain Figure 1, $\rho(X,t)$ is estimated by multiple sampling of $\rho(X,t_0)$ integrating each random drawing forwards in time using the given forecast model. Hence, at time t, we can define a perfect EPS as an accurate sampling $\{X_i\}\ 1 \le i \le N$ of the underlying density function $\rho(X,t)$, see Figure 2.

Suppose this procedure is repeated every day, and over a season or so. What mean properties would we expect such an EPS to have? One basic quantity of interest is the second moment of the ensemble – the spread. When the EPS spread is large, then a deterministic forecast from the most likely estimate of initial state (the 4D-Var initial state) will be an unreliable estimate of truth. Conversely, when the EPS spread is small, the corresponding deterministic forecast should be reliable. But what relationship between the spread of the ensemble and the skill, say, of the ensemble-mean deterministic forecast is desirable? This can be answered by considering a perfect EPS, which constitutes a perfect sampling of the underlying probability distribution of the true state of the atmosphere, "truth". In a perfect EPS, the time-mean ensemble spread about the ensemble-mean forecast equals the time-mean RMS error of the ensemble-mean forecast (using truth as verification) – see Box A.

Figure 3 shows that the relation between spread and ensemble-mean RMS error of the ECMWF EPS is good –

Box A The relationship between spread and ensemble mean RMS error in a perfect ensemble

In a perfect ensemble, i.e. a perfect sampling of the underlying probability distribution of truth, then, over a large number of ensemble forecasts, the statistical properties of the true value X_T of X are identical to the statistical properties of a member of the ensemble, X_e (when that member is removed from the ensemble). For the following analysis of spread and skill, we assume that the ensemble size N is sufficiently large that removing one member from the ensemble does not materially affect the results. Hence, for example, the mean squared distance of the J-th member $X_e(J)$ from the ensemble mean $\langle X_e \rangle$ is identical to the mean squared error of the ensemble mean

$$\overline{\left\| X_e(J) - \langle X_e \rangle \right\|^2} = \overline{\left\| X_T - \langle X_e \rangle \right\|^2} \qquad \text{(A1)}$$

where $\langle \ldots \rangle$ denotes the expectation value with respect to a particular ensemble forecast, and $\overline{\ldots}$ denotes an average over many such ensemble forecasts. Equation (A1) holds for any J and it can be applied to a scalar quantity X or to a vector $\mathbf{X}$. In the latter case, $\| \ldots \|$ should be understood as the Root Mean Square (RMS) or the Euclidean norm. Taking the expectation $\langle \ldots \rangle$ of Equation (A1) yields

$$\overline{\left\langle \left\| X_e - \langle X_e \rangle \right\|^2 \right\rangle} = \overline{\left\| X_T - \langle X_e \rangle \right\|^2} \qquad \text{(A2)}$$

Equation (A2) implies that the time-mean ensemble spread about the ensemble-mean forecast, should equal the time-mean RMS error of the ensemble-mean forecast.

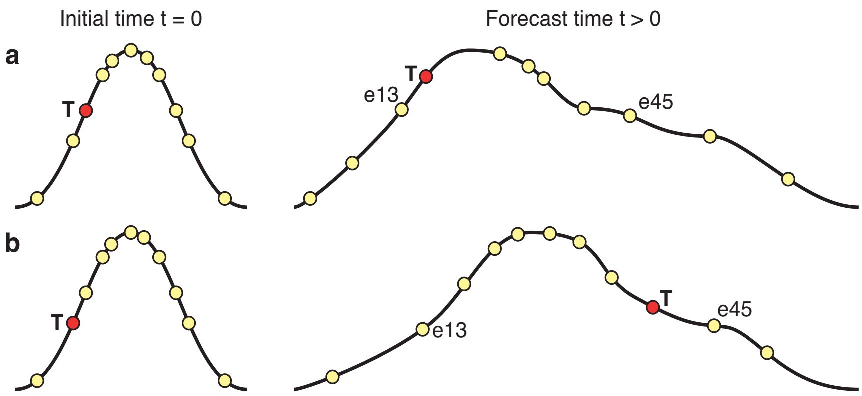

Figure 2 A schematic showing the evolution of initial probability distributions of truth, to a forecast probability distributions of truth, together with an sample of ensemble members (e_i) from a perfect EPS. Truth is shown by the letter "T". In the examples shown (a) could represent a forecast of 2-metre Heathrow temperature today, with (b) representing a forecast of 2-metre Heathrow temperature from last week, or (a) could represent a forecast of 2-metre Heathrow temperature today, whilst (b) could represent a forecast of 2-metre Washington temperature today.

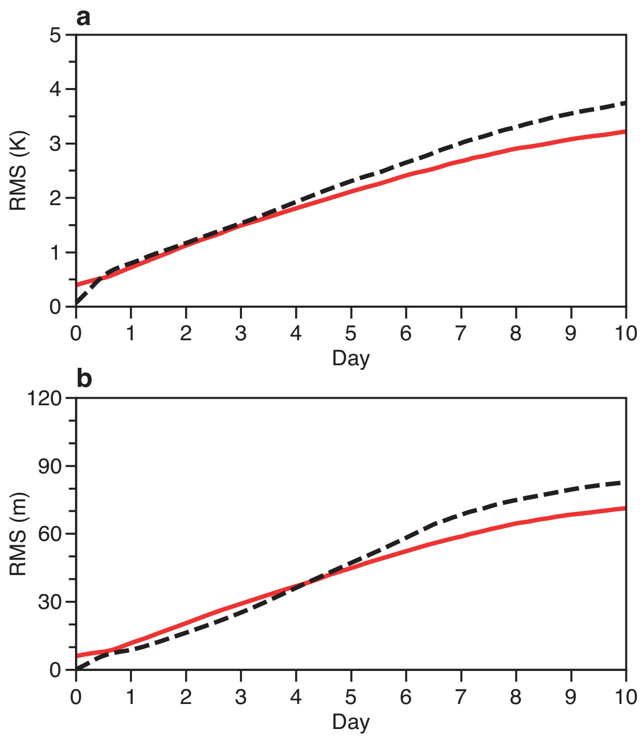

Figure 3 Spread about ensemble mean (red solid) versus ensemble mean RMS error (black dashed) from the EPS for the northern hemisphere extra-tropics. (a) 850 hPa temperature and (b) 500 hPa height. Average over 39 cases from July 2004 to June 2005 using model cycle Cy29r2 (operational since 28 June 2005).

though the ensemble is slightly under-dispersive in terms of 850 hPa temperature, and, in the early range, slightly over-dispersive in terms of 500 hPa height. Recently a comparison has been made between operational and quasi-operational EPS systems at different weather centres around the world (*Buizza et al.*, 2005). It was found that the ECMWF system has the best balance between spread and skill, relative to the ensemble mean forecast, throughout the forecast range.

What are the implications of a good balance between spread and skill? Figure 2 shows two schematic probability distribution functions (PDFs) for a perfect EPS. These could represent forecasts of Heathrow temperature today and Heathrow temperature last week, or alternatively forecasts for Heathrow and Washington temperatures today. In Figure 2(a), truth is (by chance) close to ensemble member 13 and far from ensemble member 45, whilst in Figure 2(b), the converse is (by chance) true. How far is truth from an ensemble member on average over many cases? For a perfect EPS it can be shown that the RMS distance of an ensemble member from truth, i.e. the RMS error of the ensemble member, is a factor of $\sqrt{2}$ larger than the RMS distance of the ensemble mean from truth (i.e. the error of the ensemble mean) – see Box B. Diagnostics of the ECMWF EPS are qualitatively consistent with this property of a perfect EPS. However, this fact has led to some conceptual difficulties amongst users of the EPS. *Does it mean that a perturbed EPS member is no better than a forecast which has simply been degraded everywhere relative to the control?* No! For example, the circulation over the Northern Hemisphere as a whole comprises a number of quasi-independent synoptic systems – i.e. a forecast PDF is multi-dimensional, with the number of dimensions corresponding to the number of effective degrees of freedom in the northern hemisphere flow. In a randomly-chosen member from a perfect EPS we can expect some of these synoptic systems to be more accurately predicted than the control, but others will not. By contrast, a uniformly-degraded deterministic forecast will, by construction, be everywhere worse than the control. The difference is critical.

Conversely, if we tried to make each perturbed member more skilful relative to the control, will this make a better EPS? No! A simple way to make perturbed members more skilful, is to reduce the amplitude of the initial perturbations. Figure 4 shows results from a set of experiments where just this has been done. The skill of the resulting EPS has degraded, even though individual perturbed members are, on average, more skilful. Confusing? The problem with reducing spread is that the resulting EPS suffers from being tied too closely to the "apron strings" of the control. When the control forecast is evolving through an unstable and therefore unpredictable part of state space, the resulting EPS will not give a realistic indication of the magnitude of this unpredictability and the resulting probabilistic forecast will be over-confident.

Consider a related question: how many times should we expect, in a perfect EPS, a perturbed ensemble member to be "better than" the control forecast, in the early range of the forecast when the control is essentially the same as the ensemble-mean forecast? The answer to this question depends on how large an area we base our assessment of "better than".

Box B The relationship between the RMS error of the ensemble mean and the RMS error of an ensemble member in a perfect ensemble

Here, the same notation as in Box A is adopted. In a perfect ensemble, we have

$$\overline{\left\langle \left\| X_e - X_T \right\|^2 \right\rangle} = \overline{\left\langle \left\| \left(X_e - \langle X_e \rangle \right) + \left(\langle X_e \rangle - X_T \right) \right\|^2 \right\rangle} = 2\,\overline{\left\langle \left\| X_T - \langle X_e \rangle \right\|^2 \right\rangle} \qquad \text{(B1)}$$

where the last equality exploits Equation (A2) from Box A and the fact that the term involving the (inner) product vanishes because $\left\langle X_e - \langle X_e \rangle \right\rangle = 0$. In the short range, where the ensemble mean approximates well the unperturbed control forecast we have

$$\overline{\left\langle \left\| X_e - X_T \right\|^2 \right\rangle} = 2\,\overline{\left\langle \left\| X_T - X_c \right\|^2 \right\rangle} \qquad \text{(B2)}$$

where X_c denotes the forecast value associated with the unperturbed deterministic control forecast. Equations (B1) and (B2) imply that the RMS distance between a perturbed ensemble member and truth will be, on average, $\sqrt{2} - 1 \approx 41\%$ larger than the distance between the ensemble mean, and in the short range the control, and truth.

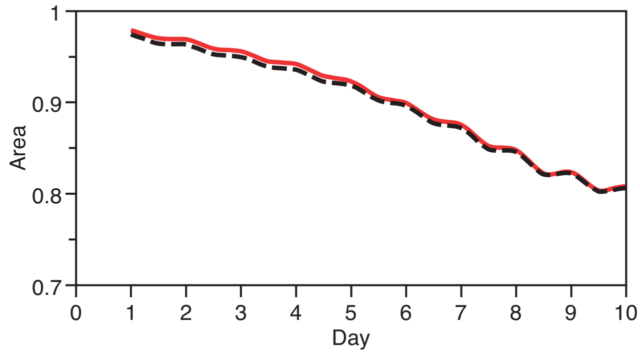

Figure 4 Area under the Relative Operating Characteristic for positive anomalies of 850 hPa temperature for the operational EPS (red solid) and for an experiment in which the amplitude of the EPS perturbations has been reduced (black dashed; initial singular vectors by 30%, evolved singular vectors by 50%). Average for the northern hemisphere extra-tropics over 29 cases in April/May 2005. Both experiments used model cycle Cy29r2.

For a variable like Heathrow 2-metre temperature (with one-dimensional Gaussian PDF), it can be shown (see the Appendix) that a perturbed ensemble member has a 35% chance of being closer to truth than the control – hence in a perfect EPS, 35% of ensemble members should be "better" than the control. However, recall that if an ensemble member is close to truth at Heathrow, it need not be close to truth at Washington, and vice versa. The larger the area over which the (deterministic) skill of the ensemble member is validated, i.e. the larger the dimension of the forecast PDF, the smaller is the probability that a randomly-chosen member will be more skilful than the control. This effect can be quantified by considering a multi-dimensional Gaussian (corresponding to multiple degrees of freedom in the flow), and again asking how many times a perturbed ensemble member is "better than" the control forecast using RMS error as measure (see Appendix for mathematical details). For a 2-dimensional Gaussian 28% of members are better, for a 10-dimensional Gaussian 7% of members are better, and for a 100-dimensional Gaussian only 10^{-4} % of members are better!

Again, this result causes confusion. In a specific ensemble forecast, if we plot the northern hemisphere RMS error of the perturbed ensemble members of an ensemble on top of the control or high resolution deterministic forecast, then because there are so many degrees of freedom over the whole northern hemisphere, it is likely, from the argument above, that none of the members will be more skilful than the control. On the other hand, as discussed above, any one perturbed member may well be more skilful than the control over a specific region, such as Southern England. This is illustrated by Figure 5 which shows the percentage of perturbed forecast with smaller RMS error than the control forecast for regions of various sizes.

The dependence of the number of ensemble members more skilful than the control on the number of degrees of freedom in the flow, is a reason why this type of diagnostic is not calculated routinely, and is certainly not one of the standard measures of skill against which the EPS is assessed. So, this raises the following question: What types of diagnostic are useful for assessing the performance of the EPS against the control or the high-resolution forecast? Indeed, can we assess quantitatively whether it really is worth running the EPS when ECMWF has such a high-quality deterministic forecast? The following sections address this question.

The EPS ensemble mean versus high-resolution deterministic forecast

The simplest product from the EPS is the ensemble-mean forecast. How does this product compare with the high-resolution deterministic forecast? In the accompanying article by Mark Rodwell in this Newsletter, it can be seen that in terms of 500 hPa height, the ECMWF high-resolution deterministic forecast outperforms the EPS ensemble mean in the first few days of the forecast. This is not surprising; in terms of 500 hPa height, the EPS ensemble mean is essentially equal to the control forecast in the first couple of days of the forecast, and the control forecast is run at a lower resolution than the high-resolution deterministic forecast. However, the results are more interesting for variables like precipitation or potential vorticity (an intrinsic model variable – i.e. based on wind, pressure and temperature – with a spectrum of variability which is more comparable with "sensible weather" than 500 hPa height, at sub-cyclone scales). For these variables, the EPS ensemble mean is, on average, virtually as skilful as the high-resolution deterministic forecast in the early ranges of the forecast (and more skilful thereafter), despite the EPS being run at lower resolution. The reason for this is that fields like precipitation and potential vorticity (unlike 500 hPa height) have significant partially-unpredictable scales, even in the short range. The nonlinear filtering effect of the ensemble mean is effective in removing such unpredictable scales.

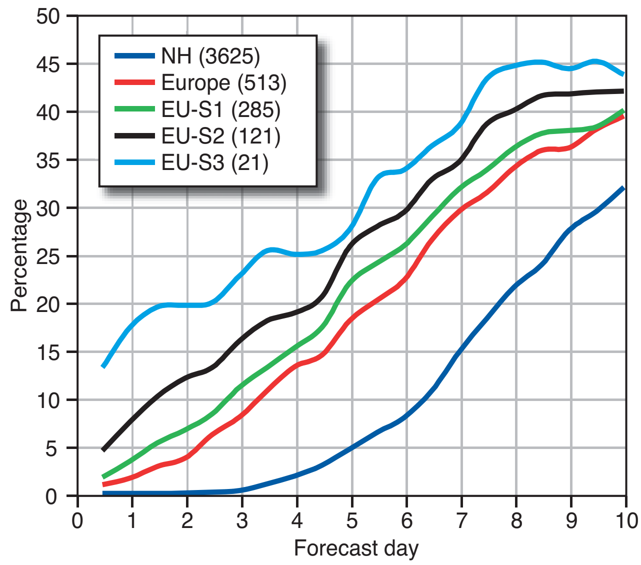

Figure 5 Percentage of perturbed forecasts with lower RMS error than the control forecast for regions of various sizes; the number of verification grid points is given in parentheses (NH refers to the northern hemisphere extra-tropics and EU-S1-3 are European sub-domains of increasingly smaller size corresponding to large, medium-size and small member states).

EPS versus deterministic forecast for binary decision making

The real value of the EPS over deterministic forecasting lies in decision making particularly for users who can quantify their "value at risk", i.e. the value of assets at risk to specific types of adverse weather event, and can take mitigating action at known cost.

Here is an example, which appears facetious, but illustrates the principle well. A colleague once phoned on a Monday morning, wanting to know whether or not it was going to rain the coming Saturday evening. He said he was having a garden party, and wanted to know whether or not to hire a marquee. He had to decide whether or not to hire the marquee in the next couple of hours. It was explained that predicting rainfall with certainty, so far ahead and for such a small area (his back garden), was virtually impossible; at best it would only be possible to give a probabilistic assessment of whether or not it would rain. What use is that, he asked? It was enquired whether the Queen was coming to the party. If the Queen was coming, then the marquee should be hired if the probability of rain exceeds 1% (i.e. if any member of the EPS predicts rain). On the other hand, if the queen was not coming but the town mayor was, then perhaps the marquee should be hired if there is more than a 10% chance of rain. However, if the party was just for friends from the pub, then perhaps it was only necessary to hire the marquee if the chance of rain exceeds 70%.

The value of the EPS against the deterministic control for such binary decision making is assessed routinely at ECMWF in the form of Potential Economic Value (Figure 6). Here the x-axis of Figure 6 denotes the user cost-loss ratio. We can relate the cost-loss ratio to the probabilistic threshold above. For example, suppose the colleague valued his potential knighthood at £50,000; this would be the value at risk if the Queen got wet. If hiring the marquee costs £500 (mitigating cost), then it would be appropriate to decide to hire the marquee if the probability of rain exceeded C/L=1%, i.e. if just one EPS member forecasts rain. On the other hand, the value of local business at risk if the town mayor got wet might only be worth £5,000, in which case the relevant cost/loss ratio would only be 10%.

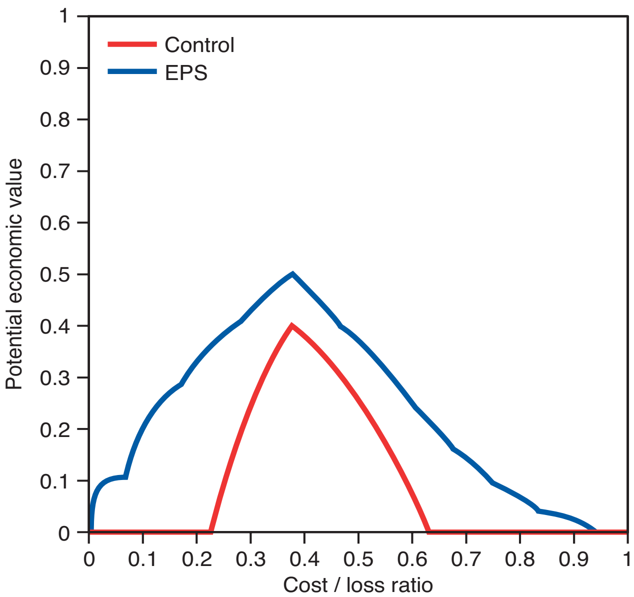

Figure 6 Potential economic value for the ECMWF EPS control and the EPS itself based on six-day forecasts of whether or not it will rain (24-hour precipitation exceeding 1 mm, August–October 2005, Europe). The potential economic value ranges between 0 (climatological forecast) and 1 (perfect forecast). For users with either low cost/loss ratio, or high cost/loss ratio, the control itself has no value for decision making (over and above decisions made with knowledge of the climatological frequency of rain).

The colleague responded that neither the queen nor the mayor was coming, but the mother in law was! On this basis, he decided he would hire the marquee if the probability of rain exceeded 25%. The EPS for Saturday showed the probability of rain was 10%. He didn't hire the marquee. (It didn't rain, and the colleague was a convert to probability forecasting!)

Realising the true economic value of the EPS requires knowledge of the forecast customers' specific circumstances. Perhaps this will be a key role for the forecaster in the future – a detailed interaction with the customer to determine the most appropriate probabilistic thresholds tailored to his or her specific needs.

EPS versus deterministic forecasts for weather trading

Not all decisions are simple binary decisions. Consider a simple gambling game – perhaps not so different to that played by energy traders – where you are betting on the Heathrow temperature seven days from now. Should you just bet on one temperature, or spread your bets across a range of temperatures, e.g. in proportion to the EPS-based probability of occurrence? Assume the "casino" you are betting against has determined the payout for a correctly-forecast temperature, based on a Gaussian distribution whose mean is the ECMWF high-resolution forecast of Heathrow temperature, and whose standard deviation is taken from past error statistics of the high-resolution forecast. This is the so-called Weather Roulette problem first posed by Leonard Smith (London School of Economics) and Mark Roulston (Pennsylvania State University). The gamble starts on the first of January with an initial stake of £1. All the winnings are reinvested. Based on day 7 forecasts, Figure 7(a) shows that, after a year, the gambler using the EPS will have made more than £10^{30} against the casino! It turns out that the EPS gambler will win against the casino at all forecast ranges, though the payout is largest at about day 6–7.

Suppose the gambler had access to the high-resolution deterministic. Could he improve his strategy by combining the high-resolution deterministic forecast with the EPS. Figure 7(b) shows that for lead-times up to 4 days, a betting system based on an optimal blend of high-resolution and EPS probabilities leads to a positive return when played against odds based solely on the EPS. However, after about day 4 there appears little extra value in adding the high-resolution deterministic forecast to the EPS. (*Rodwell*, 2005, discusses the potential impact of adding the high-resolution deterministic forecast to the EPS in terms of precipitation.)

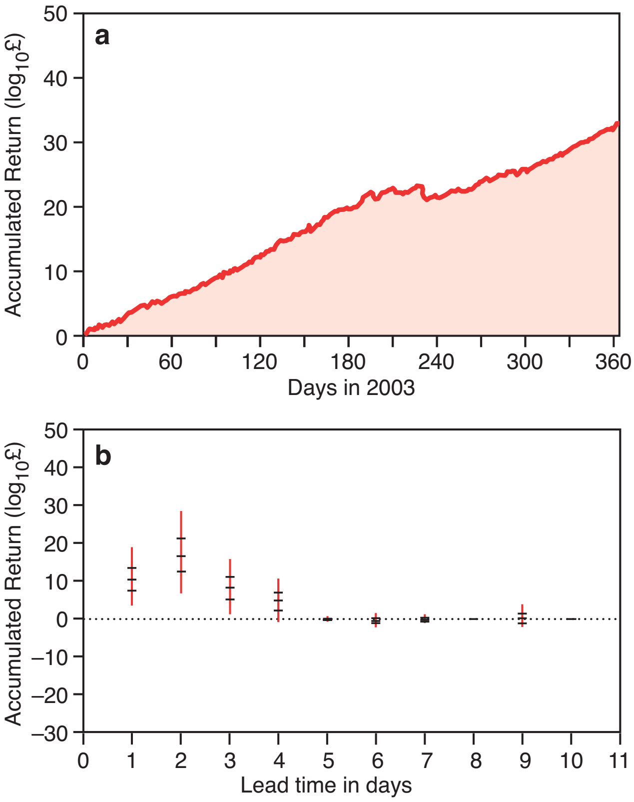

Figure 7 Weather Roulette. (a) Return accumulated over 1 year when betting against the casino which sets the odds for 2-metre temperature at Heathrow seven days ahead according to the dressed high-resolution deterministic forecast, whereas the gambler distributes the available money in proportion to dressed EPS probabilities. (b) Accumulated return after 1 year of betting on 2-metre temperatures at Heathrow for lead-times from 1 to 10 days. Here the odds are set by the dressed EPS probabilities and the gambler distributes the available money in proportion to the optimal blend of high-resolution and EPS probabilities. The vertical bars represent the range of returns determined by bootstrapping the data, with horizontal lines marking the 5% / 95% intervals and the median.

Weather Roulette is an example of a validation technique which compares the EPS and deterministic forecast in a form where both have been optimally dressed in the form of probability forecasts. It clearly demonstrates the value of the EPS throughout the forecast range.

EPS perturbation methodology

Sometimes it is asked whether the EPS is superior to a simple lagged ensemble comprising some of the most recent high-resolution forecasts. It is superior for a number of reasons. Firstly, it is impossible to create a probability forecast with any substantial resolution using just five or so members (with more than about five members, the lagged members become too unskilful at the effective initial time, to represent analysis error). Matters are actually worse than this, since the individual forecasts in a lagged ensemble are partially correlated with respect to one another. That is, on average, the error covariances in a lagged ensemble are significantly larger than the error covariances between members of the EPS. Figure 8 shows a comparison of the EPS with a lagged ensemble comprising the five most recent high-resolution deterministic forecasts. Figure 8(a) shows that the percentage of ensemble members better than the control is similar in both cases, whilst Figure 8(b) shows that the skill of the EPS is substantially greater than that of the lagged ensemble. A Weather Roulette analysis supports this conclusion: the EPS outperforms the simple lagged high-resolution forecasts.

The initial perturbation strategy for the ECMWF EPS is to draw randomly from an initial Gaussian PDF based on (a) the leading initial-time singular vectors of the first 48 hours of the forecast flow, and (b) the evolved singular vectors from the previous 48 hours (e.g. *Molteni & Palmer*, 1993, *Barkmeijer et al.*, 1999). The former are rapidly-growing, small-scale perturbations, the latter are weakly-growing, large-scale perturbations.

Figure 9(a) shows a typical initial singular vector as used in the EPS. It has sometimes been questioned whether such baroclinically-tilting structures really are a feature of analysis errors. Similarly, the uniqueness of these singular vector structures has also been questioned, since they depend on the choice of an initial metric. So, can the use of singular vectors for initial EPS perturbations be justified from sound physical principles?

The natural inner product to use for singular-vector calculations is the analysis error covariance metric, since, evolved to forecast time, these singular vectors map directly onto the eigenvectors of the forecast error covariance matrix

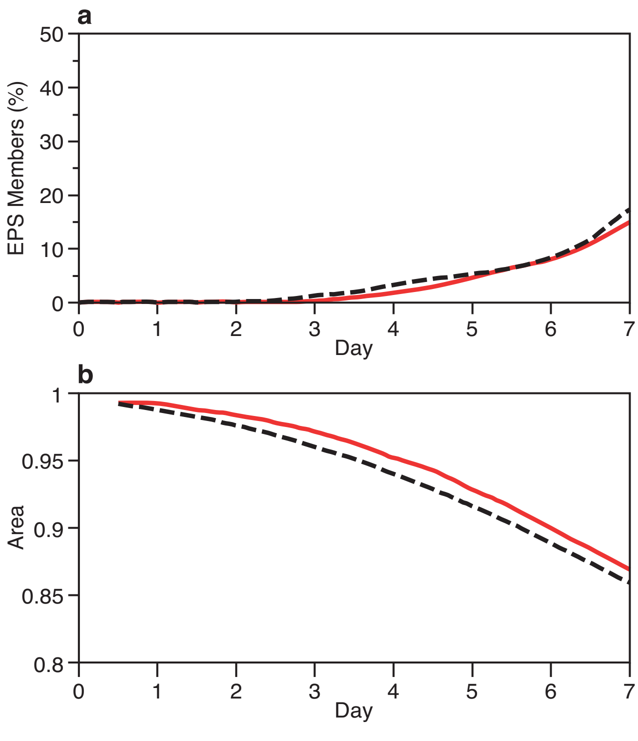

Figure 8 Comparison of the EPS (red solid) against a lagged ensemble (black dashed) comprising the most recent five high-resolution deterministic forecasts of the 500 hPa height for the northern hemisphere extra-tropics. (a) Percentage of members with lower RMS error than control forecast. (b) Area under the Relative Operating Characteristic for positive anomalies of 500 hPa height. December–February, 2004/05, 90 cases.

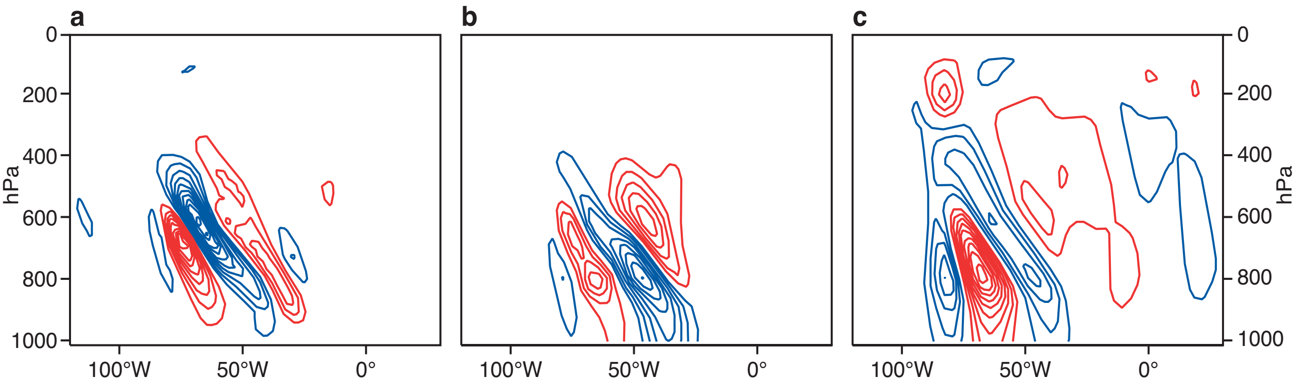

Figure 9 Example of a singular vector (temperature cross-section at 50°N): (a) based on a total energy inner product, (b) based an analysis error covariance matrix inner product, and (c) based on a background error covariance matrix inner product (positive values in red; negative values in blue).

(*Ehrendorfer & Tribbia*, 1997). Figure 9(a) shows a leading singular vector calculated with respect to a total energy inner product. *Palmer et al.* (1998) argued that such an inner product should approximate well the inner product formed from the analysis error covariance metric.

It is now possible to calculate singular vectors using the 4D-Var estimate of the analysis error covariance matrix. Figure 9(b) shows the same singular vector as Figure 9(a), but using the analysis error covariance metric, rather than the total energy metric. Figure 9(b) is very similar to Figure 9(a), suggesting that the EPS perturbations are indeed consistent with the statistics of analysis error. It is interesting to note that the structure of these singular vectors is strongly influenced by the presence of the observation term in the total analysis error covariance matrix. The role of observations is to constrain large-scale well-observed parts of the analysis. Without this constraint, i.e. by not including the observation term in the estimate of the analysis error covariance matrix, the leading singular vectors are broader and deeper than they would otherwise be – more similar to breeding vectors (Figure 9(c)).

Conclusions

The EPS is a valuable tool for decision making in applications sensitive to weather. Certain properties of the EPS have been studied, and some conceptual misunderstandings have been addressed. Above all, there can be little doubt that the resources devoted by ECMWF to the EPS are well justified.

On the other hand, there is certainly scope for improving the EPS, and ECMWF will be working with partners from the Member States on many aspects of the EPS. Such improvements will include:

- Increase in EPS resolution from T255 L40 to T399 L62;
- Unified ensembles for medium-range and monthly timescales;
- Development of back statistics from latest model cycles to calibrate probabilities;
- Incorporation of moist processes in the extra-tropical singular vector computations;
- Development of stochastic parametrisations to represent model error;
- Use of ensemble data assimilation in place of evolved singular vectors;
- Development of statistical schemes which will allow incorporation of high-resolution deterministic forecast into the EPS probability products;
- Comparison of ECMWF EPS against THORPEX grand multi-model ensemble.

In particular, the development of stochastic parameterisation and ensemble data assimilation will lead to a more realistic representation of model and initial uncertainties in the tropics, where the current EPS is, overall, underdispersive.

More information about ensemble methods for forecasting predictability can be found in *"Predictability of Weather and Climate"*, edited by Tim Palmer and Renate Hagedorn, which is due to be published by Cambridge University Press in 2006. The book addresses predictability from the theoretical to the practical points of view, on timescales from days to decades.

Appendix. Perfect ensembles sampled from Gaussian distributions

This appendix investigates how often a member of an ensemble is better than the control forecast for a particular *perfect ensemble* scenario. This idealized situation is adopted as it permits a semi-analytical solution. We assume the following:

- The system and forecasts of it are n-dimensional vectors.
- The control forecast (most likely state) is an unbiased estimate of the true state.
- The error of the control forecast (control-minus-truth) is distributed according to an isotropic Gaussian distribution.
- The "ensemble" is given by the same Gaussian distribution. The results that will be discussed are independent of ensemble size. The ensemble could consist of any number of members drawn from the Gaussian distribution or alternatively one can consider the Gaussian distribution itself as the probabilistic forecast.
- Thus, the control-minus-truth differences and the control-minus-ensemble member differences are distributed according to the same isotropic Gaussian distribution. Without loss of generality, we can assume that the control

forecast is zero (otherwise we can discuss everything in terms of differences with respect to the control forecast).
- The Euclidean norm will be used to measure the error of a forecast.

Let us start with the one-dimensional case. The Gaussian with standard deviation σ is given by:

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}$$

The probability of an ensemble member x to be closer to the true state y than the control forecast 0 is given by the double integral:

$$\rho_1 = \int_{\mathbb{R}} p(y) \int_{|x-y|<|y|} p(x)\,dx\,dy$$

where $\mathbb{R}$ denotes the set of real numbers. In this equation, the integral over x yields the probability that an ensemble state x is closer to a given true state y than the control. These probabilities are then weighted with the probability that y occurs in the outer integral. Numerical evaluation yields $\rho_1 = 0.35$.

Now, we turn to the n-dimensional case. We consider an isotropic Gaussian distribution. The probability that an ensemble member $\mathbf{x}$ is closer to truth $\mathbf{y}$ in the Euclidean norm than the control forecast $\mathbf{0}$ can be expressed by the $2n$-dimensional integral:

$$\rho_n = \int_{\mathbb{R}^n} p(\mathbf{y}) \int_{\|\mathbf{x}-\mathbf{y}\|<\|\mathbf{y}\|} p(\mathbf{x})\,d^n x\,d^n y$$

where

$$p(x_1,..,x_n) = \frac{1}{\left(\sqrt{2\pi}\sigma\right)^n} \exp\left(-\frac{1}{2}\sum_{j=1}^{n}\frac{x_j^2}{\sigma^2}\right)$$

and where the Euclidean norm is denoted by:

$$\|\mathbf{z}\| = \left(\sum_{j=1}^{n} z_j^2\right)^{1/2}$$

As in the one-dimensional case, ρ_n is independent of the standard deviation σ. Exploiting the spherical symmetry of the Gaussian probability distribution function, the $2n$-dimensional integral can be reduced to a three-dimensional integral for any n. The latter integral can be evaluated numerically (see the table). The results show that as the dimension increases a perturbed forecast is less likely to be better than the control forecast. For dimensions larger than 100, the probability drops to values below 10^{-6}.

	Dimension n								
	1	2	3	4	5	10	20	50	100
ρ_n	0.35	0.28	0.22	0.18	0.16	0.07	0.02	4×10^{-4}	1×10^{-6}

Probability that the RMSE of a perturbed member is smaller than the RMSE of the control forecast for an isotropic Gaussian in n dimensions.

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Comparing and combining deterministic and ensemble forecasts: How to predict rainfall occurrence better

Mark J. Rodwell

Present ECMWF medium-range forecast products include a high-resolution (T511) "deterministic" forecast (termed here "DET"), a lower-resolution (T255) "control" forecast (termed here "CNT") and a 50-member T255 "ensemble prediction system" ("EPS") of forecasts initiated from perturbed initial conditions. Naturally, there is considerable debate about which forecast system, DET or EPS, is better, or at least about how ECMWF should divide its resources between deterministic and probabilistic forecasts. Here these two systems are compared using deterministic and probabilistic skill scores but the main conclusion is that direct comparison is not straightforward and is actually not very useful. This led to a different approach being taken which attempts to harness the best elements of DET and EPS to produce a combined prediction system ("CPS") of European station-location precipitation.

Rainfall has fine spatial scale structure, low predictability and is important to forecast and thus offers perhaps the best chance of finding benefit in both forecast systems which is relevant to the users. It is found that the CPS is significantly better than

EPS at forecasting the probability of occurrence of European rainfall at all lead-times to D+10. The optimal weight applied to the DET forecast within the CPS is found to be equivalent to 17 EPS members at day+1 (D+1), dropping to 2.5 EPS members by D+10. It is found that the aspect of DET that leads to the increased skill is its higher resolution, and not the fact that it is initiated from a slightly better (unperturbed) estimate of the true state of the atmosphere. Results point to the variable resolution EPS (VAREPS) as the optimal framework for precipitation forecasting in that the benefits of short lead-time resolution are combined with longer lead-time probabilities.

Definition of parameters and recent improvements in deterministic forecast skill

Clearly it is important to know how good our forecasts are and to document our progress over the years in improving these forecasts. The parameter most commonly used to score weather forecasts is geopotential height at 500 hPa (Z_{500}). Spatial anomaly correlations between the forecast and observed (i.e. analysed) Z_{500} have improved over the years so that, for the Northern Hemisphere as a whole, a D+7 forecast made in 2001 was on average as good as a D+5 forecast made in 1980 (*Simmons & Hollingsworth*, 2002). Here we consider how the skill of Z_{500} and two other parameters, including precipitation, have changed since 2001.

The top set of curves in Figure 1 show annual means of the spatial Anomaly Correlation Coefficients (ACCs) of the DET forecasts for European Z_{500} as a function of forecast lead-time. Different colours represent different years. It can be seen that the trend to improved forecast skill (up to D+6) has continued year-on-year. Beyond D+6 the trend is less clear but this may simply reflect increased uncertainty in the ACC estimate at longer lead-times, as indicated by the 95% confidence intervals in the plot.

Although there has been a continual improvement in the prediction of Z_{500} over the years it is clear that, for short forecast lead-times, there is little extra skill in terms of the anomaly correlation to be gained in the future. However, this does NOT mean that our job is complete as far as extratropical medium-range forecasting is concerned. The Z_{500} field emphasises the atmospheric circulation on very large spatial scales (perhaps 1000 km). It is clearly worth investigating the forecast skill on shorter spatial scales and using variables that are of particular interest to users of forecasts. Here, we concentrate on the skill of the DET forecast to predict two additional variables: potential temperature on the PV = 2 surface (see below) and total precipitation (convective plus stratiform).

Potential temperature on the PV = 2 surface (θ_2) is chosen because it is related to Potential Vorticity (PV) which varies on smaller spatial scales. The conservation properties of PV may allow us, in the future, to investigate the causes of forecast error. The PV = 2 surface approximates the tropopause in the extratropics. An additional advantage of using θ_2 is that it is archived from both the EPS and DET forecasts.

The middle set of curves in Figure 1 show the European ACC scores for θ_2 from the DET forecast. These scores are lower than those for Z_{500}. The trend over the years is still upwards but it can now be seen that we still have plenty of scope for improving the ACC skill of forecasts of synoptic and smaller-scale features such as tropopause folds and intense cyclones.

Precipitation is one of the hardest quantities to predict yet it is something that is of particular interest to users. Here we bi-linearly interpolate forecast precipitation from the model grid to European SYNOP station locations so that we are scoring our ability to predict rainfall at a point (literally raindrops falling on your head!). The station-location point precipitation is referred to here as P_p.

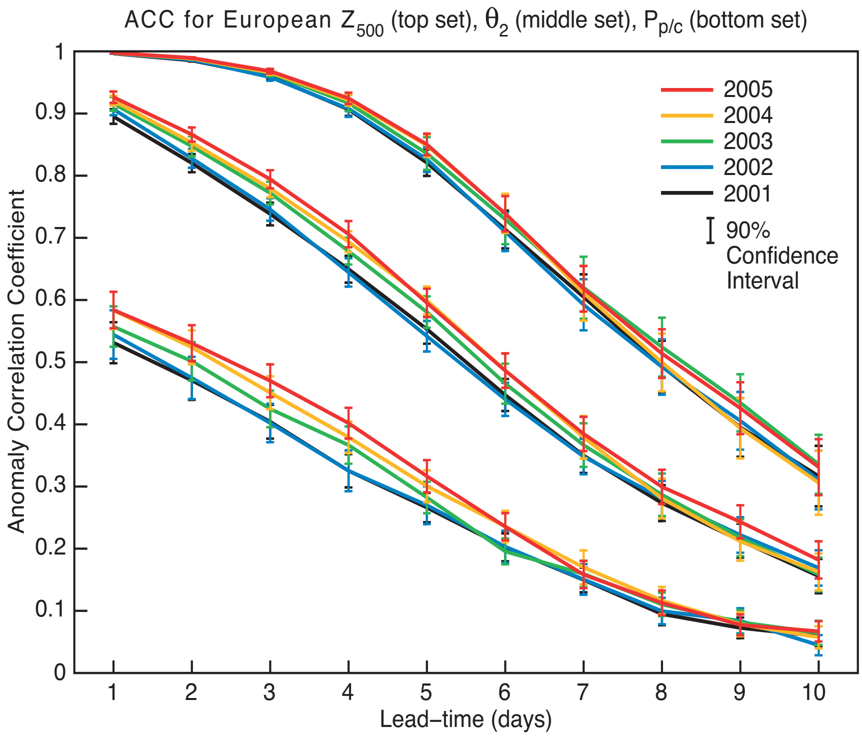

Figure 1 Spatial Anomaly Correlation Coefficients (ACCs) of European 500 hPa geopotential heights (Z_{500}, top set of curves), Potential Temperature on the Potential Vorticity (PV) surface of 2 PV units (θ_2, middle set of curves) and station-location point precipitation divided by climatology ($P_{p/c}$, bottom set of curves). Each curve is the average ACC for an entire year of 12 UTC high-resolution (T511) deterministic forecasts (termed "DET" forecasts). Different colours refer to different years. 95% two-sided confidence intervals, which take autocorrelation into account, are displayed. Z_{500} and θ_2 data are interpolated to a 2.5° regular grid before the ACCs are calculated. The climatologies used to calculate the ACCs come from the entire ECMWF 40-year re-analysis (ERA-40) for Z_{500} and θ_2 and from a 1971–2000 observational database for $P_{p/c}$. Europe is defined in this article as the region 12.5°W–42.5°E, 35.0°N–75.0°N.

Annual-mean rainfall varies strongly from place to place. For example it rains much more in mountainous regions than on the plains. To ensure that our anomaly correlation score reflects our ability to predict precipitation everywhere and not just in mountainous regions, observed and predicted precipitation is divided by the monthly-mean climatological value for each station location and referred to here as $P_{p/c}$. The ACC is based on $P_{p/c}$. For numerical reasons, only stations for which the monthly-mean climatological precipitation exceeds 4 mm are considered. Between 300 and 400 stations are used on any given day.

Assessing forecast skill averaged over SYNOP stations will give more prominence to regions where the station network density is largest. There exists at ECMWF a gridded precipitation analysis based on a high spatial resolution rain gauge network. This precipitation analysis is used in verification and routine diagnostics. Using it here would avoid the network inhomogeneity issue but this would be at the expense of the skill-at-a-point feature that users are clearly interested in. For the future development of this investigation, it is intended to divide each SYNOP station's contribution to a skill score by the station network density in its vicinity. In practice, this may not lead to very different results to those quoted here but it would take account of network inhomogeneity and yet retain the desired skill-at-a-point feature.

The bottom set of curves in Figure 1 show the European ACC scores for $P_{p/c}$. Scores at D+*n* refer to the forecast of precipitation accumulated over the preceding 24 hours: D+(*n*–1) to D+*n*. As anticipated, the scores are even lower but again the trend over the years is for improvements in our prediction of rainfall. Notice that even at D+1 for the most recent year, the ACC for $P_{p/c}$ barely reaches 0.6. The value of 0.6 is often taken as the threshold for usefulness for large-scale flows although it is unclear whether the same threshold applies for precipitation. (Usefulness is discussed later in terms of probabilistic scores.) This deterministic score is complimentary to the "True Skill Score" (TSS) because the TSS involves the definition of a rainfall threshold. One of the desirable properties of such a deterministic score is that it is not complicated by changes in the tuning of ensemble spread and thus it provides a more direct method of assessing the impact on precipitation of changes to the model physics or resolution.

Deterministic comparison of deterministic and ensemble prediction systems

A deterministic score requires as input a single prediction, not a probabilistic prediction. To get a single prediction from the EPS, the natural thing to do is, perhaps, to take the mean of all 50 ensemble members (referred to here as "EMN"). Figure 2 compares ACCs from the DET forecast (red) with those of the EMN (black).

- For Z_{500} (top two curves) the high-resolution forecast is superior to the ensemble mean up to D+5. The red circles indicate that the difference in mean ACC is significant at the 5% level. From D+7, the ACC of the EMN is significantly larger than that of the DET forecast.
- For θ_2 (middle two curves) the cross-over occurs earlier, with the ACC of the EMN becoming significantly larger by D+5. Note that the T63 truncation of the Z_{500} and θ_2 data prior to this analysis is the primary reason for the larger ACC values here than in Figure 1.
- For $P_{p/c}$ (bottom set of curves) the ACC of the EMN is significantly larger than that of the DET forecast by D+3.

Hence it appears that as the inherent spatial scale of the field gets smaller, the cross-over occurs earlier. One can argue that this is a consequence of the EMN acting as an "intelligent filter" that removes features that are less predictable and thus more potentially harmful to the ACC. However, there are many problems associated with the EMN. For example the EMN will not, in general, even represent a dynamically valid

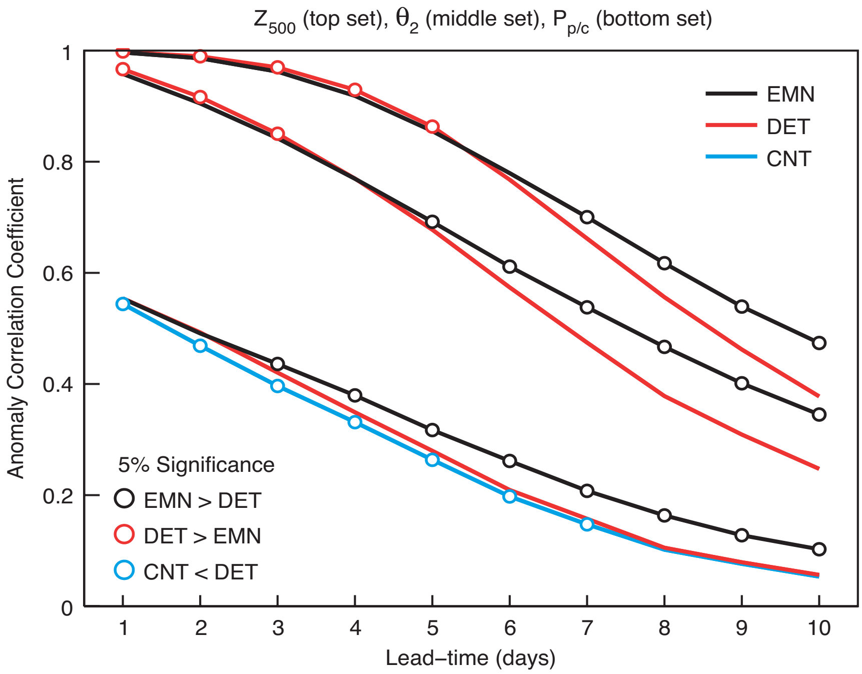

Figure 2 As Figure 1 but for Anomaly Correlation Coefficients (ACCs) of the DET forecast (red) and ensemble mean ("EMN", black) forecast. The Z500 (top two) and (2 (middle two) curves are the mean ACCs of all 12 UTC forecasts made between 6 June 2004 and 5 June 2005. Z_{500} and θ_2 data are truncated to T63 and interpolated to a 1.875° regular grid before the ACCs are calculated. The $P_{p/c}$ (bottom) curves are the mean ACCs of all 12UTC forecasts over the four years 2001–2004. Also shown is the ACC of $P_{p/c}$ for the control forecast ("CNT", blue). Circles indicate a 5% statistically significant difference using a paired t-test taking autocorrelation into account. Red circles show where the DET forecast is significantly better than the EMN, black circles show where the ACC of the EMN is significantly larger than that of the DET forecast and blue circles show where the CNT forecast is significantly worse than the DET forecast.

atmospheric state beyond the first few days of the forecast (if non-linearity is important). Also it may well be that the user is particularly interested in the less predictable features (such as extreme events for example) that have been filtered out. Hence the deterministic comparison of the two forecast systems is less clear than it might seem at first sight (particularly after the cross-over has occurred).

Also plotted in Figure 2 (blue curve) is the ACC of European $P_{p/c}$ for the single T255 control forecast "CNT". This can be more legitimately compared with the DET ACC (red curve). It is clear that the lower-resolution forecast is significantly worse (indicated by the blue circles) than the higher-resolution forecast up to D+7. Beyond D+7, there is little to be gained with the higher resolution, at least in terms of this particular rainfall score.

Probabilistic comparison of deterministic and ensemble prediction systems

Probabilistic forecasts require the definition of an "event" (here we will choose the event that 24-hour accumulated precipitation exceeds 1 mm). A probabilistic score requires as input a probability that the particular event will occur. To get a probability from the EPS is simply a matter of counting the fraction of ensemble members that predict the event will occur (if all EPS members are equally likely). To get a probability from the DET forecast one possibility is to set the probability to 1 if the DET predicts the event will occur and set the probability to 0 otherwise (refinements will be discussed briefly later). The score that has been used here is the Brier Skill Score (BSS). The BSS is a measure of how well we forecast the probability that the event will occur relative to a forecast that simply uses the climatological probability. Clearly for a probability forecast at a single location and for a single date, it is not possible in general to determine the accuracy of the probability forecast. However, the Brier Skill Score is calculated here over many forecasts (4 years of daily forecasts) and over many station locations (typically 300–400 each day). Roughly speaking, the more often the event occurs when the forecast probability is high and the less often the event occurs when the forecast probability is low, the more positive will be the BSS. A perfect forecast system would have a BSS of 1. For further information about how the BSS used in this study compares with the present operational methodology see Box A.

Figure 3 (black curve) shows the EPS BSS for the prediction of the event that 24-hour accumulated precipitation exceeds 1 mm. The BSS is based on all 1461 of the 12 UTC forecasts made between 2001 and 2004. As before, the score refers to the skill in predicting the precipitation accumulated over the preceding 24 hours. For D+1 and D+2, the BSS is around 0.33. It is unclear at present why the BSS at D+2 is as good as at D+1. It is also unknown whether this feature occurs for other precipitation thresholds. Further investigation is planned. Beyond D+2, the BSS of the EPS declines but remains positive (and thus potentially useful) to D+9.

The BSS for the DET forecast is also shown in Figure 3 (red curve). At D+1, this is already lower than the BSS for the ensemble prediction system (black) and it drops very rapidly with increasing lead-time, becoming negative beyond D+3.

Box A More about the Brier Skill Score

The BSS for station-location precipitation is calculated operationally at ECMWF but there are differences with the method used in this study. Here, the climatological probability is a function of station location and derived from a long-term climate. The operational method assumes the climatological probability is not a function of location and is derived from the "sample climatology" (i.e. the rainfall that fell within the actual month being scored). In practice, particularly in summer, the climatological frequency of rainfall events varies greatly between the arid Mediterranean region and wetter northern Europe and thus, in this respect, the present methodology seems preferable. By using a sample climate, the operational method is likely to unduly penalise the forecast because the operational BSS is effectively scoring the model's ability to predict intra-monthly variability. Now that a long-term climatology is available for Europe, the present methodology seems preferable.

The operational score is also based on forecast data that is interpolated to a regular 1.5° grid before interpolation to station locations. The rationale for this is that it homogenises the record by reducing the sensitivity of the BSS to changing model resolution. Here, on the contrary, it is thought that the impact of increased resolution should be reflected in the skill score and interpolation is therefore done directly from the model grid to the station locations.

Finally, the operational scores are based on a fixed list of SYNOP stations. Again the rationale for this is to homogenise the record. Here it was thought that, for any particular day, all reporting stations should be used because it is possible that there will be missing data from any fixed list of stations and, over the years, stations may cease to exist and others may take their place. It is unclear which option is preferable.

One may argue, therefore, that in probabilistic terms, the DET forecast is much worse than the EPS. However, the DET forecast gives a dichotomous outcome (0 or 1 of the event occurring) and simple mathematics shows that the BSS for a perfect model DET forecast should tend to -1 as the lead-time increases. (Even with a perfect model chaos will still be present and thus predictability will be lost at some lead-time.) This is in contrast to the limiting value of 0 for a perfect-model large-ensemble probabilistic forecast. Forecast "dressing" (e.g. by using past verification data to determine a non-dichotomous probability of the event occurring as a function of the magnitude of DET forecast rainfall) could be used to reduce the decline of the BSS of the DET forecast (and also possibly the decline of the EPS). Hence again, comparison of the two systems is problematic and misleading.

Note that the BSS for the single CNT forecast is also shown in Figure 3 (blue curve). The blue circles signify that this is statistically significantly worse, at the 5% level, than the BSS for the deterministic forecast (red).

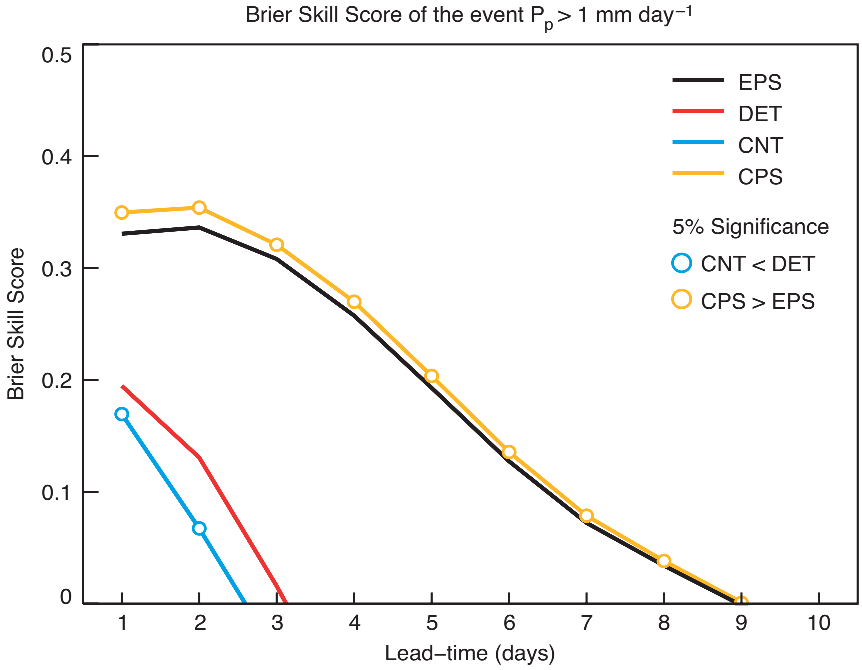

Figure 3 Brier Skill Scores (BSSs) for the event that daily-accumulated station-location point precipitation is greater than 1 mm (P_p>1): black for the ensemble prediction system ("EPS"), red for the DET forecast, blue for the CNT forecast, and orange for the combined prediction system ("CPS") which includes the EPS and the DET forecast. Blue circles indicate where the CNT forecast is significantly worse than the DET forecast and orange circles indicate where the CPS is significantly better than the EPS. The climatology used to calculate the BSS is based on a 1971–2000 observational database.

Combined Prediction Systems: How to predict rainfall occurrence better

Given that it is problematic to directly compare the DET forecast with that of the EPS, the aim here is to take a very different approach – an attempt is made to combine the forecast information of both systems in order to get a better probabilistic forecast than either system can produce alone. The focus will be on precipitation because it is one of the most important quantities that we wish to forecast and, owing to its small-scale structure, there is a good possibility that the high-resolution forecast will be able to contribute substantially to the skill at short lead-times.

Figure 4 shows schematically how two forecast systems (ten-member ensemble and single deterministic) could be combined to give a single forecast probability for the event that the daily-accumulated precipitation will be greater than 1 mm. The figure shows a frequency plot of the forecast rainfall amounts from the individual ensemble members (orange squares) and the single high-resolution deterministic forecast (yellow rectangle). We have assumed that the high-resolution forecast should have the same weight as three ensemble members to reflect the possibility that it may be more skilful. The orange squares are all the same size because each ensemble member is equally likely. Based on the schematic, the combined forecast probability for the event that precipitation is greater than 1 mm is therefore 9/13. Combined (DET with 50-member EPS) probabilities for each day and each station are calculated in this way and used in the calculation of the BSS. In reality, we do not know beforehand the weight to apply to the DET forecast. We assume that the weight is a function of forecast lead-time but independent of station and, initially, independent of the time of year. Here, the weights are determined (from an analytical equation) so as to maximise the BSS. The weights determined for year n are used in the calculation of the BSS for a year n+1, thus avoiding any artificial enhancement of skill. Note that for the first year, 2001, the weights come from 2002 so are still independent of the forecast period.

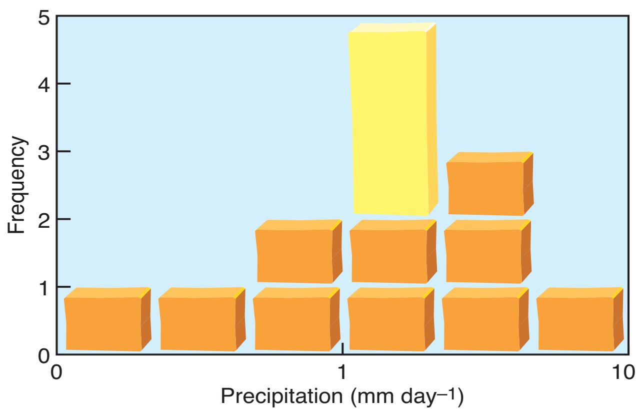

Figure 4 Schematic frequency diagram showing how the deterministic and ensemble forecast systems are combined to produce a single forecast probability for the event that 24-hour accumulated precipitation is greater than 1 mm. The orange squares represent individual ensemble members and the yellow rectangle represents the single high-resolution deterministic forecast. See the main text for further details.

Figure 3 (orange curve) shows the mean BSS for years 2001–2004 based on this "combined prediction system" (termed here, "CPS"). The orange circles signify where the CPS is statistically significantly superior at the 5% level to the ensemble system alone (based on daily contributions to the BSS). It is clear that the incorporation of the single high-resolution DET forecast improves the skill at all lead-times, particularly at short lead-times. This improvement in skill for all lead-times emphasises just how misleading is the dramatic drop of the BSS for the DET forecast alone. Further cross-validated tests reveal that the increased skill of the CPS occurs for every one of the 16 seasons in the study with perhaps the biggest increases occurring in autumn and winter.

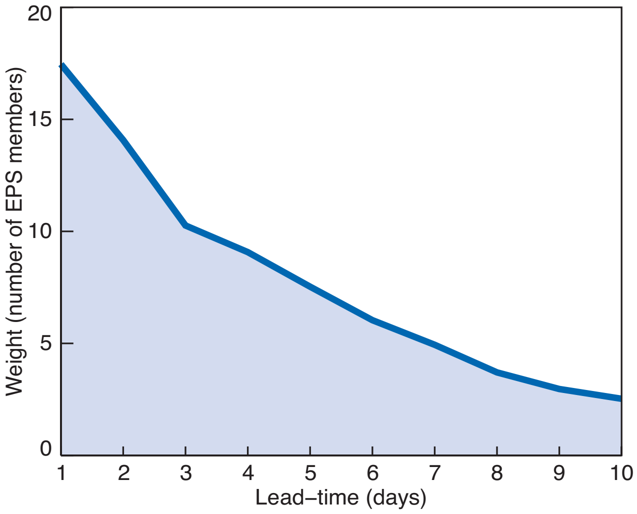

Figure 5 The optimal weight to apply to the high-resolution deterministic forecast (DET) in order to maximise the BSS in the combined prediction system (CPS) for the rainfall event that P_p>1 mm. The unit is the weight of one EPS member. Weights are applied in a cross-validated manner.

Figure 5 shows the 2001–2004 mean of the optimal weights of the DET forecast as a function of lead-time. The weights determined for each year are actually very similar to those shown in Figure 5. At D+1, the DET forecast is equivalent to about 17 EPS members. Interestingly, this is roughly the number of T255 EPS members that could be made with the same computing power as a single T511 DET forecast (under operational configurations). At longer lead-times the weight of the high-resolution forecast diminishes so that by D+10, it is equivalent to about 2.5 ensemble members.

An important question to ask is whether the benefit of the high-resolution deterministic forecast comes from its high resolution or from the fact that it is initiated from a better estimate of the truth than any individual ensemble member. (The EPS members are initiated from our best estimate of the truth plus a small perturbation to reflect the uncertainty in our knowledge of the true atmospheric state.) To address the question of resolution versus initial conditions, the CNT forecast has been used instead of the DET forecast in the CPS. The CNT forecast is also started from our best estimate of the truth but run at the same resolution as each EPS member. When CNT is combined with EPS it is found that the optimal weight for the CNT forecast is very low (it is actually equivalent to -8 EPS members at D+1 and then tends to the weight of +1 EPS member by D+5). Hence it would seem clear that the benefit of the DET forecast comes predominantly from its higher resolution.

The negative initial weight for the CNT forecast requires further investigation. One hypothesis is that a negative weight is an efficient way of increasing the effective ensemble spread at short lead-times. (At short lead-times, the CNT forecast will lie close to the centre of the EPS distribution.) If this is the reason then the same effect should be occurring in the DET+EPS combination. The fact that the optimal weight for the DET forecast is +17 EPS members at D+1 may therefore imply that the high-resolution DET forecast is bringing rather more useful information to the CPS than may appear at first sight. This speculative explanation will be investigated in the future.

Further experiments with the Combined Prediction System and extensions

Further tests were made to see if adding a seasonal dependence to the weights applied to the CPS could increase overall skill. No improvement (or degradation) was found. One possibility is that there is little seasonal dependence. Another possibility is that the reduction in available training data leads to poorer estimates of the weights and this balances improvements arising from seasonal dependence.

There is a lot of interannual variability in the BSS (for the event P_p>1). For example 2003 has a value of around 0.4 for D+1 and D+2 while 2004 has values of around 0.3. The interannual variability does not appear to be associated with changes in ensemble design (e.g. the tuning of the spread) as the same variability is apparent in the BSS for the DET forecast. Since the ACC for precipitation is actually higher at D+1 and D+2 for 2004 than for 2003, it also seems unlikely that the model deteriorated in this respect between these two years. Hence it is possible that the BSS for the event P_p>1 is highly flow-dependent. The high 2003 score is predominantly due to high scores in spring and summer and could be associated with the European heat wave/drought that occurred at that time.

The method of combining forecasts has been extended to give the option of incorporating a third forecast system. The natural choice here would be to combine the EPS, DET and CNT forecasts. However, as with just the EPS and CNT combination, the optimal weights for the CNT are negative. Nevertheless, the option of combining three (probabilistic or deterministic) forecast systems may be useful in the future.

Future prospects

We have seen that combining the high-resolution deterministic forecast and ensemble prediction system in an optimal way can lead to better probabilistic rainfall forecasts for Europe than either system alone. The "Combined Prediction System" (CPS) benefits from the high-resolution attribute of the deterministic forecast (DET) at short lead-times and the probabilistic attribute of the ensemble prediction system (EPS) at longer lead-times. Both of these attributes are incorporated in the variable resolution EPS ("VAREPS") system which is shortly to be implemented at ECMWF. VAREPS, which has a higher resolution early in the forecast and is truncated to a lower resolution later on, presents a good framework for the prediction of rainfall. Results such as those presented here could help determine the best configuration of resolutions and truncation time for VAREPS.

Clearly other skill scores and other definitions of the weather "event" to be forecast could be analysed in a similar way. Indeed different precipitation thresholds are being investigated at present. These alternatives may produce different optimal weights for the systems combined within the CPS. In the article by *Palmer et al.* in this edition of the

Newsletter there is a discussion on temperature prediction using the EPS and DET forecast. They apply a "dressing" to their forecasts which, as noted above, can improve probabilistic skill scores. Although this approach may clearly be useful in practice, here no dressing is done and the optimal weights are defined to be independent of location. The reason for this is that our goal is not to optimise predictability for specific (SYNOP) locations but to assess the typical skill for any locations (even where calibration data is not available). Hence BSS for the rainfall event P_p>1 mm is, in theory, applicable at any point and not just at SYNOP station locations.

A highly used product of ECMWF is the "meteogram". These meteograms display, for any desired location, DET and lower-resolution EPS control (CNT) forecasts of cloud-cover, precipitation, wind speed and temperature together with the quartiles of the EPS distribution. A difficulty for some users is to decide whether to "believe" the deterministic or probabilistic forecast. One could imagine giving the user the choice of an alternative meteogram that simply displays a CPS probability distribution. Tests would be required to see if the optimal weights are sensitive to the choice of threshold (1 mm, 5 mm of rainfall, etc.) and if a simple dressing of the DET forecast would be beneficial.

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"Wavelet" J_b – A new way to model the statistics of background errors

Mike Fisher

It has been estimated (*Cardinali et al.*, 2004) that only 15% of the information content of any recent ECMWF analysis is attributable to the observations assimilated during that analysis. The remaining 85% of the information is provided by the background: a short forecast from the preceding analysis. The rôle of the background is to incorporate into the current analysis information from observations that were assimilated during earlier cycles. Ultimately, any given analysis represents a synthesis of observations made over a five-to-ten day period.

The degree to which observational information can be brought forward in time to contribute to the current analysis depends both on the quality of the forecast model, and on the way in which the information is transferred from analysis cycle to analysis cycle via the background. Crucial to the success of this transfer is the statistical description of background errors.

The operational implementation of IFS cycle Cy29r1 in April 2005 saw the introduction of a new formulation for the background term of the analysis cost function, dubbed "Wavelet" J_b. This new formulation allows the modelled statistics of background error to exhibit spatial variation of vertical and horizontal correlations, while retaining important spectral characteristics. The formulation is described in rather mathematical terms by *Fisher* (2004b). The aim of this article is to provide a complementary, equation-free description of the concepts underlying "Wavelet" J_b, and the reasons for its adoption. But, let's start by putting things into context.

A brief description of the variational analysis method

Variational data assimilation defines the analysis in terms of a "cost" (or penalty) function, which is a sum of several components. Each component of the cost function measures how well the analysis meets some criterion. A perfect match for a given criterion is represented by a value of zero for the corresponding component of the cost function, whereas large values indicate that criteria have not been met. The final analysis represents the particular compromise between the different criteria that minimizes the overall "cost".

The terms of the cost function measure:

- Differences between the analysis and the background.
- Discrepancies between the analysis and observations.
- The amplitude of rapid, divergent oscillations.
- How far the evolution of the analysis deviates from a possible evolution of the model.

(This last term is zero in the current ECMWF analysis system, as the analysis is forced to evolve exactly as dictated by the model.)

In this article, we will consider only the first of these terms: the background cost function, conventionally denoted by J_b. Like the other terms of the cost function, J_b is defined statistically, and encodes our knowledge of the statistical properties of errors in the background. It heavily penalizes differences between the analysis and the background that are unlikely (in terms of magnitude, size, shape, etc.), while allowing more plausible departures from the background. The likelihood or otherwise of a given departure is measured using a covariance matrix. In principle, this matrix tabulates the covariances between all pairs of model grid-points. However, since even a low-resolution model can have well over a million grid-points, the number of covariances that must be specified is so huge that direct specification is not practical, even on a super-computer. Ways must be found to model the statistical properties of background error with fewer parameters, while retaining their chief characteristics.

Before discussing background covariance modelling in more detail, let us introduce the notion of a change-of-variable. In a variational analysis system, this is a transformation of the departures from the background that allows the background cost to be evaluated quickly and simply as the sum of the squares of the elements of the transformed vector (called the "control vector"). From the statistical point of view, the transformation makes the elements of the control vector statistically independent (i.e. their errors are uncorrelated) and with a variance of one.

From the practical point of view, expressing the analysis problem in terms of the control vector has an important "preconditioning" effect. That is, the minimization algorithm is able to locate the minimum of the cost function much more rapidly when the function is expressed in terms of the control vector, than when it is expressed directly in terms of the "raw" model variables. During the course of the minimization, the control vector must be converted into equivalent values of the model variables so that, for example, they may be compared with observations. However, it is never necessary to perform the reverse transformation that converts model variables to a control vector.

In a variational analysis system, constructing a background covariance model boils down to specifying a transformation that converts a control vector of statistically independent, unit-variance elements, into model fields with the statistical structure of background error. This transformation implicitly defines the covariance matrix of background error, which is never explicitly represented. Before considering in more detail how such a transformation may be defined, let's consider which characteristics of background error we wish to retain in the model.

Some important characteristics of background error

Perhaps the most important characteristic of background error is that it tends to be balanced. That is, errors in temperature, surface pressure and wind are related to each other via

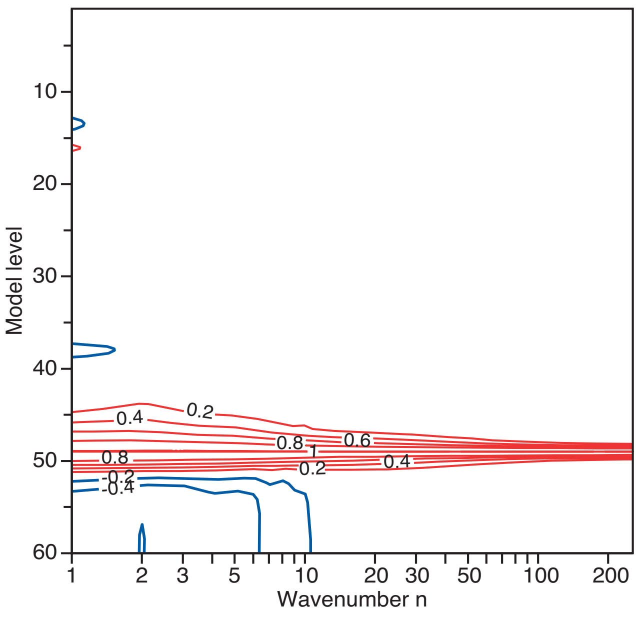

Figure 1 Mean correlation between background errors of temperature on model level 49 (near 850 hPa) and the corresponding errors on other model levels, as a function of spherical wave number.

geostrophic and hydrostatic balances. The *Derber & Bouttier* (1999) approach to accounting for balance is to express the control vector in terms of a single "balanced" variable, and a number of residual, "unbalanced" variables. They chose vorticity as the balanced variable. With this approach, the last step of the transformation from control vector to model fields is to calculate balanced components of other variables from the vorticity (using geostrophy, for example) and add them to the residual components. It is assumed that this process accounts for all the correlations between variables, so that the different variables of the control vector are assumed to be statistically independent. This approach to representing balance has been retained for "Wavelet" J_b.

A second important characteristic of background error is "non-separability". This simply means the tendency for broad horizontal error structures to be deep, and for narrow horizontal structures to be shallow. This property is illustrated in Figure 1, which shows the mean vertical correlation between temperature background errors at model level 49 (near 850 hPa) and temperature errors at other levels. The horizontal axis shows spherical wavenumber n: a measure of horizontal scale, with small scales corresponding to large values of *n*.

One important reason for wanting to retain non-separability in the covariance model is its interaction with balance. The strict, functional relationship between the balanced components of background error (e.g. between vorticity and the balanced part of the temperature error) means that specifying a covariance model for one variable (vorticity, say) implicity imposes a covariance model on other variables. It has been found that a separable model, in which all horizontal scales have the same vertical correlation, is unable simultaneously to represent the correlations of both wind and temperature (see *Bartello & Mitchell*, 1992).

A third feature of background error correlation is spatial variation. We expect background error correlations to vary geographically. Tropical error structures are different from those in mid-latitudes, and errors over data-dense regions are different from those over data-sparse regions.

The Derber-Bouttier J_b

The background covariance model devised by *Derber & Bouttier* (1999) (hereafter referred to as the "Derber-Bouttier J_b") was used operationally at ECMWF from May 1997 until April 2005, and had a very positive impact on forecast skill. It attempts to capture the first two properties described above: balance and non-separability. It also achieves a limited degree of spatial variability.

The treatment of balance has already been described. Non-separability is addressed by having different vertical correlation matrices for each spherical wavenumber. Because wavenumber is a global concept, this approach does not allow any horizontal variation of the correlations. However, this is only true of the variables that make up the control vector (vorticity, "unbalanced" temperature, etc.). Since the full temperature and surface pressure fields are calculated as the sum of an "unbalanced" residual and balanced fields derived from the vorticity, their covariance structure is

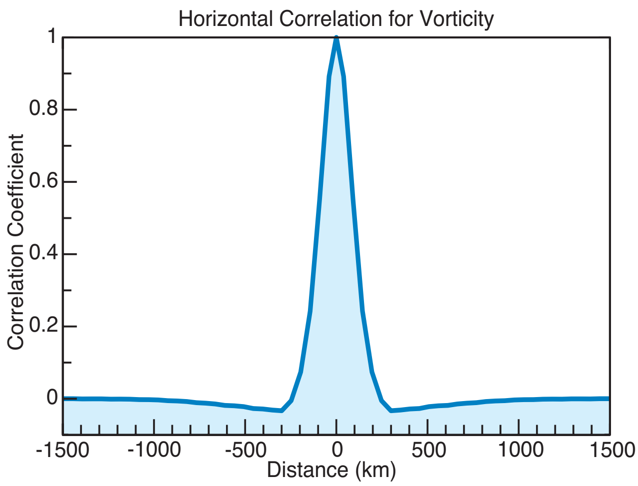

Figure 2 Mean horizontal correlation of vorticity at model level 49 (near 850 hPa) as a function of distance.

determined in part by the statistics of the "unbalanced" component, and in part by the statistics of the vorticity error. In mid-latitudes, the balanced component is dominant, and the correlations of temperature error are effectively those implied through the balance equations by the vorticity correlations. In the tropics, by contrast, the residual components dominate, and the correlations are those prescribed for the "unbalanced" components. The result is that the implied temperature statistics vary with latitude.

Horizontal correlations are handled in the Derber-Bouttier J_b using "convolution". To create a horizontally-correlated field (e.g. vorticity on some model level), each horizontal grid-point of the field is calculated as a weighted average of the values of the control vector at nearby points. The weight given to each point is a function of distance from the central grid-point. A typical weighting function for vorticity is shown in Figure 2.

This type of averaging is used because it can be implemented very efficiently using spherical transforms. Specifically, convolution of a field with a function of distance f (such as that shown in Figure 2) can be achieved by multiplying the spectral coefficients of the field by coefficients $\hat{f}_n$ that depend only on the wavenumber n. There is a simple mathematical relationship between the coefficients $\hat{f}_n$ and the function f.

The disadvantages of this approach are first that the weighting function, f, cannot be varied from grid-point to grid-point, so that spatial variation of horizontal correlation is not allowed, and second that the averaging is isotropic (the same in all horizontal directions).

Musical interlude

By now, you must be wondering when I'm going to get round to talking about wavelets. I'll get there soon. But first, a little music.

Consider the snippet of a well-known tune shown in Figure 3. A purely spectral representation of the tune would identify the frequencies present, but would not identify when these frequencies appear. This is illustrated schematically by the graph to the left of the musical stave, showing amplitude as a function of frequency. By contrast, a purely temporal representation would identify the time at which each note is played and its loudness, but not the frequency, as illustrated by the graph below the stave. Clearly, neither the spectral nor the temporal representations capture the full nature of the music.

If we now replace time by spatial position, and frequency by spatial scale, we have rough analogues of two approaches to covariance modelling. The purely spectral approach, as exemplified by the Derber-Bouttier J_b, identifies vertical correlations as a function of scale, but does not identify where the correlations apply. It is like the spectral representation of the melody to the left of the stave. An alternative (separable) approach is to specify vertical correlations as a function of horizontal position, and apply them to columns of the model's grid. This provides spatial information, but applies the same correlations to all scales, rather in the way that the temporal description of the melody fails to identify the pitches of the notes. It is clear that, as with the musical example, neither the purely spectral nor the purely spatial approach captures all the characteristics of the correlations. What is needed is an equivalent of musical notation that identifies correlations as a function of both scale and location. This is the aim of "Wavelet" J_b.

"Wavelet" J_b

Have another look at Figure 1. The variation of vertical correlation with wavenumber is rather smooth, yet the Derber-Bouttier J_b describes this spectral variation with individual matrices for each of the 256 wavenumbers of the T255 truncation. Horizontal correlations, too, are described by 256 spectral coefficients per model level, despite being smooth functions of wavenumber.

The first step towards "Wavelet" J_b is to realise that both the vertical and horizontal correlations may be described fairly accurately by specifying matrices and coefficients for a few selected wavenumbers, and simply interpolating between them. One way to do this would be to generate the 256 matrices and 256 coefficients required by the Derber-Bouttier J_b explicitly from the matrices and coefficients for

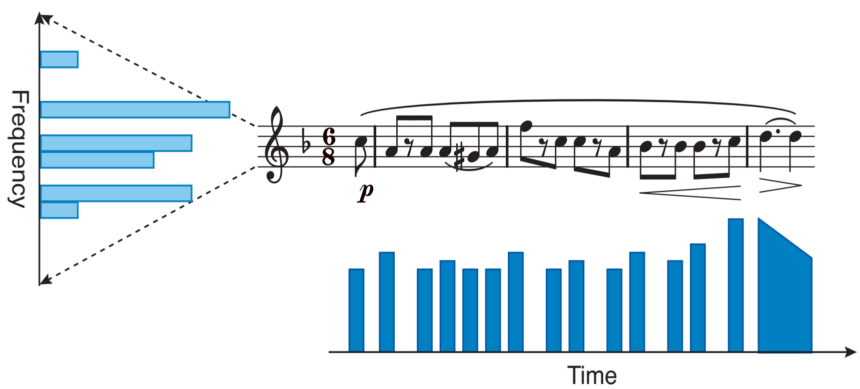

Figure 3 An illustration of the benefits of resolving both temporal and spectral information.

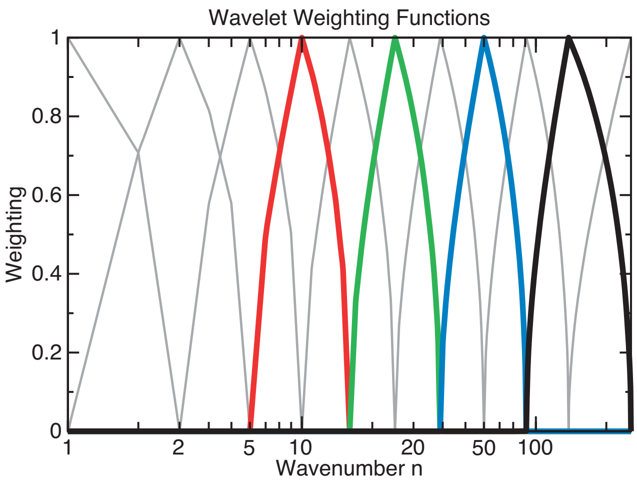

Figure 4 Weighting functions for the different wavenumber bands in "Wavelet" J_b. The coloured curves are referred to in Figure 5.

the selected wavenumbers, and then proceed as before. This does not gain us much, except to provide a more compact description of the statistics. However, there is a different way to perform the interpolation, as described below.

The Derber-Bouttier J_b identifies horizontal scale using wavenumber, n, and there is a separate part of the control vector for each n. "Wavelet" J_b does things differently. It identifies horizontal scale with overlapping bands of wavenumbers centred on each of the selected wavenumbers to be interpolated. There is a separate part of the control vector for each band, and each part is assumed to be uncorrelated with other parts of the control vector. Because the wavenumber bands overlap, each wavenumber is represented in two or more different parts of the control vector, corresponding to two or more different bands. To construct the model background-departures for a particular wavenumber from the control vector, we multiply the corresponding wavenumber coefficients in each part of the control vector by the matrix and coefficient defined for the band. We then multiply each contribution to the wavenumber by a weight, and add the resulting values. The weights define the interpolation in wavenumber between the matrices and coefficients defined for the central wavenumbers of each band. The effect is identical to what we would have achieved by first interpolating the matrices and coefficients, and then applying the Derber-Bouttier J_b.

The weighting functions used in the current implementation of "Wavelet" J_b are shown in Figure 4. Four arbitrarily-chosen functions have been highlighted. The functions are, in fact, the square roots of triangular functions, and produce a linear interpolation of covariance between the wavenumber bands.

Now, the weighting functions are functions of wavenumber, n, and as described earlier, multiplication by a function of n is equivalent to convolution with a particular spatial function. Each point of the convolved field corresponds to a spatial average of nearby points.

Figure 5 shows the spatial averaging functions implied by the spectral functions highlighted in Figure 4. Note that the functions are quite localised, especially for the higher wavenumber bands.

Consider now what happens if we allow the matrices and coefficients that define the correlations to vary with latitude and longitude. For example, suppose we use different matrices and coefficients for points over North America than we do for points over Europe. For all but the lowest wavenumbers (corresponding to planetary scales) the spatial averaging functions for points over Europe give nearly zero weight to points over North America, and vice versa. So, the correlations in effect over Europe will essentially be those we would have got had we used the European correlations and coefficients everywhere. Likewise, the correlations over North America will effectively be those defined by the correlations and coefficients we specify for North America. In other words, we have succeeded in introducing spatial variation into the correlation statistics, while retaining the ability to describe their spectral variation. To return to the analogy of the previous section, we might say that we have improved on the constant drone of the Derber-Bouttier J_b and the drum-solo of the separable formulation, and produced a background covariance model that can represent the full "music" of the background error covariances! Some examples of the ability of "Wavelet" J_b to produce spatially-varying correlation structures are given in *Fisher* (2004a) and *Fisher* (2004b).

Why call this "Wavelet" J_b?

The term "wavelet" describes a particular class of mathematical functions that are localised in both space and frequency. These functions have become quite popular in recent years for analysing problems for which a purely spectral or a purely spatial (or temporal) approach is insufficient. Applications include image compression, signal analysis and linear algebra.

Although the exact definition of what constitutes a "wavelet" varied a little after their introduction in the 1980's, it is now generally accepted that the term should be restricted to functions that have the mathematical property of orthogonality. The weighting functions used in "Wavelet" J_b do not have this property, for reasons explained in *Fisher* (2004b), and should not strictly be called "wavelets". Nevertheless, the term neatly sums up the most important property of the functions, which is their simultaneous localization in both wavenumber and space. Some other properties of orthogonal wavelets, such as the ability to define transforms, also apply (see *Fisher*, 2004b), making the distinction between true wavelets and the functions described here somewhat technical. Since the term "Wavelet" J_b is also much snappier than any more precise alternative, I have chosen to use it, and to indicate its inexactness with inverted commas.

Practical issues

Astute readers will have noted that the need to represent each wavenumber in more than one band results in some redundancy. (This can be regarded as a consequence of the lack of orthogonality between the weighting functions.) A practical consequence is that the control vector must be larger than the corresponding vector of model variables. Although the size of the control vector is not directly related to the computational cost of the minimization, it is nevertheless a good idea to reduce its size as much as possible. In the current implementation, we take advantage of the fact that each of the weighting functions is exactly zero outside its band, and store the corresponding part of the control vector on a grid appropriate to its spectral truncation. In the current implementation, the total dimension of the control vector is approximately three times the dimension of a grid-space representation of the model variables.

The storage required for the vertical correlation matrices is potentially huge. In principle, we could define a different matrix for each grid-point and for each band of wavenumbers. This is completely impractical, and would also require an enormous sample of background errors to generate stable statistics. To reduce the storage requirements, the matrices are stored on a lower resolution grid than the parts of the control vectors, with a maximum resolution (for higher wavenumber bands) of 5°×5°. This still results in statistics files that are uncomfortably large (a few gigabytes). Further ways to reduce their size will be investigated in the future.

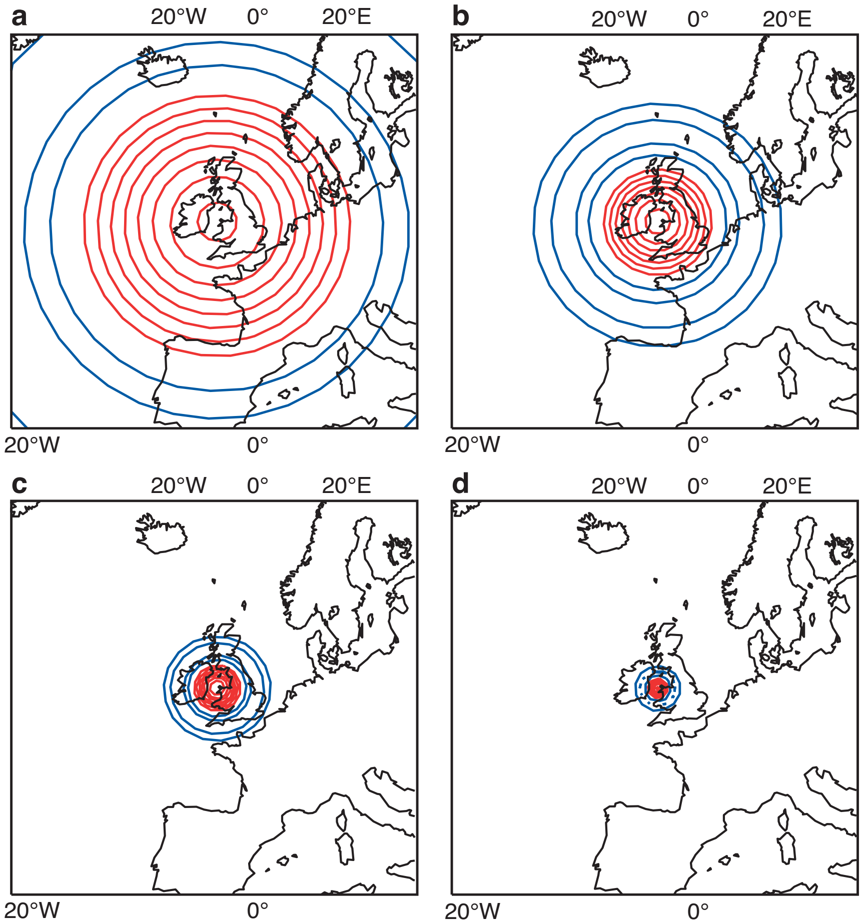

Figure 5 The spatial weighting functions corresponding to the functions of wavenumber highlighted in Figure 4, for a point over the Irish Sea. Red and blue contours represent positive and negative weights. The zero line is not plotted. Plots (a), (b), (c) and (d) refer to the red, green, blue and black curves of Figure 4.

Where next?

In conclusion, "Wavelet" J_b provides an elegant way of encapsulating in the covariance model an important property of the statistics of background error, that was not captured by its predecessor. There remain important properties that are not represented, such as the day-to-day variability of background error correlation, and the tendency for error structures to be strongly anisotropic (i.e. functions of direction as well as distance) and to tilt in the vertical. There is a range of possibilities that could be explored to address these issues, each of which captures some or other aspect of background error covariance. But, whatever approach is taken, it is impossible to escape the fact that the covariance model is a distillation of a vast matrix into a relatively small number of parameters. It is inevitable with any distillation that some of the "spirit" is lost, in this case to the detriment of the analysis.

Ultimately, the only way to produce a truly optimal analysis system is to eliminate the dependence of the analysis on a background error covariance matrix. I noted earlier that any given analysis can be regarded as a synthesis of observational information over a period of five-to-ten days, and that the function of the background error covariance model is to propagate this information between analysis cycles. But, what would happen if the analysis could simultaneously take into account all the observations over a five-to-ten day period? In this case, there would be no need to propagate information between cycles, and a background covariance model would be unnecessary. A 4D-Var analysis system of this sort, applied to a simple, low-dimension model of mid-latitude dynamics has been examined (*Fisher*, 2006). The analysis produced by this 4D-Var system is as good as that produced by a full extended Kalman filter. It is likely that attempts to make the background covariance model less important, by increasing the length of the analysis window, have even more potential to improve the analysis than attempts to improve the covariance model itself.

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Progress in ocean wave forecasting at ECMWF

Peter Janssen

In the 1980s the introduction of the first supercomputers and the promise of the wealth of data on the ocean surface from remote-sensing instruments on board of new satellites such as ERS-1 and Topex-Poseidon provided a significant stimulus to the development of a new generation of ocean wave prediction models. The WAve Model (WAM) Group emerged and the main goal was to develop a spectral ocean wave model based on solving the energy balance equation which included explicitly the physics of wind-wave generation, dissipation due to white capping and nonlinear interactions. Development of this new wave prediction system was rapid and ECMWF helped by providing resources (in terms of computing facilities, advice by staff and office space). In June 1992 the WAM model became operational at ECMWF.

It soon became clear that the quality of wave forecasts was to a large extent determined by errors in the forcing wind field. Since the winds gave such a large contribution to the error budget of, for example, the significant wave height, it was expected that it would be difficult to show the effect of improvements from the wave model.

In this article, which is based on *ECMWF Technical Memo. No. 478* (where more details are given), we discuss progress in ocean wave forecasting during the past ten years. It will be shown that during this period there have been substantial improvements in the quality of the forecast wind and wave height fields. This follows from comparisons with the verifying analysis, in-situ buoy data and altimeter data. The main reasons for these large improvements are the introduction of 4D-Var, increases in atmospheric resolution, improvements of the physics of the atmospheric model and the two-way interaction of wind and waves.

Because of the large error reduction in the forcing winds, it is nowadays easier to see the consequences of wave model improvements. Two examples of recent wave model improvements after WAM CY4 are discussed: the introduction of the effects of unresolved bathymetry and the revised formulation of wave dissipation. There is then a discussion of the improvement in the quality of the forecasts of wave height over the last decade. Finally, we discuss the following two new developments.

- An important element of severe weather forecasting over the oceans is the prediction of freak waves. We will describe the steps that led to the introduction of the first operational freak wave prediction system.
- The sea state is affected by ocean currents, tides and storm surges. We will discuss preliminary results regarding the impact of ocean currents on the significant wave height field on a global scale. Also discussed is the forecasting of the sea state in the coastal zone, an area of important economic significance.

CY4 version of the WAM model

The present version of the ECMWF wave forecasting system is based on WAM CY4 (see *Komen et al.*, 1994). The WAM model is the first model that explicitly solves the energy balance equation. See Box A for more details.

The WAM model became operational at ECMWF in June 1992. Since that date there has been a continuous programming effort to keep the software up to date. For example, in order to improve efficiency, options for macrotasking (later replaced by open MP directives) and massive parallel processing were introduced. In addition, the software now fully complies with Fortran 90 standards. The advantage of this is that only one executable is needed for all the relevant applications, such as the deterministic forecast with resolution of 55 km, the ensemble forecast with resolution of 1 degree and the limited area forecasts with a resolution of 28 km. The same executable can also be run as a one grid point model, which is convenient when testing changes in physics, for example. Finally, over the past ten years a number of model changes were introduced which will be discussed in some detail in the next section.

Documentation of the present version of the ECMWF wave model may be found on the web (www.ecmwf.int/; click research, click on "Full Scientific and technical documentation of the IFS" and finally choose Chapter VII).

Presently the wave model is run for the global domain and as a limited area model for the waters surrounding Europe. The wave model software is furthermore run for the boundary conditions suite, monthly forecasting, seasonal forecasting and for the reanalysis. This note will concentrate on the global domain. The global model covers an area of 81°S to 81°N.

Since the 29 June 1998 the wave model is part of the Integrated Forecasting System (IFS) enabling a two-way interaction between wind and waves, hence, the sea surface roughness, as seen by the atmosphere, is sea state dependent. An additional consequence of the coupling is that, just as for the atmosphere, there are for the globe two medium-range applications, namely, ten-day deterministic forecasts and probabilistic forecasts.

Box A Basic formulation of CY4 version of the WAM model

The usual wave number spectrum is denoted by $F(\boldsymbol{k};\boldsymbol{x},t)$, where $\boldsymbol{k}$ denotes wave number vector, $\boldsymbol{x}$ the position and t the time. In wave dynamics the fundamental quantity to predict is, however, the action density spectrum $N(\boldsymbol{k};\boldsymbol{x},t)$. It is defined as:

$$N = \frac{gF}{\sigma} \quad \text{with} \quad \sigma = \sqrt{gk\tanh(kD)}$$

where g is acceleration of gravity and D is the water depth. The action density plays the role of a number density of waves, hence (apart from the constant water density) the energy E of the waves is given by $E = \sigma N$, while the wave momentum $\boldsymbol{P}$ is given by $\boldsymbol{P} = \boldsymbol{k}N$.

The energy balance equation follows from Whitham's variational approach in a straightforward manner (*Janssen*, 2004) and the result for waves on a slowly varying current $\boldsymbol{U}$ is:

$$\frac{\partial N}{\partial t} + \nabla_{\boldsymbol{x}}\cdot\left(\nabla_{\boldsymbol{k}}\Omega N\right) - \nabla_{\boldsymbol{k}}\cdot\left(\nabla_{\boldsymbol{x}}\Omega N\right) = S$$

Here, Ω represents the dispersion relation:

$$\Omega = \boldsymbol{k}.\boldsymbol{U} + \sigma$$

The source function S represents the physics of wind-wave generation (S_{in}), dissipation by wave breaking and other causes (S_{dissip}) and four-wave interactions (S_{nonlin}). In other words:

$$S = S_{in} + S_{dissip} + S_{nonlin}$$

In the 1980s there was a major effort to develop realistic parametrizations of all the source functions. The present version of the WAM model has:

- S_{in} based on *Miles* (1957) critical layer mechanism (including the feedback of the wave stress on the wind profile – see *Janssen*, 1989).
- S_{dissip} based on the work of *Hasselmann* (1974).
- S_{nonlin} represented by means of the direct-interaction approximation of *Hasselmann et al.* (1985).

An account of this version of the WAM model is given by *Komen et al.* (1994), while a more up to date account of the status of wave modelling, including most of the new developments discussed in this article, can be found in *Janssen* (2004).

Developments after WAM CY4

Apart from the extensive code developments in order to be able to run the WAM model software on multi-processor machines, changes to the software have been introduced as well. In the first instance these have been mainly of a numerical nature; there were no changes to the formulation of the physical processes, only to its numerical representation. Recently, warranted by the considerable improvements in the model surface winds, a number of changes to the physics of the model have been implemented as well:

- Introduction of the effects of unresolved bathymetry
- Revised formulation of wave dissipation.

These changes will be described after consideration of the impact of the two-way interaction of wind and waves.

Two-way interaction of wind and waves

A two-way interaction of wind and waves was introduced in operations in June 1998. At the same time this made the operational running of ensemble wave forecasts easier.

The impact of two-way interaction on the atmosphere has been reviewed (*Janssen et al.*, 2002). At the time of operational introduction of the coupling there was an evident reduction of the systematic error in forecast wave height (verified against analysis) and the standard deviation of error was reduced by about 5%. Also, as illustrated in Figure 1, the RMS error in first-guess wind speed verified against scatterometer winds was reduced by 10%. There was also some impact on the accuracy of forecast atmospheric parameters (e.g. the 1000 and 500 hPa geopotential in the southern hemisphere).

It has been found that the impact of sea-state dependent drag on the atmospheric flow has increased over the years simply because the resolution of the atmospheric model has increased. This increase in resolution has resulted in a more realistic representation of the sub-synoptic scales, which are the ones that are relevant for the interaction of wind and waves. The point is perhaps best illustrated by the operational introduction of the T_L511 atmospheric system. At the same time it was decided to increase directional resolution of the wave spectrum by a factor of two from 12 to 24 directions while also a more accurate determination of the energy fluxes in the advection scheme was introduced. In the context of the lower resolution T_L319 atmospheric model it was possible to show that the proposed wave model changes had a small but positive impact on atmospheric and wave scores. However, with T_L511, impact was much more pronounced (for a more detailed discussion see *Janssen et al.* (2002)). The main reason for this is probably that in Tl 511 the sub-synoptic scales are better represented.

Unresolved bathymetry

Inspecting maps of monthly mean analysis wave height increments, especially during the Northern Hemisphere summer (Figure 2), it appears that there are areas where the

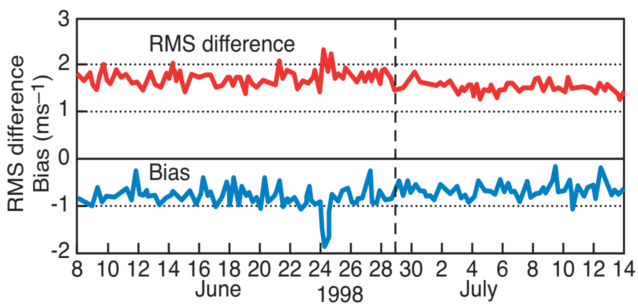

Figure 1 Bias and RMS difference between the background ECMWF surface winds and the ERS-2 scatterometer wind measurements. The vertical dashed line shows the date when two-way interaction was introduced operationally.

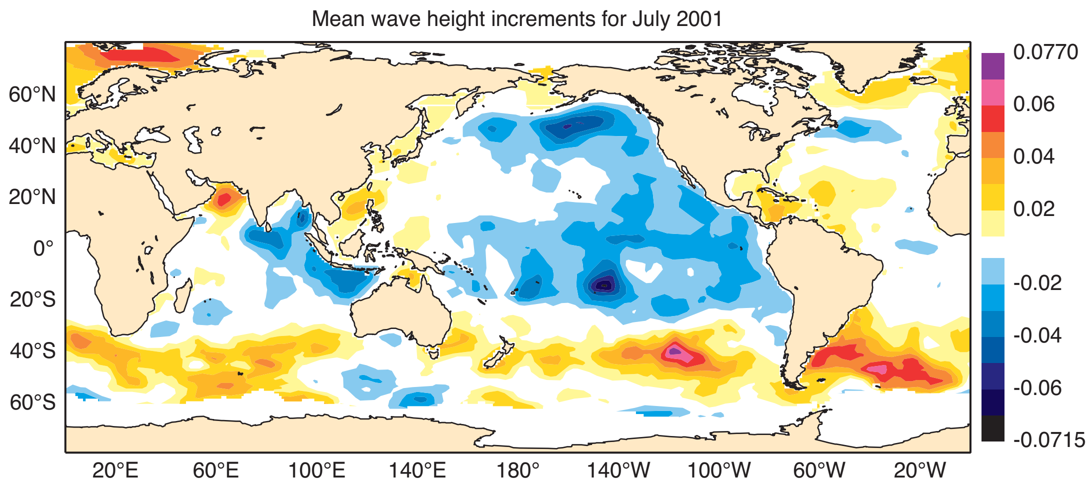

Figure 2 Mean wave height analysis increments for July 2001 (in metres). ERS-2 altimeter data were the only data used in the data assimilation. The stand alone WAM model on a 55 km grid was used.

wave model first guess is systematically too high or too low. The underestimation in wave heights tends to be located in the active storm track areas or in areas affected by the Indian sub-continent monsoon. The likely reason is that the model winds are too weak. On the other hand, the overestimation for most of the tropical and northern Pacific cannot be explained in terms of local winds. After further scrutiny, it appears that these systematic overestimations are often present in areas where small island chains exist (French Polynesia and Micronesia in the Pacific Ocean, Maldives Islands and Andaman Islands in the Indian Ocean and Azores and Cape Verde Islands in the Atlantic Ocean).

These small scale features are not well-resolved by the present operational grid which has a resolution of 55 km, and it would be far too expensive to resolve these features explicitly. Nevertheless, small islands can block considerable amounts of wave energy. In order to represent these unresolved features we have introduced in the wave model's advection scheme a wave number dependent blocking factor. Here the blocking factor was determined by estimating from the high resolution ETOPO2 topographic data set how much energy the unresolved features will block. This change resulted in a large positive impact on the wave height scores in the tropics, in particular the anomaly correlation (Figure 3). The

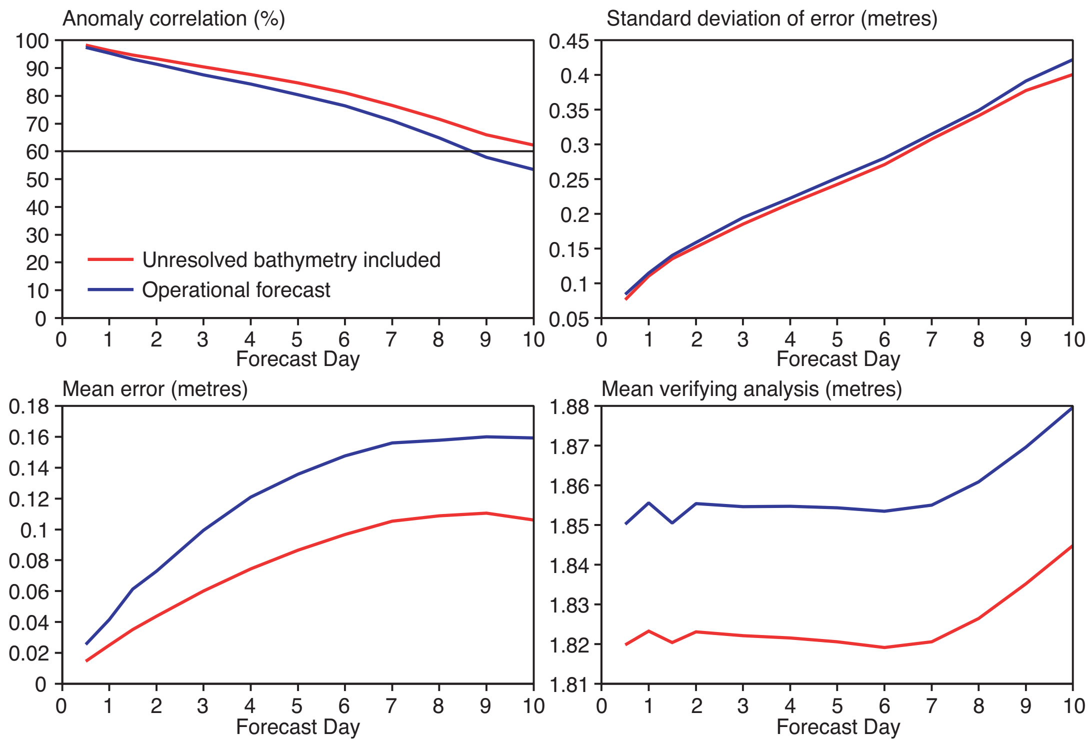

Figure 3 Wave height scores against own analysis for the tropical area for the operational forecast (blue) and the forecast with the treatment for unresolved bathymetry included (red) for the period 1 to 27 April 2003.

scheme for the treatment of unresolved bathymetry became operational in March 2004.

Dissipation

The dissipation source function is probably the least known source function in ocean wave modelling. In the past it has been determined starting from the assumption that wind input and nonlinear transfer are well-established and the dissipation term is then determined in such a way that in the steady state the observed Pierson-Moskowitz spectrum is reproduced (*Komen et al.*, 1984).

In this tuning exercise the dissipation source function is given by the general form $S_{dissip} = -\gamma_d N$ where γ_d depends upon the mean frequency and mean wavenumber defined in some suitable manner. Since 1985 the mean wavenumber has been calculated in such a way that emphasis was put on the slowly-varying low-frequency part of the spectrum as this produced less noisy fields than using an earlier formulation (see ECMWF Technical Memo. No. 478 for more details). Recently, however, a drawback of the use of this approach has been realized. In the presence of low-frequency swell the dissipation of windsea turns out to be largely determined by the swell part of the spectrum. In fact, because the steepness of swell is usually small, the dissipation of windsea in the presence of swell is much smaller than in its absence. As a consequence, windseas have more energy in the presence of swell, which contrasts common knowledge and belief.

It was decided to define the mean wave number in terms of the so-called first moment which puts more emphasis on the high frequency part of the wave spectrum. This "new" definition does not suffer from the drawback mentioned above. In addition, as now the dissipation of windsea is much larger in the presence of swell, we could also relax dynamic range of the integration of the source functions in the energy balance equation so that windseas are properly generated, also in the presence of low-frequency swells.

The combination of these two changes gave a considerably positive impact on the analysis of parameters such as the mean frequency as shown in Figure 4, which gives a comparison of scores of the operational and experimental suites against buoy observations over a three-month period. A reduction in random error of 40% is an example of a large improvement. Note that this is not even the most extreme example of improvement. From around the Indian continent we recently started receiving buoy data. Against these data the experimental suite showed a reduction in the error of the mean frequency by a factor of two.

It is emphasized that these considerable improvements in spectral shape are caused by the introduction of a much wider dynamical range, made possible by the revised formulation of the dissipation source function. This allows the proper treatment of windsea in the presence of low-frequency swell. The consequence is, however, that variability in wave height has increased, in particular in the tropics. Also, since the dissipation source function is now determined in terms of the

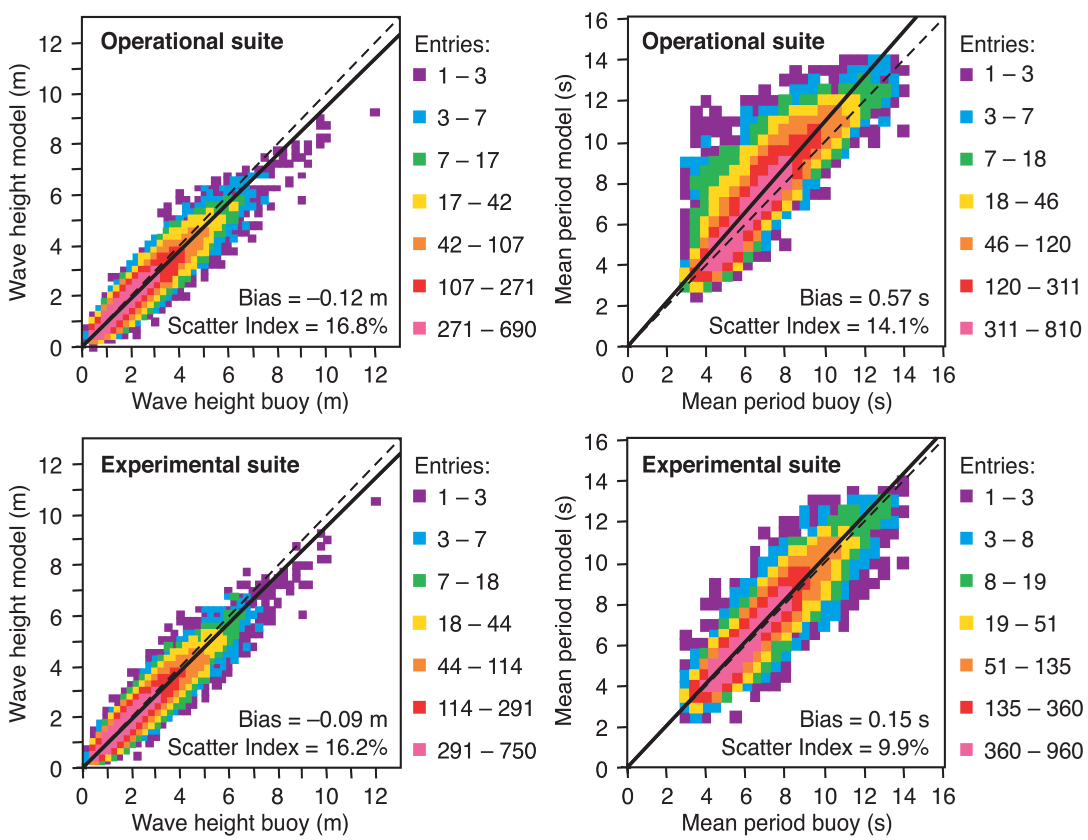

Figure 4 Comparison of wave height and mean period scores against United States and Canadian buoy observations from the operational suite and experimental suites for the three-month period of January to March 2005.

first moment of the spectrum, wave model results have become more sensitive to details in the high-frequency part of the spectrum. As the short waves are determined to a large extent by the wind, wave model results have become more sensitive to changes in the wind, in particular more sensitive to errors in the wind forcing. Therefore, when comparing wave forecasts against the own analysis, wave height scores of the experimental suite were in the medium range slightly worse compared to the operational suite. However, scoring the forecast results against ENVISAT altimeter data showed a small improvement in wave height scores, in particular in the Southern Hemisphere. The change was introduced in operations in April 2005.

Verification and sensitive dependence on wind speed error

At ECMWF there is an extensive effort to validate analysis against available, independent buoy data, while the forecast is compared with buoy data, altimeter wave height data and the verifying analysis. For an overview of the quality of the ECMWF wave forecasting system in 1995 see *Janssen et al.* (1997), while the period between 1995 and 2003 is discussed in *Janssen* (2004). From the comparison of forecast surface winds and wave heights with the verifying analysis it turns out that over the last ten years the standard deviation of error in wind speed and wave height has been reduced by 40% in the northern hemisphere, while improvements in the southern hemisphere are similar. Also, when comparing first-guess wave height and analyzed wind speed with their counterparts measured by the ERS-2 altimeter, considerable reductions in the standard deviation of error are found (*Janssen*, 2004). For example, first-guess wave height error is reduced from about 50–60 cm in 1994 to around 30 cm presently, while the analyzed wind speed error reduced from about 2 ms^{-1} to about 1.3 ms^{-1}.

This picture of improved wave forecast skill over the last decade is confirmed by means of a validation of wave height forecast and analysis against independent buoy data. This is illustrated in Figure 5 by plotting the RMS error of wave height as function of forecast time for the past nine winter periods. We infer from the figure an improvement in forecast skill of two days over a ten year period.

It is of considerable interest to try to understand some of the reasons for this massive improvement. Based on the verification results of forecast wind and waves against the analysis, *Janssen* (1998) found a close relation between wave height error and wind speed error. Therefore, one would expect that improvements in wind speed forecast could explain a considerable part of the improved skill in wave height forecast. In order to illustrate this, we study Figure 6 which shows a plot of the RMS error in wind speed as function of forecast time. Indeed, similar improvements in accuracy in forecast wind are seen as are found for the wave height forecasts (see Figure 5). From 1996 and onwards these improvements in the accuracy of the surface winds have been caused by:

- Formulation of the new J_b in May 1997 and the introduction of 4D-Var in November 1997 (which allowed a better treatment of satellite data from, for example, (A)TOVS).
- Introduction of the T_L319 version of the IFS in March 1998.
- Two-way interaction of wind and waves in June 1998.
- Introduction of the T_L511 version of the IFS and doubling of the angular resolution in the wave model in October 2000.
- Operational assimilation of ERS-2 scatterometer winds in January 1996 and of QuikScat winds in January 2002.

In addition in 2003 we have seen a large increase in the amount of satellite data used in the analysis scheme. Despite the impressive improvements seen in the quality of the wind speed it should be pointed out that analyzed winds, for example, are still biased low with respect to the buoy observations. Presently, the bias is about -25 cms^{-1} in the Northern Hemisphere wintertime but ten years ago the bias was close to -50 cms^{-1}. Accordingly, wave heights are biased low in wintertime by about 15 cm.

The consequence of improved quality in surface winds is that the contribution of the wind speed error to the wave height error has reduced, so that wave model errors now play a much more prominent role in wave forecasting than ten years ago. As mentioned earlier we have therefore started

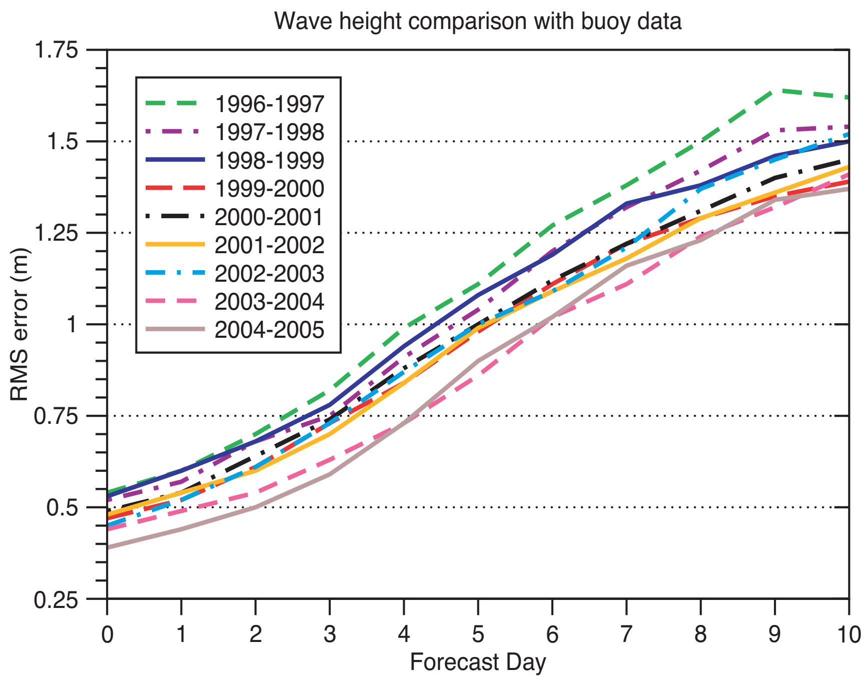

Figure 5 RMS error of analyzed and forecast wave height against buoy wave height data for all winters (October to March) from 1996 onwards. Forecasts are from 12 UTC.

improving some aspects of the model physics.

Extreme sea state forecasting

In the early 1960s there was a rapid development of the statistical theory of ocean waves, culminating in the basic evolution equation for the ocean wave spectrum (see the energy balance equation in Box A). In lowest order, the probability distribution function (pdf) for the surface elevation was found to be a Gaussian, corresponding to the case of linear waves. It was not realized at that time, however, that dynamical effects of finite amplitude on the pdf can be calculated and result in valuable information on extreme sea states.

The starting point for deriving the energy balance equation for the wave spectrum are a set of deterministic, nonlinear evolution equations for the amplitude and phase of the surface gravity waves. Because of nonlinearity, the equation for the second moment (i.e. the wave spectrum) is coupled to the third and fourth moment, and so on. An infinite hierarchy of equations follows and usually this hierarchy is closed by making the statistical assumption that the system remains close to Gaussian. However, finite deviations from the normal distribution are required in order to get a meaningful evolution of the spectrum (due to nonlinear three and four wave interactions). These deviations from normality can be obtained using the Chapman-Enskog Method to calculate the transport properties (such as the molecular viscosity) of fluids. Applied to the appropriate evolution equations for water waves, the result is the well-known Hasselmann equation for four-wave interactions. The deviations from normality contain, however, useful statistical information in itself, for example one may determine interesting parameters such as the skewness and the kurtosis of the pdf of the surface elevation.

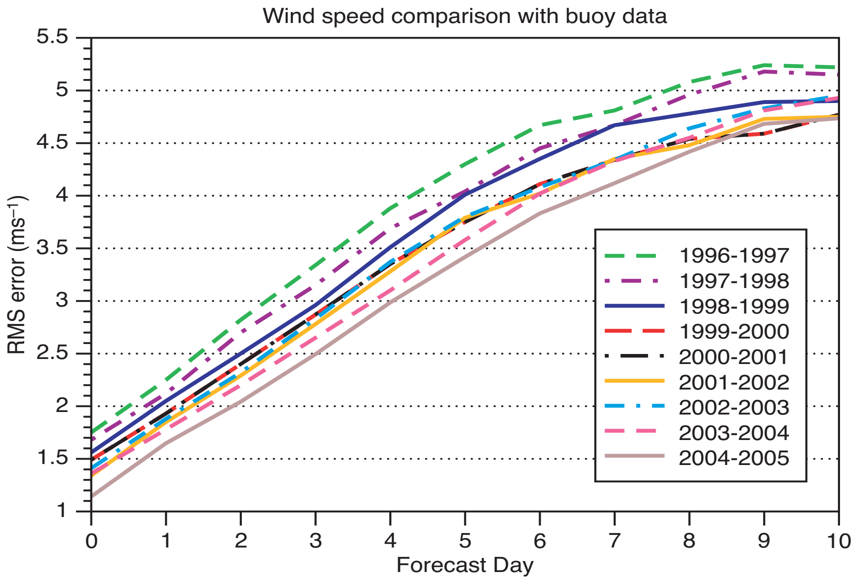

Figure 6 RMS error of analyzed and forecast surface wind speed against buoy wind speed observations for all winters (October to March) from 1996 onwards.

Explanation of the formation of freak waves

An intuitively appealing explanation of the formation of freak waves is the following. If waves have a small amplitude then they behave in a linear manner, hence the superposition principle applies. This means that when two wave trains with nearly the same amplitude and wavenumber meet then, depending on the phases of the wave trains, one finds as extreme twice the amplitude at best (constructive interference). The corresponding pdf of the surface elevation is the normal distribution and this pdf is regarded as the norm against which to measure extreme events. Finite amplitude waves are different because due to nonlinearity there are four-wave interactions, hence it is possible to borrow energy and momentum from the neighbouring waves. This is called *nonlinear focussing* and may result in amplification rates of a factor of five (rather than the factor of two in linear theory). Therefore, when nonlinear focussing is present extreme events are more likely to occur.

Under what circumstances do we have an efficient formation of freak waves? Clearly, the waves need to be sufficiently nonlinear. This is measured by an integral measure of wave steepness which depends upon the product of a typical wave amplitude and peak wave number. In addition, the interaction between the waves should exist and should be efficient. For surface gravity waves it can be shown that resonant four-wave interactions do exist and they are the most efficient when the interacting waves have more or less the same phase (i.e. they enjoy a coherent interaction). Coherency is measured in terms of the relative width of the (frequency) spectrum; hence the smaller the relative width of the spectrum, the more coherent the corresponding wave trains.

An analysis of the relevant evolution equations for surface gravity waves reveals that for narrow-band spectra the nonlinear focussing is controlled by a single parameter, namely the ratio of integral steepness to relative width. This parameter is called the Benjamin-Feir Index (BFI). Large values of the BFI (in practice of the order 1) indicate that nonlinear focussing is important, resulting in large deviations from the normal distribution and therefore increased probability for the occurrence of freak waves.

The theoretical approach regarding spectral evolution and the corresponding statistical properties of the sea surface have been validated by means of Monte Carlo simulations of the deterministic evolution equations (*Janssen*, 2003).

In addition, the theoretical approach compares favourably with wave tank observations (*Onorato et al.*, 2005). This is shown in Figure 7 which gives the probability $P(h)$ that instantaneous wave height exceeds h times the significant wave height H_S, according to observations, theory (*Mori & Janssen*, 2005) and according to linear theory (Rayleigh distribution). As can be seen from the Figure 7, for positive kurtosis there are considerable increases in the probability of extreme sea states, and, indeed, from the observed time series a number of freak waves were visible.

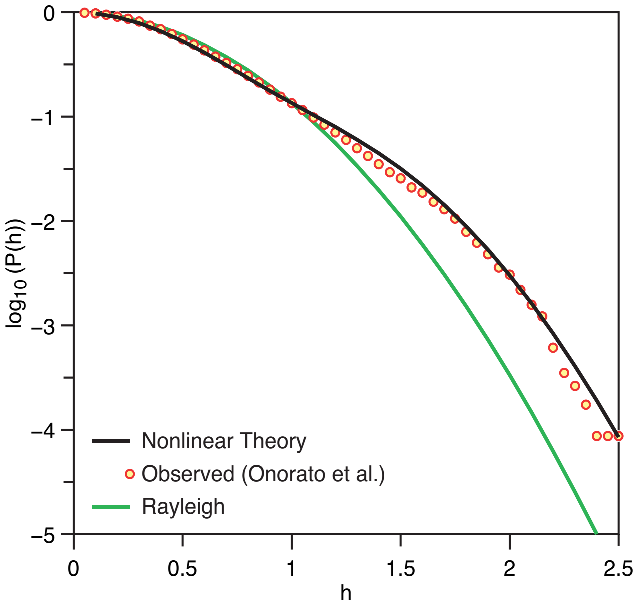

Figure 7 Comparison of theoretical and observed (Onorato et al., 2005) wave height distribution. For reference, the linear Rayleigh result is shown as well. Here h is the ratio of the instantaneous wave height (H) to the significant wave height (H_S) and P(h) is the probability of h occurring.

Operational Implementation

The first consequences of this approach have already been implemented in operations. An essential step in this implementation is a procedure to forecast the kurtosis parameter (defined in such a way that it vanishes for a normal distribution). Theoretically, the kurtosis is a very complicated expression in terms of the (action) wave spectrum. However, for Gaussian-shaped spectra in the narrow-band approximation the kurtosis shows a particularly simple dependence on the Benjamin-Feir Index (for a detailed derivation see *Mori & Janssen*, 2005). Here, this Index is obtained from the predicted wave spectrum; the kurtosis and other relevant statistical parameters of the sea surface then follow immediately.

It is emphasized that this approach is really an important step forwards. For the past fifty years we have concentrated on the description of the mean sea state. Now, there is perspective to start predicting deviations from the mean sea state, but it is clear that over the oceans a lot of validation of the skill of the new aspects of the wave forecasting system is still required. Validation of the skill of the probabilistic aspects of the wave forecasting system will be pursued in two directions.

- Using results from the new interim reanalysis we will collocate ship accidents with modelled sea state and kurtosis estimates. This work will be done together with the University of Leuven, Météo-France and the Met Office.
- We will attempt to validate modelled kurtosis with estimates from the radar altimeter. Namely, the radar return signal depends on the surface elevation probability distribution at zero slope and using the known, theoretical shape of the probability distribution function we might be able to estimate parameters such as the kurtosis directly from the observed return signal. This work will be carried out in collaboration with Dr Seymour Laxon (University College London) and Dr Nobuhito Mori (Osaka City University).

Finally, we note that freak wave prediction is an example of severe weather forecasting. The Ensemble Prediction System will no doubt play an important role in assessing the uncertainty of the prediction of these extreme waves.

Effects of currents and coastal zone modelling

The WAM model has an option to allow for the effects of ocean currents on wave propagation. Currents may affect ocean waves in the following ways. First, the frequency of the waves gets a Doppler shift, given by the wavenumber times the current velocity (see Box A). Second, when the current has a horizontal gradient then waves are refracted in a similar way as in the case of depth refraction. However, the most dramatic effects may be found when waves propagate against an ocean current. For sufficiently high current and high frequency, wave propagation is prohibited and wave breaking and wave reflection occurs. The most prominent example of the process of wave blocking is found in the Agulhas current, east of South Africa. The combined effect of current refraction and wave steepening (just prior to wave blocking) is thought to play a role in the formation of freak waves, which occur fairly frequently in the Agulhas current.

We have investigated the impact of currents on the significant wave height field by doing a standalone run with the wave model using monthly mean currents provided by the seasonal forecasting group. Figure 8 shows the monthly mean difference in wave height field from an experiment with and without currents. All major current systems are visible in this difference plot except perhaps the Gulf Stream. However, the amplitude of the differences is fairly small, of the order of 10 cm at best. A comparison with results from *Komen et al.* (1994) suggests that in the North Atlantic the modelled current is most likely too weak. Nevertheless, it is expected that in the near future the effects of currents will be included in the seasonal forecasting version of the wave prediction system.

Although on a global scale effects of the current may be fairly modest, it is known that in the coastal zone, in the presence of large tidal currents and surges, currents may modulate wave spectra to a considerable extent. A proper modelling of the sea state in the coastal zone, will require therefore the introduction of a coupled storm-surge, ocean wave prediction system. In addition, near the coast additional shallow water effects need to be taken into account. Examples are bottom-induced wave breaking, refraction and perhaps even quasi-resonant three wave interactions.

Part of the scientific development (for example the coupling of a storm-surge model and the WAM model) has already taken place during the European Union project Promise. Therefore, an operational version of the coastal zone, wave forecasting system (presumably replacing the

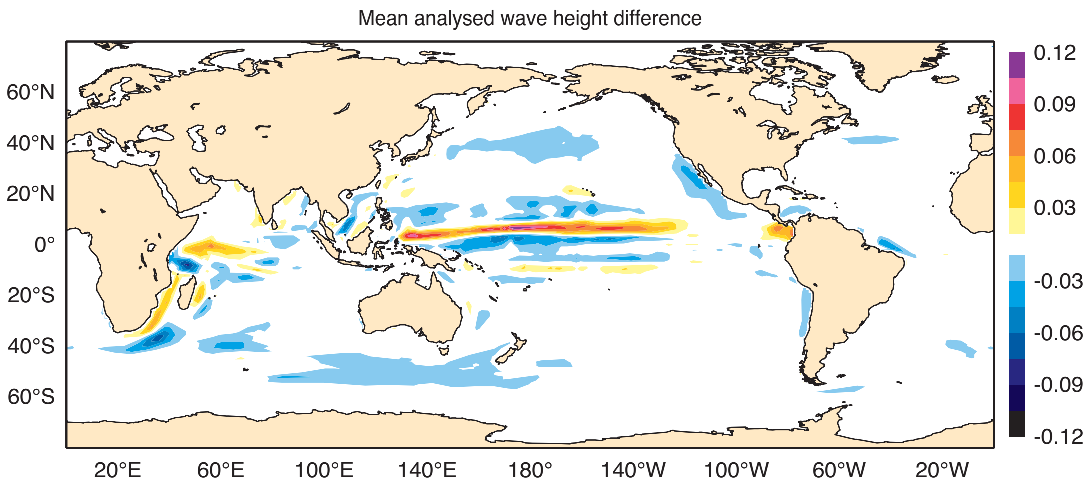

Figure 8 Impact of monthly mean currents from the seasonal forecasting system on the monthly mean significant wave height field for the period 00 UTC on 1 December to 18 UTC on 31 December 2003. All major current systems are visible except perhaps the Gulf Stream.

present European Shelf Model) is expected to be ready in a time frame of 5 years. This work will be done in collaboration with the Proudman Oceanographic Laboratory and other partners of the Promise project.

Need there be further wave model improvements?

At ECMWF there has been a considerable improvement in wave forecasting skill, in particular during the past ten years. Although wave model improvements have contributed to a considerable extent to the improved skill for predicting significant wave height and parameters such as the mean period it is argued that the major reason of the improvement comes from a higher quality wind field.

Clearly wave model results are sensitive to errors in the forcing wind speed. We have utilized this property of ocean waves to our advantage by using wave model forecast results as a tool to diagnose problems in the atmospheric model (*Janssen et al.*, 2000). Examples are the inconsistency between surface wind and stress, the over-activity of the atmospheric forecast, and the lack of small-scale variability. Combined with the two-way interaction of wind and waves this has contributed to maintaining a high quality weather forecasting system.

One may ask the question whether there is any further need for wave model improvements. Evidently, there is, at least if one is interested in a realistic representation of the properties of the sea surface. Examples are the coupling of wind and waves which had a beneficial impact on the forecast and the recent improvements seen in the mean frequency of the ocean waves. It is emphasized that forecasting of significant wave height is only one aspect of the wave forecasting problem, the final aim is to obtain a reliable and accurate two-dimensional wave spectrum. This is relevant for many practical applications ranging from ship response studies to sea state effects on altimeter measurements.

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Special Project computer allocations for 2006–2008

Member State		Institution	Project title	2006		2007		2008	
				HPCF units	Data storage	HPCF units	Data storage	HPCF units	Data storage
Continuation Projects									
Austria	1	Univ. Vienna (Beck, Ahrens)	Alpine regional downscaling of reanalysis data using the LAM ALADIN	1,000	100	X	X	X	X
	2	Univ. Innsbruck (Ehrendorfer)	Mesoscale predictability and ensemble prediction	8,000	5	8,000	5	X	X
	3	Univ. Graz (Kirchengast)	Climate monitoring by advanced spaceborne sounding and atmospheric modelling	30,000	300	35,000	350	40,000	400
	4	Universitat fur Bodenkultur, Vienna (Kromp-Kolb)	Modelling of tracer transport (MoTT)	500	5	500	5	500	5
	5	Univ. Vienna (Steinacker)	Mesoscale alpine climatology	100	10	100	10	100	10
	6	Univ. Vienna (Steinacker)	4D OMEGA FORM – 4 dimensional objective mesogamma analysis of Foehn in the Rhine Valley during MAP	100	10	100	10	100	10
Denmark	7	DMI (Sattler)	Investigations on LAM ensembles for wind power prediction (WEPS)	50,000	250	50,000	250	50,000	250
France	8	LOCEAN-UPMC (Herbette)	Inter-annual variability of the Canary upwelling system	40,000	500	X	X	X	X
	9	CERFACS (Morel)	PALM: Universal software for data assimilation	5,000	180	5,000	180	5,000	180
	10	CERFACS (Rogel)	Seasonal to interannual predictability of a coupled ocean-atmosphere model	10,000	150	10,000	150	10,000	150
	11	CERFACS (Weaver)	Development and application of variational data assimilation with the OPA OGCM	87,000	1,500	100,000	1,500	100,000	1,500
Germany	12	MPI, Hamburg (Bengtsson)	Numerical experimentation with a coupled ocean/atmosphere model	243,000	5,000	300,000	7,000	320,000	8,000
	13	MPI, Hamburg (Bengtsson)	Regional downscaling of ERA40 data and validation of the hydrological cycle	303,000	2,200	420,000	3,000	450,000	3,500
	14	Freie Univ. Berlin (Cubasch, Kirchner)	Investigation of systematic tendency changes and their influence on the general circulation simulated with climate models	5,000	600	5,000	800	5,000	1,000

Member State		Institution	Project title	2006		2007		2008	
				HPCF units	Data storage	HPCF units	Data storage	HPCF units	Data storage
Continuation Projects									
Germany	15	ISET (Czisch)	Evaluation of the global potential of energy towers	100	20	100	20	X	X
	16	DLR (Doernbrack)	Influence of non-hydrostatic gravity waves on the stratospheric flow for fields above Scandinavia	130,000	80	200,000	80	250,000	80
	17	Univ. Munich (Egger)	Landsurface – atmosphere interaction	1,500	50	1,500	50	1,500	50
	18	DLR & MPI Chemistry, Mainz (Eyring, Steil)	Impact of anthropogenic emissions on tropospheric chemistry with a special focus on ship emissions	217,000	3,300	250,000	4,000	250,000	4,000
	19	DLR (Gierens)	Ice-supersaturation and cirrus clouds	173,000	100	200,000	100	200,000	100
	20	Univ. of Göttingen (Gravenhorst)	Downscaling of ECMWF seasonal forecast in the tropical region Central Sulawesi, Indonesia using the climate limited area model CLM of the German Weather Service	87,000	200	100,000	200	100,000	200
	21	DLR (Hoinka)	Climatology of the global tropopause	5,000	10	5,000	10	5,000	10
	22	Univ. Karlsruhe (Jones)	The impact of tropical cyclones on extratropical predictablity	130,000	350	150,000	400	150,000	450
	23	DLR (Keil, Craig)	Ensemble Modelling for the improvement of short range quantitative precipitation forecasts	87,000	80	100,000	80	100,000	80
	24	IMK-IFU (Kuntsmann)	Onset of the rainy season in West Africa	1,000	100	1,000	100	1,000	100
	25	Leibniz-Institut – Univ. Kiel (Latif)	Seasonal to decadal forecasting with coupled ocean-atmosphere general circulation models	691,000	5,500	900,000	9,000	900,000	11,000
	26	MPI-A Heidelberg (Masciadri)	Forecasting of the optical turbulence for Astronomy applications with the MesoNH mesoscale model coupled with ECMWF products	4,000	30	4,000	30	4,000	30
	27	DLR (Mayer)	Remote sensing of water and ice clouds with Meteosat Second Generation	50,000	20	50,000	20	50,000	20
	28	Alfred Wegener Institute (Rinke)	Sensitivity of HIRHAM	200	50	200	50	200	50
	29	Alfred Wegener Institute (Schollhammer, Rex)	Changes in ozone transport: residual circulation and the isentropic transport	200	100	200	100	200	100
	30	MPI, Hamburg (Schultz)	Global atmospheric chemistry modelling	139,000	3,300	300,000	6,000	300,000	6,000
	31	Univ. Koln (Speth)	Interpretation and calculation of energy budgets	100	10	110	10	120	15
	32	Univ. Munich (Spichtinger, Damoah)	Validation of trajectory calculations	1,000	100	1,000	110	1,000	120
	33	Univ. Bremen (Weber)	Chemical and dynamical influences on decadal ozone change (CANDIDOZ)	100	20	100	20	100	20
	34	Univ. Mainz (Wirth)	Water vapour in the upper troposphere	1,000	20	1,000	20	1,000	20

Member State		Institution	Project title	2006		2007		2008	
				HPCF units	Data storage	HPCF units	Data storage	HPCF units	Data storage
Continuation Projects									
Ireland	35	Univ. College Dublin (Lynch)	Community Climate Change Consortium for Ireland (C4I)	260,000	2,000	300,000	2,000	X	X
	36	Univ. College Cork, Met Éireann (Moehrlen, McGrath, Joergensen)	Verification of ensemble prediction systems for a new market: wind energy	173,000	50	200,000	50	X	X
Italy	37	ISMAR-CNR (Cavaleri)	Evaluation of the performance of the ECMWF meteorological model at high resolution	20,000	150	20,000	150	20,000	150
	38	INGV, Bologna (Manzini)	Middle atmosphere modelling	234,000	1,600	290,000	1,700	310,000	1,900
	39	ARPA-SMR, Emilia Romagna & MeteoSwiss (Montani, Walser)	Improvements of COSMO limited-area ensemble forecasts	139,000	620	180,000	640	200,000	660
	40	ARPA-SMR, Emilia Romagna & Italian Met. Service (Paccagnella, Montani, Ferri)	Limited area model targeted ensemble prediction system (LAM-TEPS)	104,000	100	150,000	120	180,000	140
	41	Univ. Genova (Parodi)	High resolution numerical modelling of intense convective rain cells	30,000	200	50,000	200	20,000	200
	42	ARPA-SMR, Emilia Romagna & UCEA (Pavan, Esposito)	Seasonal Prediction for Italian Agriculture (SPIA)	1,000	100	1,000	100	1,000	100
Netherlands	43	KNMI (van Meijgaard)	Multi-annual integrations with the KNMI regional climate model RACMO2	433,000	500	500,000	2,500	500,000	2,500
	44	KNMI (van Velthoven)	Chemical reanalyses and sensitivity studies with the chemistry-transport model TM4	30,000	70	20,000	100	X	X
Norway	45	DNMI (Frogner)	NORLAMEPS: Limited Area Ensemble Prediction System for Norway	173,000	500	200,000	500	200,000	500
	46	DNMI (Iversen, Frogner)	REGCLIM: optimal forcing perturbations for the atmosphere	173,000	500	X	X	X	X
	47	Univ. Oslo (Isaaksen)	Ozone as a climate gas	15,000	5	15,000	5	15,000	5
Portugal	48	Univ. Lisbon (Soares)	HIPOCAS-SPEC	0	10	0	10	0	10
Spain	49	Univ. Illes Balears (Cuxart)	Study of the stably stratified atmospheric boundary layer through large-eddy simulations and high-resolution mesoscale modelling	87,000	200	100,000	200	100,000	200
Sweden	50	SMHI (Undén)	The HIRLAM 6 project	433,000	25,00	700,000	3,500	1,000,000	5,000
United Kingdom	51	Univ. Reading (Hoskins)	Routine back trajectories	5,000	4	5,000	4	5,000	4
	52	Univ. Reading (Hoskins)	Stochastic physics	5000	25	X	X	X	X
	53	DARC, Univ. Reading (Lahoz)	How good are simulated water vapour distributions in the UTLS region?	50,000	180	70,000	250	100,000	360
	54	DARC, Univ. Reading (O'Neill)	Assimilation of retrieved products from EOS MLS	130,000	1,000	200,000	1,000	200,000	1,000
	55	Univ. Oxford (Pall)	Probabilistic attribution of the UK autumn 2000 floods	8000	110	X	X	X	X

Member State		Institution	Project title	2006		2007		2008	
				HPCF units	Data storage	HPCF units	Data storage	HPCF units	Data storage
Continuation Projects									
United Kingdom	56	BAS, Cambridge (Turner)	Assessment of ECMWF forecasts over the high latitude areas of the Southern Hemisphere	0	1	0	1	0	1
JRC	57	JRC-IES (Dentener)	The linkage of climate and air pollution: simulations with the global 2-way nested model TM5	217,000	160	X	X	X	X
New Projects									
Austria	1	Univ. Vienna (Haimberger)	Homogenization of the global radiosonde temperature and wind dataset	500	200	500	200	500	200
Denmark	2	DMI (Amstrup)	EUCOS/EUMETSAT data impact studies	649,000	8,000	0	0	0	0
Finland	3	FMI (Jarvinen)	Stochastic sub-grid scale parametrizations for coupled earth system models	191,000	1,620	280,000	1,840	340,000	2,060
France	4	CNRM/GMAP, Météo-France (Fischer)	Investigation of coupling the ALADIN and AROME models to boundary conditions from ECMWF and ERA model data	20,000	600	25,000	700	30,000	800
Germany	5	Univ. Cologne (Elbern)	GEMS: work package WP_RAQ_2	10,000	120	20,000	150	30,000	200
	6	MPI, Hamburg (von Storch)	Numerical experimentation with a high-resolution ocean model	433,000	3,300	500,000	7,000	500,000	7,000
Italy & United Kingdom	7	ARPA-SMR, Emilia Romagna & UK Met Office (Montani, Mylne)	Limited-area ensemble forecasts of windstorms over Northern Europe	691,000	100	900,000	120	1000,000	140
Netherlands	8	KNMI (Drijfhout)	Water mass pathways in a high-resolution isopycnic model	173,000	40	300,000	40	150,000	40
	9	KNMI (Hazeleger)	Patterns of climate change: coupled modelling activities	182,000	40	210,000	40	210,000	40
	10	KNMI (Siebesma)	Rain in Cumulus	2,5000	30	30,000	40	35,000	50
United Kingdom	11	ESSC, Univ. Reading (Bengtsson)	Predictability studies with emphasis on extra-tropical and tropical storm-tracks and their dependance on the global observing systems	303,000	300	400,000	300	450,000	300
ICTP	12	ICTP (Molteni)	Dynamical downscaling of seasonal predictions with a regional climate model	50,000	500	50,000	500	50,000	500
	13	ICTP (Molteni)	Decadal interactions between the tropical Indo-Pacific Ocean and extratropical modes of variability in an intermediate coupled model	50,000	300	50,000	300	50,000	300
Total Requested				7,998,400	49,985	8,964,410	57,920	8,991,320	61,810

Member State computer allocations for 2006

Member State	HPCF (kunits)	Data Storage (Gbytes)
Belgium	3,348	20,925
Denmark	2,832	17,703
Germany	14,237	88,981
Spain	5,889	36,807
France	10,889	68,058
Greece	2,603	16,272
Ireland	2,384	14,900
Italy	9,230	57,686
Luxembourg	1,875	11,717
Netherlands	4,369	27,306
Norway	2,923	18,268

Member State	HPCF (kunits)	Data Storage (Gbytes)
Austria	3,048	19,052
Portugal	2,498	15,612
Switzerland	3,560	22,250
Finland	2,580	16,125
Sweden	3,282	20,511
Turkey	2,887	18,042
United Kingdom	11,566	72,285
Allocated to Special Projects	7,998	49,985
Reserved for Special Projects	2,002	12,515
Total	**100,000**	**625,000**

ECMWF Council and its committees

The following provides some information about the responsibilities of the ECMWF Council and its committees. More detail can be found at: www.ecmwf.int/about/committees

Council

The Council adopts measures to implement the ECMWF Convention; the responsibilities include admission of new members, authorising the Director to negotiate and conclude co-operation agreements, and adopting the annual budget, the scale of financial contributions of the Member States, the Financial Regulations and the Staff Regulations, the long-term strategy and the programme of activities of the Centre.
President: Prof Anton Eliassen (*Norway*)
Vice President: Mr Adérito Vicente Serrão (*Portugal*)

Policy Advisory Committee (PAC)

The PAC provides the Council with opinions and recommendations on any matters concerning ECMWF policy submitted to it by the Council, especially those arising out of the Four-Year Programme of Activities and the Long-term Strategy.
Chair: Generale Massimo Capaldo (*Italy*)
Vice Chair: Dr Fritz Neuwirth (*Austria*)

Finance Committee (FC)

The FC provides the Council with opinions and recommendations on all financial matters submitted to the Council and shall exercise the financial powers delegated to it by the Council.
Chair: Ms Laurence Frachon (*France*)
Vice Chair: Mr Fabrice Carton (*Belgium*)

Scientific Advisory Committee (SAC)

The SAC provides the Council with opinions and recommendations on the draft programme of activities of the Centre drawn up by the Director and on any other matters submitted to it by the Council. The members of the SAC are appointed in their personal capacity and are selected from among the scientists of the Member States.
Chair: Prof Thor Erik Nordeng (Norwegian Meteorological Institute)
Vice Chair: Prof Gerhard Adrian (Deutscher Wetterdienst)
The other members of the SAC are:
Dr François Bouttier (*Météo-France*)
Dr Luigi Cavaleri (*ISMAR*)
Prof Dr Martin Ehrendorfer (*Universität Innsbruck*)
Dr John R Eyre (*Met Office*)
Dr Hans Huang (*Danish Meteorological Institute*)
Dr Henny Kelder (*KNMI*)
Dr Ernesto Rodriguez-Camino (*Instituto Nacional de Meteorologia*)
Prof Hannu Savijärvi (*University of Helsinki*)
Prof Julia Slingo (*University of Reading*)
Prof Michael Tjernström (*Stockholm University*)

Technical Advisory Committee (TAC)

The TAC provides the Council with advice on the technical and operational aspects of the Centre including the communications network, computer system, operational activities directly affecting Member States, and technical aspects of the four-year programme of activities.
Chair: Mrs Kristiina Soini (*Finland*)
Vice Chair: Dr Alan Dickinson (*United Kingdom*)

Advisory Committee for Data Policy (ACDP)

The ACDP provides the Council with opinions and recommendations on matters concerning ECMWF Data Policy and its implementation.
Chair: Mr Detlev Frömming (*Germany*)
Vice Chair: Dr Lillian Wester-Andersen (*Denmark*)

Advisory Committee for Co-operating States (ACCS)

The ACCS provides the Council with opinions and recommendations on the programme of activities of the Centre, and on any matter submitted to it by the Council.
Chair: Mr Jozef Roskar (*Slovenia*)
Vice Chair: Mr Ion Sandu (*Romania*)

TAC Representatives, Computing Representatives and Meteorological Contact Points

Member States	TAC Representatives	Computer Representatives	Meteorological Contact Points
Belgium	Dr D. Gellens	Mrs L. Frappez	Dr J. Nemeghaire
Denmark	Mr L. Laursen	Mr N. Olsen	Mr G. Larsen
Germany	Mr H. Ladwig	Dr E. Krenzien	Mr T. Schumann
Spain	Mr P. del Rio	Mr E. Monreal	Ms A. Casals Carro
France	Mr B. Strauss	Mrs M. Pithon	Mr J. Clochard
Greece	Mr D. Kapniaris	Major J. Alexiou	Dr I. Papageorgiou Mr P. Xirakis
Ireland	Mr J. Logue	Mr P. Halton	Mr M. Walsh
Italy	Dr S. Pasquini	Mr G. Tarantino	Dr T. La Rocca
Luxembourg	Mr C. Alesch	Mr C. Alesch	Mr C. Alesch
Netherlands	Mr T. Moene	Mr H. de Vries	Mr J. Diepeveen
Norway	Mr J. Sunde	Ms R. Rudsar	Mr P. Evensen
Austria	Dr G. Kaindl	Dr G. Wihl	Dr H. Gmoser
Portugal	Mrs T. Abrantes	Mrs M. da C. Periera Santos Mr J. Monteiro	Mrs I. Soares
Switzerland	Dr S. Sandmeier	Mr P. Roth	Mr R. Mühlebach
Finland	Mrs K. Soini	Mr K. Niemelä	Mr P. Nurmi
Sweden	Mr I. Karro	Mr R. Urrutia	Mr M. Hellgren
Turkey	Mr M. Fatih Büyükkasabbaşi	Mr F. Kocaman	Mr M. Kayhan
United Kingdom	Dr A. Dickinson	Mr R. Sharp	Mr A. Radford
Co-operating States			
Croatia	Mr I. Čačić	Mr V. Malović	Mr Č. Branković
Czech Republic	Mr M. Janoušek	Mr M. Janoušek	Mr F. Sopko
Estonia	Mr T. Kaldma	Mr T. Kaldma	Mrs M. Merilain Mrs T. Paljak
Hungary	Dr Z. Dunkel	Mr I. Ihász	Mr I. Ihász
Iceland	Mr H. Björnsson	Mr V. Gislason	Mrs S. Karlsdottir
Romania	Dr I. Pescaru	Mr R. Cotariu	Mrs T. Cumpanasu
Slovenia	Mr J. Jerman	Mr P. Hitij	Mr B. Gregorčič
Serbia/Montenegro	Ms L. Dekic	Mr V. Dimitrijević	Mr B. Bijelic
Observers			
EUMETSAT	Mr M. Rattenborg	Dr K. Holmlund	
WMO	Mr M. Jarraud		

ECMWF Calendar 2006

February 1–2	TAC Subgroup on Use of GRID Technology
February 6–10	GEMS Assembly
February 16–17	Computer Training Course – SMS/XCDP
February 20–24	Computer Training Course – Introduction for new users/MARS
February 27–28	Computer Training Course – MAGICS
March 1–3	Computer Training Course – METVIEW
March 6–10	Computer Training Course – Use of supercomputing resources
March 13–17	Meteorological Training Course – Use and interpretation of ECMWF products
March 22–31	Meteorological Training Course – Data assimilation and use of satellite data
April 24–28	Meteorological Training Course – Predictability, diagnostics and seasonal forecasting
April 24–25	Finance Committee (*76th Session*)
April 25–26	Advisory Committee on Data Policy (*7th Session*)
April 26–27	Policy Advisory Committee (*23rd Session*)
May 2–12	Meteorological Training Course – Parametrization of diabatic processes
May 15–24	Meteorological Training Course – Numerical methods and adiabatic formulation of models
May 16–17	Security Representatives' Meeting
June 5–9	Meteorological Training Course – Use and interpretation of ECMWF products
June 8–9	Computer Representatives' Meeting
June 14–16	Forecast Products Users Meeting
June 19–22	Workshop – Preparation for a new generation of atmospheric reanalyses
July 5–6	Council (*65th Session*), Oslo
September 4–8	Annual Seminar – Polar Meteorology
October 2–4	Scientific Advisory Committee (*35th Session*)
October 4–6	Technical Advisory Committee (*36th Session*)
October 9–13	Meteorological Training Course – Use and interpretation of ECMWF products for WMO Members
October 16–17	Finance Committee (*77th Session*)
October 18–19	Policy Advisory Committee (*24th Session*)
October 23	Advisory Committee of Co-operating States (*12th Session*)
October 30–November 3	Workshop – High performance computing in meteorology (*12th Workshop*)
November 8–10	Workshop – Parametrization of clouds in large-scale models
November 27–28	Council (*66th Session*)

ECMWF publications

(see http://www.ecmwf.int/publications/)

Technical Memoranda

483 **Ferranti, L.** & **P. Viterbo**: The European summer of 2003: sensitivity to soil water initial conditions. *January 2006*

482 **Majumdar, S.J., S.D. Aberson, C.H. Bishop, R. Buizza, M.S. Peng** & **C.A. Reynolds**: A comparison of adaptive observing guidance for Atlantic tropical cyclones. *December 2005*

481 **Tompkins, A.M., K. Gierens** & **G. Radel**: Ice supersaturation in the ECMWF Integrated Forecast System. *December 2005*

480 **Balmaseda, M.A., D. Dee, A. Vidard** & **D.L.T. Anderson**: A multivariate treatment of bias for sequential data assimilation: Application to the tropical oceans. *November 2005*

479 **Andersson, E., M. Fisher, E. Holm, L. Isaksen, G. Radnoti** & **Y. Tremolet**: Will the 4D-Var approach be defeated by nonlinearity?. September 2005

478 **Janssen, P., J-R. Bidlot, S. Abdalla** & **H. Hersbach**: Progress in ocean wave forecasting at ECMWF. *September 2005*

477 **Tremolet, Y.**: Accounting for an imperfect model in 4D-Var. *November 2005*

476 **Doblas-Reyes, F.J., R. Hagedorn, T.N. Palmer** & **J-J. Morcrette**: Impact on increasing greenhouse gas concentrations in seasonal ensemble forecasts. *October 2005*

475 **Di Michele, S.** & **P. Bauer**: Passive microwave radiometer channel selection based on cloud and precipitation information content estimation. *July 2005*

Index of past newsletter articles

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Useful names and telephone numbers within ECMWF

Telephone
Telephone number of an individual at the Centre is:

International:	+44 118 949 9 + three digit extension
UK:	(0118) 949 9 + three digit extension
Internal:	2 + three digit extension

e.g. the Director's number is:
+44 118 949 9001 (international),
(0118) 949 9001 (UK) and 2001 (internal).

E-mail
The e-mail address of an individual at the Centre is:
firstinitial.lastname@ecmwf.int
e.g. the Director's address is: D.Marbouty@ecmwf.int

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Internet web site
ECMWF's public web site is: http://www.ecmwf.int

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