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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 The ECMWF Newsletter is not peer-reviewed.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
Flooding in the village of Sonning, near Reading UK, January 2003. Photograph courtesy of Rob Hine.

Editorial

NWP in Europe

The cost of running NWP systems has increased significantly over recent years for several reasons.

- Assimilation systems have become incredibly complex and have to deal with not only enormous amounts of data but also a large number of different types of instruments, particularly from satellites.
- The complexity of models is increasing dramatically in order to allow a better representation of processes, in particular the water-cycle and radiation.
- A modern NWP system is no longer a model of the lower atmosphere but has evolved into an Earth-system model that includes several components such as surface processes, ocean waves, stratosphere and atmospheric chemistry.
- Ensemble forecasting is now the norm for seasonal and extended medium-range forecasts and is developing for all ranges.
- The evolution of supercomputer architectures towards higher parallelism has resulted in significantly reduced growth in application performance, at least for meteorological models. This means that Moore's law no longer applies to our applications and needs to be compensated by larger machines.

As a result, individual organisations cannot afford the necessary computing and human resources required for developing and running such systems. Indeed this was the driving force for the creation of ECMWF to produce medium-range forecasts. It has also led to the creation of European groupings for the development of limited area, high-resolution systems for short-range forecasts (ALADIN, COSMO, HIRLAM).

As these costs continue to rise, further co-operation will still be required, as can already be observed for HIRLAM and ALADIN. For ECMWF it means that it is of particular importance that the development of its forecasting system not only results in providing the best possible products to its Member States, but also contributes to the building of their national monitoring and forecasting systems.

This point was strongly expressed in the EUMETNET workshop on the future of NWP in Europe, organised by the Met Office and hosted by ECMWF, in March 2006. In particular the need for more interoperability and a more general use of common software tools, specifically those developed at ECMWF, was emphasized.

From this point of view the second complementary goal developed in ECMWF's strategy for 2006–2015 is of particular importance: "to enhance support to Member States' national forecasting activities by providing suitable boundary conditions for limited-area models". A significant improvement was achieved in March when the Boundary Condition (BC) suite was reconfigured so that it is now based on 4D-Var.

Enhancing such co-operation at all levels will be key to developing the vision guiding our strategy that "European citizens will continue to receive the best meteorological forecasting services at all ranges, particularly regarding severe weather", at a time when facing increasing costs is particularly difficult.

Dominique Marbouty

Changes to the operational forecasting system

David Richardson

Changes made on 7 February

Revised satellite radiance bias files were introduced on 7 February 2006, reducing temperature biases of the analysis compared against aircraft and radiosondes. The new radiance bias correction is derived from a trial variational bias correction scheme which is being tested for full operational implementation in the next model cycle.

Changes to the Optional Project: Boundary Condition Suite

Following new guidelines agreed by Council in December 2005, the Boundary Condition (BC) Suite Optional Project has been reconfigured so that all four daily assimilation cycles for the BC suite use 4D-Var.

- BC products from the 00 and 12 UTC analyses are taken from the core operational suite runs.
- BC products for 06 and 18 UTC are BC Project products, but now use 4D-Var instead of the previous 3D-Var FGAT.

The new configuration was introduced on 14 March 2006.

Planned changes

Testing of a new model cycle has begun. The new version includes changes to the cloud and convection parametrizations and variational bias correction of satellite radiances. Technical changes in preparation for the extension of the EPS to day 15 at reduced resolution (VAREPS) are also included.

New items on the ECMWF web site

Andy Brady

ERA 40 Atlas Web Site

The ERA-40 Atlas describes the climate during 1979–2001, the period with the best and most time-consistent product quality for the globe as a whole. The web-version of the ERA-40 Atlas includes all the material in the printed version of the Atlas. The Atlas contains:

- Surface and column-integrated fields.
- Upper-air fields derived on pressure levels, on isentropic levels and on the 2 pvu potential-vorticity level from values on the model's native hybrid levels.

Also included are the invariant fields used in the data-assimilation system. The climate of the period 1979–2001 is presented for the four seasons, the annual average and the interannual variability. These products are based on the ERA-40 monthly/diurnal averages together with six-hourly analysis and forecast fields. A selection of time series, showing for example the quasi-biennial oscillation of stratospheric winds, is presented for the full period 1958–2001.

www.ecmwf.int/research/era/ERA-40_Atlas/

ECMWF 2006 Annual Seminar

In the context of the impending International Polar Year (IPY, 2007–9), 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.

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

Retirement of Dr Gerd Schultes

Dominique Marbouty

Gerd Schultes retired from ECMWF on 1 May 2006 after nearly 20 years as Head of Administration.

Gerd developed a truly international career. He graduated in business administration from the Vienna School of Economics in 1974 following studies in the Universities of Darmstadt and Cologne. From 1974 to 1978 he was a Personnel Officer at the Food and Agriculture Organization (FAO) in Rome. He then moved to UNICEF, first at the Office for Europe in Geneva for five years and then at the newly developed Procurement and Assembly Centre in Copenhagen in 1983 as Chief of Personnel and Administration.

On the 1 November 1986 Gerd joined ECMWF as Head of Administration. During his long employment, he always showed a strong dedication to the Centre and its staff. Put simply Gerd ensured that the ECMWF administration remained efficient and fit to the needs of the organisation: this has been an important contribution to the successful development of the Centre. Among his many achievements at ECMWF was the development of the Health Scheme, joining the Co-ordinated Organisations (the CCR) in 1988, and developing a new Pension Scheme which entered into force in 2003. Recently he ensured the successful completion of the computer hall extension and the new office building.

Gerd organised regular visits to the Member States to explain the budget requirements and facilitate the discussions in the various Committees. Finance Committee delegates will certainly remember the careful attention of Gerd and his wife Helga to the good spirit of their meetings. Among the Member States Gerd paid particular attention to the relations with our host country, and spent much time ensuring the proper maintenance of the Centre's premises.

A specific area of interest for Gerd has always been the Pension Schemes and the well-being of pensioners. Without any doubt Gerd now deserves to have the opportunity to be on the receiving end and benefit from this long-standing involvement. We wish him and Helga a long and happy retirement.

A new Head of Administration for ECMWF

Dominique Marbouty

At its 64th session on 7 December 2005 the Council approved the appointment of Mrs Ute Dahremöller from Germany to become the next Head of Administration following the retirement of Dr Gerd Schultes at the end of April 2006.

Ute graduated in economics at the University of Bonn. Since then her career has been mainly concerned with public administration, especially in the fields of finance, international economic cooperation and public procurement.

Immediately before joining ECMWF Ute held the post of Head of Finance Division of the German Federal Agency for Post and Telecommunication for 11 years. During her tenure, she had been instrumental in implementing forward-looking financial planning and monitoring systems and a funded pension scheme, with special emphasis on hiring, training and coaching divisional staff. Her duties included the privatisation of the government-owned stock of Deutsche Telekom AG and Deutsche Post AG and the preparation of the respective contracts. Prior to this she worked for the German Federal Ministry of Economics for more than 10 years, where she acquired in-depth knowledge of economic cooperation and liaison in an international environment. During a one-year period in Brussels she further intensified her international experience. As a price negotiator for the German Federal Office of Army Technology and Procurement she closely cooperated with technical army staff and translated their requirements into procurement contracts, thus gaining a good understanding of technical matters. Before that, she designed and implemented a reliable economic forecasting system at the University of Bonn that was run on a supercomputer.

Ute recently successfully completed a two-year part-time Executive Master of Business Administration (MBA) course of studies organised by the US Kellogg School of Management, Northwestern University, and the Wissenschaftliche Hochschule für Unternehmensführung (WHU) in Vallendar, Germany. The course covered all aspects management training for internationally orientated executives, with special emphasis on teamwork and cooperation in an international environment and among participants from different cultures.

I take this opportunity to congratulate Ute on her appointment and to welcome her to ECMWF's management team.

A real application of seasonal forecasts – malaria early warnings

Renate Hagedorn,
Francisco Doblas-Reyes, Tim Palmer

It is sometimes asked whether seasonal forecasts are skilful enough to be useful for real applications. One of the main goals of the DEMETER project was to find evidence for answering this question, one way or the other. Thus, DEMETER set out not only to assess the general skill of a multi-model ensemble system for seasonal to interannual forecasts, but also to establish its degree of utility in real-life decision-making processes. For more information about DEMETER go to www.ecmwf.int/research/demeter.

One of the most outstanding results of this research was published on 2 February 2006 (*Nature*, vol. **439**, 576–579, doi: 10.1038/nature04503). In this publication, the DEMETER team at ECMWF (Francisco Doblas-Reyes, Renate Hagedorn and Tim Palmer) along with researchers from Columbia University's IRI (International Research Institute) in New York, the University of Liverpool, and the Ministry of Health in Botswana report on the development of a malaria early warning system based on seasonal climate forecasts from the DEMETER multi-model ensemble system.

Malaria and climate are linked through the lifecycle of the mosquito, which carries the parasite that causes malaria. In simple terms: the higher the precipitation, the more mosquitoes occur, and the more malaria is transmitted amongst the population. This relationship, which in practice is not as simple and linear as described here, has already been used in the past to predict malaria epidemics. However, such predictions were based on observations of the strength

The control of epidemic malaria is a priority for the international health community. The mosquito-borne illness infects 500 million people worldwide each year, killing an estimated one million, most of them children. The problem is greatest in sub-Saharan Africa.

of the present rainy season. Since malaria epidemics occur approximately 1 month after the rainy season, at best a lead time of 2–4 weeks could be achieved with this method. By contrast, the new system described in the letter to Nature uses seasonal climate predictions available before the start of the rainy season. With the rainy season lasting from November to February in Botswana, the region used in this pilot study, the lead time for predicting the probability of the occurrence of a malaria epidemic could be extended by about four months. Though this new system based on seasonal climate predictions is slightly less accurate than malaria forecasts based on precipitation observations, the significant gain in lead time more than outweighs this drawback. In fact, the increase in warning time is extremely important for health officials, giving them crucial time to optimize the allocation of the limited resources available in the fight against malaria.

We are extremely pleased to report that the new system not only has been developed and tested for the past, but is actively used in the national malaria control programme in Botswana and surrounding countries. This might actually be the most exciting aspect of this work, i.e. the speed at which cutting-edge climate research has been translated into operational activity in Africa. This was possible because the unique interdisciplinary composition of the scientific team ensured that the research activities were linked directly to the operational needs and policy objectives of decision makers in the field. Due to its high societal relevance, the publication - and with it ECMWF as the lead organisation in the DEMETER project – received a considerable amount of media attention ranging from reports of the major news agencies (e.g. CNN, Reuters), articles in global newspapers (e.g. The Guardian, Economist, Le Figaro) to interviews broadcast by various radio stations (e.g. BBC World Service, Deutschlandradio). This not only confirms the public interest in new and promising developments demonstrating the value of weather and climate forecasts, but also gives scientists the motivation to explore new avenues for realising the full potential of our forecasts for real end-user applications.

The article in *Nature* can be found at:

www.nature.com/nature/journal/v439/n7076/abs/nature04503.html

A kick-off workshop for THORPEX

Philippe Bougeault

THORPEX is a WMO/World Weather Research Programme initiative to accelerate improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, economy and the environment. A kick-off workshop was held at the University of Reading on 20–24 March 2006. This was the first occasion for all working groups under THORPEX to meet and discuss cooperation towards the common goal. Fifty representatives from all continents attended the event. ECMWF was represented by the following.

- Walter Zwieflhofer, co-chair of the THORPEX Technical Advisory Board.
- Carla Cardinali, member of the working group on data assimilation and observation strategies.
- Thomas Jung, member of the working group on predictability and dynamical processes.
- Philippe Bougeault, co-chair of the TIGGE working group (the Thorpex Interactive Global Grand Ensemble).

Several members of the Scientific Advisory Committee of ECMWF also attended.

The workshop reviewed the science objectives, the status of adaptive observations and multi-model ensembles, the future field experiments and the links with GEO (Group on Earth Observations) and WCRP (World Climate Research Programme). Plans for developing research on societal and economic applications of weather forecasts were also discussed. The Scientific and Technical Advisory Boards formulated recommendations for the various working groups.

ECMWF is very active in developing the global component of TIGGE, which will allow scientists of all continents to access an archive of operational and research ensemble forecasts from all NWP centres. This will therefore enable a more active cooperation between operational centres and the academic community. The content of the TIGGE global data base was finalized at the workshop, with due consideration to the requirements expressed by the other working groups. Access to TIGGE data is expected to open at ECMWF, NCAR and CMA in the second half of 2006.

The next THORPEX event is the International Science Conference to be held in Landshut (Germany) on 4-8 December 2006. For further information see:

www.wmo.int/thorpex/2nd_Symposium.html

Progress with the GEMS Project

Anthony Hollingsworth

The GEMS project (Global Earth-system Modelling using Space and in-situ data) is an Integrated Project funded under the EU's initiative for Global Monitoring for Environment. The aim of the project is to extend the modelling, forecasting and data assimilation capabilities used in numerical prediction to problems of atmospheric composition. This will deliver improved services and products in near-real time (e.g. global air quality forecasts to provide boundary conditions for more detailed regional air-quality forecasts). In addition the operational analyses and retrospective reanalyses will support treaty assessments (e.g. the Kyoto protocol on greenhouse gases and the Montreal protocol on the ozone layer) while the joint use of satellite and in-situ data will enable sources, sinks and transports of atmospheric constituents to be estimated. The project involves about thirty institutes in fourteen European countries and has an EU contribution of 12.5 million Euro. It will run for four years from spring 2005 to spring 2009 with coordination carried out by ECMWF.

The objectives of GEMS fall into two categories.

- The global elements of GEMS are to produce by 2009 a validated, comprehensive, and operational global data assimilation/forecast system for atmospheric composition and dynamics.
- The regional elements in GEMS are to assess the value of information on long-range trans-boundary air pollution for operational air-quality forecasts in Europe.

The core operational products of GEMS will be gridded data assimilation and forecast fields of key atmospheric trace constituents with high spatial and temporal resolution. These will include greenhouse gases (initially including CO_2, and progressively adding CH_4, N_2O, plus SF_6 and Radon to check advection accuracy), reactive gases (initially including O_3, NO_2, SO_2, CO, HCHO, and gradually widening the suite of species) and aerosols (initially a 15-parameter representation, later ~30).

The GEMS Annual Assembly convened at ECMWF on 6–10 February 2006 to review progress since the start of the project, and to make plans for the coming 18-months. The Assembly was organised by Olivier Boucher (Met Office), Guy Brasseur (Max-Plank Institut für Meteorologie), Henk Eskes (KNMI), Anthony Hollingsworth (ECMWF), Vincent-Henri Peuch (Météo-France), Peter Rayner (LSCE/IPSL) and Adrian Simmons (ECMWF).

Based on discussions at the Assembly, we describe some of the developments which have occurred in the first year of GEMS and outline future plans.

Progress in the first year of GEMS

Progress on data issues

The GEMS project has had considerable help from major Space Agencies, including ESA EUMETSAT, NASA and NESDIS, in the acquisition of the very large amounts of satellite observations needed by the project. As the data are acquired the observations are reformatted in BUFR and archived at ECMWF.

Within the GEMS project, considerable work has been done to reconcile the differing data format requirements of the operational partners, who prefer BUFR and GRIB formats, and the research partners who prefer netCDF. A means to accommodate the needs of both communities is being developed.

Early in 2005 the Canadian Meteorological Service circulated for comment a draft proposal on extension of the BUFR format to encompass atmospheric chemistry observations. A revised proposal was discussed by the relevant WMO technical committee in December 2005. After further revision it is expected to be adopted as the WMO format for real-time international exchange of air chemistry measurements.

Progress on global modelling and data assimilation

Substantial efforts have been devoted to extending the modelling needs of the project. ECMWF's Integrated Forecast System (IFS) has introduced the generic capability to advect many (~100) trace species by the model's dynamics, and to transport them in the parametrizations, such as the convection parametrization. In-line parametrizations have been implemented for greenhouse gases and aerosols, with surface fluxes specified climatologically (CO_2) or dynamically (aerosols). Year-long test runs with specified meteorology and free-running chemistry have provided valuable checks on the models (see Figure 1).

For reactive gases it is essential that the assimilating model has the benefit of an advanced chemistry scheme. Since it is believed premature to introduce a full-blown chemistry representation into the IFS, the IFS model has been coupled to the three participating Chemistry Transport Models (CTMs). At the time of writing the coupling has been achieved technically for two of the three CTMs, so attention is moving from technical issues of the coupling to assessing the scientific issues raised by the possible mismatches or dislocations introduced by the coupling.

A key requirement of the GEMS modelling and assimilation capability is an accurate representation of the stratospheric Brewer-Dobson circulation, which is involved in the control of the stratospheric distribution of many stratospheric constituents, and in key aspects of tropospheric-stratospheric exchange. There is evidence that there have been important improvements in this regard since the completion of the ERA-40 reanalyses in 2002. Consequently the meteorological components of the preliminary GEMS system have been used to reanalyse 2003–2004. Preliminary results are encouraging.

The IFS's 4D-Var system has been adapted to provide three separate data assimilation systems for greenhouse gases, reactive gases and aerosols. Depending on which of the domains is addressed, the assimilation systems will use radiances via fast forward models and their adjoints (greenhouse gases

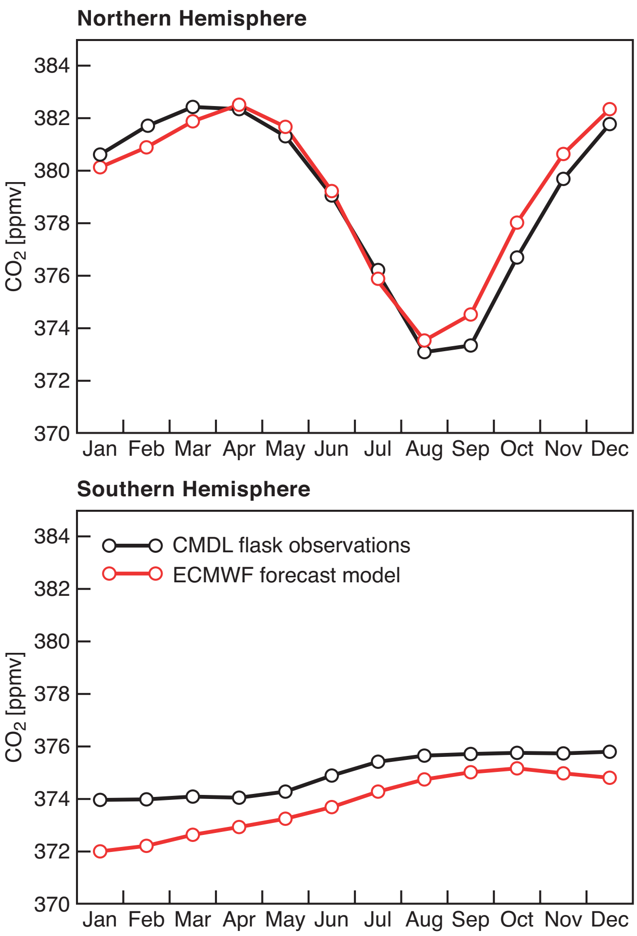

Figure 1 Comparisons between NOAA/CMDL surface flask measurements of CO_2 and a year-long run of the ECMWF model where the meteorology is corrected every 12 hours and the CO_2 is free-running, with specified climatological surface fluxes. The figure shows good qualitative agreement for the seasonal cycle. (Courtesy R.Engelen and S. Serrar).

initially, aerosols later), or retrieved profiles (aerosols, reactive gases) or total column amounts.

The specification of natural and anthropogenic emissions is a key issue for both the global and regional elements of the GEMS project. Agreement has been reached on the use by GEMS of the global anthropogenic emissions calculated by the RETRO project of the Fifth Framework Programme.

Emissions by wildfires and biomass burning are a key issue for the GEMS project. A proposed approach to the issue was developed recently through discussions between the HALO, GEMS, GEOLAND and ACCENT projects. Efforts will be made to include the issue in the Work Programme of the Seventh Framework Programme.

Progress on regional modelling and assimilation

The GEMS regional models will consider a common European domain (35°N–70°N; 15°W–35°E), or a larger area, for ensemble activities and inter-comparisons. Vertical and horizontal resolutions depend upon the model: many will start with 20–50 km resolution with a target resolution of 5–20 km. Nested domains at higher resolution will also be developed. The main goal of the regional activity is to enhance and improve Regional Air Quality (RAQ) forecasts, hindcasts and analyses across Europe through the use of information on long-range trans-boundary air pollution. All ten GEMS regional models (Figure 2) have demonstrated good progress in building-up their GEMS-RAQ configuration.

An area of common concern is surface emissions. The EMEP (Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) inventory of anthropogenic emissions is the up-to-date reference in Europe, and is generally of good quality. For GEMS, the main limitation of the EMEP dataset is the resolution of ~50 km which does not meet all RAQ requirements in terms of a good temporal resolution (hourly, weekly, monthly and annual) over the GEMS European domain and at a 5 km resolution. The creation of a dataset of European emissions, shared and used by a large number of groups involved in regional air-quality forecasting, would represent an important step. The GEMS Management Board will arrange the preparation of such a dataset through a sub-contract.

An important goal for GEMS is to provide coordinated access to air quality verification data across Europe for near-real time operations and to exploit the hindcasts. Consequently efforts will be made to agree a Memorandum of Understanding on data and forecast exchange for purely scientific and technical objectives with air-quality agencies. Also there is a need for preparation of similar agreements for the post-2009 phase involving institutions such as regional and national agencies and the European Environment Agency (EEA).

In preparation for pre-operational near-real time daily forecasts, work is progressing on the definition of methodologies for meaningful evaluation and comparison of partner hindcasts and forecasts over the GEMS domain. Included will be metrics for assessing forecasts of basic chemical species and metrics specific to user communities (e.g. air quality indices for human health and crop damage, and metrics for city level forecasts). Plans are also in preparation for software development based on 'Verify/MetPy' system developed at ECMWF which will allow central verification and user-tailored metrics.

One of the goals of GEMS is to assess the value of the GEMS data in epidemiological studies of the public health effects of long-range aerosols and reactive gases. Preliminary studies are being planned to identify the types of health effects that can be meaningfully studied using GEMS-RAQ data.

Next steps in the development of GEMS

Plans for research and development

Table 1 illustrates the main phases of the work of the production team, based on the plans of the global modelling and assimilation partners, and of the regional partners. After further validation in the course of 2006, three separate global reanalyses of the study period 2003–2004 will begin later in 2006 with separate assimilation systems for greenhouse gases, reactive gases and aerosols. With completion expected in mid-2007, the reanalyses will be subjected to elaborate validation and check-out before being exploited in a number of ways.

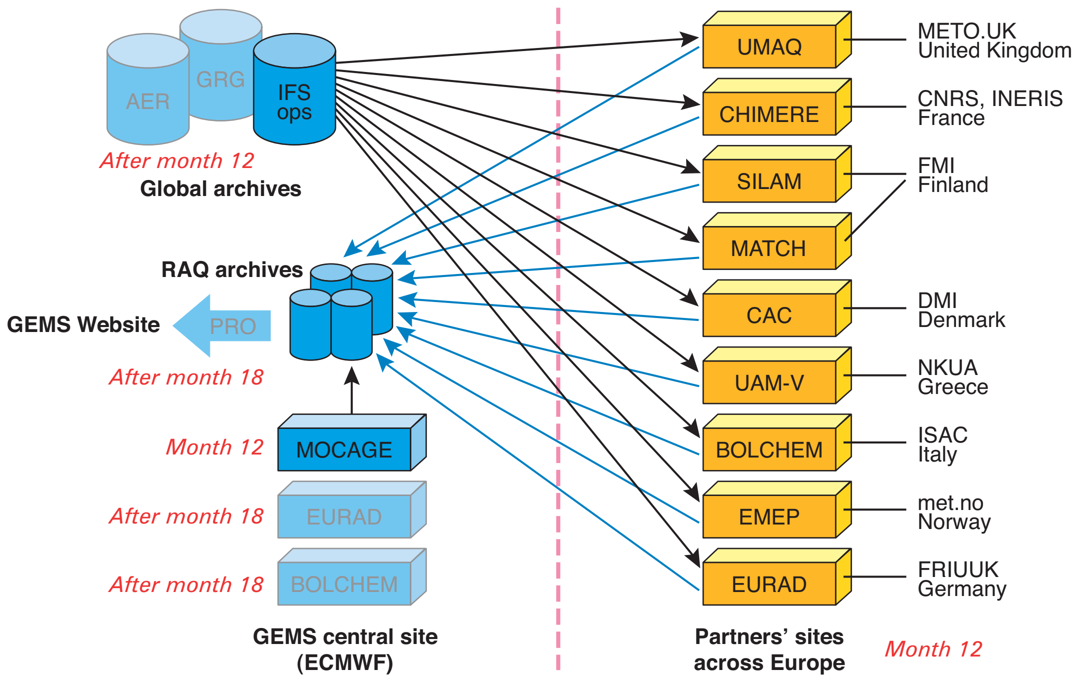

Figure 2 Illustration of the data flows between the central site and the GEMS regional modelling partners.

The validation of the first reanalyses will lead to preparation of a second integrated reanalysis of the same period and scheduled to begin in late 2007. At the same time the integrated system will be the basis for development of a pre-operational system which will be designed to be ready for operational implementation in the first half of 2009.

Institutional arrangements needed for a transition to operations in 2009

Institutional arrangements are not yet in place for a transition of GEMS to operational status in 2009. Discussions with the EU are expected to begin in 2006 in the context of the preparation of an atmospheric service for implementation in 2009 as part of Global Monitoring for Environment and Security (GMES). The EU has already begun work on three GMES services for implementation in 2008, and it is expected that the atmospheric service preparation will follow a similar template. Issues to be considered include governance and definition of service level agreements for core services; for down-stream services consideration needs to be given to issues such as data policy and data access.

Satellite data provision in 2009–2019

The availability of adequate satellite data provision is a key issue in planning the first decade of operational GEMS activity. In terms of security and adequacy of satellite provision, the greenhouse gas project probably has the most secure provision with operational advanced sounders (IASI in 2006 plus GOME_2 on METOP, CrIS on NPP in 2009) for upper-tropospheric measurements and the research OCO and GOSAT missions from 2009 onwards. The least secure provision is probably the air-quality (lower-tropospheric chemistry), as no missions are planned beyond the demise of ENVISAT and AQUA. The satellite provision for aerosols and UTLS (upper troposphere-lower stratosphere) are comparable, with aerosols relying mainly on the VIIRS instrument on NPP and NPOESS and the UTLS chemistry relying on GOME-2 on METOP and OMPS on NPOESS (from 2012).

Period	Activity
Year 1 May 2005–Aug 2006	• Build and validate three separate assimilation systems for greenhouse gases, reactive gases and aerosols. • Acquire data; build web-site.
Year 2 Aug 2006–Aug 2007	• Produce three different reanalyses for greenhouse gases, reactive gases and aerosols. • Make reanalyses available for validation by all partners. • Provide feedback to data providers.
Year 2–2.5 Aug 2007–Jan 2008	• Merge the three assimilation systems into a unified system. • Upgrade the models and algorithms based on experience.
Year 2.5–3.5 Jan 2008–Nov 2008	• Build operational system and interfaces to partners. • Produce unified reanalyses for greenhouse gases, reactive gases and aerosols.
Year 3.5–4 Nov 2008–May 2009	• Carry out final pre-operational trials. • Prepare documentation and scientific papers.

Table 1 Main phases of the work of the GEMS production team, based on the plans of the global modelling and assimilation partners, and of the regional partners.

Final thoughts

The GEMS Assembly showed that significant progress has been made with the project since spring 2005. This is due to the high level of expertise and commitment amongst the partners coupled with effective international collaboration between various research groups and project teams. There is every reason to be confident that by May 2009 the GEMS project will deliver a new European operational system which can monitor the composition, dynamics and thermodynamic of the atmosphere and produce forecasts of greenhouse gases, reactive gases and aerosols.

More information about the GEMS project can be found via the ECMWF web site at:

www.ecmwf.int/research/EU_projects/GEMS

Recent developments in extreme weather forecasting

Ervin Zsótér

The forecasting of extreme weather events has gained special emphasis in recent years. The gradual improvement of the NWP models has offered a better treatment of hazardous weather phenomena such as tropical cyclones and squall lines. In addition, an Ensemble Prediction System (EPS), such as that at ECMWF, can deliver more reliable and user-specific warnings of extreme events in a probabilistic way. However the extraction of the extreme weather-related information from the huge volume of EPS data is a complex and difficult task. A possible and efficient way of summarising the available information about extreme weather is to scale the EPS forecast distribution with respect to the model climate.

The Extreme Forecast Index (EFI) has been developed to indicate where the EPS forecast distribution is substantially different from the model climate (see *Lalaurette*, 2002 for more details). It is considered to be useful supplementary information to other EPS products, such as probability maps or EPSgrams. The real advantage of using the EFI lies in the fact that it is an integral measure referenced to the model climate that contains all the information regarding variability of a parameter in location and time. Therefore, the users can recognise the abnormality of the weather situation without defining different space- and time-dependant thresholds.

EFI products and recent developments

More than four years ago the EFI became available to users from Member and Co-operating States via the ECMWF website. In addition, from October 2003 the EFI has been archived in MARS. In the dissemination system and on the ECMWF website the following EFI products are currently available.

- ◆ 2m temperature EFI for D+1 to D+5 (computed for each 12 UTC).
- ◆ 10m wind speed EFI for D+1 to D+5 (computed for each 12 UTC similarly to 2m temperature).
- ◆ Wind gust EFI for D+1 to D+5 (computed for the daily maximum wind gust during each 24-hour period starting at 00 UTC).
- ◆ Total precipitation EFI.
  - – 1-day (24 hours) accumulation for D+1 to D+5 (computed for each 24-hour period starting at 06 UTC).
  - – 5-day (120 hours) accumulation for D+1 to D+5 and D+2 to D+6 (computed for the two 120-hour periods starting at 06 UTC).
  - – 10-day (240 hours) accumulation for D+0 to D+10 (computed for the whole forecast period).

In the last few years two main changes have taken place in the operational production of the EFI.

- ◆ Implementation of a revised formulation of the EFI (operational from October 2003) to make the index more sensitive to infrequent and unusual events located in the tails of the distribution.
- ◆ Replacement of the original pseudo model climate used by the EFI with the 30-year EPS control climate based on ERA-40 reanalyses to take into account the EPS model climate in a more realistic way. This used consistent model versions in the EPS forecast and the model climate over a long period.

These developments will now be discussed in more detail.

Revised formulation of the EFI

The first version of the EFI has been criticised for being too sensitive to a shift in the median of the forecast distribution, and for not being sensitive enough to shifts in the tails, where unlikely, but potentially damaging events are located. This characteristic of the EFI is due to it being modelled on the Kolmogorov-Smirnov test. In order to improve the EFI response around the distribution tails, we revised the EFI by introducing an extra weight term into the formulation according to the Anderson-Darling test (*Anderson & Darling*, 1952) – see Box A.

The statistical Anderson-Darling test is a modification of the Kolmogorov-Smirnov test which gives more weight to the tails. Figure 1 illustrates the difference between the original and the revised formulations, given the simple case which occurs when the EPS members have two values: (a) the record-breaking extreme (Q100, forecast by proportion *r* of all the EPS members, where Qn refers to the n'th percentile of a Cumulative Probability Distribution) and (b) a specified percentile of the climate (results are given for the four cases where Q0, Q50, Q75 and Q90 are forecast by the remaining proportion 1–*r*). The impact of using the revised formulation is obvious. It results in higher values, demonstrating that the presence of EPS values in the tail of the distribution is sufficient to keep the EFI values high, even if other EPS members are close to the median (Q50).

Figure 2 gives an example of a 2m temperature EFI from October 2005 when the weather in Western Europe was affected by an intense warm spell. This case illustrates the relation between the original and revised EFI formulations. The revised EFI covers a significantly larger area and also

Box A Revised formulation of the Extreme Forecast Index

The original Extreme Forecast Index (EFI_n) is defined as follows:

$$EFI_n = -(n+1)\int_0^1 \left(p - F_f(p)\right)^n dp \text{ if } n \text{ is even}$$

$$\text{and} \quad \int_0^1 F_f(p)dp > \tfrac{1}{2}$$

$$EFI_n = (n+1)\int_0^1 \left(p - F_f(p)\right)^n dp \quad \text{otherwise}$$

where $F_f(p)$ denotes the proportion of EPS members lying below the p quantile of the climate record. The pre-operational version of the EFI used $n = 3$.

The revised Extreme Forecast Index (EFI_{AD}) scales departures from the reference climate Cumulative Distribution Function using an extra weight term in the quotient so that:

$$EFI_{AD} = \frac{2}{\pi}\int_0^1 \frac{p - F_f(p)}{\sqrt{p(1-p)}}dp$$

The weight $p(1–p)$ is used because it is a quadratic function that takes its maximum value for $p = 0.5$ and goes to zero at both ends of the probability range. In a different context, this quantity is also known as the "uncertainty" in the Brier Score decomposition and the variance of the binomial distribution.

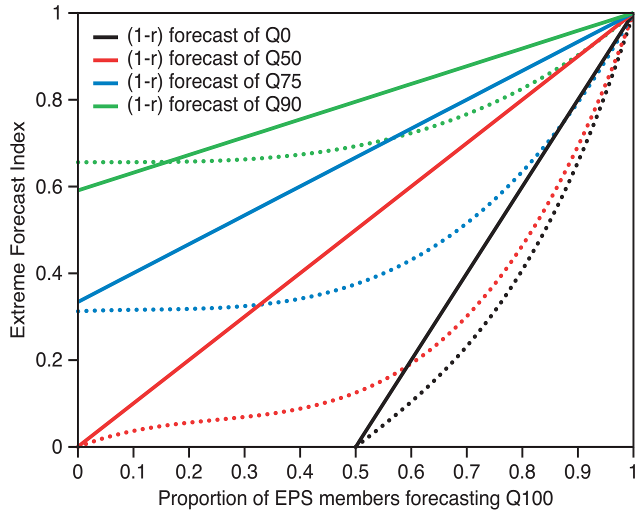

Figure 1 EFI variations for an EPS forecast with two values: a proportion r of EPS members have a forecast of record-breaking values (Q100), and a proportion (1-r) have a forecast of different percentiles of the climate distribution (see legend). Full lines refer to the revised EFI based on the Anderson-Darling formulation, while dotted lines show the original EFI configuration (i.e. the pre-operational version). Consider an example where 60% of the EPS members forecast the climate maximum (Q100). In this case, depending on the forecast of the remaining 40%, the original and revised EFIs (in this order) give the values of 0.1 and 0.2 for Q0 (i.e. 40% of the EPS members forecast the minimum value of the climate – Q0), 0.19 and 0.6 for Q50 (median), 0.43 and 0.73 for Q75 (upper quartile) and 0.72 and 0.84 for Q90 (last quintile).

tends to slightly decrease the maximum, compared to the original version. By analysing the tail characteristics in the area highlighted by the EFI we could also conclude that the revised EFI clearly gives a better indication of the existence of climatologically extreme EPS members (see also Figure 10(a) which will be discussed later).

The new EFI climate

General requirements

For the production of any climate-based forecast product with high quality, it is not sufficient to just have an outstanding forecast model. It is also essential to have a reliable model climate that reflects in every aspect the long-term characteristics of the associated forecast model. For example, different representation of orography or land-see mask in the climate could directly introduce a significant EFI bias over mountainous or coastal areas; this is related to the induced shift between the Cumulative Distribution Functions (CDFs) of the forecast and climate. Besides the requirement for consistent orography and resolution, it is also desirable to have the same physical parametrizations. This will introduce similar model error characteristics and therefore guarantee that any differences in the EFI values are indeed the result of dissimilar forecast situations.

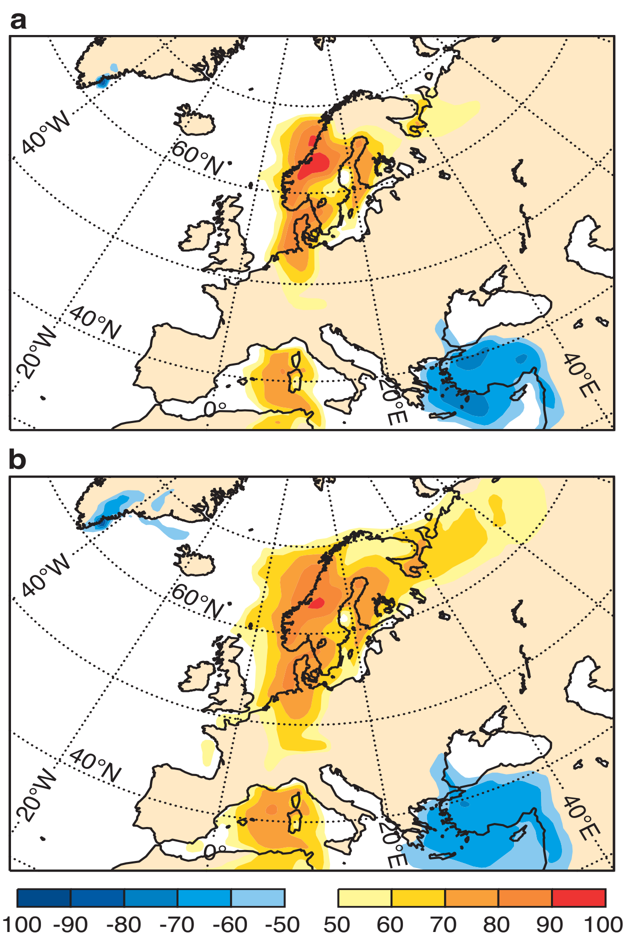

Figure 2 Comparison between (a) original EFI and (b) revised EFI for the t + 108 EPS forecast of 2m temperature valid at 12 UTC on 31 October 2005. Positive values are shown with shades of orange (only from 50% to 100%) and negative with shades of blue (only from -50% to -100%).

WMO defines a climate as a collection of statistics over three decades (30-year period). For the model climate it is hard to satisfy this requirement, since there are no operational forecasts available for such a long period. Moreover the countless model upgrades that have taken place would inevitably ruin the consistency of such a visionary data set. To use model reanalyses, such as ERA-40, is not an ideal solution either, because of the inconsistency between the model cycles being used to generate the reanalyses and the operational forecasts. The ideal solution would be to rerun the model (preferably for 30 years) based on reanalyses. However, this would make extremely high demands on computational resources, particularly for the EPS, where numerous forecasts would need to be run for each day.

The old pseudo climate

At the time of the EFI construction there was no medium-range model climate available at ECMWF. Also it was not appropriate to develop the system of model re-forecasts since the ERA-40 had only recently been completed at ECMWF in 2003. Therefore a temporary solution, the so-called pseudo climate (*Lalaurette*, 2002), was used for the computation of the EFI. This pseudo climate was based on a relatively consistent set of EPS forecasts. It was generated for each calendar month, and the EFI climate for a particular day was determined by interpolating between pseudo climates of two adjacent months. In the climate files of each month, three calendar months of EPS data were put together. The ensemble analyses and the day-5 and day-10 forecasts were kept from each 12 UTC run of the EPS. They were considered to be different realisations of the model climate. This super-ensemble contained the order of 10,000 fields ($\sim 3 \times 30 \times (1 + 50 + 50) = 9{,}090$).

The new EPS control re-forecast suite

The development of the medium-range model climate for the EFI started a few years ago, and the new system was implemented operationally on 1 February 2006 (with the latest main model resolution upgrade). The idea is based on the previously mentioned criteria of an ideal model climate with sampling from over a sufficiently long 30-year period. However, in order to limit the computational cost, instead of running a full or even partial (only with a few members) set of EPS re-forecast for 30 years and for the whole forecast range, it has been decided to run an EPS control version up to 48 hours. The computational cost is the equivalent of adding only six 10-day EPS control runs per day.

The EPS control re-forecasts have two components, the atmospheric and wave segments. The common EPS post-processing (surface parameters and some pressure levels of some values of potential temperature and potential vorticity) has been used and the time frequency is 6 hours. The data is archived in MARS with the stream specifications of "*Ensemble Forecast Atmospheric Hindcast*" = *efhc* and "*Ensemble Forecast Wave Hindcast*" = *ewhc*.

At the time of writing, the EPS control re-forecast suite runs on a daily basis (instead of a "once per every model upgrade" version), performing 30 model integrations each day from 1971 to 2000, starting from the interpolated ERA-40 analyses of the base day (which is ahead by about three weeks compared to the date of run in order to provide the necessary re-forecast files for the EFI computation, see later). We only prepare the forecasts starting at 12 UTC, having run the model up to 48 hours to be able to provide model estimates of the actual weather conditions for each day. An illustration of how the model climate is produced from the re-forecasts for one day is given in Box B.

Box B Preparation of the model climate for one day

Here is an example of how the element for one day of the model climate is prepared for 2 of January.

The 30 control runs at 12 UTC on 1 January will provide the model climate for 2 January. The t+24 hour control re-forecasts are taken as the model climate elements for 12 UTC on 2 January for the 2m temperature and 10m wind speed. For the 24-hour wind gust climate (00 UTC on the 2nd to 00 UTC on the 3rd) the wind gust maximum is computed in the re-forecasts from t+12 to t+36. And finally for 24-hour total precipitation (climates for 5-day and 10-day total precipitation are also composed of the daily, 24-hour precipitation climate files) the forecast range of t+18 to t+42 (06 UTC on the 2nd to 06 UTC on the 3rd) is taken into account.

The new EPS control model climate has the important characteristic that it provides climate elements (i.e. re-forecast files) for each day of the year; this is similar to the real climate constituted from real observations from a sufficiently long period (30-year). In this sense the EFI climate produced on the basis of these re-forecasts will be the "close as possible" model version of the truth.

The other key characteristic of this new system is that the model configuration used in the re-forecast suite is always the latest in operations, having the current resolution and physics (the only exception is the stochastic physics computation, which is not used in the EPS control re-forecast). Therefore the EFI climate constituted from the re-forecasts will always be as consistent as possible within itself and also with the actual EPS forecasts.

The sample size criteria for the EFI climate

In order to develop an appropriate model climate for the EFI, the sample size of the data that constitute the EFI climate had to be considered with great care. To get a good estimate of the mean characteristics (such as the median) of the underlying climate distribution, we can rely on relatively small data sets. However, determining the tails of the distribution, where the rare events lie, based on a small sample could easily result in large sampling noise. In order to adequately sample the tails we need significantly more realisations of the model. For example to sample the 99th percentile we need at least the order of a hundred model reruns, not to mention the case of the hypothetical climate extremes. The new EFI formulation is more sensitive to the tails and moreover the most hazardous weather events are related to the last part of the distribution's tails. Therefore it is important to have climate CDFs which are good estimate of the hypothetical model climate distribution including the upper and lower tails.

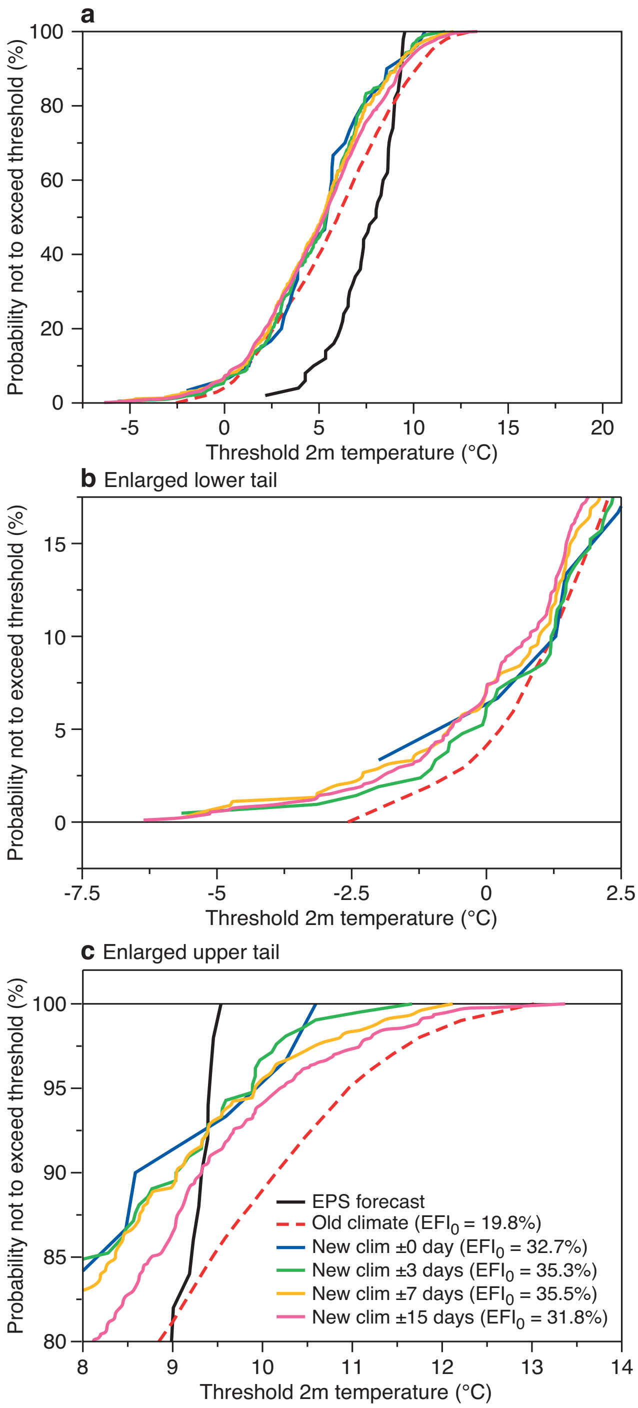

Figure 3 (a) Cumulative Distribution Functions for different EFI model climate distributions for a t+108 EPS 2m temperature forecast from 00 UTC on 16 January 2005 (solid black line) for Reading, UK. Besides the pseudo climate (dashed red line) the new reference climate based on ERA-40 is plotted with different combinations of ±0 (solid blue line), ±3 (solid green line), ±7 (solid orange line) and ±15 (solid magenta line) days of re-forecasts each year from 1971 to 2000. Enlarged versions of the lower and upper tails are given at (b) and (c). The EFI values (denoted by EFI_0) computed by different climate references are shown in the legend.

Although the EPS control re-forecast system provides the climate for every day, the number of available forecasts for a single day is only 30. In order to create a realistic and detailed description of the underlying daily climate variability we need a significantly larger sample size. Therefore we have to combine many of these daily data sets. However this climate accumulation has to be done very carefully since, by gathering climate files from too longer period, we might sample climate representations of a period with significantly different climate characteristics.

Figure 3 shows how the EFI model climate behaves at a specific location when we combine different numbers of daily re-forecast files. We have tested different samples, from the shortest daily climate to the case when we gather fields from the next ±15 days. The re-forecast elements in the sample are considered as equal representations of the model climate, with no weighting applied at present. The number of files in each tested combination are 30 (±0 day, altogether 30 years times 1 day), 210 (±3 days, 30 years times 7 days), 450 (±7 days) and finally 930 (±15 days). The results presented are for Reading, with a 5-day forecast of 2m temperature from January 2006. Please be aware that in the old pseudo climate only the percentile values are archived, and therefore only these values now plotted. The climate versions based on ERA-40 are relatively similar for most of the probability range; the medians of the distributions cluster close to each other and the EFI values, being computed with the different climates, are close together. However, as expected, much larger differences occur in the tails. This is highlighted by the enlarged upper and lower ends of the distributions. As we increase the sample size by merging from 1 (±0) to 31 (±15) days of re-forecasts, the minimum (maximum) values get systematically lower (higher). At Reading in the middle of January this results in a difference of -4°C and +3°C respectively.

For operational production of the EFI we decided to base the model climate on the 31-day option that provides a distribution consisting of 930 re-forecast values (30 years times 31 days). With this choice we actually keep the original idea of having a month-long EFI climate; however this time they are generated specifically for each day, instead of using interpolation between climate files of different calendar months. The accumulation of model re-forecasts from the 15 days closest to the actual date is probably short enough for most of the areas to sample only the location and time related variability of the daily climate.

Having about 1,000 fields seems to be large enough to reasonably sample the infrequent events in the tails of the distribution. In the old EFI climate configuration, the vast number of EPS forecast fields (almost 10,000) that were used made it possible to have a very small sampling noise. Although it is not possible to simulate the sample size of the old system, the new reference EFI climate has a reasonably smooth spatial behaviour.

Regarding 2m temperature there is hardly any sampling noise, not even in the new climate. Figure 4 shows the maximum fields of the old pseudo climate (Figure 4(a)) and the new reference climate (Figure 4(b)) in January where both fields are in line with the topographical and climatological

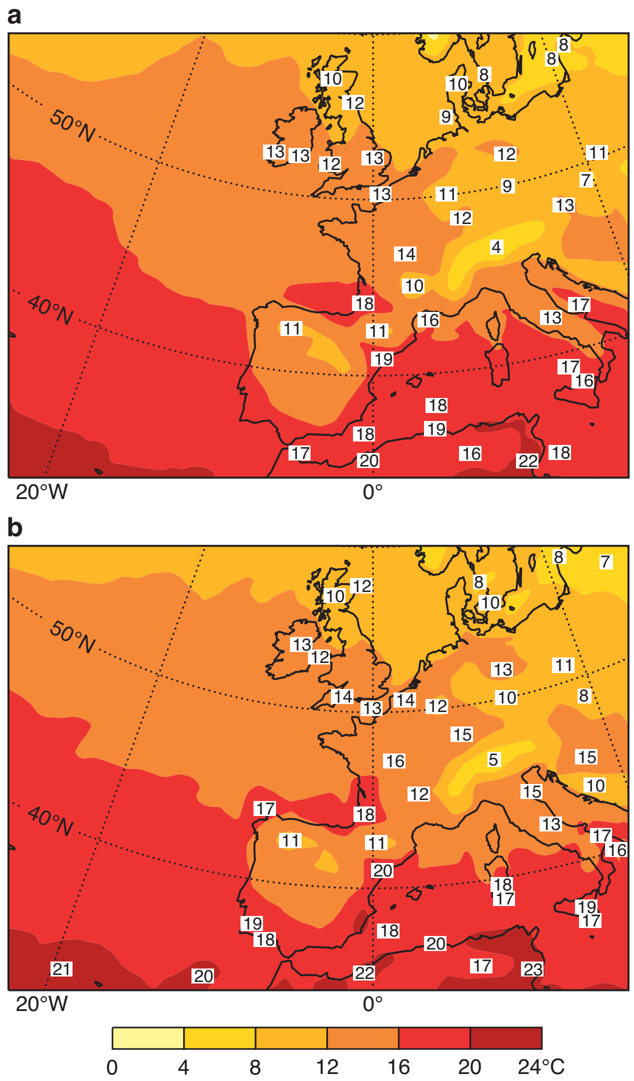

Figure 4 The 100 percentile (Q100) fields for 2m temperature of the (a) old pseudo climate and (b) new reference climate based on ERA-40 for January. The numbers with white blanking represent the local minima and maxima.

characteristics. However for wind and precipitation - which have high intrinsic variability - the level of sampling noise is higher close to the end of the distribution tails, especially in the new climate where the sample size is significantly smaller. It is found though, that the fields of the 98th and partially the 99th percentile values show already quite smooth behaviour even for precipitation.

Impact of the new reference climate on the EFI

The relation between the original and latest versions of the EFI (i.e. how much they differ from each other) might also be of interest to the users. Since the last change in the EFI affected only the reference climate formulation, the characteristics of the change can be determine directly by examining the difference between the previous pseudo climate and the new reference climate (i.e. ERA-40 based model climate). In Figure 3 we have already seen a specific example for the city of Reading in January. In that case the old pseudo climate was shifted by almost 1°C to the positive side, and the EFI values computed with the old climate was almost 15% lower compared to the EFIs based on the new reference climate. As already indicated, the climate distributions and thus the EFI values can differ significantly depending on location and time. The difference between the EFIs using the pseudo climate and the new reference climate can be rather striking.

As an example, Figure 5 shows the EFIs computed using the two climates for a case from October 2005 (the same case as used for Figures 2). The difference varies significantly from place to place, and areas of potentially extreme weather can appear from nowhere or simply disappear in the EFI using the new climate compared to that using the pseudo version.

To demonstrate the global characteristics of the change we have chosen the example of January for 2m temperature again. Consider the difference between the two model climates as indicated by the deviations in the minimum, median and maximum values of the distributions. The temperature range covered by the new reference climate is larger for most of the locations (see Figure 6). The minimum value of the climate distribution tends to be lower (Figure 6(a)), while the maximum value higher (Figure 6(c)) in the

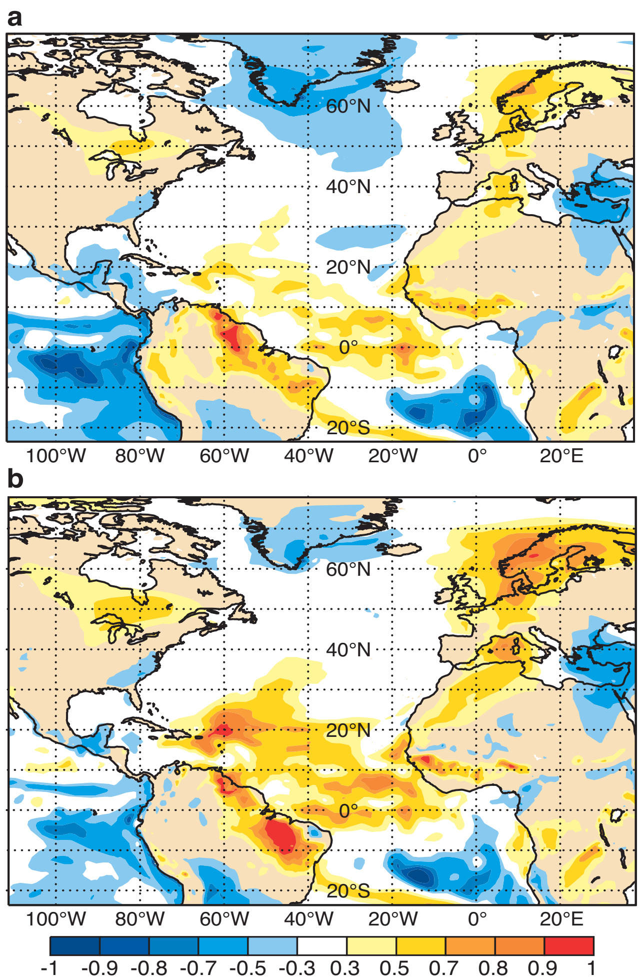

Figure 5 Extreme Forecast Index maps computed for the same t+108 EPS 2m temperature forecast (from 00 UTC on 27 October 2005) using the (a) pseudo climate and (b) new reference climate based on ERA-40. Positive values are plotted by shades of orange (only above 0.3 (30%)) and negative values with shades of blue (only below –0.3 (–30%)).

new climate. This is in line with the fact that the ERA-40 based sampling is better by relying on a 30-year period in the new reference climate instead of a 3-year one in the pseudo climate, even though the sample size is drastically smaller in the new system (an order of 1,000 instead of 10,000).

The overall difference between the two model climates can also be measured by the EFI itself (i.e. by computing the integral distance between the CDFs in the new reference climate and the old pseudo-climate). The EFI-measured differences are shown for 2m temperature, 10 m wind speed and 24-hour total precipitation in Figures 7(b), 7(c) and 7(d), this time for July. For 24-hour total precipitation we find significantly larger signals in the tropics; the EFI-measured differences can reach locally even 40-50%, whilst over the extra-tropics the agreement is much stronger where EFI values are usually below 5%. For the 10m wind speed the tropics still hold larger signals, though we find more areas with larger differences outside the tropics. The behaviour of the 2m temperature is different – the distribution of the EFI values is rather homogeneous over the globe. The EFI-measured deviation is above 20% over large areas and the maximum values are not too far from 100%. In addition the effect of the sea seems to be important. Over most of the extra-tropical areas the difference between the two climates are significantly larger.

There are significant differences in the way the two EFI climate versions are generated (50 EPS members with different lead-times within the 10-day period versus EPS control only up to 48 hours). This means that the explanation for the EFI deviations is probably related to the different climate characteristics of the period, from which the climate elements are gathered (3 years in the old pseudo climate versus 30 years in the new formulation). The relation between Figure 7(a) and Figure 7(b) supports this idea. The difference between the old and the new 2m temperature model climates in terms of the EFI shows very similar characteristics compared to the temperature anomaly of the 3-year period in the old climate, referenced to the 30-year period of the ERA-40 reanalyses (1971–2000). Although the agreement is far from perfect, the areas with positive shift in the EFI climate usually correspond to negative temperature anomaly; i.e. colder conditions in the 3-year period (old pseudo climate) compared to the 30-year period (new reference climate), and vice versa.

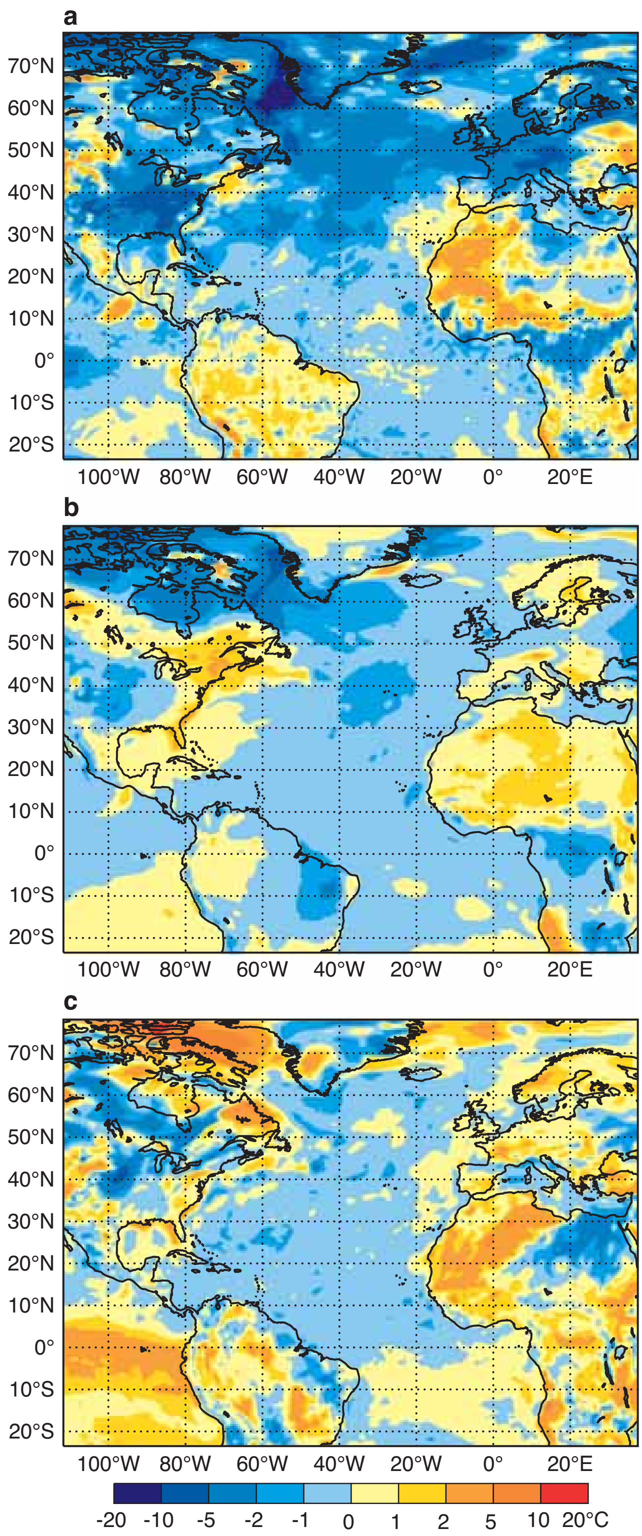

Figure 6 Difference between the new 2m temperature reference model climate and the old 2m temperature pseudo climate for January for the (a) minimum, (b) median, and (c) maximum values of the climate CDFs.

Ongoing developments

The multi-parameter extreme weather risk map

One of the reasons for the success of the EFI is that the information on parameters directly related to extreme weather (i.e. wind, precipitation and temperature) is provided in the form of a synoptic map without having to decide any arbitrary threshold that would not be relevant on a continental scale or throughout the whole year. The extreme weather risk map is a further step in synthesizing the available information related to extreme weather. Based on the EFI, two main categories of abnormal weather have been defined. The range of EFI values from 50% to 80% is regarded as unusual (warm, windy etc.) and for areas with EFI values above 80% the very unusual or extreme label is allocated (for temperature the negative range is also of equal interest). On the multi-parameter map the areas where one or more of these conditions are met are highlighted by different shadings or markers. We show an example of this combined extreme weather risk interpretation in Figure 8.

The extreme weather risk map is able to summarise the “far from normal” forecast characteristics in a simplified, easily understandable way. However the questions - how was the model behaving in the previous runs and whether the underlying abnormality was forecast in a consistent way – arise from the forecaster’s point of view. The answer is given in the distribution plot associated with the extreme weather risk map.

In the background numerous distribution diagrams are prepared for each EFI parameter with the information on the climate and the available forecast distributions, including the corresponding EFI values (see Figure 9). We have extreme weather risk maps for each EFI timestep from the latest EPS forecast, and separate distribution diagrams for each EFI parameter. As the forecast lead-time increases the diagram contains fewer forecast distributions (since currently the EFI is computed only up to D+5). The system currently runs in test mode pre-operationally; the distribution plots are prepared in advance as postscript files. In order to keep the generated volume of data relatively low, it has been decided to create the diagrams based on 10° × 10° gridboxes as the first option to be tested. The gridbox diagram will hold the data from the gridpoint which has the highest EFI value in the shortest

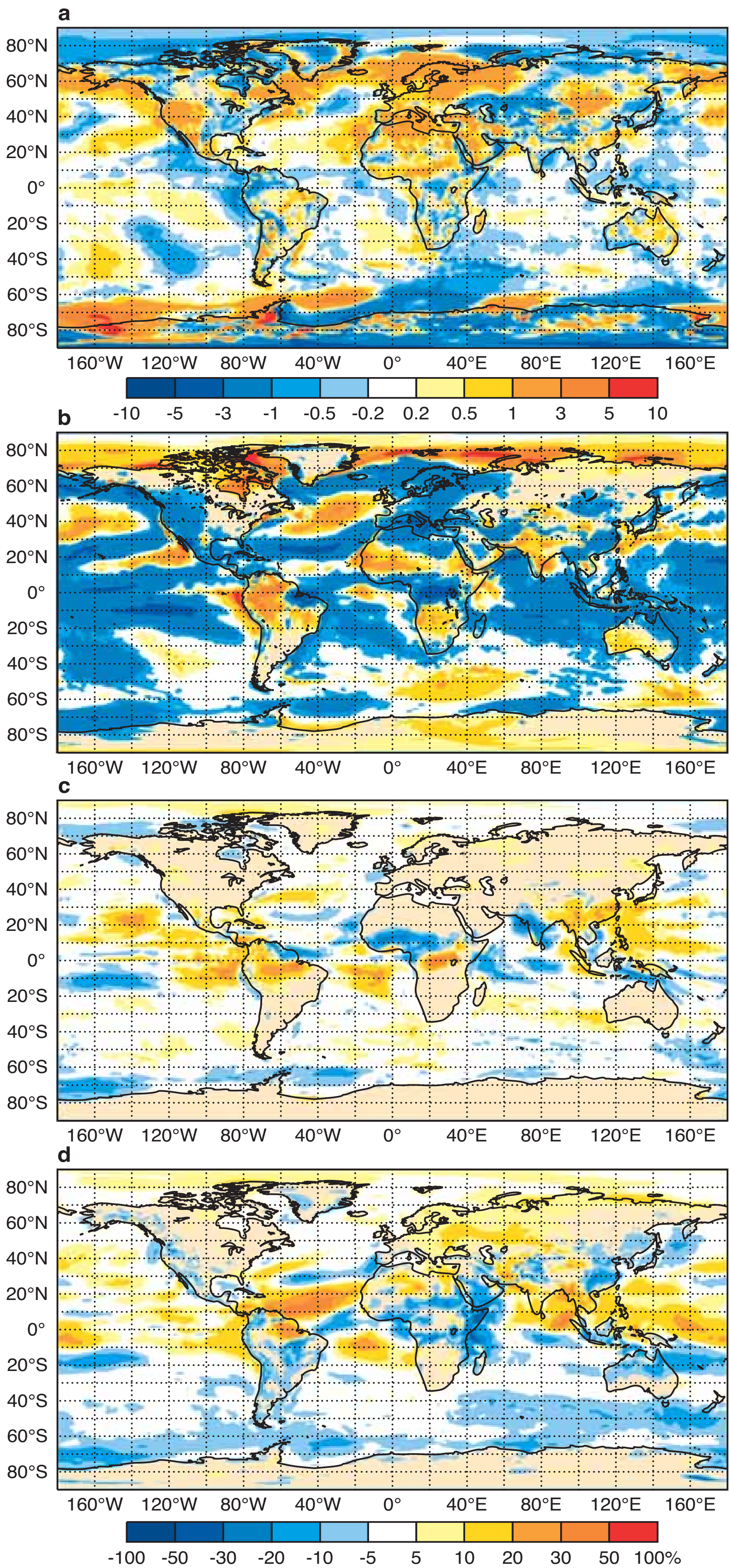

Figure 7 (a) 2m temperature anomaly for July as a three-year average (period of 2003–2005). Operational model analyses are taken as observations, while the reference climate is generated from the ERA-40 reanalyses (1971–2000). The shades of blue (negative values) indicate colder than normal conditions, and the shades of orange (positive values) warmer ones. (b) Difference between the two model climates as measured by the integral distance (EFI) between the CDFs in the new reference climate and the old pseudo-climate for the 2m temperature in July. Positive values (shades of orange) indicate areas where the new climate has shifted to warmer conditions, while negative (shades of blue) values indicate generally colder conditions in the new reference climate based on ERA-40. (c), (d) The same as in (b) but for the 10m wind speed and 24-hour total precipitation.

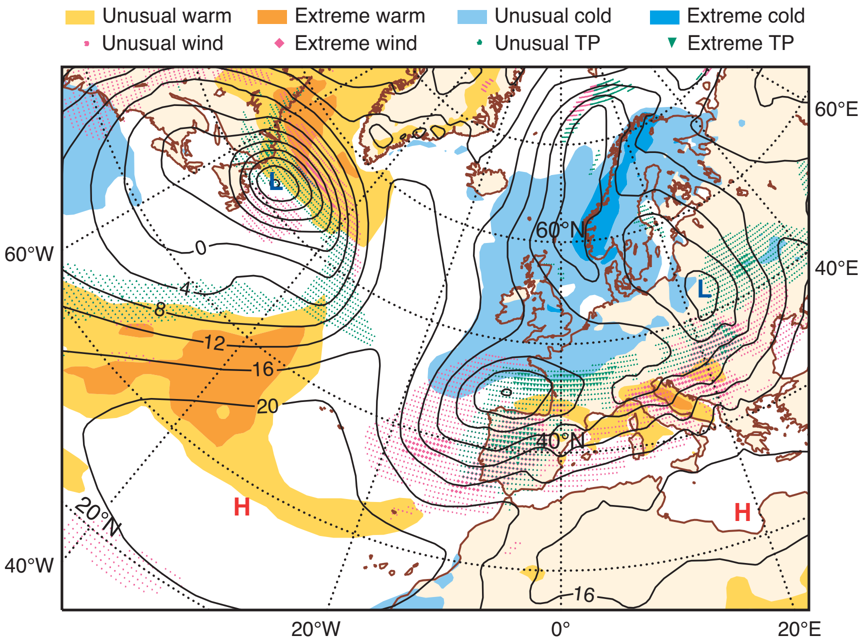

Figure 8 Extract from a global extreme weather risk map. The EFI fields for 2m temperature (different colour shadings), 10m wind speed (magenta markers) and total precipitation (green markers) are combined with the EPS mean of the 1000 hPa geopotential height (black lines). Unusual weather is assigned to EFI values above 50%, while extreme weather conditions are taken to be those above 80%.

available EPS forecast (i.e. the location of the maximum EFI on the corresponding extreme weather risk map). The distribution diagrams can be accessed simply by clicking onto the desired gridbox of the extreme weather risk map.

Additional indices for extreme weather forecasting

The EFI is a useful summary tool to interpret the extreme characteristics of the EPS distribution. Since the revised formulation has been implemented the EFI has become more sensitive to the tails, where the potentially hazardous weather events lie. In addition to using the revised formulation of the EFI, the level of extremity in the tails of the forecast distribution can be explored in a more direct way by measuring the probability distance in the tails. The "Shift in Probability Space" index (SPS) can provide some information on how "extreme" the tail of the EPS distribution is, compared to the climate – see Box C.

The Shift in Probability Space index can complement the EFI with interpreting the abnormality level in the EPS. However, neither the EFI nor even the SPS can give information about some of the characteristics of the EPS tail. There are rare, potentially devastating weather scenarios, when a significant fraction of EPS members predict climatologically (relative to the model climate) unprecedented values. The level of extremity could remain hidden if they are analysed only by either the EFI or SPS indices. In order to measure the abnormality of such situations, we can consider the "Shift of Tails" (SOT) index – see Box D.

In line with the SPS, the use of the negative version of the SOT makes sense for the 2m temperature but not for wind and precipitation. Besides, the SOT is referenced to the model climate (as is the EFI), since the quotient depends on the climate range. On the other hand it is a disadvantage that the SOT can take any values. However, in practice the weather conditions which can realistically happen will reasonably bound the SOT. The cases of potentially abnormal weather – which are of interest to the users – will have SOT values close to or above 0% (which actually correspond to the case when a certain proportion of the EPS reaches the climate maximum). It is important to mention that, in order to be able to use a reliable SOT, it is necessary to have a smooth, appropriately detailed model climate, since the SOT is referenced to the tails of the climate.

Figure 10 gives two examples which demonstrate how the SPS and SOT indices can add extra information to the EFI. Figure 10(a) refers to the same case as the one shown in Figures 2. The chosen parameter is the 2m temperature with SPS and SOT values of p = 0.1 (Q10) and p = 0.9 (Q90). As expected, the SPS and SOT in general cover very similar areas as the EFI. However, they also highlight regions, especially the SPS, where the EFI is relatively low. In Figure 10(a), the white triangle in Scandinavia denotes the place of maximum SOT, where the EFI is in fact below its maximum.

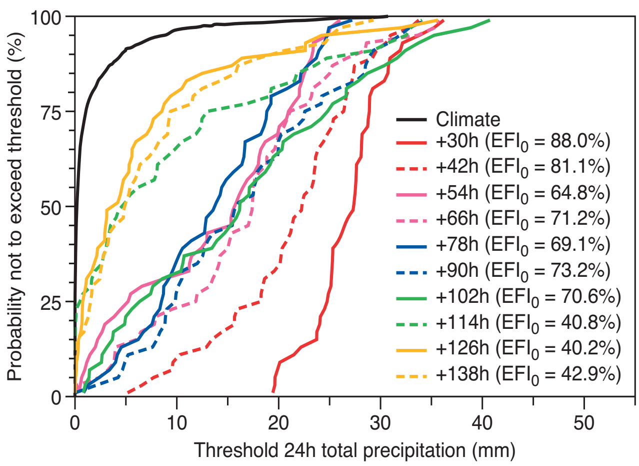

Figure 9 Example of the distribution plot attached to the multi-parameter extreme weather risk map. The thick black line represents the ERA-40 based model climate, while the other lines in different colours show the distribution of EPS runs verifying on the actual date, advancing backward in time. The corresponding EFI values are indicated in the legend for all the EPS forecasts.

Figure 11 shows the corresponding forecast and climate distributions at that location. This highlights that, despite of the lower EFI, in this case 25% of the EPS members predicted climate outliers, namely a temperature above 6°C (please be aware that this point has a model orography of approximately 900 m). Although the SPS also takes its maximum

Box C "Shift in Probability Space" index (SPS)

The distance in probability space:

$$SPS(p) = F_c(p) - p$$

where $F_c(p)$ is the value indicating where the p quantile of the EPS distribution ranks in the climate record (0 being the absolute minimum, 1 the absolute maximum).

It should be noted that the $SPS(p)$ has a similar form to the quantity present in the EFI formulation given by $p - F_f(p)$ (see Box A) except that in this case it is a function of the EPS forecast rank, and not of the climate rank (in the EFI definition p is the quantile of the climate distribution).

The maximum shift for $SPS(p)$ is $1-p$, when at least a proportion $1-p$ of the EPS is already outside of the climate range. For example in case of the last decile (p = 0.9, Q90) the maximum *SPS* that can be reached is 0.1 or 10%. For total precipitation and wind, only the upper part of the distribution is of real interest regarding extreme weather forecasting. However, for the 2m temperature, the negative shift of the lower distribution fractions is equally informative (for Q10, for example, with an absolute minimum value of –0.1 or –10%).

Box D "Shift of Tails" index (SOT)

The SOT is the scaled distance in the space of the meteorological variable:

$$SOT_+(p) = -\frac{Q_f(p) - Q_c(1)}{Q_c(p) - Q_c(1)} \qquad SOT_-(p) = -\frac{Q_f(p) - Q_c(0)}{Q_c(p) - Q_c(0)}$$

where $Q_c(0)$ is the minimum, $Q_c(1)$ is the maximum value found in the model climate record, whilst $Q_c(p)$ and $Q_f(p)$ are the p quantiles of the climate and the forecast Cumulative Distribution Functions (CDFs) respectively.

The SOT_+ is the index for measuring the abnormality level in the upper tail, while the SOT_- is for the lower tail of the CDFs. The *SOT* value of –1 corresponds to the case of $SPS(p) = 0$, when the forecast CDF intersects the climate CDF exactly at the level of p. If $SOT(p) = -1$ for all p, then the climate and forecast CDFs are identical, which is also the case when *EFI* is 0. Nevertheless the SOT index only has a value of 0 if the p quantile in the forecast equals the maximum climate value, $Q_c(1)$.

In addition, if the tail of the EPS is beyond the range covered by the model climate, the SOT becomes positive and is proportional to the distance to the climate maximum in the meteorological variable space. These positive values will indicate climate outliers (EPS members out of the range of the model climate); and the SOT value will also give an indication of the degree of extremity (scaled by the relative distance to the climate CDF). For example $SOT(0.9) = 1$ would mean that at least five EPS members are outliers, all of them exceeding the climate maximum by the value of $Q_c100–Q_c90$ or more.

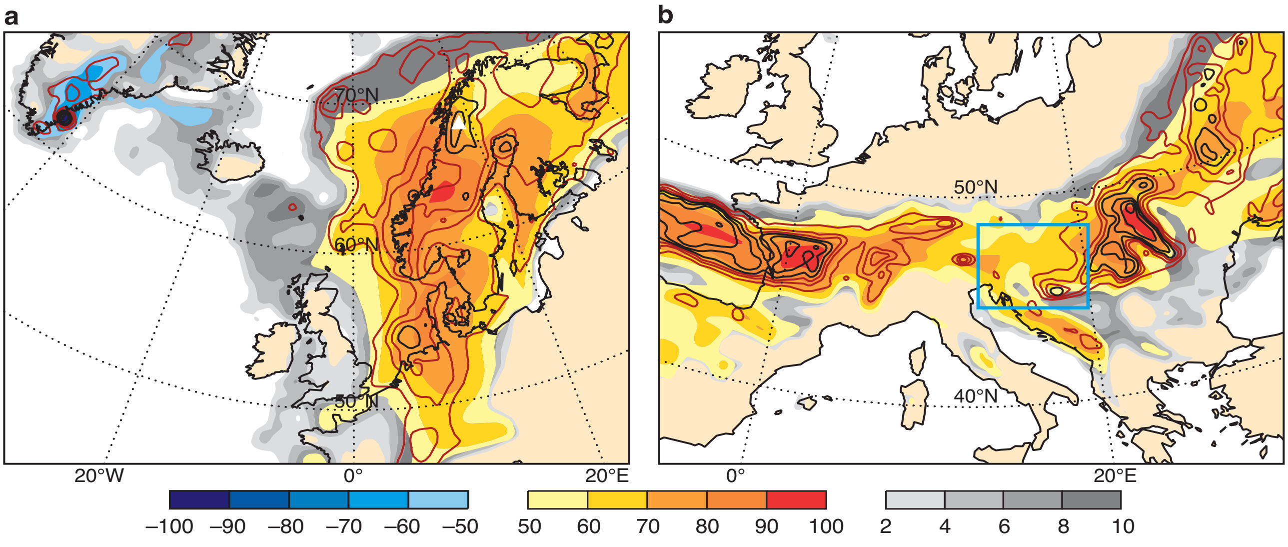

Figure 10 EFI, SPS and SOT indices based on (a) t+108 EPS forecast of 2m temperature valid at 12 UTC on 31 October 2005 and (b) t+06 to t+126 EPS forecast of 120-hour total precipitation valid for the period 06 UTC on 3 March to 06 UTC on 8 March 2006. Positive EFI values are shaded by tones of orange and negative ones by tones of blue (only 2m temperature). The Shift in Probability Space is plotted by grey shades for p = 0.9 and with 2m temperature for p = 0.1, as well (legend is shown only at p = 0.9). The Shift of Tails with p = 0.1 (only temperature) and p = 0.9 are plotted with dashed brown lines for values between 0 and –0.5 (areas where the forecast tail $Q_f(0.9)$ or $Q_f(0.1)$ are close to the climate maximum) , whereas values above 0 (areas where the forecast tail is beyond the climate range) are shown by black thick solid lines. The white triangle in (a) indicates a point in Scandinavia which is the location for the distributions shown in Figure 11. The blue box in (b) is referred to in the text.

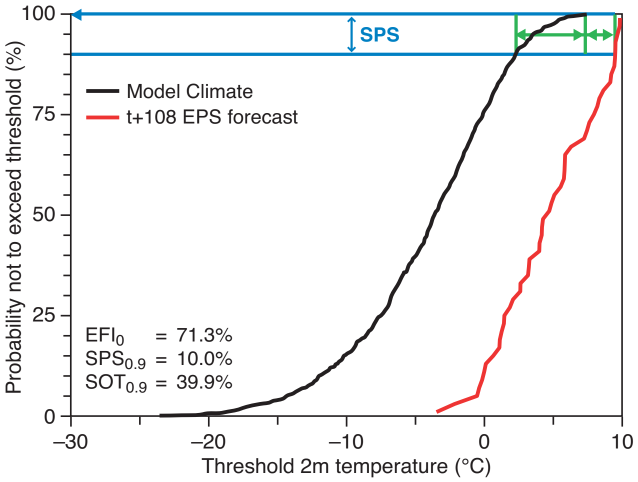

Figure 11 Cumulative Distribution Functions of model climate (black) and t + 108 EPS forecast valid at 12 UTC on 31 October 2005 (red) of the 2m temperature at the location where the SOT index has its maximum in Scandinavia (67.7°N, 18.1°E). The location is marked by white triangle in Figure 10. The corresponding values for the EFI (denoted as EFI_0), $SPS_{0.9}$ and $SOT_{0.9}$ are also shown. The blue and green lines illustrate the computation of $SPS_{0.9}$ (blue) and $SOT_{0.9}$ (green).

value, showing a high risk of extremity, in this situation it would have reached the same value even if the last tenth of the EPS distribution had been 2°C lower.

Figure 10(b) is another informative example representing a wet period from early March 2006. On the western half of the map, the three extreme weather indices are consistent with each other. However, this is not the case for the eastern side. The SPS and SOT identify some subregions which are detached from the area of potential extreme weather as shown by the EFI alone. Consider for example the area indicated by the blue box. At the bottom of the box, just on the edge of the 50% EFI range, the SOT indicates more extreme EPS members, whilst in the middle there is no sign of any extreme members, even if the EFI is higher.

Conclusions and future work

The demand for reliable early warnings of hazardous weather seems to have increased continuously in recent years. The Extreme Forecast Index together with the proposed Shift in Probability Space and Shift of Tails indices can provide useful information in forecasting extreme events. However, we still need to gather more experience about the capabilities and usefulness of these indices, though evaluation of these products is particularly difficult as there is no comprehensive observed climate available. This means that the definition of extreme events is ambiguous. Regarding the EFI some preliminary verification has been done already, but more detailed, comprehensive evaluation is needed in the future.

In order to make the EFI more reliable, the old pseudo model climate has been recently replaced by the more realistic reference model climate based on ERA-40. Although this formulation already favours the criteria of having a 30-year climate and using the latest model configurations, this system is not yet perfect. We have EPS control re-forecasts only up to 48 hours, so these short-range model forecasts have to be used to constitute the EFI model climate for all the required lead-times. This seems to be a very good approximation for short lead-times of the EPS. However, the EPS variability at larger time steps cannot be simulated with the same accuracy by only sampling from short-range control forecasts.

The effect of different model error characteristics between the control and the EPS members might to some extent deteriorate the similarity between the current EFI reference climate (constituted of 930 EPS control reruns) and the hypothetical EPS model climate. It is important to note that the stochastic physics probably play a major role in developing these differences, since it is an additional factor (not applied to the EPS control) to increase the spread and it is significantly more active for surface parameters. This effect is also probably responsible for the EPS members too often falling outside of the climate range which is reflected in the positive SOT values.

The ongoing project to develop EPS re-forecasts for the calibration of ensemble forecast will have an effect on the EFI climate preparations. Also the development of the ECMWF seamless forecast system (i.e. introducing VAREPS and merging the medium and monthly forecast ranges) will inevitably require further consideration about how to provide forecasts of extreme weather.

As we have shown, at present only the EFI is computed and archived operationally for a few basic surface weather parameters. In addition the extreme weather risk map is still in a pre-operational phase while the other extreme weather indices (SPS and SOT) are only in test status.

Based on experience and user recommendations we plan to produce the EFI and selected SOT or SPS fields for some new parameters, such as minimum and maximum temperatures. In addition, consideration will be given to further improving and implementing into operations the extreme weather risk map supported by the related distribution diagrams. The development of new forecast products which are referenced to the model climate are also considered as future activities.

The various developments that are planned will broaden the range of tools that can be used in the field of extreme weather forecasting.

The developments described in this article build upon the work carried out by François Lalaurette during his period at ECMWF.

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A variational approach to satellite bias correction

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Satellite instruments, like any other measurement system, are not perfect and are prone to error. While errors which are purely random are undesirable (such as noise at the radiation detector) their adverse effect can be significantly reduced within a data assimilation scheme by a combination of spectral, spatial and temporal filtering/averaging. However, errors which are systematic (i.e. a bias) cannot be handled in this way. Any observation which is biased can systematically damage the data assimilation scheme and ultimately the quality of the forecasting system. There are well documented examples of particular countries using certain (biased) radiosonde instrument types which introduce local anomalies in the analysis when the data are assimilated. However, biases in satellite observations are of particular concern as they have the potential, if uncorrected, to damage the NWP system globally in a very short space of time.

At ECMWF considerable effort has gone into dealing with satellite biases and a new system has been developed based on an objective approach. The Variational Bias Correction (known as VarBC) updates satellite bias corrections every analysis cycle. VarBC is being tested for operational implementation.

Diagnosing satellite biases

The bias in a particular satellite observation can only be determined by comparison with some unbiased ground truth. Special measurement campaigns involving surface or aircraft mounted radiometers and balloon borne sensors (launched to coincide with the satellite overpass) provide a highly accurate ground truth, but are inevitably limited to certain locations and times. While they can (and have) been used to expose problems with satellite instruments and/or radiative transfer models, they cannot tell us about potentially important variations in the systematic errors for different areas (e.g. biases over warm humid tropical oceans compared to cold dry polar regions).

Note that the radiative transfer model, henceforth referred to as the RTM, links the atmospheric state to the radiation measured by the satellite and for the purposes of this discussion may be considered as an integral component of the satellite observation.

The limited spatial and temporal availability of campaign data has led to the practice of NWP centres monitoring and diagnosing satellite biases using the NWP assimilation system itself. The obvious advantage of this approach is the in-house real-time availability of what is arguably (in the case of the NWP analysis or short-range forecast) the best estimate of the global atmospheric state. However, this approach has the disadvantage that it does not provide a completely unbiased ground truth. Indeed for some atmospheric variables and regions of the atmosphere, biases in the NWP system can be a significant fraction of (or even exceed) the biases we are attempting to diagnose in the satellite information. Despite these concerns the overwhelming benefits of monitoring satellite biases against the NWP system have led to its widespread adoption.

What biases do we see and where do they come from?

In general the biases we observe when satellite data are monitored against the NWP model are not fixed offsets as the pure use of the word "bias" might suggest. Instead they can vary with time (e.g. diurnal or seasonal changes), with geographic location or air-mass (including changes in the underlying surface e.g. land/sea/ice), and even with the scan position of the satellite instrument. Some examples are shown in Figure 1.

These biases we observe between the data and the model arise due to systematic errors in any one of (but more usually a combination of) the following sources:

- The satellite instrument itself (e.g. due to poor calibration/characterization and adverse environmental effects).
- The radiative transfer model (RTM) (e.g. errors in the physics/specroscopy and non-modelled atmospheric processes).
- Systematic errors in the background atmospheric state provided by the NWP model used for monitoring.

In principle we do not wish to correct the observations for the latter because that would only reinforce the model errors. Given the complicated nature of the various sources of systematic error (and how they may combine in a complicated way), it is not surprising that a considerable amount of effort has been directed towards bias correction at ECMWF and other NWP centres.

A brief history of satellite bias correction at ECMWF

The very first attempts to assimilate satellite data at ECMWF assumed fixed constant offsets applied to each channel, but these were very quickly exposed as inadequate (particularly for the rather poorly calibrated MSU and HIRS instruments that were available at the time, see *Kelly & Flobert*, 1988) and a more sophisticated correction was needed. A scheme which aimed to apply a geographically varying bias correction (depending on air-mass) was proposed in *Eyre* (1992). The air-mass was characterized by predictors based on the radiance observations themselves and the appropriate bias correction generated by linear regression (having been trained previously on a representative sample of observed minus background radiance departures). A modification of this scheme where the observation based predictors were replaced by NWP model based predictors of air-mass was proposed in *Harris & Kelly* (1998) - this has survived in essence to the present day. The aim of the scheme (and its predecessor) was very clear: to predict and apply a correction to the satellite data that effectively removed every systematic departure between the NWP model and the

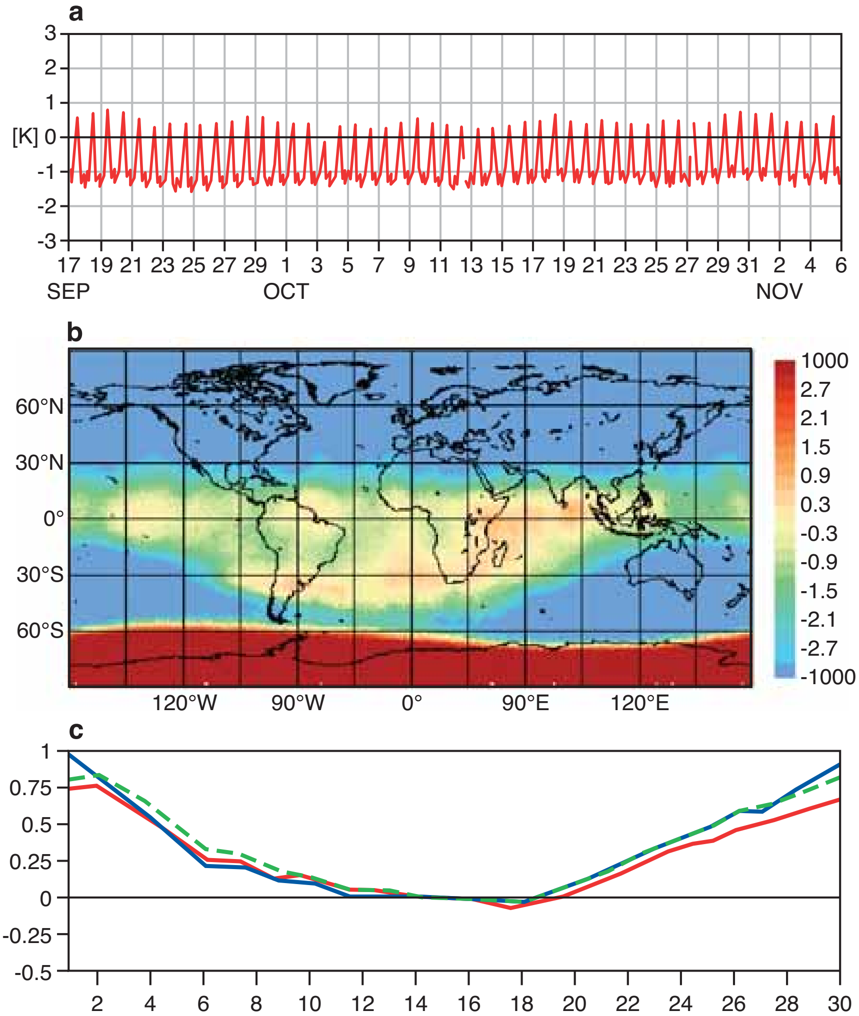

Figure 1 Examples of bias variation. (a) Diurnal varying bias in a METEOSAT window channel. (b) Air-mass (geographically) dependent bias in AMSU-A channel 14. (c) Scan dependent bias in AMSU-A channel 7.

observed radiances (i.e. correct the data to the model). To this end the regression was given many degrees of freedom (predictors) and the regression coefficients were frequently re-trained (or updated) to capture any possible drift in time. This arguably proved a very successful strategy and played no small part in the operational assimilation of satellite radiance data becoming so well established at ECMWF.

In the late 1990s two coincident events challenged the existing view of how satellite bias correction should be done.

- The arrival of radiance data from the Advanced Microwave Sounding Unit (AMSU-A).
- The extension of the ECMWF NWP model boundary into the upper stratosphere and lower mesosphere.

In the past there were many examples where satellites had been rather poorly calibrated and/or not particularly stable in time, while the model (at least in comparison) was thought to be relatively unbiased. When stratospheric radiance observations from the AMSU-A were monitored against the new NWP model it quickly became clear that situation had been reversed (see Figure 2).

There was strong evidence from a number of independent sources that the stratospheric temperatures provided by the NWP model had large time varying systematic errors whereas the AMSU-A (while not perfect) was rather well calibrated and very stable. Thus the rather courageous decision was taken to assimilate the uppermost channel of the AMSU-A with no bias correction applied.

Having sown the seeds of heresy and questioned the strategy of bias correcting the radiance data completely towards the model, investigations soon started to reveal evidence (although not as clear as the stratospheric example) of other aspects where a significant component of the bias correction being applied to the radiance data was actually due to systematic model error. Over the following years a number of steps were taken to mitigate this problem.

- The practice of frequent updates of the bias coefficients was abolished, acknowledging that the AMSU-A instruments (which formed the backbone of the assimilation system in the early 2000s) were generally stable and that time varying biases were most likely seasonal variations in the model systematic error.
- Some of the air-mass predictors which allowed the bias correction system to absorb known errors in the NWP (e.g. stratospheric and humidity) were removed (at least for some sensors) and partially replaced by new physically based corrections (so called gamma corrections, *Watts & McNally*, 2006) introduced into the AIRS and AMSU-A RTMs.

There has thus been a slow evolution towards a more minimal and constrained bias correction of the satellite radiances

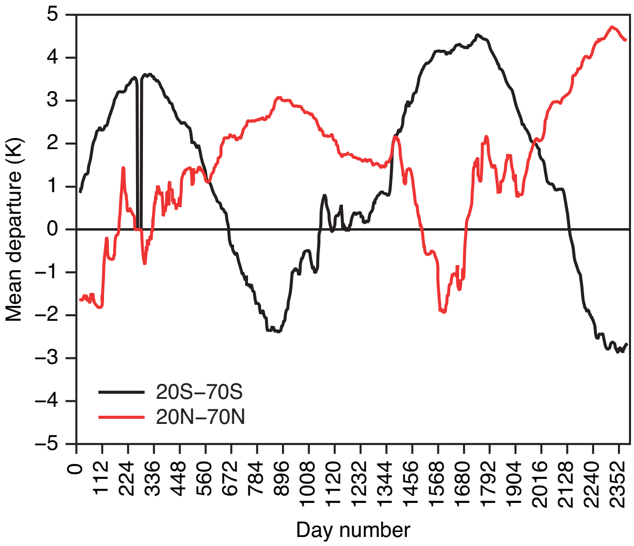

Figure 2 Time varying systematic errors in the temperature of the model stratosphere for the Northern Hemisphere from 20°–70°N (red line) and Southern Hemisphere from 20°–70°S (black line) between 1 November 1998 and 26 June 2000 compared against radiances in channel 14 from the NOAA-15 AMSU-A instrument.

which aims to correct only biases in the observations and RTM, and not remove NWP model error (although there are some examples of pragmatic departures from this). However, to this day any constraint placed upon the bias correction has always been rather subjective and ad hoc. It has ultimately depended on which predictors we choose to make available to the bias correction scheme and how frequently we choose to update the corrections.

A new way of computing and updating satellite bias corrections

When changes to the bias correction are made, the usual measure of success is whether the new system improves the fit to other assimilated observations (such as radiosondes which have not been bias corrected to the model). While the changes in the past have always been motivated by sound reasoning and often in response to an identified problem, the process of updating the satellite bias correction has effectively been on a trial and error basis. A new system has been developed within the Integrated Forecasting System (IFS) which aims to put this process on a more objective footing, based on ideas developed at NCEP and implemented in their operational 3D-Var system in the mid-nineties (*Derber & Wu*, 1998).

The Variational Bias Correction (VarBC, *Dee*, 2004 and *Auligné & McNally*, 2005) updates the satellite bias correction (not the choice of predictors, but the regression coefficients) every analysis cycle (e.g. every 12 hours). However, it does this *inside* the assimilation system by finding corrections which minimise the systematic differences between the satellites and model while simultaneously preserving (or improving) the fit to other observed data inside the analysis. This is achieved by including the regression coefficients used for bias correction in the control vector of the variational analysis, so that the bias estimates are adjusted simultaneously with the model trajectory based on all information available to the analysis. The fitting is optimal in that it respects the uncertainty of the observations and any background or inertia constraints we wish to impose on changes to the satellite bias estimation. In essence the VarBC can objectively estimate what proportion of the systematic differences between the satellites and the model should be corrected (and what should not) on the basis of all the other information we have available within the assimilation system.

Another significant benefit of the VarBC approach is that it goes a long way toward *automating* the updating and management of satellite bias corrections. The need for an adaptive bias correction system became painfully obvious during the production of ERA-40, which had to be interrupted and restarted on many occasions for manual retuning of the bias corrections. In the early days of satellite data assimilation we were typically using two satellite instruments which together provided radiance information in about 20 channels. Today in operations the 30 or so satellite instruments provide radiance information in more than 500 channels. When we consider that all of these may require different bias corrections depending on the environment in which they are used (e.g. the operational assimilation suite, the experimental *e-suites* and general research department experiments) it can be seen that even technical management of these is very difficult. Add to this the effort involved to monitor possible changes and manually decide (in the event of a change) what new bias correction should be applied, we see that automation of the process is practically unavoidable.

Early successes

The VarBC has been tested within the ECMWF 4D-Var assimilation system (but can be applied inside a 3D-Var system equally well). It has proved to be technically very robust and produced some dramatic improvements. Figure 3 shows the mean fit of the Cy30r1 assimilation system to radiosonde temperature observations averaged over the Northern Hemisphere for a period in August 2005.

It can be seen that the radiosonde temperature data suggest there is a cold bias in the short-range forecast background and in the analysis for the lower stratosphere. Similar statistics for radiances from the AMSU-A in channels sensitive to the lower stratosphere show no such disagreement. However, closer inspection reveals that this agreement is only by virtue of their bias correction towards the model. In the absence of this correction the radiance data would also suggest a similar cold bias. This situation has been known about for some time, and an obvious interpretation is that the short-range forecast does have a cold bias in the stratosphere, which is sustained in the analysis by the assimilation of wrongly bias corrected radiances. Attempts in the past to manually resolve this problem (e.g. by completely removing bias corrections from some of the stratospheric AMSU-A channels) have failed to achieve an appropriate balance between different overlapping AMSU-A channels. The same radiosonde data fits after the VarBC has been allowed to adjust the satellite bias correction are shown in Figure 4.

The time evolution of the bias correction in AMSU-A channel 10 and the fit to radiosonde data at 50 hPa are shown

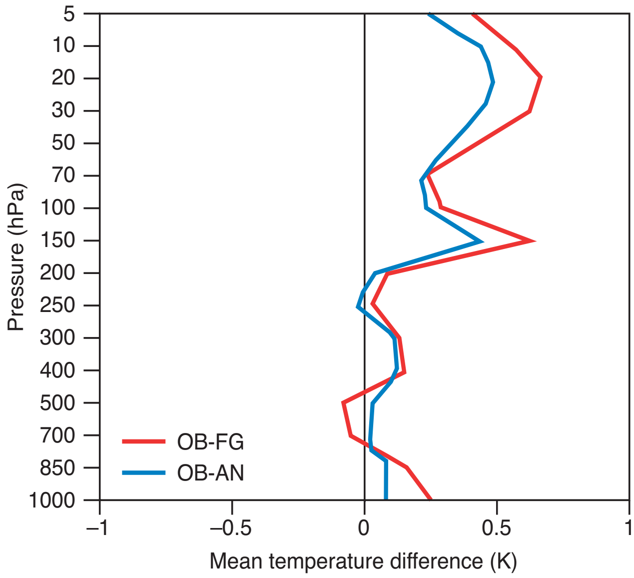

Figure 3 Mean observed minus background (red) and observed minus analysis fit (blue) for radiosonde temperatures in the Northern Hemisphere for August 2005 using the Cy30r1 assimilation system.

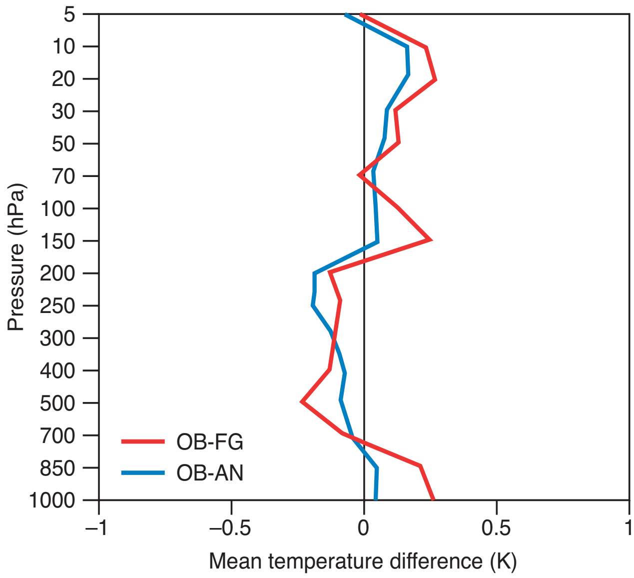

Figure 4 Mean observed minus background (red) and observed minus analysis fit (blue) for radiosonde temperatures in the Northern Hemisphere for August 2005 after VarBC has adjusted the satellite bias correction.

in Figure 5. The striking improvement in the radiosonde agreement is achieved by the VarBC progressively reducing the amount of bias correction applied to the radiance data. This results in more of the information from the AMSU-A forcing mean increments and warming the analysis accordingly. However, the successful removal of the cold bias has not been achieved quickly. The VarBC has taken several weeks of assimilation to gradually reduce the original satellite bias correction to a more appropriate level.

Another success of the VarBC is in the handling of satellite instrument changes. From previous reanalyses there are a number of well documented cases where a satellite instrument has suddenly degraded (or been contaminated by an extreme event such as volcanic emmisions). The usual result, if the event is not known about in advance, is a serious contamination of the analysis (as happened in ERA-15). If the event is known about and expected, blacklisting the affected channel can still disturb the time consistency of the

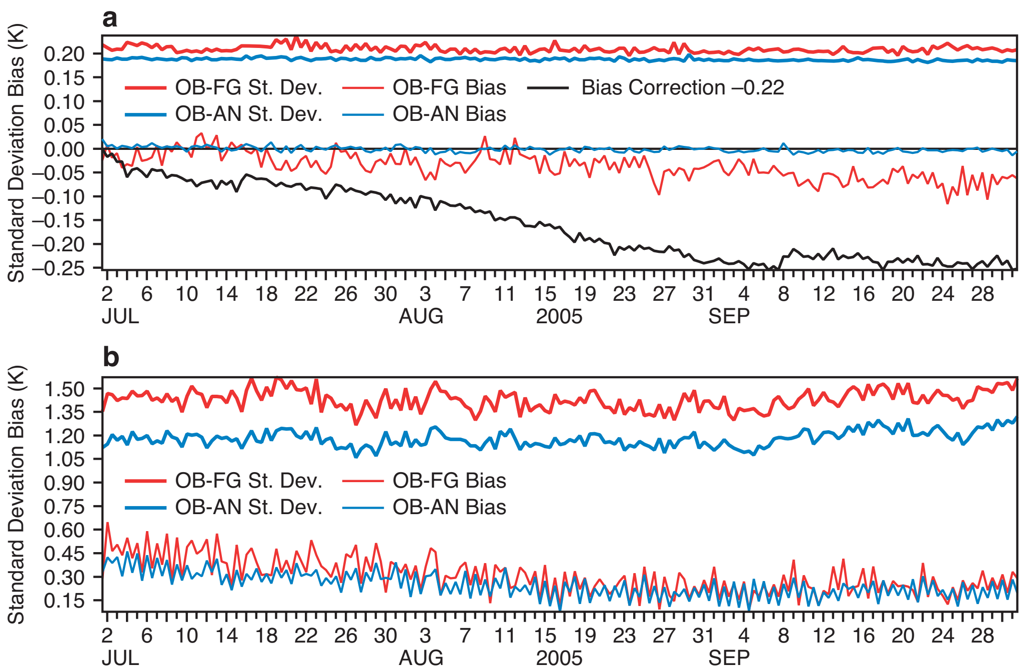

Figure 5 (a) Standard deviation (full line) and bias (dotted line) of observed minus background (red) and observed minus analysis fit (blue) for NOAA-16 AMSU-A channel 10 temperatures in the Northern Hemisphere, with the bias correction shown in black (offset by 0.22 K). (b)As (a) but for 50 hPa radiosonde temperatures in the Northern Hemisphere.

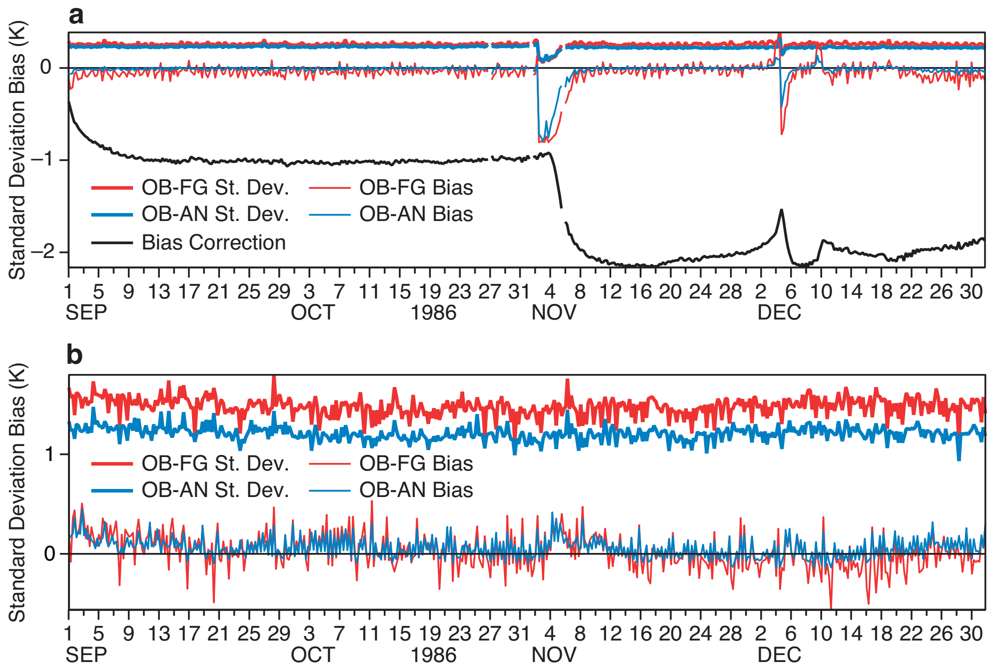

Figure 6 (a) Standard deviation (full line) and bias (dotted line) of observed minus background (red) and observed minus analysis fit (blue) for NOAA-9 MSU channel 3 temperatures in the Tropics, with the bias correction shown in black. (b) As (a) but for 200 hPa radiosonde temperatures in the Tropics.

analysis. However, in this context the VarBC has demonstrated an ability to handle sudden systematic changes to the data and minimise damage to the analysis. An extreme example of this is shown in Figure 6 for November 1986 when a cosmic storm event changed the response of the microwave (channel 3) detector on the NOAA-9 satellite.

The sudden shift in values initially results in almost all of the observations being rejected from the analysis. However, as the VarBC system is progressively exposed to more of the shifted data it automatically adjusts the bias correction (black line) to compensate. After a few days a completely new bias correction is established allowing all the radiance data to be used again with very little disruption to the analysis system (as seen in the radiosonde data fits).

Some concerns

The two examples of the previous section show that the VarBC can successfully correct satellite biases even in the presence of systematic errors in the model. The ability to discriminate between different sources of bias (and apply appropriate corrections to the satellite data) clearly depends on the nature of the bias model used, as well as on the availability of some type of anchoring data such as radiosonde observations. For example, in the upper stratosphere where no observations exist (other than satellite data) the VarBC is prone to drifting with the NWP model error. Simulations predict that a completely unconstrained adaptive bias correction will cause the assimilation system to drift, ultimately to the climate of the NWP model by progressively applying larger and larger corrections to the data (to make the data look like the biased model). We have evidence of only a very small and slow drift in the experiments performed to date. This may indicate that the VarBC is still partially constrained by the chosen bias predictors and the indirect influence of radiosondes. However, this potential drift is a cause for concern (particularly in the reanalysis environment) and will require a robust solution.

The future for VarBC

The technical and scientific benefits of VarBC are such that it is currently being tested for operational implementation at ECMWF as part of the Cy30r2 upgrade. It is also being tested for application to the reanalysis project where, on the one hand, the automation of satellite bias correction is an inescapable practical necessity, but, on the other, the possible effects on the representation of the climate signal are a serious concern.

As a precursor to implementing the fully evolving scheme, static bias correction coefficients derived from a long offline run of the VarBC have already been implemented into operations on 8 February 2006. This has allowed an early exploitation of the improvements obtained in lower stratosphere that have been described in this article (i.e. the improved fit to radiosonde temperature data).

More work will be needed to address the concerns of drift in parts of the atmosphere unconstrained by conventional observations. The imminent availability of high quality temperature information from GPS radio occultation data (e.g. CHAMP) will provide more constraining observations for bias correction in the lower stratosphere. However, in the upper stratosphere and mesosphere we may revisit the choice of parameters available to the bias correction as this has proved, in the past, to be a powerful constraint upon the correction process. It remains to be seen any drift can be sufficiently controlled to satisfy the requirements of climate studies with reanalysis.

Having effectively automated the bias correction process, possibly the greatest threat with VarBC in the future is complacency. While the VarBC will always optimise on the basis of information within the assimilation system, we must ensure that we continue monitoring the bias corrections that are being applied to the satellite data (e.g. to ensure that they are physically reasonable and not very different to what other NWP centres apply). To support this, we also plan to automate the monitoring process to detect changes in the bias correction and send alerts when pre-defined thresholds are violated.

We close with two quotations which will either concern or reassure the reader as required.

"Nothing is more fatal to happiness or virtue, than that confidence which flatters us with an opinion of our own strength, and, by assuring us of the power of retreat, precipitates us into hazard" (Samuel Johnson)

"Pessimists have already begun to worry about what is going to replace automation" (John Tudor)

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Limited area ensemble forecasting in Norway using targeted EPS

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The forecasting of severe weather is a high priority for national weather services and weather prediction centres. Extreme weather events outside the tropics often occur over small areas and last a short time. They are frequently micro- to meso-scale structures embedded into larger meso-scale and synoptic-scale phenomena. Some small-scaled structures can be associated with geographically fixed features like topography, coastlines, sea-ice, and thermal contrasts, whilst others are caused by internal non-linear dynamics which produce sharp fronts, squall lines, etc. Upscale cascading of atmospheric un-predictability, from the range of hours for convective systems to a week or two for planetary scales, renders the prediction of pure dynamically-produced structures a considerable challenge. Structures associated with geographically fixed forcing, however, leave more hope for the forecaster (*Anthes et al.*, 1985; *Boer*, 1994). There are reasons for optimism if a high quality prediction of large meso- and synoptic-scale phenomena can be combined with a better representation of the lower boundary forcing.

Hazardous weather is, by nature, unusual. A probabilistic approach is particularly appropriate for predicting such weather. The existing global ensemble prediction systems (e.g. the ECMWF Ensemble Prediction System – EPS) presently have considerable probabilistic skill on synoptic and large meso-scales. However, a number of meso-scale processes are not well captured, and the fixed boundary forcing will frequently be too smooth with the present resolution. A well-designed high-resolution, limited-area ensemble prediction system (LAMEPS) using a skilful synoptic-scale EPS at the open boundaries should improve this situation. Running a LAMEPS provides an ensemble with higher horizontal resolution. Furthermore, limiting our forecast interest to a smaller target domain enables a large fraction of the prediction spread to be covered with a small ensemble size.

At the Norwegian Meteorological Institute we have run such a LAMEPS quasi-operationally since mid-February 2005. LAMEPS is run with the Norwegian version of the HIRLAM model and it is driven by members of the ECMWF EPS which are targeted to produce maximum spread amongst ensemble members after 48 hours in northern Europe and adjacent sea areas. This system is abbreviated to targeted EPS, or simply TEPS. We have made a comparison between the 50 member EPS and the 20 member TEPS for an area covering much of the target area. The TEPS system is described in *Frogner & Iversen* (2001).

Pre-operational studies of LAMEPS in Norway have shown promising results. For further information see the article by *Frogner et al.* (2005).

A multi-model ensemble system (NORLAMEPS) is also used which simply combines LAMEPS and TEPS by using all ensemble members from both systems simultaneously. This combination gives a larger ensemble without extra model runs. Even though the combined system is to some extent an auto-duplication, the ensemble spread is larger for two reasons: there are un-correlated differences between fields from the different models, and the LAMEPS control forecast with HIRLAM can deviate considerably from the TEPS control with the ECMWF Integrated Forecast System (IFS).

Here we describe the model setup for LAMEPS, TEPS and NORLAMEPS, and show some verification results for the summer and spring of 2005. We also discuss different verification methods before we give our conclusions and suggest future work.

Brief descriptions of the various systems used in the investigation are given in Table 1.

Model setup

LAMEPS is an ensemble of runs with the Norwegian version of the limited area model HIRLAM (horizontal resolution of 0.2° with 40 levels). It uses ensemble members from TEPS to perturb both the initial and the lateral boundary conditions.

TEPS uses the same model version and the same set-up as used for the operational EPS. Only 10 singular vectors are calculated as opposed to 25 in the EPS. These singular vectors are targeted to maximize the total energy at final optimization time (48 h) in Northern Europe and adjacent sea areas (see Figure 1). Singular vectors at initial time and 48 hours evolved singular vectors valid at the same time are combined to form initial state perturbations. These are added to and subtracted from the initial state analysis (the "control") with amplitudes based on estimates of analysis error. TEPS thus contains 20 ensemble members in addition to the control forecast. The TEPS forecast length is 72 hours and is run at ECMWF once per day at 12 UTC.

Each LAMEPS ensemble member is constructed by running HIRLAM from 20 alternative initial states obtained by adding the 20 time-developed (6 hours forecasts) TEPS ensemble perturbations (the difference between each TEPS ensemble member and the TEPS control) to the HIRLAM 18 UTC analysis. At the open lateral boundaries the time-developed TEPS ensemble members, corresponding to those used for initial perturbations, are imposed. Thus we obtain 20 different forecasts in addition to the HIRLAM control run.

Abbreviation	Description
EPS	ECMWF Ensemble Prediction System using 50 + 1 ensemble members
LAMEPS	Limited-area ensemble prediction system using 20 + 1 ensemble members based on the Norwegian version of the HIRLAM model
TEPS	Targeted version of EPS using 20 + 1 ensemble members with Northern Europe and adjacent sea areas as the target area
NORLAMEPS	Multi-model ensemble system using 41 + 1 ensemble members which combines LAMEPS and TEPS

Table 1 Descriptions of the various systems used in the investigation of limited area ensemble forecasting.

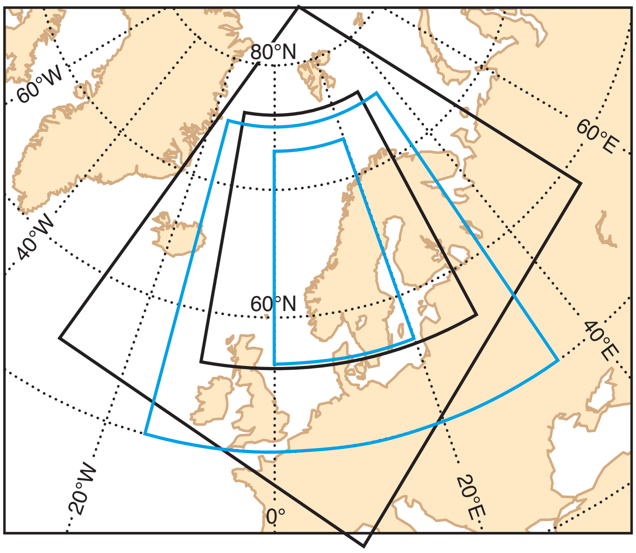

Figure 1 Areas used in the experiments. The large black area is the HIRLAM integration area, the large blue area is the target area for optimization of singular vectors, and the small blue area is the small verification domain and the small black area is the verification domain for the EPS/TEPS comparison.

Since HIRLAM starts with an 18 UTC analysis and TEPS with a 12 UTC analysis, the forecasts from LAMEPS are 6 hours shorter than the forecasts from TEPS and EPS. LAMEPS is run at 18 UTC every day and the forecast length is 60 hours.

NORLAMEPS combines the forecasts from TEPS and LAMEPS to provide a single statistic for events, even though they are not entirely independent of each other. Without extra cost, the total number of ensemble members is then 41 in addition to the HIRLAM control forecast. In this way NORLAMEPS is supposed to partly account for uncorrelated forecasts errors caused by model imperfections. The differences between the initial fields in TEPS and LAMEPS are partly caused by these model differences.

Verification methodology

Verification of precipitation forecasts against SYNOP observations is not straightforward because of the very different scales of observations and the forecasts. Furthermore, LAMEPS and TEPS/EPS also have different resolutions. Hence comparison of the different systems using either the analysed fields from the HIRLAM or the ECMWF IFS model as "the truth" would favour one of the systems. To overcome this problem we use the approach proposed by *Ghelli & Lalaurette* (2000) and construct so-called "super-observations" which are representative of precipitation grid-squares. Here all precipitation stations in Norway (several hundreds) inside the verification area (Figure 1) are aggregated to regular grids. Precipitation "super-observations" representative of our 0.2°×0.2° HIRLAM grid are thus calculated. All the verification of precipitation described here uses such super-observations.

Total precipitation from LAMEPS, TEPS, EPS and NORLAMEPS are compared to the super-observations using Rank Histograms, Reliability Diagrams, Brier Skill Scores, ROC curves, and cost/loss analysis (*Katz & Murphy*, 1997). The diurnally accumulated precipitation observations are taken at 06 UTC. Since the forecasts starts at 12 UTC and 18 UTC and are 66/60 hours long, this leaves only two possible time-intervals in the forecast range for verification: (+12/18 h to +36/42 h) and (+36/42 h to +60/66 h). Note that since LAMEPS is started 6 hours later than TEPS and EPS, the forecast from LAMEPS is 6 hours shorter than the other two forecasts.

The distribution of precipitation in Norway is dominated by sharp gradients, caused by predominant westerly winds, a long coastline, and a complex topography. The gradient across the divide between the western and eastern watersheds in Southern Norway is particularly large: western watersheds receive large amounts of precipitation, while the eastern ones are frequently sheltered by the mountains. Typically the annual difference amounts to a factor of 2 to 3 (Figure 2), but in several cases the differences are even much larger. It was noted by *Hamill* (2005) that agglomerations of samples spanning locations and times with different climatological frequencies can lead to spurious skill measures. To circumvent this problem we verify separately three sub-regions with grossly different precipitation climatologies (Figure 2). The precipitation frequencies also vary over the year, and we split the verification results into spring (February-April) and summer (May-July). Averages are calculated using weights reflecting the area of the sub-regions and by the number of days in the two periods.

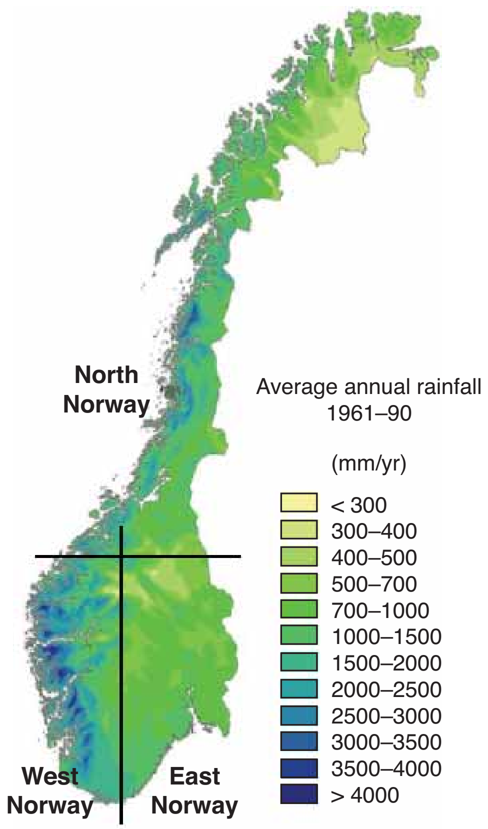

Figure 2 Average annual precipitation amounts in Norway from 1961-90 (mm). Also shown are the three different verification areas based on precipitation frequency.

Box A Definition of ensemble spread

The spread is the rms-difference between the ensemble members and the ensemble mean defined as:

$$S = \frac{1}{I}\sum_{i=1}^{1}\sqrt{\frac{1}{N \cdot D}\sum_{n=1}^{N}\sum_{d=1}^{D}\left(e_{ind} - m_{id}\right)^2}$$

where I is the number of grid-points inside the verification area, N is the number of ensemble members, D is the number of cases, e_{ind} is the ensemble member value for member n in the case d and at the specific point i, and m_{id} is the ensemble mean for the same case and at the same point.

A small spread is an indication of high skill. However, a large spread does not necessarily indicate high skill though it does give an indication of low predictability.

The ensemble spread

The spread of an ensemble forecast can be used as an indicator of quality – see Box A for the definition of the ensemble spread.

Table 2 shows the spread of total precipitation forecasts for each ensemble system. The spread increases with forecast time, which is in line with expected behaviour of unstable systems starting from small perturbations. The EPS has the smallest spread for both forecast times. The main reason for targeting is to constrain the perturbations to a predefined area of particular interest over a certain forecast range. It is expected that a targeted system will have a larger spread between ensemble members in this target area than a system that is not targeted, given the same number of singular vector based perturbations. Thus a 20-member TEPS ensemble has a considerably larger spread between the members than EPS with 50 members. Hence the TEPS ensemble includes a wider selection of fast-growing disturbances over the time-range and area of interest than the EPS ensemble. As a consequence forecasts made from TEPS over the selected time-range can quantify risks of more extreme cases better than those based on EPS. The realism of the increased risk needs to be investigated.

The EPS ensemble with 50 members has considerably smaller spread than both ensembles from TEPS and LAMEPS, each of which has only 20 members. The LAMEPS ensemble has a slightly larger spread than the original TEPS ensemble, even though the initial and boundary perturbations are entirely based on TEPS.

NORLAMEPS, which is a simple combination of the TEPS and LAMEPS, has the largest ensemble spread of all the systems for forecast range 36/42 h. Hence, LAMEPS triggers slightly different unstable structures in HIRLAM than the global model used for generating TEPS. This difference can partly originate from the higher resolution of LAMEPS and partly from the fact that two different models are used to compute the ensemble members in NORLAMEPS. The spread in the NORLAMEPS ensemble and the associated

	LAMEPS	TEPS	EPS	NORLAMEPS
+36/+42	2.15	2.08	1.56	2.19
+60/+66	2.47	2.38	2.07	2.47

Table 2 Spread around ensemble mean (in mm/day) for total precipitation for the four ensemble systems.

risks of potentially extreme weather developments should therefore be taken as due to a combination of chaos and model uncertainty. It is impossible to tell to what extent the additional spread from model uncertainty stems from uncorrelated model errors or if it is due to equally realistic but different time developments.

Skill of the four ensemble systems

All four ensemble systems are evaluated for total precipitation accumulated over the two verification periods using several measures of skill. The observations of precipitation are mainly at 06 UTC and therefore we use this time for the verification. The verification period for LAMEPS differ from that for TEPS and EPS because of the forecast starts 6 hour later for LAMEPS. The verification periods are therefore 12–36 h and 36–60 h for LAMEPS, 18–42 h and 42–66 h for TEPS/EPS and a combination of these periods for NORLAMEPS. The scores are calculated separately for each of the three sub-domains shown in Figure 2 and for the two seasons (spring and summer). The area-weighted average over the domains and the two seasons are computed.

Figure 3 shows the Brier Skill Scores for the 12/18–36/42 h and 36/42–60/66 h forecasts as a function of precipitation threshold. The Brier Skill Score measures the improvement of the probabilistic forecast relative to climatology with 0 indicating no skill compared to climatology. Figure 3 shows that LAMEPS has considerably lower scores than the other systems for both forecast periods, especially for small precipitation amounts. For 12/18–36/42 h TEPS has higher scores than EPS up to around 20 mm/day, but for larger thresholds EPS has higher scores. During 36/42–60/66 h TEPS has higher scores than EPS for all thresholds. NORLAMEPS has higher scores than any of the other systems for the high precipitation amounts (10–15 mm/day) for both forecast periods.

The ROC curve is a plot of the hit rate against the false alarm rate and it gives an indication of the ability to distinguish between events and non-events. A measure of skill is the area under the curve which has a maximum value of 1 with no skill being indicated by a value of 0.5. Figure 4 shows the area under the ROC curves for the various precipitation thresholds for the four ensemble systems. TEPS is comparable with EPS for both verification periods with EPS a bit better. For low thresholds LAMEPS has clearly lower scores than for the other systems. NORLAMEPS has the highest scores for mid to high thresholds.

For both Brier Skill Scores and area under ROC curves the 20 members of TEPS and the 41 members of NORLAMEPS give as good or better results than EPS with 50 members.

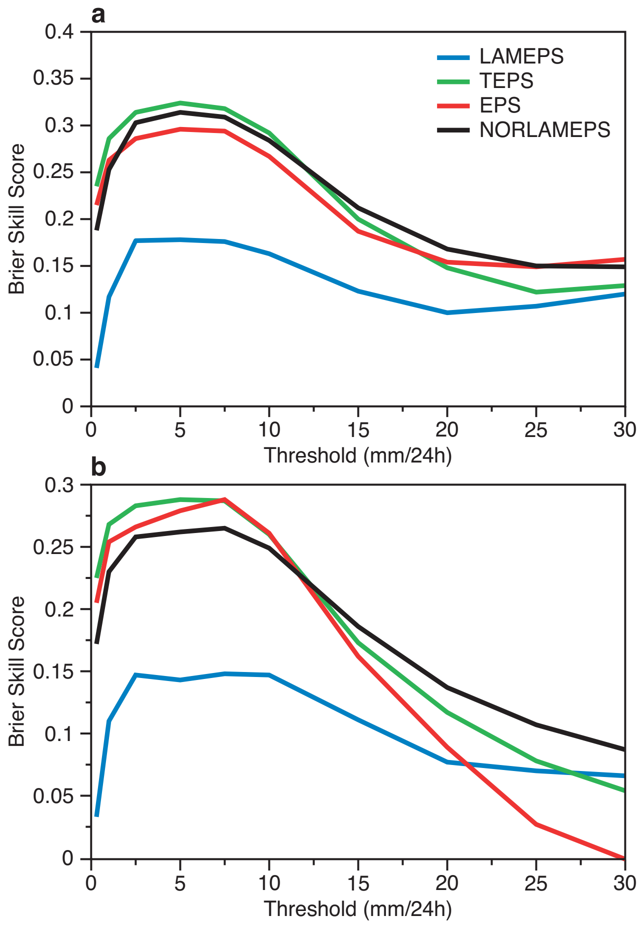

Figure 3 Brier Skill Score for precipitation as a function of threshold for LAMEPS, TEPS, EPS and NORLAMEPS for (a) 12/18-36/42 h and (b) 36/42-60/66 h forecasts. Mean over all verification areas and both seasons.

An alternative way of assessing the quality of probability forecasts is to consider the relative improvement in economic value (Relative Value) as a function of the cost/loss ratio with climatology as the reference. As with the other skill scores, a Relative Value of 1 indicates a set of perfect forecasts. Figure 5 shows the Relative Value for the weighted mean over the three areas and the two seasons with an event threshold of 5 mm/day. For the Relative Value the EPS gets the highest values, but NORLAMEPS has the widest distribution.

Note that all three measures of skill indicate that LAMEPS has a considerably lower score for the low precipitation thresholds. For mid to high thresholds NORLAMEPS has very good scores, showing that LAMEPS gives extra and valuable information to the TEPS.

We have also looked at the Rank Histograms and the Reliability Diagrams for the four systems (not shown here). The Rank Histograms indicate a bias in all four systems where they all underestimate the variability. The underestimation is small in TEPS and especially large in EPS. The Reliability Diagrams show good reliability up to about 70% for TEPS and NORLAMEPS, after which the two systems over-forecast the higher probabilities. LAMEPS and EPS over-forecast the probabilities from about 30–40%.

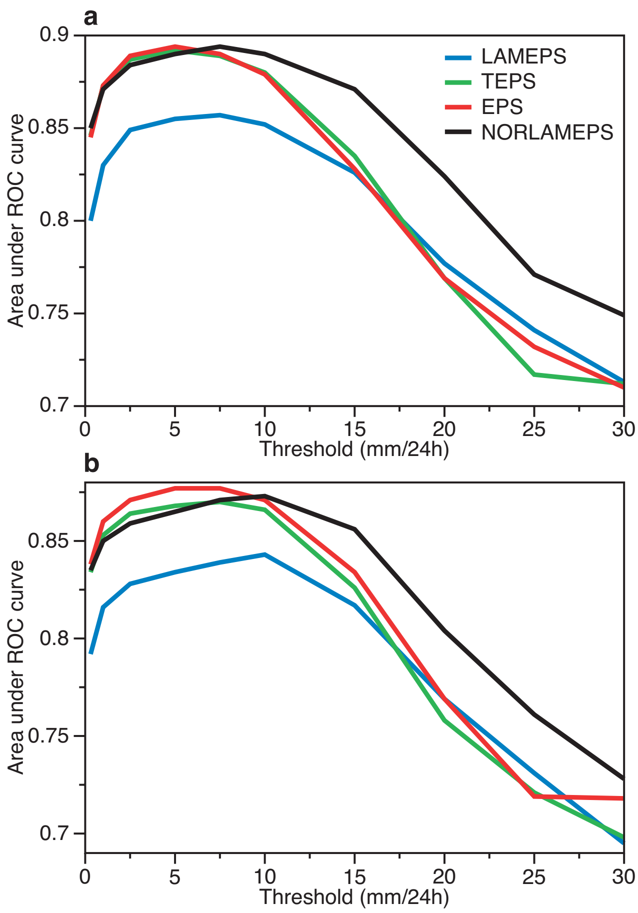

Figure 4 Area under the ROC curve for precipitation as a function of threshold for LAMEPS, TEPS, EPS and NORLAMEPS for (a) 12/18–36/42 h and (b) 36/42–60/66 h forecasts. Mean over all verification areas and both seasons.

Additional comparison between EPS and TEPS

The precipitation observations used to compare the four ensemble systems cover only a small part of the targeting domain. Therefore an additional investigation was carried out to study the differences between the EPS and TEPS for a larger targeting domain. The aim was to assess whether there are benefits in the targeting for larger areas than Norway. This should be interesting for others wanting to use TEPS, both in itself and as an input to limited area models. Given the different ensemble size of EPS and TEPS, we have compared the 20 member TEPS against both the 50 member EPS and against only the 20 first members of the EPS.

For this larger area we did not have observations of precipitation, so we have used 30 hour forecasts of 24 hours accumulated total precipitation from the deterministic ECMWF model (T511L60) as the truth. The verification area covers much of Scandinavia and the sea areas west of Norway (the small black area shown in Figure1).

We have used the same 0.2 ×0.2 degree grid as used earlier in the study, and the statistical scores are the same as for the verification against observations.

Here we display the same probabilistic scores that we used for the previous comparisons: Brier Skill Scores (Figure 6) and area under the ROC curves (Figure 7) for different precipitation thresholds, and ROC curves and cost/loss analysis (Figure 8) for an event threshold of 5 mm/day.

The results given in Figures 6, 7 and 8 can be summarised as follows.

- For all measures of skill, the full 50 member EPS has, as one should expect due to the higher ensemble members, higher scores than the 20 member EPS as well as the 20 member TEPS.
- For the Brier Skill Score, the 20 member EPS has a somewhat higher score than TEPS for small and medium precipitation amounts, but for high precipitation amounts TEPS has a higher score than the EPS with the same number of members.
- For the Brier Skill Score, the scores for TEPS is closer to the scores from EPS for the second verification period, but for the area under the ROC curve the scores for TEPS are better compared to the others for the first verification period.
- For the other verification parameters it seems as if TEPS is as good as or better than the low member EPS for the first verification period.

Discussion and conclusion

From the results we have seen that LAMEPS is able to produce more spread than EPS for precipitation over Norway. For events with small precipitation amounts the probabilistic scores for TEPS and EPS are better than for LAMEPS, but for larger precipitation amounts LAMEPS scores better.

The combined system NORLAMEPS gets the largest spread and also best probabilistic scores from mid to high precipitation amounts. This shows that combining LAMEPS and TEPS adds value to the two individual systems. The improvement by NORLAMEPS can partly be due to the increase in resolution for LAMEPS, and partly from the fact that it combines results from two model systems with different characteristics.

For the Norwegian verification area the comparison of the 20 members TEPS and 50 members EPS provides some interesting results. The increase in ensemble spread of TEPS compared to EPS demonstrates the advantage of targeting. Also for many of the probabilistic scores TEPS is better or comparable to EPS, even though it has fewer members.

Using the larger verification area for the comparison one clearly sees the advantages of having an ensemble with more members. However, one can also see that the targeting gives extra value to the ensemble forecast of precipitation, especially for the shorter-range forecast.

The verification has shown that TEPS gives better results for the short-range verification period. This may indicate that the method of perturbing TEPS gives very good results early in the forecast range, but that the weather system then moves out of our target area. In this case the ordinary EPS has an advantage. One way of dispensing with this is to combine TEPS and EPS as input to LAMEPS.

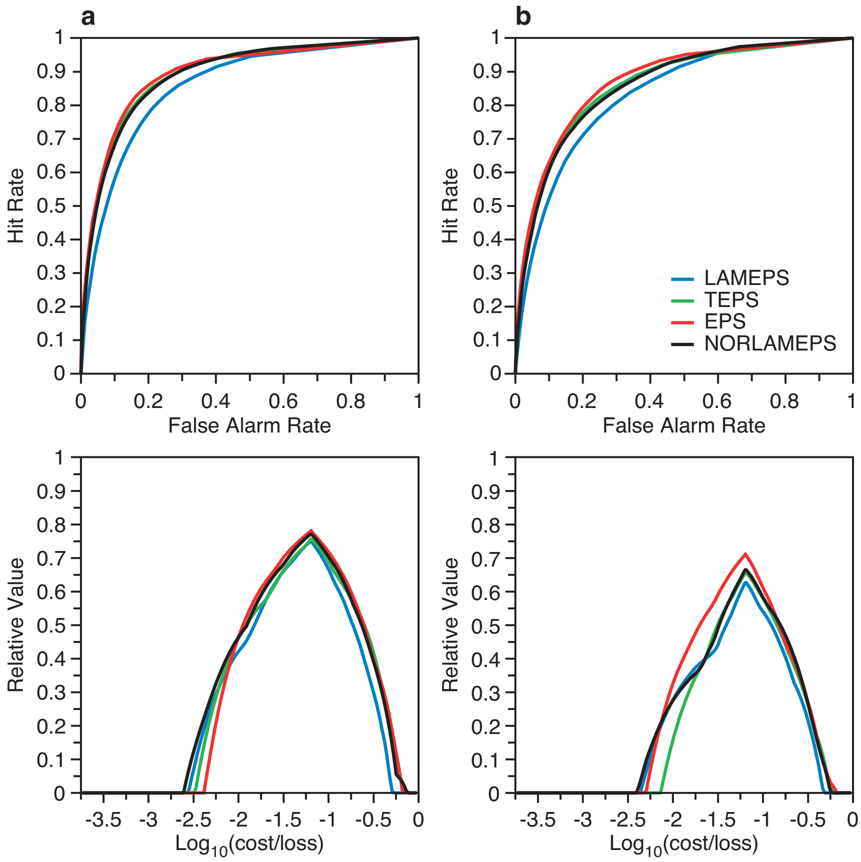

Figure 5 (a) ROC curves (top) and Relative Value analysis (bottom) for total 24 hour precipitation for LAMEPS, TEPS, EPS and NORLAMEPS for 12/18–36/42 h forecasts. (b) As (a) but for 36/42–60/66 h forecasts. The threshold is 5 mm/day. Mean over all verification areas and both seasons.

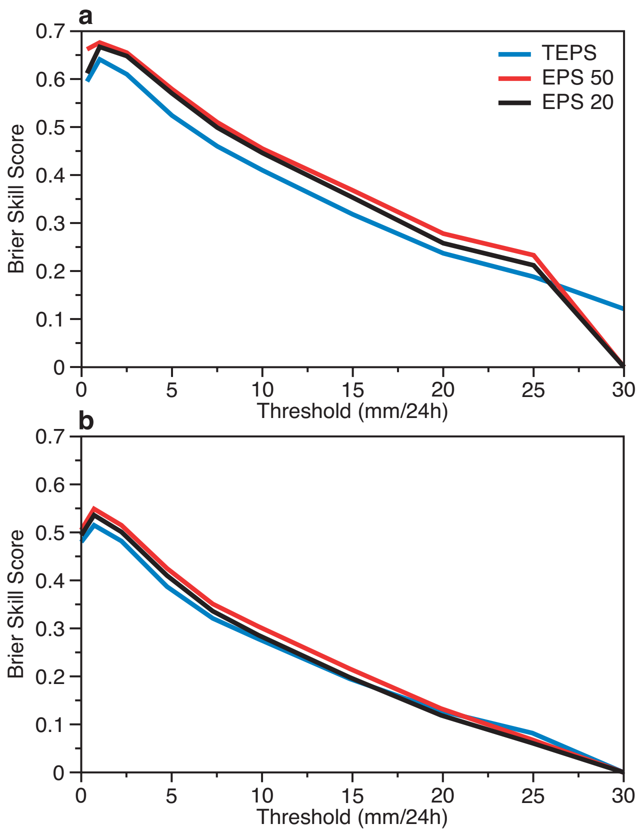

Figure 6 Brier Skill Score for precipitation as a function of threshold for TEPS, 50 member EPS (EPS 50) and 20 member EPS (EPS 20) for (a) 18–42 h and (b) 42–66 h forecasts.

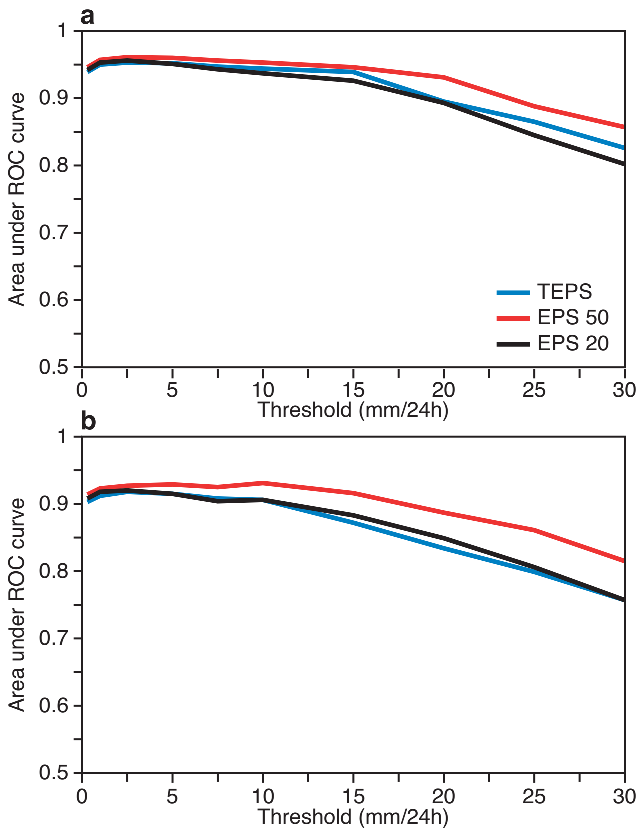

Figure 7 Area under the ROC curve for precipitation as a function of threshold for TEPS, 50 member EPS (EPS 50) and 20 member EPS (EPS 20) for (a) 18–42 h and (b) 42–66 h forecasts.

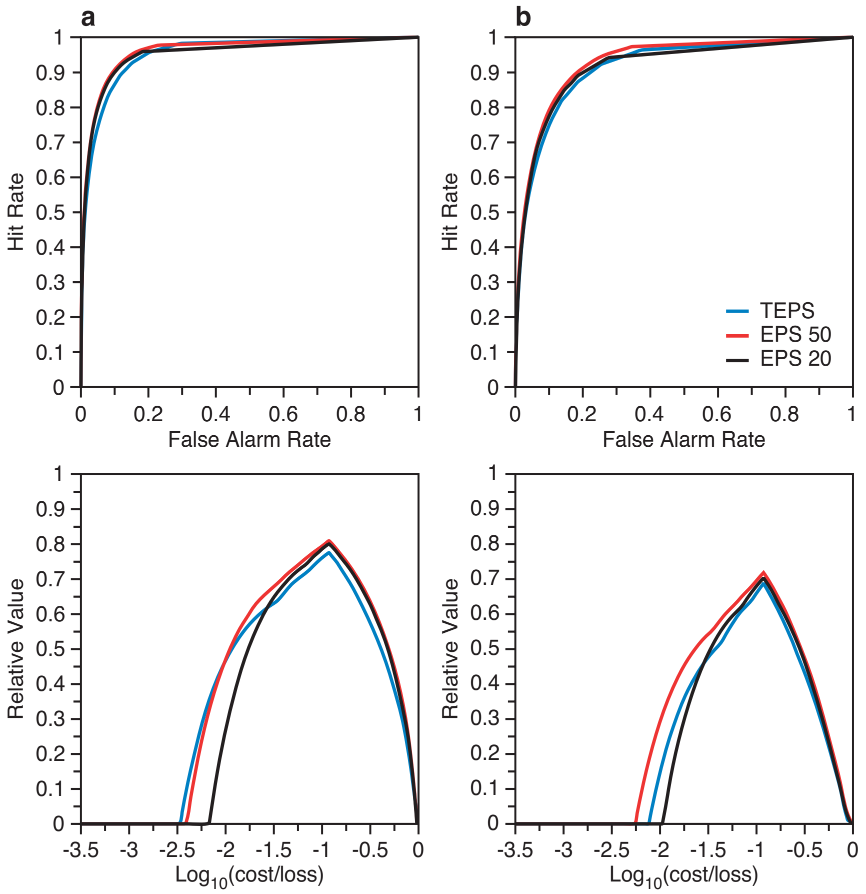

Figure 8 (a) ROC curves (top) and Relative Value analysis (bottom) for total 24 hour precipitation for TEPS, 50 member EPS and 20 member EPS for 18–42 h forecasts. (b) As (a) but for 42–66 h forecasts. The threshold is 5 mm/day.

Ongoing work

Our plans are to continue to develop LAMEPS/NORLAMEPS by, for example, perturbing the physics in HIRLAM model and increasing the resolution of LAMEPS (first to 15 km and then to 10 km). Experience with the operational HIRLAM models shows that HIRLAM with 10 km resolution is capable of predicting polar lows not resolved at 20 km resolution. As polar lows are important for our area of interest and often give intense precipitation and strong winds, it is desirable that LAMEPS should be able to resolve these features. The focus will also be extended to include more weather parameters such as temperature and wind.

Different ways of making perturbation for TEPS will be tested together with staff at ECMWF. Indeed we are grateful that the computing resources necessary to run TEPS have been partly provided by an ECMWF Special Project.

FURTHER READING

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May 2–12	Meteorological Training Course – Parametrization of diabatic processes
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June 8–9	Computer Representatives' Meeting
June 14–16	Forecast Products Users Meeting
June 19–21/22	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*)

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492 **Kucukkaracac, E. & M. Fisher**: Use of analysis ensembles in estimating flow-dependent background error variances. *April 2006*

490 **Eden, C. & T. Jung**: Wind-driven eddies and plankton blooms in the North Atlantic Ocean. *March 2006*

488 **Bauer, P., P. Lopez, D. Salmond, A. Benedetti, S. Saarinen & M. Bonazzola**: Implementation of 1D+4D-Var assimilation of precipitation affected microwave radiances at ECMWF, Part II: 4D-Var. *February 2006*

487 **Bauer, P., P. Lopez, A. Benedetti, D. Salmond & E. Moreau**: Implementation of 1D+4D-Var assimilation of precipitation affected microwave radiances at ECMWF, Part I: 1D-Var. *February 2006*

486 **Bauer, P., E. Moreau, F. Chevallier & U. O'Keeffe**: Multiple-scattering microwave radiative transfer for data assimilation applications. *February 2006*

485 **Jung, T., S.K. Gulev, I. Rudeva & V. Soloviov**: Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model. *February 2006*

484 **Jung, T., L. Ferranti & A.M. Tompkins**: Response to the summer 2003 Mediterranean SST anomalies over Europe and Africa. *February 2006*

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ECMWF/EUMETSAT NWP-SAF Workshop on Bias Estimation in Data Assimilation. *8–11 November 2005*

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