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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 The *ECMWF Newsletter* is not peer-reviewed.

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Scalability of codes

Earlier this year, ECMWF upgraded the horizontal resolution of its operational forecasting system and an article outlining details of the upgrade is featured in this edition of the ECMWF Newsletter. Over the years, increases in resolution have contributed significantly to improvements of forecast skill at all ranges. Newer and faster generations of supercomputers have provided the computational capability required for the implementation of such resolution increases, as well as the assimilation of large volumes of satellite data and the continuous enhancement of the process descriptions within the model. In terms of sustained performance, the current IBM POWER6 system installed at ECMWF is 400,000 times faster than the CRAY-1A system used to deliver the Centre's first operational forecast in August 1979. Computer vendors have achieved such improvement by running processors faster, increasing their effectiveness and using more of them.

Nowadays, as some parts of modern chips are only several atoms thick, it is impossible to increase the clock frequency (or speed) of a chip without disproportionately increasing power consumption. For the foreseeable future, no significant increase in chip speed can be expected as reducing power consumption has now become the overriding design criteria. For the same reason, complex processors with ever increasing cache sizes and clever but power-consuming logic, which enhance the sustained performance of an individual processor, are no longer in favour.

For future supercomputer systems, to compensate for the stagnation in clock speed and processor effectiveness, we will see an accelerated growth in the number of processors. NWP applications that do not scale well, i.e. that cannot run efficiently on massively parallel computers, will be unable to benefit from the improved performance offered by the systems of the future.

In 2008 ECMWF set up a project to investigate the scaling properties of the operational forecasting system. The algorithms chosen and their implementation are inevitably limiting the number of processors that can usefully be employed. The study concluded that the forecast model, as used for the deterministic and ensemble runs, scales reasonably well. However, the data assimilation system is already constrained and substantial improvements to its scaling properties can only be made by reviewing the algorithms used.

NWP models are tightly-coupled applications requiring significant processor-to-processor communication. As such, most NWP centres are (or will soon be) faced with the challenging task of improving the scaling properties of their codes. Some will opt for a major re-write. At ECMWF, the focus will initially be on algorithmic developments for the data assimilation system. Ensemble-based techniques inherently scale more easily but may have significantly higher total costs associated with them.

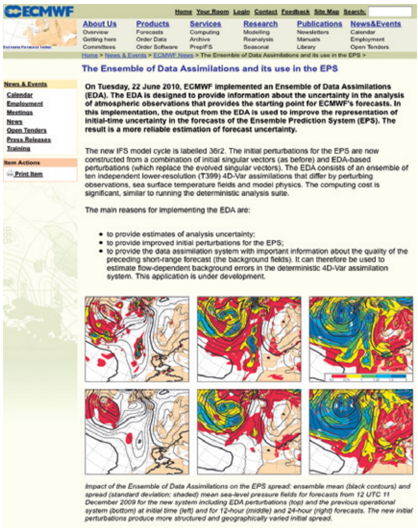
The next upgrade of the horizontal resolution of ECMWF's forecasting system is planned for 2015. By then, we can expect a supercomputer with a vastly increased number of processors. In preparation for this, intensive work on the scaling properties of our key forecast codes will feature highly in ECMWF's plans.

Walter Zwieflhofer

New items on the ECMWF website

ANDY BRADY

The Ensemble of Data Assimilations and its use in the EPS



On 22 June 2010, ECMWF implemented an Ensemble of Data Assimilations (EDA). The EDA is designed to provide information about the uncertainty in the analysis of atmospheric observations that provides the starting point for ECMWF's forecasts. In this implementation, the output from the EDA is used to improve the representation of initial-time uncertainty in the forecasts of the Ensemble Prediction System (EPS). The result is a more reliable estimation of forecast uncertainty.

- http://www.ecmwf.int/publications/cms/get/ecmwfnews/1277473483350

2010 ECMWF Corporate Brochure

The ECMWF Corporate Brochure for 2010 is now available in English, French and German versions. The brochure gives a high-level overview of ECMWF and its activities.

- http://www.ecmwf.int/about/corporate_brochure/index.html

Workshop on 'Assimilating satellite observations of clouds and precipitation into NWP models'

The ECMWF/JCSDA Workshop on '*Assimilating satellite observations of clouds and precipitation into NWP models*' was held from 15 to 17 June 2010. This workshop was organised in collaboration with the Joint Centre for Satellite Data Assimilation (JCSDA) in the USA. Presentations are now available.

- http://www.ecmwf.int/newsevents/meetings/workshops/2010/Satellite_observations/

New web products from the ECMWF Ensemble Prediction System

ECMWF has extended the range of weather forecast products that are available freely and with no restrictions from its web site. The new products are from the ECMWF Ensemble Prediction System (EPS) that provides guidance on the day-to-day predictability of the atmosphere. This gives an important complement to the information that is already available from the single deterministic model.

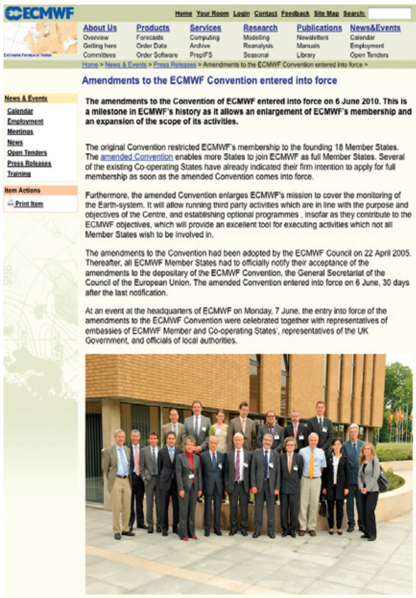
- http://www.ecmwf.int/publications/cms/get/ecmwfnews/1273755207538
- http://www.ecmwf.int/products/forecasts/d/charts/medium/eps

ECMWF 2010 Annual Seminar

Every year ECMWF organizes a seminar with a pedagogical objective, whereby a selected topic related to NWP is highlighted. The subject of the seminar this year was '*Predictability in the European and Atlantic regions from days to years*', and was held from 6 to 9 September 2010. Presentations are now available.

- http://www.ecmwf.int/newsevents/meetings/annual_seminar/2010/

Amendments to the ECMWF Convention entered into force



The amendments to the Convention of ECMWF entered into force on 6 June 2010. This is a milestone in ECMWF's history as it allows an enlargement of ECMWF's membership and an expansion of the scope of its activities.

- http://www.ecmwf.int/publications/cms/get/pressreleases/259
- http://www.ecmwf.int/about/basic/volume-1/convention_and_protocol/amending_convention/amendments.html

21st meeting of the European Working Group on Operational Meteorological Workstations (EGOWS)

The 21st annual meeting of the European Working Group on Operational Meteorological Workstations (EGOWS) took place at ECMWF from 1 to 4 June 2010. Presentations are now available.

- http://www.ecmwf.int/newsevents/meetings/workshops/2010/EGOWS/

73rd Council session on 24–25 June 2010

MANFRED KLÖPPEL

Under the chairmanship of its President, Mr Wolfgang Kusch (Germany), the Council held its 73rd session at the ECMWF headquarters in Reading, United Kingdom.

The Council congratulated the Director-General on the main achievements since its last session in December 2009, noting in particular that:

- A new cycle of the forecasting system had been implemented on 26 January 2010 with increased horizontal resolution of the deterministic and ensemble prediction system.
- In February 2010, ECMWF had reached a landmark in the performance of its deterministic forecasting system, when for the first time the headline measure of skill had exceeded the forecast range of 10 days.
- The Centre had prepared for IFS cycle 36r2 that would introduce the Ensemble of Data Assimilations (EDA). The EDA is designed to provide information about the uncertainty in the analysis of atmospheric observations. This cycle was implemented two days before the Council session on 22 June 2010.
- Comparisons with other global forecasting centres had shown the continuing lead of ECMWF.
- The amendments to the Centre's Convention entered into force on 6 June 2010. The amended Convention enables more States to join ECMWF as full Member States, enlarges ECMWF's mission to cover the monitoring of the Earth-system, and broadens the possibility for externally funded activities, namely Third Party Activities.

Besides several decisions made on financial and staff matters (such as adoption of Reports from the Co-ordinating Committee on Remuneration), the main results of this session were as follows.

Celebration of the amended ECMWF Convention. In the evening of the first day of the Council session, the entry into force of the amended Convention, a milestone in the history of ECMWF, was celebrated. All Council attendees and all ECMWF staff were invited. Speeches were given by Wolfgang Kusch (President of the Council), John Hirst (Chief Executive of the Met Office) and Dominique Marbouty (Director-General of ECMWF).

Recruitment of a new Director-General. The contract of the current Director-General, Dominique Marbouty, will end in summer 2011. In an in-camera session preceding the plenary the Council agreed on the procedure for the recruitment of a new Director-General (for a five years contract), as well as on the composition of the interview board. The corresponding vacancy notice was issued on 14 July 2010.

Third Party Activities and Optional Programmes. The Council unanimously adopted the procedures for approval and implementation of Third Party Activities and Optional Programmes now manifested in the amended Convention.

Co-operation. The Council unanimously authorised the Director-General to:

- Negotiate a co-operation agreement with Bosnia and Herzegovina and with the Former Yugoslav Republic of Yugoslavia (FYROM).
- Negotiate and conclude a one-year extension of the current co-operation agreement with the Joint Research Centre (JRC) on the development and testing of the European Floods Alert System (EFAS) to cover a project fully funded by the Monitoring and Information Centre (MIC) of the EC.

Financial Matters. The Council took note of the Auditor's Report regarding the financial year 2009 and gave discharge to the Director-General in respect of the implementation of the budget for 2009.

GMES (Global Monitoring for Environment and Security). The Council unanimously adopted the ECMWF strategy regarding GMES:

- The main involvement of ECMWF in GMES will remain in the atmosphere core services where the Centre intends to continue to play both the role of coordinator and main player.
- ECMWF intends to continue to be a

partner in land and emergency response core services where its role will be defined by the agreed scope of the core services.

- Reanalysis is recognised as a crucial input for climate monitoring and, therefore, it is expected that the GMES Climate Services will be the right framework for a European sustained reanalysis activity. ECMWF is willing to continue coordinating European efforts in reanalysis.
- ECMWF is prepared to coordinate the GMES Marine Core Services "if requested by the oceanographic community and by the GMES governing bodies".
- The main task of ECMWF will be to prepare with the EC and the Member States an appropriate framework for its contribution to the implementation of sustained GMES core services from 2014 at the latest.

View Services. The Council adopted the proposed modifications to the "Rules governing the distribution and dissemination of ECMWF real-time products" to bring them into line with the Oslo Declaration in regard to view services.

WMO. The Council unanimously:

- Authorised the continuation of ECMWF's ongoing support for WMO's severe weather forecast demonstration projects (SWFDP) as a Global Centre.
- Approved ECMWF's plan to respond positively to WMO's request at the forthcoming Commission for Basic Systems (CBS) for nomination as Lead Centre for Deterministic NWP Verification.
- Authorised the continued provision of deterministic and ensemble tropical cyclone track information in real time, for research use only, in support of THORPEX and other WMO-led research activities

Vice-President. The Council unanimously elected Mr François Jacq (France) as its Vice-President for a first term of office of one year.

Assimilation of satellite observations related to clouds and precipitation

PETER BAUER (ECMWF),
GEORGE OHRING (JCSDA)

The assimilation of satellite measurements in NWP models is still mostly focused on the clear atmosphere. However, satellite observations in the visible, infrared, and microwave provide a great deal of information on clouds and precipitation as well as clear regions above the clouds. A major issue is how to use this information to improve the initialization of cloudy and precipitating atmospheric regions in NWP models. Since clouds and precipitation often occur in sensitive regions in terms of forecast impact, such improvements are likely necessary for continuing significant gains in weather forecasting.

In 2005, the Joint Center for Satellite Data Assimilation (JCSDA) sponsored an international workshop that covered the three main topics related to assimilating observations in cloudy/precipitating regions, namely satellite observing capabilities, modelling radiative transfer and cloud/precipitation formation, and data assimilation. From 15 to 17 June 2010 a joint ECMWF-JCSDA workshop has been hosted at ECMWF to document the developments since the 2005 workshop and to produce recommendations to ECMWF, JCSDA, and other NWP centres and scientific communities for future research developments and collaboration. About 65 participants attended the workshop representing most major NWP centres around the world as well as research institutes and universities.

The workshop sessions covered the current status of cloud/precipitation assimilation in NWP, special issues

ECMWF/JCSDA Workshop. Participants of the ECMWF/JCSDA Workshop on 'Assimilating satellite observations of clouds and precipitation into NWP models' hosted by ECMWF on 15–17 June 2010.

Major problems identified by the workshop's working groups on modelling, data assimilation and verification

- ***Modelling***. A prominent model problem has been the quick loss of observational information gained in the analysis during the early time steps of the model forecast that limits the impact of cloud observations on dynamics and more pronounced large-scale forecast impact. While satellite data has a large potential for verifying cloud and microphysics parametrizations, the apparent scale mismatch produces noisy statistics. In conjunction with data assimilation, cloud modelling includes the development and maintenance of linearized/regularized models used in the minimization with similar characteristics as the non-linear versions. With increasing model complexity and better spatial resolution non-linear and linear models may diverge.
- ***Data assimilation***. The non-linearity of physical parametrizations and radiative transfer models as well as the non-Gaussian error characteristics can be limiting factors for data assimilation. The difficult match between spatial representativeness of satellite observations and model grid points in general and the frequent mis-location of clouds in model forecasts add to this problem and may require spatial smoothing or more statistical alternatives for comparing models with data.
- ***Verification***. The verification of the impact of satellite data affected by clouds and precipitation is very difficult since this data produces only short-range impact so far and verification with relevant observations is sparse and noisy. General forecast skill score evaluation with model analyses often shows neutral impact and strongly depends on the verifying analysis.

related to cloud and precipitation affected observation, radiative transfer modelling, cloud and precipitation representation in numerical models, and problems of integrating such data in operational data assimilation systems. A novel approach to working group organization has been taken by running groups composed of experts in observation, modelling and data assimilation in parallel. Each group has been asked to discuss the same set of questions and to produce recommendations across these disciplines.

Since 2005, most operational NWP centres have begun to use cloud-affected radiances either in research or already in operational use. This includes both infrared sounder and microwave imager/sounder radiances, of which the latter are also sensitive to precipitation. At ECMWF, the 1D+4D-Var system for SSM/I radiances has been implemented in June 2005 (*ECMWF Newsletter No. 110*), followed by the all-sky microwave imager radiance assimilation (*ECMWF Newsletter No. 121*) in March 2009 and the use of infrared sounder radiances in overcast cloud conditions (*ECMWF Newsletter No. 120*).

The workshop recommendations emphasized that, while existing model biases are large and existing data assimilation systems are not ideal, substantial improvements can be obtained with pragmatic modifications applied to existing systems. Data assimilation techniques should be adjusted to facilitate the usage of cloud information through better choice of control variables, more specific (flow-dependent) background error statistics in clear-sky and cloud covered areas. In this context, studies on critical analysis errors should be performed for the understanding of errors that drive forecast performance. According to the working groups, the fundamental model biases require attention, in particular biases associated with the lifecycle of cloud development and decay that may greatly inhibit forecast impact. Continuous resources should be allocated for the maintenance of linear models required in current variational assimilation schemes.

Longer-term research was proposed to invest in work on model error definition when longer assimilation windows do not allow assuming a perfect model anymore. Alternative assimilation techniques should be explored that are better suited to treat non-linear inversion problems. Also, model ensembles allowing the exploitation of differences between observations and ensemble members in a more statistical way have been proposed. The ensemble data assimilation system introduced with Cy36r2 is expected to pave the way towards hybrid methods that combine the advantages of ensemble techniques with 4D-Var.

Interestingly, there was general consensus among the working groups that currently existing satellite observations are rather under-exploited so that the groups did not produce explicit requirements for future observing systems. Among the most promising, sub-millimetre radiometer observations sensitive to ice clouds, high-frequency advanced sounders (both infrared and microwave) to capture highly dynamic cloud and water vapour features, and radar/lidar observations were identified providing detailed information on cloud phase, water and ice contents with excellent spatial resolution. The fundamental question whether direct wind observations inside and outside clouds could produce a stronger forecast impact on dynamics, temperature and cloud state than cloud parameter observations was raised. Answering this question, however, may require observing system simulation experiments that occupy significant resources.

More details on the workshop and all presentations can be accessed from:

- http://www.ecmwf.int/newsevents/meetings/workshops/2010/Satellite_observations/index.html

ECMWF Annual Report for 2009

BOB RIDDAWAY

The ECMWF Annual Report 2009 has been published. It provides an overview and a broad, non-technical description of ECMWF's main activities. There is also an indication of ECMWF's future plans.

The report draws attention to some of the key events of 2009 that are associated with operational activities.

- ***Implementation of IFS Cycle 35r2***. The implementation of IFS Cycle 35r2 was an important step towards increasing the use of satellite data, with the direct 4D-Var assimilation of microwave imager radiances in areas affected by cloud and rain. Also the operational use of Jason-2 data was implemented. *10 March*
- ***Operational forecasting using the first cluster***. The operational forecasting suite began running routinely on the first cluster, which was processing about 135,000 parallel jobs and over 600,000 serial jobs per day. *1 April*
- ***Upgrade of services to WMO Members***. ECMWF upgraded the service for members of the World Meteorological Organization (WMO) to download high-resolution analysis and model data from the deterministic forecasting system. The spatial resolution was increased from 2.5°×2.5° to 0.5°×0.5° latitude/longitude. *8 September*
- ***Implementation of IFS Cycle 35r3***. The new IFS Cycle 35r3 was implemented; it included several important changes that resulted in a significantly positive impact on the skill of the forecasting system. *8 September*
- ***Phase I of the new IBM HPCF accepted.*** Phase I of the new IBM high-performance computing facility (HPCF) was accepted. The configuration is composed of two identical POWER6 compute clusters. The service of the Centre's 'old' computer system was terminated. *30 September*
- ***Installation of the ATL.*** The new automated tape library (ATL) was installed and the formal acceptance tests were started. *7 October*
- ***Upgrade of the limited-area wave model.*** ECMWF implemented the increase in spectral resolution of the limited-area wave model to 36 directions and 36 frequencies. *13 October*
- ***Usage of the ECMWF's HPCF resources.*** Member States' usage of the ECMWF's HPCF resources reached a new milestone. The usage for one single day surpassed 1 million units for the first time. *19 November*

In addition, the Annual Report describes a wide range of activities and achievements in 2009 that are of benefit to the operational activities of Member and Co-operating States as well as supporting the endeavours of the international meteorological community.

Dominique Marbouty, ECMWF Director-General, starts his foreword to the Annual Report by stating that: "2009 was another year showing significant achievements at ECMWF. The research programme continued to play a key role in the remarkable advancement of operational weather forecasting capabilities and in making best use of satellite and in-situ

observations of the Earth. ECMWF was able to keep its worldwide reputation and leadership in global numerical weather prediction."

As outgoing President of the Council, Adérito Vicente Serrão, states that: "I am confident that ECMWF, in close collaboration with its Member States, will maintain its leading role in global numerical weather prediction. In this way it will continue to deliver high-standard products to its Member and Co-operating States as well as playing a full role in supporting the activities of the international meteorological community." Adérito Vicente Serrão concluded his statement by congratulating the Director-General of ECMWF and the extremely qualified staff working at the Centre on the progress made during 2009.

The Annual Report can be downloaded from:

- www.ecmwf.int/publications/annual_report

Use and development of ECMWF's forecast products

DAVID RICHARDSON

The 2010 Forecast Product Users Meeting took place at ECMWF on 9–11 June. The purpose of these annual meetings is to:

- Present recent and planned developments of the ECMWF operational forecasting system, especially the forecast products.
- Give users of ECMWF forecasts the opportunity to discuss their experience with and to exchange views on the use of our medium-range and extended-range products.

Representatives from 20 National Meteorological Services of the Member States and Co-operating States and from a number of commercial companies that use ECMWF weather forecast products took part.

Two new cycles of the operational assimilation and forecasting system have been implemented since the last meeting. These changes and the impact on the forecasts were presented. They included a parametrization for non-orographic gravity waves which improved the circulation in the stratosphere of the model, improved quality control of conventional observations (using a Huber norm), assimilation of cloud-affected radiances for infra-red instruments, and a 'weak-constraint' 4D-Var that takes account of systematic model errors in the stratosphere. The representation of model uncertainty in the Ensemble Prediction System (EPS) using stochastic physics was revised. In January 2010, the horizontal resolutions of deterministic forecast and the EPS were increased.

- Deterministic model resolution increased from T799 (25 km grid) to T1279 (16 km).
- EPS resolution changed from T399 (50 km) to T639 (32 km) for the first 10 days of the forecast and from T255 (80 km) to T319 (65 km) for day 10 onwards.

The higher resolution resulted in a better representation of features such as tropical storms, fronts, heavy rainfall and land/sea transitions.

Plans for future changes to the forecasting system were also presented; these included the following.

- Revision of the EPS initial perturbations to include uncertainty information from an ensemble of data assimilations (implemented on 22 June 2010 – see articles in *ECMWF Newsletter No. 123*).
- Revised surface analysis, including new soil analysis and new snow analysis schemes. The new snow analysis will resolve some of the problems experienced during the past winter.
- Changes to the model physics, including prognostic rain and snow with more comprehensive cloud microphysics.

Overall, users reported good performance of the ECMWF forecasting systems over the past year and a growing range of applications using ECMWF data. Examples presented included products for supporting disaster relief agencies (including in Haiti), forecasting the dispersion of ash plumes from the volcanic eruption in Iceland, and predicting the dispersion of oil slicks.

ECMWF data is used to provide initial and boundary conditions to a range of limited area weather forecast and ocean wave models. The importance of the EPS to alert forecasters to potential severe weather events was emphasised; use both within forecast offices and in products for end users continues to increase.

ECMWF has introduced a number of new products during the last year, including an interactive web chart of the Extreme Forecast Index (EFI), 100-metre wind (important for wind energy producers) and swell and wind-sea components of the ocean waves. Examples of using the new products were presented by the users. Participants also provided valuable feedback on the products that are currently being developed such as the extra-tropical cyclone tracking and the new EPS clustering.

A new system to improve forecasters' access to our products via the web is being developed. Participants had the opportunity to try out the features of the test system and to provide some initial feedback on the features and usability. Participants also made a number of requests for additional products including the extension of some of the severe-weather products into the later medium-range.

The presentations and summary from the meeting are available on the ECMWF website:

- www.ecmwf.int/newsevents/meetings/forecast_products_user/Presentations2010/

Web Re-engineering Project

The main aim of the Web Re-engineering Project is to provide an interactive web tool for our Member State and Co-operating State forecasters and commercial customers, which they can use to access and interact with our operational forecast products.

Motivations

- Increasing use of our web products by our supporting Member States and many commercial customers means that there is a demand for a high-availability service.
- Users request more tailored products so there is a need for on-demand plot production.

Goals

- Redesign the web infrastructure so that the web service is highly available.
- Provide more interactivity (e.g. zoom, pan, overlay parameters).
- Allow product customisation (e.g. control the event threshold on probability maps).
- Use open (OGC) standards so that ECMWF products can be embedded in users' own software.

The Web Re-engineering Project officially started in May 2009 after a significant amount of preliminary discussion and requirement gathering. The system is currently undergoing 'alpha testing' by forecasters in the Member and Co-Operating States. Their feedback will help improve the final configuration, which is expected to become operational during 2011. Development is principally being provided by a number of teams including Web, Data Services, Graphics and Met Ops.

What was the first TV picture from space?

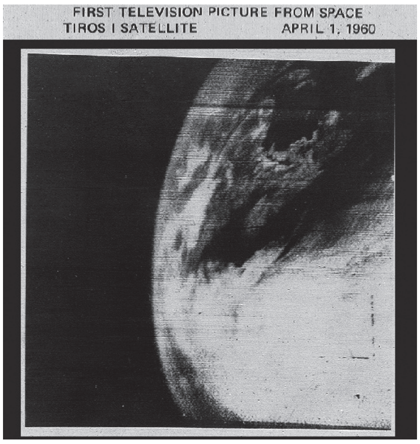
BOB RIDDAWAY

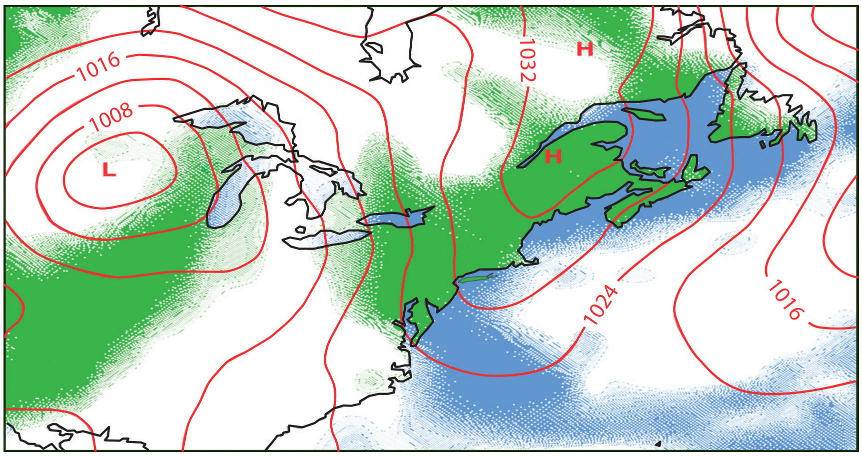
In a recent article celebrating 50 years of satellite images, George Anderson described the first TV picture from space that was taken by TIROS 1 launched on 1 April 1960 (*Weather*, **65**, 87). This picture has been widely accepted for more than a decade as being the first one.

The reanalysis technique feeds weather observations collected in past decades into a modern data assimilation system to produce a consistent set of high-quality analyses. Per Kållberg, Sakari Uppala and Adrian Simmons have used the ERA-40 reanalyses produced at ECMWF to examine the period when TIROS 1 was launched. They found that the picture labelled as 1 April was in fact a better fit to the reanalysis for 1800 UTC on 2 April (this did not use TIROS 1 data) – see their recently published article for more details (*Weather*, **65**, 211–212). In the article they concluded that the picture labelled 1 April "is almost certainly not the first such picture".

George Anderson has confirmed that the picture labelled as the first TV picture dated 1 April was indeed taken on 2 April as indicated by the reanalysis (*Weather*, **65**, 212–213). He speculated that one possible explanation of this mistake is that for publicity purposes the picture chosen was one of the best of the early images. This was then misinterpreted as being the first picture. There is no doubt that receipt of the first picture started at 1331 UTC on 1 April 1960, about two hours after launch.

This episode illustrates the power of the reanalysis technique in providing high-quality analyses that can be used for a wide variety of purposes. It also shows how some of the earliest ever weather-satellite pictures can still be used to validate the capabilities of today's data assimilation systems.





Weather situation on 2 April 1960. Left: The so-called "first TV picture from space, 1 April 1960", showing clear skies over Nova Scotia, now confirmed by NASA as taken at 1608 UTC on 2 April 1960. Below: The closest ERA-40 product, a three-hour forecast valid at 1500 UTC on 2 April, showing surface pressure and cloud cover.

Athena Project

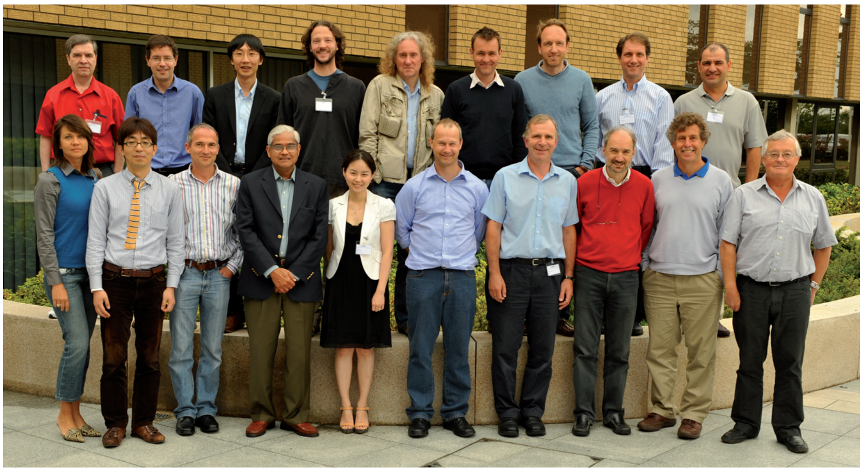
THOMAS JUNG

Following the World Modelling Summit at ECMWF in May 2008, the US National Science Foundation (NSF) recognised the importance of increasing the resolution of weather and climate models and realised that a resource was available that could be used to test the benefit of employing very high resolutions. The NSF offered to dedicate the Athena supercomputer to this issue over a period of six months from 1 October 2009 to 31 March 2010. This supercomputer is located at the National Institute of Computational Sciences, which is managed by the University of Tennessee. NSF's initiative led to the establishment of the 'Athena Project'.

As part of the project ECMWF is carrying out long integrations with an atmospheric model covering the period 1960–2007. The aim is to investigate the impact of increased resolution on the climate of the ECMWF model and its variability, including severe and other high-impact weather events.

The first workshop of the Athena project was held on 7–8 June at ECMWF. The workshop was attended by the project partners from the Center for Ocean-Land-Atmosphere Studies (COLA, USA), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), University of Reading and ECMWF.

Preliminary results were presented which suggest that increasing horizontal resolution of the atmospheric model from T159 to T511 does indeed improve the simulation of some important atmospheric phenomena such as Euro-Atlantic blocking and tropical wind biases. Furthermore, evidence has been presented that the quality of seasonal forecasts could benefit from increased resolution during boreal winter. However, from the results presented, it also became clear that simply increasing horizontal resolution to T1279 or even T2047 without further tuning is not sufficient to 'cure' all model problems (e.g. those associated with the Madden-Julian Oscillation or Indian Summer Monsoon).



First workshop of the Athena Project. Participants in the first workshop of the Athena Project that was held on 7–8 June at ECMWF.

European Working Group on Operational Meteorological Workstations (EGOWS)

STEPHAN SIEMEN

The 21st annual meeting of the European Working Group on Operational Meteorological Workstations (EGOWS) was hosted this year by ECMWF. The meeting lasted from the 1–4 June and was organised by ECMWF's Graphics Section.

EGOWS was founded in 1990 as an informal forum for people working in the development field of operational meteorological workstations. The annual EGOWS meeting offers a platform for exchanging information and furthering co-operation among the experts from European National Meteorological Services, ECMWF and other institutes. The meeting was attended by 36 developers and forecasters from 18 organisations.

The meeting consisted of presentations, software demonstrations, and working group sessions. These focused on the latest developments and gave the participants the opportunity to demonstrate their current operational systems.

One focus of the meeting was the adoption of web standards developed by the Open Geospatial Consortium (OGC) to reach interoperability between the various systems and set-ups. Various standards were discussed, but the main focus this year was on OGC Web Map Services (WMS). This service delivers maps, which can be overlaid in the client system.

A practical session was organised in which various WMS clients and servers delivering meteorological maps were tested between each other. This included ECMWF's Metview 4's WMS client and the WMS server, which is part of the Web re-engineering project. There followed a productive discussion about how interoperability can be improved between the systems. The work will be continued within the OGC MetOcean Domain working group.

The meeting also contained a demonstration session in which various meteorological workstations and visualisation systems from across Europe were presented.

The presentations from the meeting can be found at:

- http://www.ecmwf.int/newsevents/meetings/workshops/2010/EGOWS/Presentations/presentations.html

Increased resolution in the ECMWF deterministic and ensemble prediction systems

MARTIN MILLER, ROBERTO BUIZZA, JAN HASELER, MARIANO HORTAL, PETER JANSSEN, AGATHE UNTCH

ON 26 JANUARY 2010, ECMWF upgraded the horizontal resolution of the deterministic forecasting system and Ensemble Prediction System (EPS) which form components of the Integrated Forecasting System (IFS):

- For the deterministic forecast and analysis the horizontal resolution increased to T1279 (~16 km grid spacing) from T799 (~25 km).
- The resolution of the inner loops of the 4D-Var analysis changed to T159/T255/T255 (~125 km/78 km/78 km) from T95/T159/T255 (~210 km/125 km/78 km).
- The EPS resolution increased to T639 (~32 km) from T399 (~50 km) for leg1 (the first 10 days of the forecast) and to T319 (~65 km) from T255 (~80 km) for leg2 (day 9 to day 15 and day 32 for the monthly forecast).
- The coupled ocean wave model resolution was upgraded to 0.25° (~28 km) from 0.36° (~40 km) in the deterministic system, and to 0.5° (~56 km) from 1° (~111 km) in the EPS.

The vertical resolution remained unchanged at 91 levels for the deterministic system and at 62 levels for the EPS.

The various resolution increases have been implemented as IFS Cycle 36r1. In addition, a correction to the interaction of short-wave radiation with clouds is also included in this cycle.

Extensive experimentation accompanies a major operational change such as those described here.

This article describes the resolution upgrades in the different components of the Centre's forecasting system, their rationale, and expected impacts and benefits. It should be noted, however, that many people at ECMWF other than the authors of this article have contributed to the scientific development work for these resolution upgrades, their operational implementation and to the results presented here.

Previous resolution upgrades

IFS Cycle 36r1 is the sixth major horizontal resolution upgrade for the deterministic system in the 30 years or so of the Centre's operational activities and the fourth upgrade for the EPS.

The ECMWF model is a spectral model based on a spherical harmonics expansion. For the deterministic forecast, the previous resolution increase to T799, which also included an upgrade of the vertical resolution to 91 levels, was implemented four years ago on 1 February 2006. The notation T799 indicates that the largest wave number retained in the expansion is 799 and the letter 'T' specifies that a 'triangular truncation' is used to limit the number of terms in the expansion sum. Sometimes the notation is expanded to include the number of vertical levels – in this case the full resolution would be specified as T799L91.

The resolution of the EPS has previously been upgraded three times since it became part of the Centre's operational suite in December 1992: from T63L19 to T159L31 in December 1996, to T255L40 in November 2000, and then to T 399L62 on 1 February 2006. In October 2006 the Variable Resolution Ensemble Prediction System (VAREPS) comprising two forecast-legs (leg 1: 10-day forecast at T399L62 followed by leg 2: 6-day forecast from day 9 to day 15 at the lower resolution of T255L62) became operational, and in October 2008 the EPS was merged with the monthly prediction system which extends out to 32 days once per week.

Increases in horizontal and vertical resolutions of the Centre's assimilation-forecasting system have been a cornerstone of the long-term development plans, and during its history have contributed major improvements to the forecast skill at all ranges. Each change to higher resolution has been based on realistic expectations of improved accuracy in (a) the representation of basic components such as orography and land/sea definition, (b) synoptic and sub-synoptic systems, (c) weather features and parameters such as fronts, cloud and rain bands, jets, and (d) assimilating observations both space-based and surface-based. Also, these refinements in resolution have brought systematic improvements to the ocean wave forecasts, not least in their quality near coastlines and in confined waters (typical of the European region) which particularly benefit from more accurate surface winds. Each change has contributed significantly to the long-term positive trend in forecast skill and the systems' ability to forecast severe weather.

Resolution increase in the deterministic system

In IFS Cycle 36r1 the horizontal resolution of the deterministic model has increased by about 60%, from T799 to T1279.

The new grid used for grid-point computation (linear Gaussian grid) has 1280 latitude rows, an increase by 480 rows with respect to the T799 grid (800 latitude rows). Along each latitude row near the equator there are 2560 grid points in the new resolution. In the 'reduced' Gaussian grid, used by the Centre's model, the number of grid points along a latitude is decreased gradually towards the poles, thereby reducing the total number of grid points by roughly ⅓ compared to the unreduced Gaussian grid. In total, the new horizontal grid has 2,140,704 grid points, 1,297,214 more than the T799 reduced Gaussian grid (843,490 grid points). This corresponds to a 2.5 fold increase in the number of grid points.

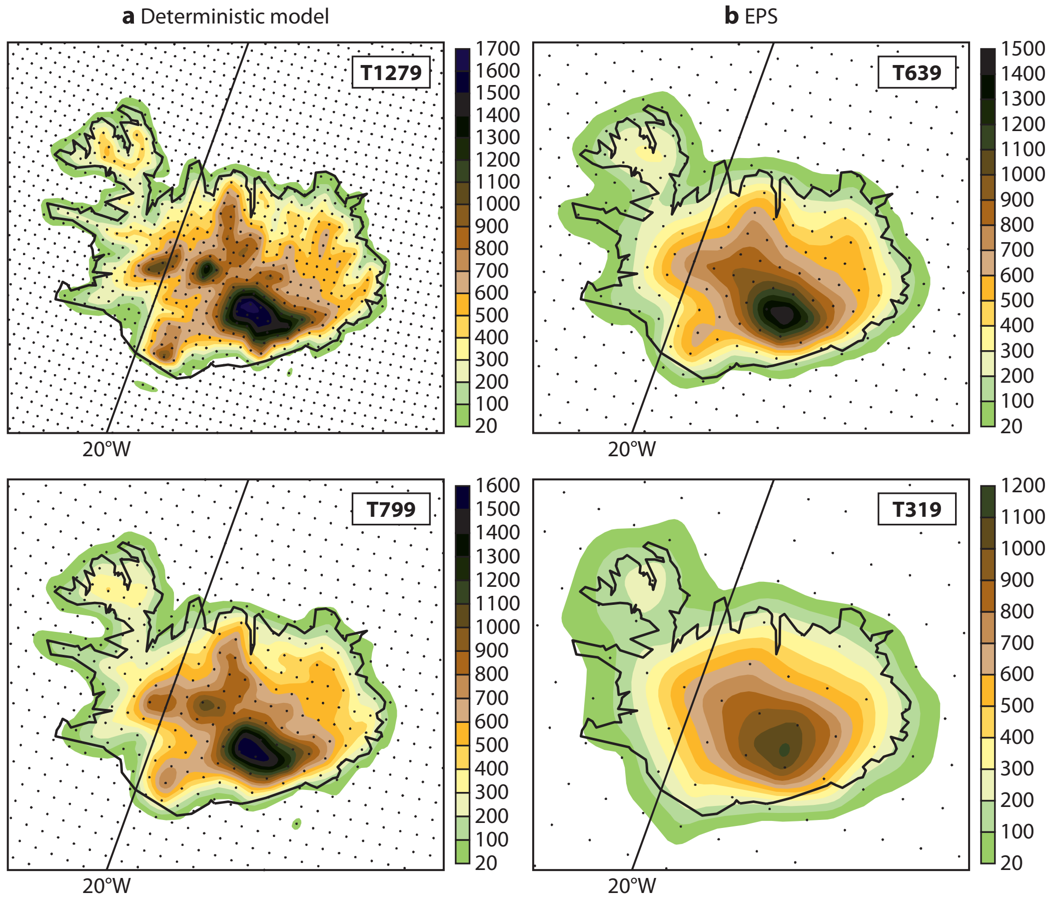


Figure 1 Orography and location of grid-points for (a) the deterministic model: new resolution T1279 (grid spacing ~16 km) (top) and previous operational resolution T799 (grid spacing ~25 km) (bottom), and (b) for the new resolutions of the two legs of the EPS: T639 (grid spacing ~32 km) (top) and T319 (grid spacing ~65 km) (right).

Figure 1 gives an impression of the difference between the new and the old resolutions by contrasting the orography of Iceland at T1279 and T799. Also shown are the locations of the grid points of the corresponding reduced Gaussian grids. The coastline of the higher resolution orography follows much more closely the real coastline of Iceland. Most striking is the improvement in the shape of the large bifurcated peninsula in the northwest of Iceland. The increase in orographic detail and realism with T1279 for the mountainous interior of the island is also noteworthy. Such improvement in the representation of the orography leads directly to improved forecasts of weather events which are strongly influenced by orographic features.

The horizontal resolutions of the different components in the 4D-Var assimilation system have also been upgraded: the outer loop changed to T1279 like the deterministic model, while the resolutions of the first and second inner loops have been upgraded to T159 (from T95) and T255 (from T159), respectively. The resolution of the third inner loop remained unchanged at T255. Experimentation with a third inner loop resolution of T399 did not give the anticipated improvement in analysis and forecast quality due to problems with the new background error statistics computed at T399. Work is in progress to gain a better understanding of the problems and how to solve them, with the aim of upgrading the resolution of the third inner loop to T399 in the future.

Numerical stability constraints usually require a reduction in the length of the time step whenever the model resolution is increased. However, with a semi-implicit semi-Lagrangian time stepping scheme, as used in the ECMWF model, the stability constraints are not very strict. Nevertheless, mainly for accuracy reasons, the time step was reduced to 10 minutes from the 12 minutes used with the T799 resolution. All three inner loops of 4D-Var are run with a 30-minute time step.

Resolution increase in the coupled ocean wave model

The spatial resolution of the WAve Model (WAM), which is part of the IFS and coupled to the atmospheric model, has also been upgraded: from 0.36° (~40 km) to 0.25° (~28 km) in the T1279 deterministic model and from 1° (~111 km) to 0.5° (~56 km) in the ensemble prediction system. At the same time the representation of the wave spectrum was improved, with the spectrum now consisting of 36 frequencies and 36 directions (previously 30 frequencies and 24 directions). In addition, the correlation length scale which controls the spread of observed information in the wave data assimilation was reduced from 300 km to 150 km.

Resolution increase in the ensemble prediction system

Since 2006 ECMWF has been running operationally a Variable Resolution Ensemble Prediction System (VAREPS) where each

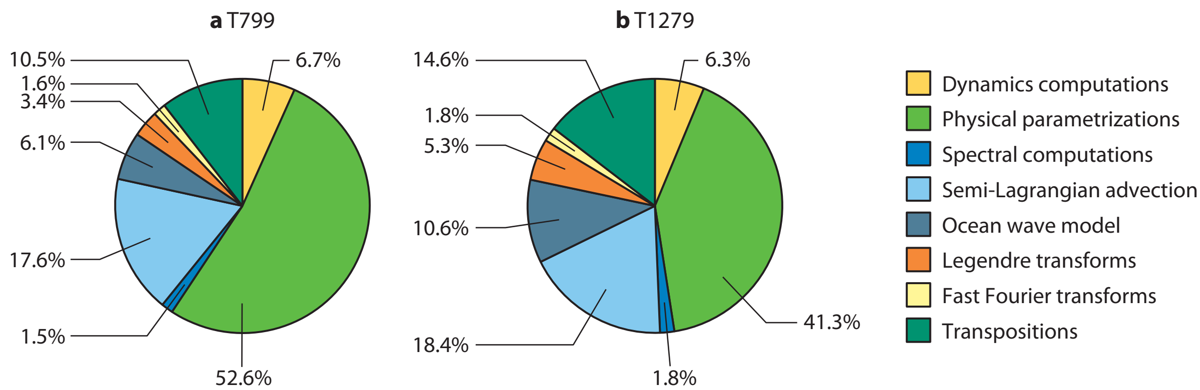


Figure 2 Pie charts showing the relative cost of various parts of the model at horizontal resolutions (a) T799 and (b) T1279.

ensemble member is generated by a two-leg forecast with different horizontal resolutions in the two legs. The vertical resolution is the same for both legs (62 levels). For a detailed description of this system and the rationale behind it see the article by *Buizza et al.* in *ECMWF Newsletter No. 108*.

Concurrent with the resolution upgrade of the deterministic system for IFS Cycle 36r1, the horizontal resolution of the EPS has also been increased: leg 1 is now run at T639 with a time step of 20 minutes and leg 2 at T319 with a 45-minute time step. These two resolutions are illustrated in Figure 1 along with the old and new resolutions of the deterministic model.

The resolution of the ocean wave model coupled to the EPS forecasts has also been increased from 1° to 0.5° for both legs of the EPS forecasts (i.e. for the whole 15 days). The representation of the wave spectrum was upgraded for leg 1 to 36 frequencies and 36 directions (from 30 frequencies and 24 directions), and for leg 2 to 30 frequencies and 24 directions (from 25 frequencies and 12 directions).

The number of vertical levels in the EPS has been kept to 62. No changes have been introduced in the initial perturbations, and both the ensemble size (50 perturbed and one unperturbed member) and the forecast lengths of the two legs have been kept the same. The increased resolution EPS will be denoted throughout this article as 639v319 EPS and the previous operational system as 399v255 EPS.

Computational cost of the resolution upgrade

The 2.5 fold increase in the number of grid-points and the reduction in the time step to 10 minutes, together with the upgrades to the coupled wave model have led to a 3.7 fold increase in the total number of floating point operations necessary to complete a 10-day forecast (at the operational vertical resolution of 91 levels). Hence there are 6.3×10^{15} floating point operations at T1279 as compared to 1.7×10^{15} at T799.

Figure 2 shows the relative contributions to the cost from the different parts of the model for the two resolutions. Not surprisingly, the relative cost of the wave model has increased (from 6.1% to 10.6% of the total cost) due to the resolution increase and the enhancement of the spectrum. Also, the relative costs of the Legendre transforms and of the transpositions, required for the spectral computations, have grown faster with increased resolution than much of the rest of the model, as was expected. However, the spectral model is still very affordable, and work is in progress on adapting a fast Legendre transform algorithm for the IFS to keep the spectral model affordable at future, much finer, resolutions.

Performance of the T1279 deterministic system

The high-resolution system has undergone extensive testing by the Research Department for the forecast period December 2008 to July 2009 and then by the Operations Department in e-suite mode (used for pre-operational testing) for the forecast period mid-July 2009 to 25 January 2010.

Objective verifications scores show statistically significant improvements in geopotential height at 1000 and 500 hPa for both hemispheres and for Europe out to at least day 5. Figure 3 shows the normalised difference in anomaly correlation of 500 hPa geopotential height between T1279 and T799 together with the 95% confidence interval computed from over 600 assimilation/forecast cases. The resolution increase results in a clear forecast improvement at all ranges up to eight days in the northern hemisphere and five and a half days in the southern hemisphere and in Europe. There is also a systematic improvement of 850 hPa temperature and winds at all levels.

The improved representation of the orography at T1279 leads to a significant increase in the number of near-surface observations accepted by the first-guess quality control in the 4D-Var assimilation. For example, 1.5% more temperature observations from upper-air soundings were assimilated at 1000 hPa in the northern hemisphere and 2% more in the tropics in the T1279 e-suite than in the T799 control. Similar increases are also seen for wind soundings.

In general, the intensity and location of synoptic features are improved in the high-resolution system and the frequency of occurrence of intense rainfall events has increased, resulting in a better agreement with precipitation observations as shown in Figure 4. The overall impact on weather parameters is however modest.

As was anticipated, the enhanced resolution has a positive effect on the analysis and forecast quality of tropical cyclones, and both position and intensity errors are reduced on average in the higher-resolution system.

The T1279 model has also been tested in two continuous 47-year integrations as part of Project Athena. This is an

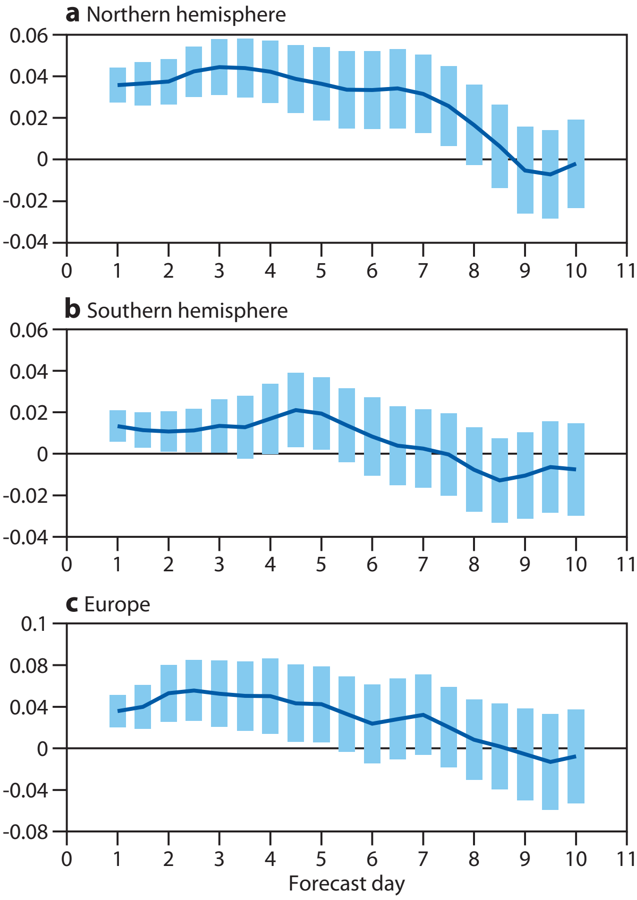


Figure 3 Impact of the horizontal resolution upgrade on the deterministic forecast skill. The figure shows the normalised difference in anomaly correlation of 500 hPa geopotential height between T1279 and T799 (blue line) together with the 95% confidence interval (blue bars) for (a) northern hemisphere, (b) southern hemisphere and (c) Europe. The sample comprises 615 forecasts from December 2008, and the verification of the two models is against their own analysis.

international project led by the Center for Ocean-Land-Atmosphere Studies (COLA), USA on the importance of high spatial resolution in climate modelling. One of the long integrations is a 'historic' run for the period 1961–2007 with observed sea surface temperatures and the other is a 'future scenario' run (A1B-scenario) for 2071–2117. Forty eight 13-month hindcasts for the years from 1960 to 2007 were also run at T1279. The computer resources for these runs were made available by the U.S. National Science Foundation on the CRAY-XT4 supercomputer 'Athena' at the National Institute for Computational Sciences at Oak Ridge National Laboratory, USA, and are gratefully acknowledged. (For more information about Project Athena see the news item on the Athena Workshop in this issue of the *ECMWF Newsletter.*) While most of the diagnostics on the vast amount of data generated by these simulations have still to be produced, these runs show that the T1279 model in its operational configuration (no changes were made specifically for these simulations) can be run stably and efficiently over long time periods and for different boundary forcings.

Performance of the wave model

The e-suite has shown considerable improvements in the wave-related forecast scores in all areas. Figure 5 shows the improvement in wave height anomaly correlation in the northern and southern hemispheres.

For a large part these improvements are thought to be caused by the reduction of the correlation length scale and the improved representation of the wave field. However, the accuracy of the forcing wind field has increased as well. This can be shown with the help of the European shelf model, which is a standalone version of WAM at 11 km resolution forced by 3-hourly winds produced by the deterministic forecast. With the introduction of the T1279 model the specifications of the European shelf model remained unchanged, only the forcing wind fields changed. By verifying the forecasts performance against independent wave height observations from buoys it is therefore possible to attribute the improvements seen with T1279 forcing winds over T799 winds directly to the improved quality of the T1279 winds. The average reduction in root-mean-square error scores of forecast wave height and wind speed verified against buoy data obtained with forcing winds from the T1279 e-suite is shown in Figure 6.

The resolution increase and enhancements made to the wave model have led to an improved specification of the sea state, in particular in coastal areas. Based on the evidence presented here it is thought that even freak wave prediction should have improved, as this depends sensitively on how accurate the mean sea state is modelled. On 3 March 2010 in the north-western Mediterranean near Marseilles the cruise ship Louis Majesty was hit by freak waves causing two fatalities and 14 injuries. Figure 7 shows the 15-hour forecast of maximum wave height for this date. In the area of the accident, the maximum wave height exceeds 10 m, in good agreement with the reported height of the waves that damaged the Louis Majesty.

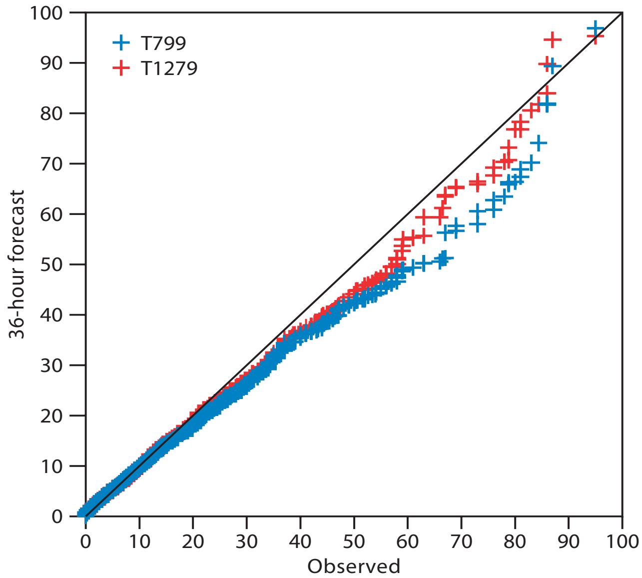


Figure 4 Quantile-Quantile plot comparing the 36-hour forecast and observed distributions of precipitation for T1279 (red) and T799 (blue) for the month of December 2008.

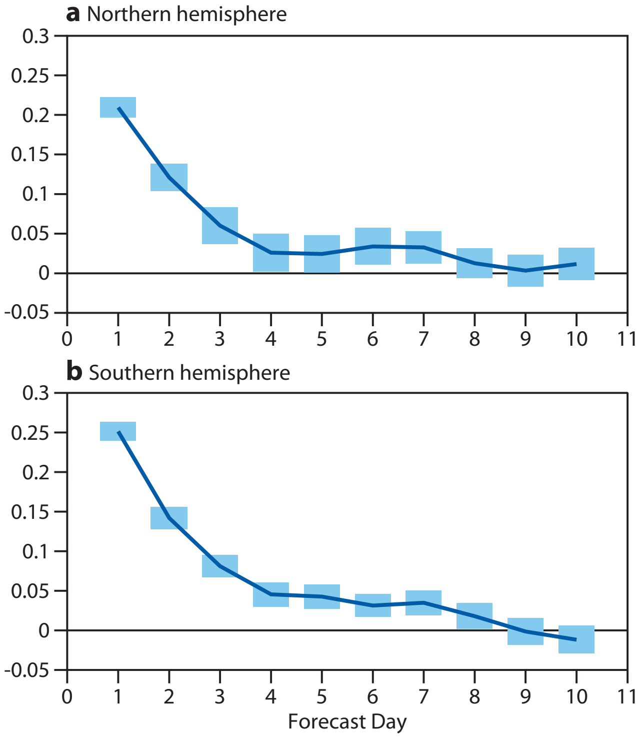


Figure 5 Improvement in wave height correlation of the wave height forecasts against own analysis for (a) northern hemisphere and (b) southern hemisphere. Shown are the normalised differences between the new system and the old. Large improvements are seen up to day 5 in the forecast. Results are shown for 16 July 2009 to 24 January 2010.

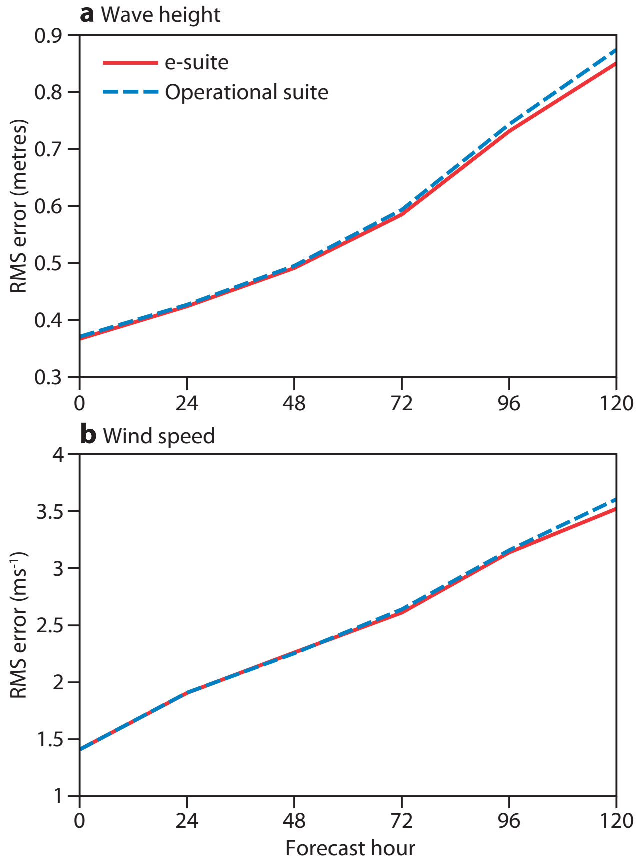


Figure 6 Root-mean-square (RMS) error scores of forecast (a) wave height and (b) wind speed from the e-suite (red) and the operational suite (blue) verified against buoy observations for the European shelf model for the period 1 November 2009 to 31 January 2010. A reduction in RMS error of wave height due to improved T1279 winds is clearly seen.

Performance of the new 639v319 EPS

Forecasts from the new 639v319 EPS starting from T1279L91 unperturbed initial conditions have been compared to forecasts from the old 399v255 EPS starting from T799L91 initial conditions for 88 cases (5 October to 31 December 2009). This comparison gives the users an estimate of the improvements that they should be able to detect, on average, following the resolution increase. Each system has been verified against its own unperturbed analysis.

Average results based on these 88 cases indicate that the error of the 639v319 ensemble-mean is lower and the 639v319 probabilistic forecasts have higher skill. The spread of the 639v319 EPS starting from T1279 analysis is slightly larger (~5%) than the spread of the 399v255 EPS starting from T799 analysis. This is due to the T1279 analysis error estimate being locally larger than that of the T799 analysis, which is used to scale the ensemble initial perturbations. With this and the reduction of the error of the ensemble-mean, the new 639v319 EPS has a larger spread overestimation in terms of 500 hPa geopotential over the northern hemisphere, but it has a better tuned spread in terms of 850 hPa temperature, for which the old 399v255 EPS used to be under-dispersive.

Figure 8a shows the impact of the resolution increase on the root-mean-square error of ensemble-mean forecasts of 500 hPa geopotential and 850 hPa temperature over the northern hemisphere extra-tropics. The positive impact (i.e. smaller root-mean-square error) of the resolution increase is statistically significant at the 5%-level at all forecast ranges, with the largest positive impact shown at around forecast day 6.

Figure 8b shows the impact on the rank probability skill score (RPSS) of 500 hPa geopotential forecasts over the northern hemisphere. Positive differences (i.e. larger RPSS) are statistically significant at the 5%-level between forecast day 2 and day 10 for the geopotential. Similar positive impacts are also seen on other variables over different areas (not shown). Overall, these differences correspond to gains of up to 8 hours in forecast accuracy.

The impact of increased EPS resolution has also been evaluated using a series of 15-member ensemble integrations with a 32-day forecast length starting from the 15th day of November, December and January 1989 to 2008 (a total of 90 winter cases). The probabilistic skill scores of weekly forecasts obtained for the two sets of hindcasts are very close, except for temperature at 850 hPa for the time range day 5–11 where the new 639v319 EPS has slightly improved probabilistic scores. Model biases of the two systems are very similar.

Forecast of the European winter storm Xynthia

Between 27 and 28 February 2010 a violent storm, named Xynthia, caused much damage and loss of lives along the

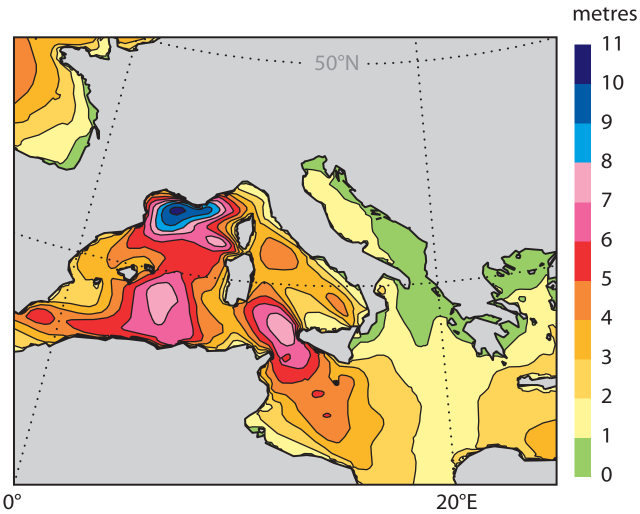


Figure 7 15-hour forecast of maximum wave height at the time that the Louis Majesty was hit by a freak wave causing two casualties and 14 injuries. The reported individual wave height was estimated at around 10 metres. The forecast was run from 00 UTC on 3 March 2010.

western European coast and in northern Europe. In France it was described by the civil defence as the most violent since storms Lothar and Martin struck the country in December 1999, with more than 50 people killed. Most of the deaths in France occurred when a powerful storm surge, topped by battering waves of up to 7.5 metres high and a high tide, smashed through the sea wall of the coastal towns of L'Aiguillon-sur-Mer and La Faute-sur-Mer. The severe storm surge (up to 1.5 metres) was also the principal cause of the damage. The surge was the result of the combination of a high astronomical tide, very low pressure (965 hPa) and very strong winds.

The maximum wind gusts observed at several airports in Portugal (e.g. at Porto) and western France (e.g. at La Rochelle) have been well predicted by the new 639v319 EPS, as shown by the Cumulative Distribution Functions of wind gusts at these two locations (Figure 9).

The following analysis concentrates on mean sea-level pressure (MSLP) forecasts valid at 12 UTC on 28 February 2010, a time when the operational T1279 analysis recorded a minimum MSLP of 973 hPa at (51.5°N, 3.5°E). For this verification time the intensity and position error of MSLP forecasts from the operational T1279 deterministic system, the new 639v319 EPS, and from the old 399v255 EPS have been compared. There is little sensitivity to resolution for forecasts up to 48 hours. At 60 hours all three forecasts have a MSLP minimum that is too deep, with intensity errors of 8.0 hPa for both EPS control runs and of 6.5 hPa for the deterministic run. In terms of position error, the old 399v255 EPS control has the largest error (~200 km). For longer forecast times, the three forecasts start to diverge both in terms of intensity and position error. Up to 84 hours, the T1279 deterministic system provides the best forecasts, confirming the benefit from higher resolution to severe weather prediction.

Figure 10 shows the number of 639v319 EPS and 399v255 EPS perturbed members with intensity and position errors smaller than, respectively, 2.5 hPa and 100 km. On average, the 639v319 EPS has a larger number of skilful members than the 399v255 EPS showing that there is a clear advantage for the 639v319 EPS up to 84 hours, while the signal is more mixed afterwards.

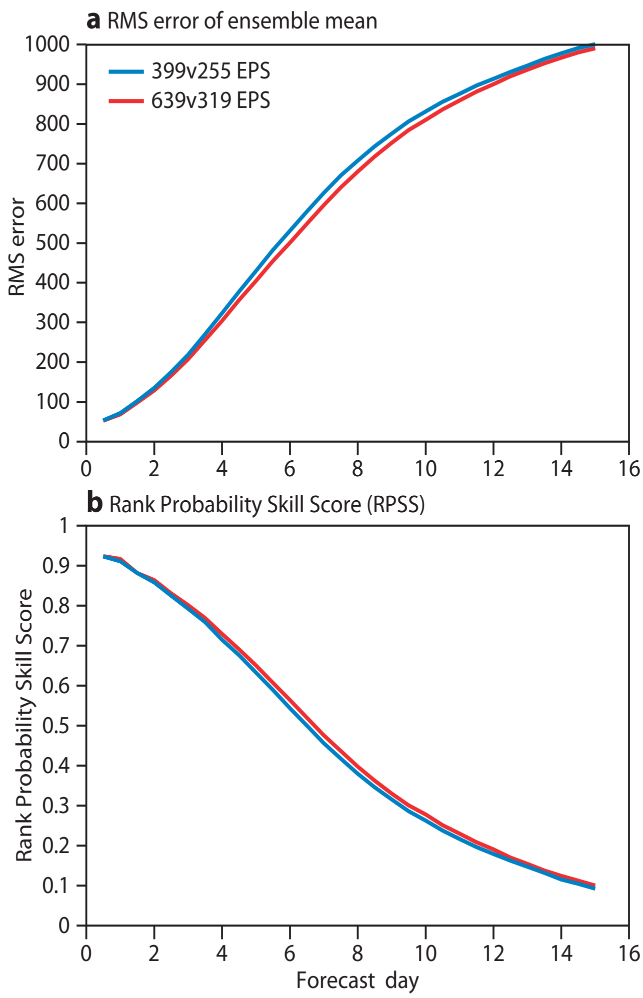


Figure 8 88-case average (5 October to 31 December 2009) of (a) root-mean-square error of the ensemble-mean (EM) and (b) rank probability skill score (RPSS) for forecasts of the 500 hPa geopotential height for the northern hemisphere from the old 399v255 EPS (blue lines) and the new 639v319 EPS (red lines).

Plans for future resolution upgrades

Following this major upgrade in horizontal resolution across the ECMWF forecasting system, an upgrade in vertical resolution by about 50% from the current 91 levels is planned for mid-2011.

The next horizontal resolution upgrade is planned to bring the grid spacing down to 10 km (T2047) in the middle of this decade. Some experimentation with this resolution has already been carried out. In particular, twenty 13-months and nine 4-months hindcasts have been run as part of Project Athena.

Preliminary results from these tests indicate that this resolution will probably require only small changes to the current dynamics, numerics and physical parametrizations, but no data assimilation has yet been run.

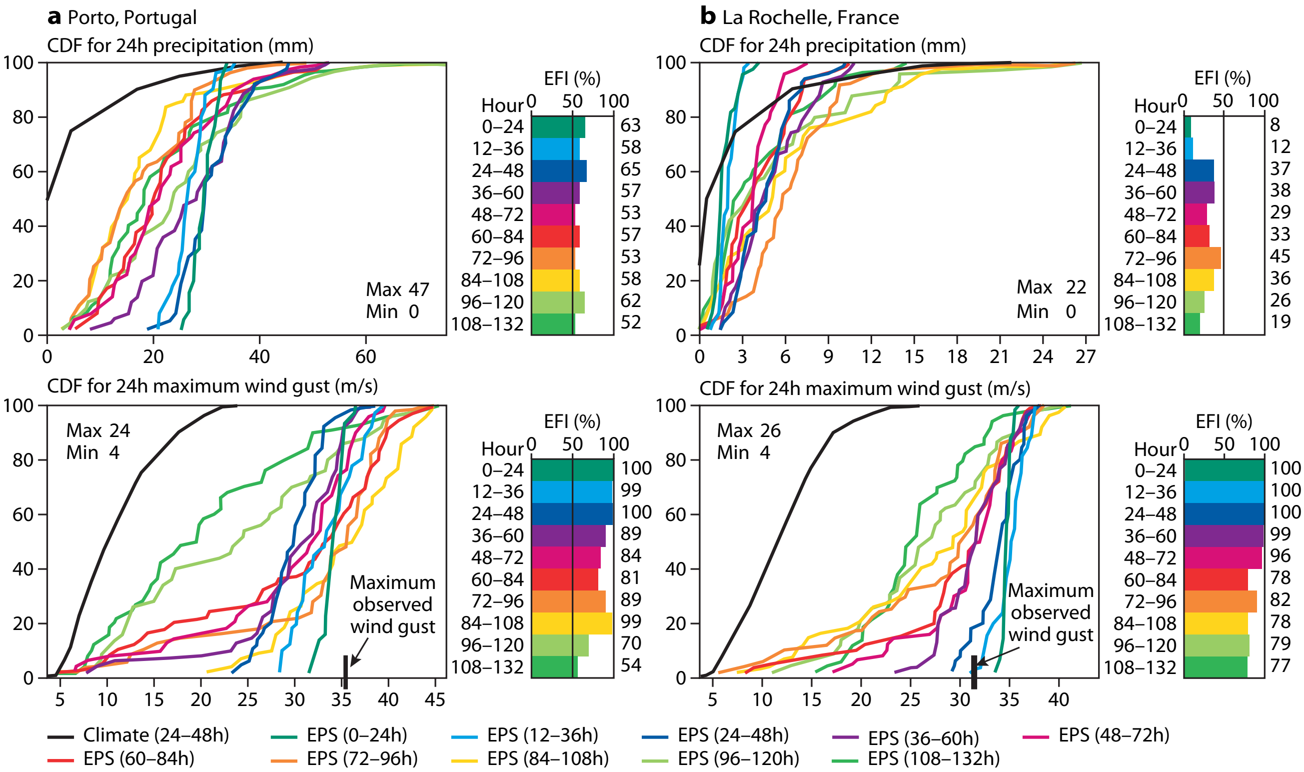


Figure 9 Storm Xynthia at (a) Porto, Portugal and (b) La Rochelle, France: Cumulative Distribution Function (CDF, left panels) and Extreme Forecast Index (EFI, right panels) forecasts of 24-hour precipitation and wind gust issued by subsequent 639v319 EPS forecasts from 12 UTC on 22 (t+132 h) to 27 (t+24 h) February 2010 for 00 UTC on the 28 February. The EFI indicates the difference between the model climatic distribution the EPS forecast, measured by the area between the climate (black line) and the forecast CDF computed between the minimum and maximum climate values; it scales from –1 to 1 (for more information see 'Recent developments in extreme weather forecasting', *ECMWF Newsletter No. 107*, 8–17).

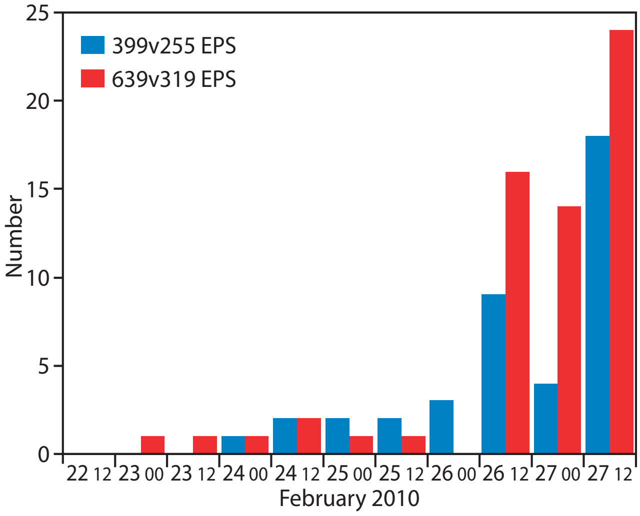


Figure 10 Storm Xynthia: number of EPS members with intensity error less than 2.5 hPa and position error less than 100 km for mean sea-level pressure (MSLP) perturbed forecasts from the 399v255 EPS (blue) and the 639v319 EPS (red). The forecasts are issued every 12 hours from 12 UTC on 22 to 12 UTC on 27 February 2010 and valid at 12 UTC on 28 February. At the verification time the ECMWF operational T1279 analysis had a minimum MSLP of 973 hPa at (51.5°N, 3.5°E).

Beyond this resolution however, more fundamental changes to the Centre's IFS will be required. As the horizontal grid spacing decreases to well below 10 km, the hydrostatic approximation to the pressure field (used in the operational version of the IFS) becomes progressively less accurate, making a non-hydrostatic dynamical core for the IFS essential. Also, the numerics of the IFS will have to be adapted to cope with the very steep gradients such fine resolution can resolve. Furthermore, convection will become partly resolved by the dynamics and the convection parametrization will have to account for this new regime.

The Centre is already taking steps to prepare for the new challenges by working on a non-hydrostatic dynamical core in collaboration with Météo-France, ALADIN and HIRLAM, the implementation of a fast Legendre transform algorithm, and the development of a more scalable data-assimilation system.

FURTHER READING

Buizza, R., J.-R. Bidlot, N. Wedi, M. Fuentes, M. Hamrud, G. Holt, T. Palmer & F. Vitart, 2006: The ECMWF Variable Resolution Ensemble Prediction System (VAREPS). *ECMWF Newsletter No. 108*, 14–20.

On the relative benefits of TIGGE multi-model forecasts and reforecast-calibrated EPS forecasts

RENATE HAGEDORN

THE MAIN motivation for investing into research activities on Numerical Weather Prediction (NWP) lies in the expectation that improved weather forecasts lead to enhanced socio-economic benefits. As such, the ultimate goal of all research related to NWP is to improve the quality and utility of weather forecasts. There are of course many ways to achieve this goal, ranging from work on the model system per se to research on the provision of user-optimized forecast products. All of these activities are valuable and necessary contributions in their own right, and therefore none of them should be judged as more important than others. On the contrary, only through the complementary diversity of approaches can the overall goal be achieved.

Post-processing of Direct Model Output (DMO) from NWP models is one of the many ways to improve weather forecasts. The term 'post-processing' encompasses any means of manipulating the DMO to provide improved predictions. However, here we will concentrate on two specific methods:

- ***Multi-model***. Combining single-model forecasts from several models into a multi-model forecast.
- ***Reforecast-calibration***. Calibrating single-model forecasts with the help of specific training datasets.

Both approaches considered here have proven in the past to be successful in improving forecast quality. For example, the concept of multi-model forecasting has been extensively studied in the context of seasonal forecasting in the DEMETER and ENSEMBLES projects (see *ECMWF Newsletter No. 99 & 103*). It was concluded that overall the multi-model ensemble seems the most reliable approach for seasonal forecasts. However, on the medium-range timescale, it is less well established whether the multi-model concept is as successful as in the case of extended-range forecasting. Thus, one of the main goals of the THORPEX Interactive Grand Global Ensemble (TIGGE) project (see *ECMWF Newsletter No. 116*) is to investigate the applicability and potential benefits of the multi-model concept for medium-range weather forecasts. The method of calibrating the Ensemble Prediction System (EPS) forecasts based on a reforecast dataset has also been studied in the past, and its potential of improving predictions has been documented (see *ECMWF Newsletter No. 117*).

One can expect that both post-processing methods, the multi-model concept and the reforecast calibration, have their own strengths and weaknesses. Hence it is only natural to compare the benefits (and costs) of both approaches, and to investigate the mechanisms behind the potential improvements (the main aim of this article). However, in doing so it is not intended to make a final judgement on which is the better method. Instead the aim is to provide some information that helps users decide which approach might be the more appropriate choice for their specific circumstances.

Performance of TIGGE multi-model versus reforecast-calibrated forecasts

The TIGGE archive at ECMWF contains global ensemble predictions from ten modelling centres. For detailed information on the individual characteristics of the TIGGE models (e.g. resolution and number of ensemble members) refer to the ECMWF TIGGE website: http://tigge.ecmwf.int.

Since the predictions from the Météo-France model are limited to a lead time of 108 hours, here we consider only the remaining nine model contributions: Bureau of Meteorology (BOM, Australia), China Meteorological Administration (CMA), Meteorological Service of Canada (CMC), ECMWF, UK Met Office, National Centers for Environmental Prediction (NCEP, USA), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA) and Centro de Previsão de Tempo e Estudos Climáticos (CPTEC, Brazil).

Benchmarking the EPS

A first impression on the level of skill of these nine single-model systems is given by comparing the Continuous Ranked Probability Skill Score (CRPSS) of the 850-hPa temperature over the northern hemisphere for forecasts of the winter season (DJF – December, January, February) of 2008/09 (Figure 1). The performance of these forecasts varies significantly for the different models, with the CRPSS dropping to zero for the worst models at a lead-time of five days and for the best models around day 15. That is, the time range up to which the model predictions are more useful than the reference forecast, which is in this case the climatological distribution, varies considerably from one model to another.

Because not all forecasting centres integrate their models out to 15 days, the performance of the multi-model ensemble combining all nine single-model systems can only be assessed up to the maximum forecast range covered by all individual models, which is nine days. The multi-model ensemble is constructed by giving equal weights to all contributing members, noting that through

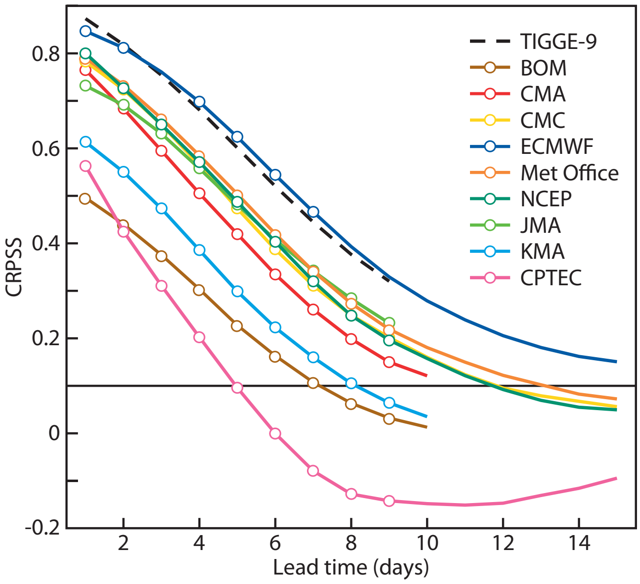


Figure 1 Continuous Ranked Probability Skill Score (CRPSS) versus lead time for 850-hPa temperature forecasts. The TIGGE-9 multi-model composed of nine single models and the scores of all nine contributing single models are shown. Symbols are only plotted for cases in which the single-model score differs significantly from the multi-model score on a 1% significance level. The significance levels have been assessed using a paired block bootstrap algorithm following *Hamill* (1999). All scores are for forecasts starting in DJF (December, January, February) 2008/09 and averaged over the northern hemisphere (20°–90°N).

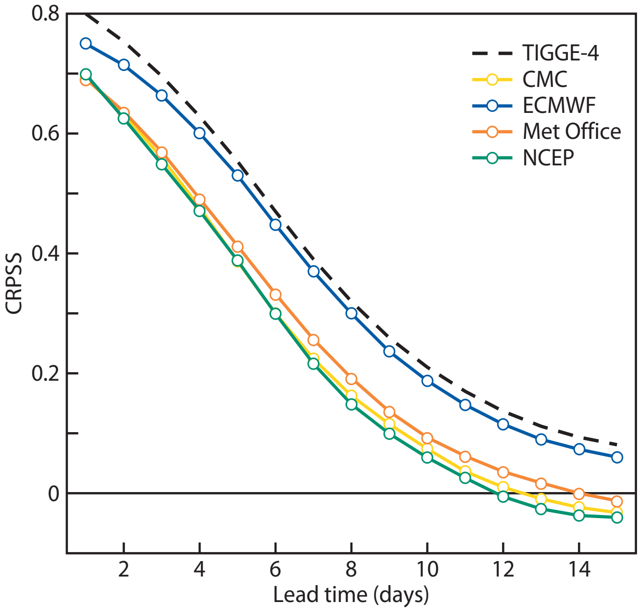


Figure 2 Continuous Ranked Probability Skill Score (CRPSS) versus lead time for 850-hPa temperature forecasts. The TIGGE-4 multi-model composed of the four best single models with lead-time up to 15 days is shown in addition to the CRPSS of the four contributing single models. Symbols are only plotted for cases in which the single-model score significantly differs from the multi-model score on a 1% significance level. All scores are for forecasts starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

the different number of members in the individual model systems an implicit weighting will be applied. That is, model systems with a higher number of ensemble members will have a greater impact in the final multi-model prediction than model systems with fewer members. Except for the first two forecast days, this multi-model prediction (TIGGE-9) does not significantly improve over the best single model (i.e. the ECMWF EPS). Similar results can be observed for other variables such as the bias-corrected 2-metre temperature.

Note that all results presented in this article are based on using ERA-Interim reanalyses as verification dataset. Further information on the rationale of this choice can be found in Box A.

The inability of the multi-model ensemble to significantly improve over the best single-model system might be caused by the fact that it consists of all nine single models (i.e. it includes the models with rather poor performance). To eliminate these possibly detrimental contributions, a new multi-model (TIGGE-4) containing only the four best single-model systems with lead time up to 15 days was constructed and compared to the four contributing single models from the National Meteorological Services in Canada (CMC), UK (Met Office) and the USA (NCEP), plus ECMWF (Figure 2). In fact, this reduced version of the full multi-model ensemble now gives significantly improved scores over the whole forecast period and for both upper-air and surface variables. This result indicates that a careful selection of the contributing models seems to be important for medium-range multi-model predictions.

Calibrating the EPS

After having established a new benchmark for the best single model, the ECMWF EPS, the next question is whether it might be possible to achieve similar improvements by calibrating the ECMWF EPS based on its reforecast dataset. Detailed information on the methodology applied to create the reforecast-calibrated ECMWF EPS forecasts (ECMWF-CAL) can be found in Box B. Essentially, this calibration methodology corrects both for errors in the mean and spread of the ensemble.

Comparing the CRPSS of the ECWMF-CAL forecasts with the TIGGE-4 multi-model scores reveals that indeed the calibration procedure significantly improves ECMWF's scores (Figure 3). Overall the performance of the ECMWF-CAL predictions is as good as the TIGGE-4 multi-model ensemble, and for longer lead times it can be even better.

For 850-hPa temperature predictions (Figure 3a) the CRPSS of ECMWF-CAL lies above the multi-model value for early lead times, and for longer lead times the skill scores are slightly lower than for the multi-model ensemble, though not statistically significant. Considering the slight advantage in the early lead times for ECMWF forecasts when using ERA-Interim as verification and the lack of statistical significance of the difference in the CRPSS for longer lead times, it can be concluded that for 850-hPa temperature the reforecast-calibrated ECMWF EPS forecasts are of comparable quality as the TIGGE-4 multi-model forecasts.

A

Choice of verification dataset

A number of considerations have to be taken into account when choosing the verification dataset to assess the performance of different single models and multi-models. On the one hand, using model independent verification data, such as station observations, ensures a fair treatment of all models. On the other hand, comparisons of the model performance over larger areas or for variables not directly available in observational datasets require the use of analyses, which commonly exhibit some of the bias of the forecast model used. There are a number of possibilities for the choice of analysis product in the context of comparing single and multi-model predictions.

- Each model's own analysis could be used as the verification dataset. However, there are two issues with this option: (a) the multi-model ensemble has no own analysis, and (b) it would be difficult to draw conclusions from the resulting scores and skill scores when their calculation is based on different reference datasets.
- The average of all analyses of the participating models or some weighted average, also called multi-model analysis, could be used. Such an average analysis would fulfil the condition of being as fair as possible to all models participating in the comparison. On the other hand, averaging all analyses, including less accurate ones, might not necessarily lead to an analysis closest to reality. Additionally, such a multi-model analysis cannot be used as verification dataset in this reforecast-comparison study because it is only available for the TIGGE forecast period (i.e. from 2007 onwards). This is not sufficient because the calibration of ECMWF forecasts based on the reforecast training dataset requires a consistent verification dataset for the entire training and test period (i.e. the verification dataset has to be available from 1991).

A possible compromise between the requirement of being as fair as possible to all models involved and being as accurate as possible is to choose the ECMWF ERA-Interim reanalysis as verification dataset. The two main advantages of this choice are the acknowledged high quality of this analysis product and the availability of this dataset for the entire training and test period (1991 up to near-real time). The obvious drawback of this option is that the ERA-Interim reanalyses are certainly not entirely independent of one of the models in the comparison, the ECMWF model. As such, one might expect that it is more difficult for non-ECMWF models to achieve good scores when verified against the ERA-Interim reanalysis. However, it can be demonstrated that the skill scores of all models are affected by the choice of verification dataset. Using ERA-Interim as verification leads to diagnosing a reduced performance, in particular for early lead times. For longer lead times, the impact tends towards negligible differences.

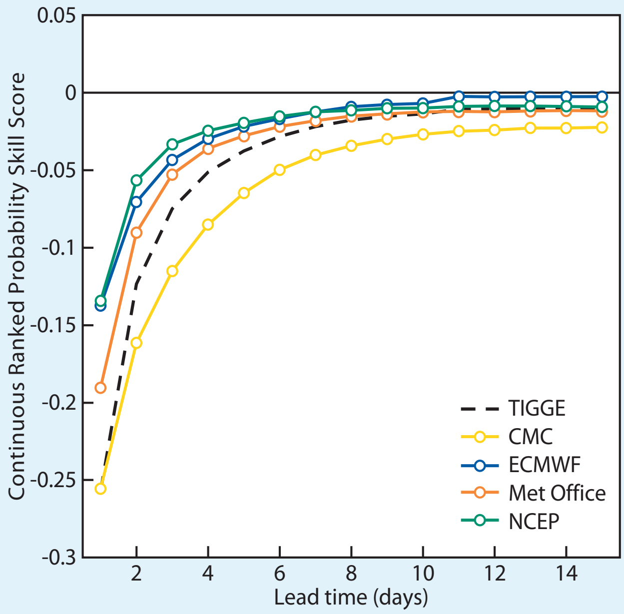


Illustration of the impact of the verification dataset on the relative skill of the predictions. Negative values indicate a worse performance when verified against ERA-Interim reanalyses, a value of zero indicates no impact of the chosen verification dataset. Scores are calculated for forecast of 850-hPa temperature from the TIGGE multi-model and the single models (CMC, ECMWF, Met Office and NCEP) starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

It is important to note that the performance of all forecasts is similarly affected by the choice of verification dataset, i.e. there is only little impact on the relative performance of individual models with respect to each other. Although model systems that are quite close in their performance (like CMC, NCEP and Met Office) can change their ranking relative to each other, the choice of verification has no impact on the clear superiority of the ECMWF EPS.

For surface variables such as 2-metre temperature the impact of using ERA-Interim is larger, but can be reduced by applying a bias-correction procedure. Overall, we regard using ERA-Interim analyses as general verification dataset to be the best option for this study. Also by keeping in mind the sensitivities towards the choice of verification dataset one can ensure a fair interpretation of the results.

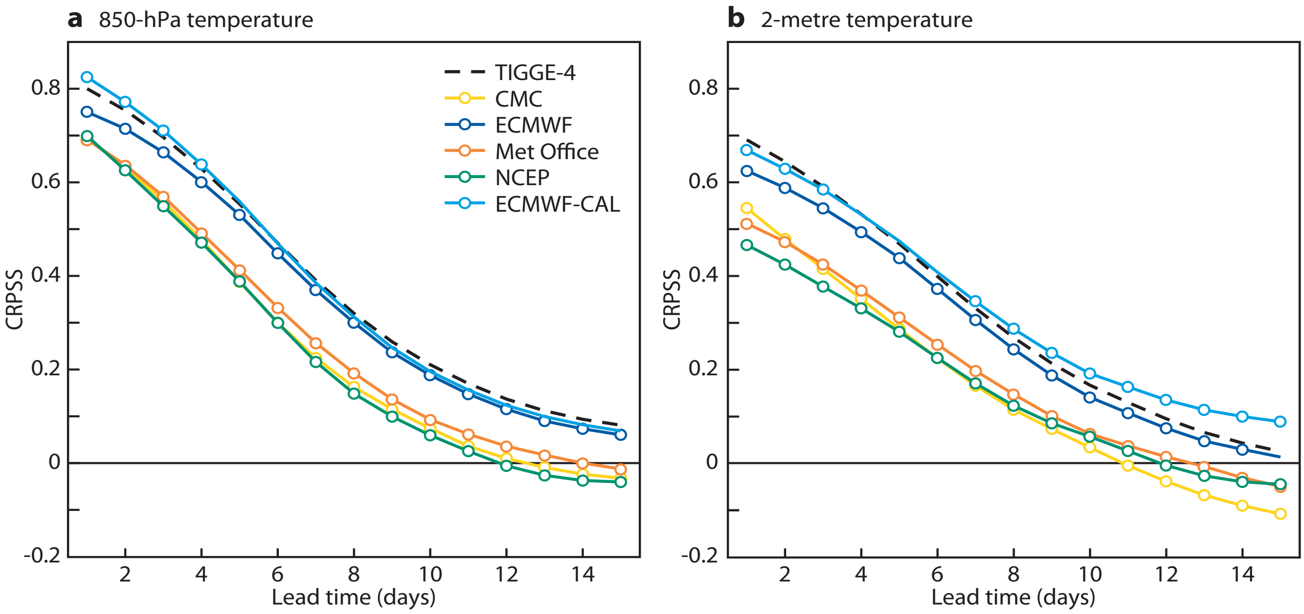


Figure 3 Continuous Ranked Probability Skill Score (CRPSS) versus lead time for (a) 850-hPa temperature forecasts and (b) 2-metre temperature forecasts. The TIGGE-4 multi-model composed of the four best single models with lead-time up to 15 days is shown in addition to the CRPSS of the four contributing single models and the reforecast-calibrated ECMWF EPS (ECMWF-CAL). Symbols are only plotted for cases in which the single-model score differs significantly from the multi-model score on a 1% significance level. All scores are for forecasts starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

Reforecast-calibration methodology

B

The methodology developed to produce reforecast-calibrated ECMWF EPS forecasts (ECMWF-CAL) is based on combining calibration results from the Non-homogeneous Gaussian Regression technique (NGR) and pure bias-correction (BC).

The NGR technique itself has already been applied to ECMWF EPS forecasts (see *Newsletter No. 117*). Essentially, NGR is an extension to conventional linear regression by taking into account information contained in the existing spread-skill relationship of the raw forecast. Using the ensemble mean and the spread as predictors, it fits a Gaussian distribution around the bias-corrected ensemble mean. The spread of this Gaussian is on the one hand linearly adjusted according to the errors of the regression model using the training data, and on the other hand depends on the actual spread according to the diagnosed spread-error relationship in the training dataset. Thus, one important feature of this methodology is being able to not only correct the first moment of the ensemble distribution but also correct spread deficiencies.

After applying the NGR calibration, the forecast Probability Density Function (PDF) consists of a continuous Gaussian distribution, not an ensemble of realizations. However, to be able to compare the performance of the calibrated probabilities, retrieved from a full PDF, with the probabilities simply based on counting individual ensemble members, a synthetic ensemble is created from the calibrated Gaussian by drawing 51 equally likely ensemble members from the calibrated PDF. That is, the synthetic ensemble is realized by sampling the members at the 51 equally spaced quantiles of the regressed Cumulative Distribution Function (CDF).

Experimenting with the choice of training dataset and calibration method revealed that combining a simple bias correction using training data from the 30 previous days (BC-30) and the NGR calibration based on reforecasts (NGR-RF) is superior to the pure NGR-RF calibration, particularly for early lead times. The two ensembles are not combined by taking all members from both ensembles to form a new ensemble with twice the number of members, but by first ordering both the bias-corrected and NGR-calibrated ensembles and then averaging the corresponding members. In this way the final combined calibrated system still contains only 51 members. Some experimentation with different weights for the NGR-RF and BC-30 ensembles revealed that applying equal weights at all lead times leads to overall best results.

For the current version, the slightly improved performance might be caused by the fact that the BC-30 calibration contains information on the bias more relevant to the current weather regime than the overall bias diagnosed from the reforecast dataset. However, using a refined version of the NGR-RF calibration by, for example, including soil moisture as an additional predictor might diminish the positive impact the BC-30 contribution can have. A further advantage of adding the BC-30 calibrated ensemble to the Gaussian NGR-RF ensemble is that through this procedure any non-Gaussian characteristics of the original ensemble may be retained to some degree.

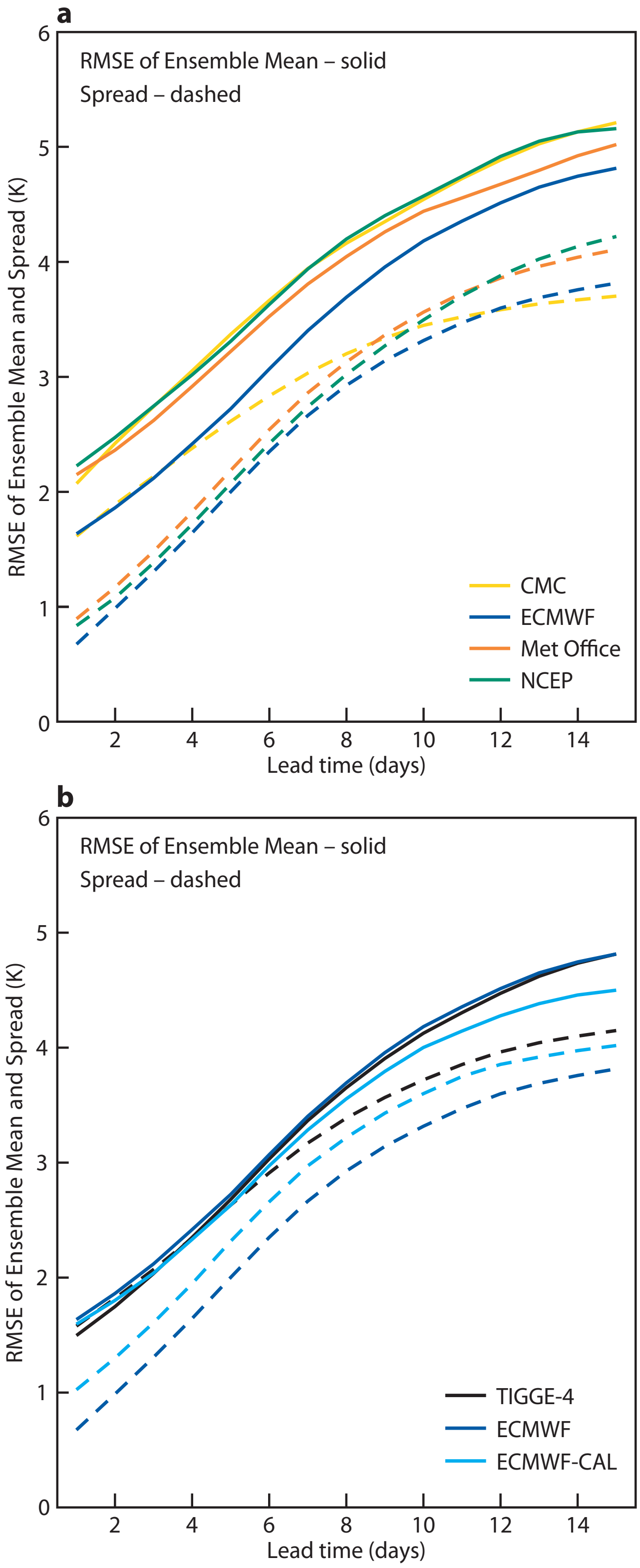


Figure 4 Root-mean-square error (RMSE) of the ensemble mean (solid lines) and ensemble standard deviation ('spread', dotted lines) versus lead-time for 2-metre temperature forecasts. (a) Results for the single-model forecast (CMC, ECMWF, Met Office and NCEP). (b) As (a) but without the CMC, Met Office and NCEP results, including instead the results for the reforecast-calibrated ECMWF (ECMWF-CAL) and TIGGE-4 multi-model results. All scores are for forecasts starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

This result is confirmed when studying other variables, regions or seasons. In fact, for 2-metre temperature forecasts the calibration is even more effective for longer lead times (Figure 3b). This indicates that the systematic component of the error is more dominant for the 2-metre temperature, and thus the calibration procedure is able to further reduce the root-mean-square error (RMSE) of the ensemble mean. However, the general level of skill at those long lead times is very low. Therefore, these improvements – as relevant as they might look in terms of overall scores – might not add very much in terms of improving the usefulness of the predictions in a real forecast situation.

Comparing, for example, the ECMWF EPS with the reforecast-calibrated and TIGGE-4 multi-model forecasts for individual cases at single grid point locations can give an indication of how much (or how little) a real forecast product would change. On the one hand, one can find locations at which the calibrated or multi-model ensemble distributions are significantly different from the ECMWF EPS. These are usually locations with complex orography, where for example different grid resolutions can cause detectable systematic errors. In such cases the NGR calibration is able to correct both such biases and serious spread deficiencies. However, as mentioned above, for longer lead times the predicted distributions are already close to the climatological distributions. Consequently it is not clear whether the improvements seen in the scores can be really translated into practical benefits of better decision-making based on such 'theoretically' improved forecast products. Additionally, there are also many locations with less pronounced systematic errors or spread deficiencies. At such locations, the calibration obviously has much less impact.

Mechanisms behind improvements

To further investigate the mechanisms behind the improvements, Figure 4 focuses on the spread-error relation of the different ensembles. Ensemble forecasting aims to construct uncertainty information so that the observations can be considered as statistically indistinguishable from the ensemble members of the forecast. This requires the spread of the ensemble (ensemble standard deviation) to be close to the root mean square error (RMSE) of the ensemble mean. However, for 2-metre temperature all single-model systems are seriously under-dispersive as shown in Figure 4a. CMC has the lowest spread deficiency at the beginning of the forecast, but due to a serious mismatch in the growth of spread and error it has the worst spread-error relation for longer lead times. The remaining three models have a similar level of spread. However, the significantly lower RMSE of the ECMWF EPS implies not only a slightly better spread-error relation compared to the Met Office and NCEP ensembles, but it is also one of the main reasons for its significantly better probabilistic scores discussed earlier.

The effect of combining the single-model systems or calibrating the ECMWF EPS can be seen in Figure 4b. The RMSE of the multi-model ensemble is slightly reduced for early lead times, but the most noticeable change is the very much improved spread-error relation, particularly up to day 6. In contrast to that, the reforecast-calibrated ECMWF EPS has not such a perfect spread-error relation, though it is improved compared to the original EPS spread. The reason for this is the specific methodology of combining bias-corrected and NGR-calibrated forecasts (see also Box B).

Applying the pure NGR calibration should lead to a near perfect spread-error relation, but the advantages of possible reductions in the systematic error provided by the 30-day bias-corrected ensemble may outweigh the slight disadvantage of a poorer second-moment (i.e. spread) calibration. Since the under-dispersion is not fully corrected in the reforecast-calibrated ensemble, the main improvement of its probabilistic scores comes from the reduction in the RMSE, in particular for longer lead times.

We note that the theoretical disadvantage of the ECMWF-CAL methodology (i.e. the sub-optimal spread correction) in certain situations might even be regarded as a positive aspect. Discussions with operational forecasters revealed that – although theoretically correct – the extent of the full NGR spread is sometimes regarded as counterproductive in real forecast situations. There might be many reasons for this subjective opinion, such as a general reluctance to integrate uncertainty information into operational forecast practice. Although not part of the current investigation, we feel that these aspects are worth considering in further discussions with users on how to achieve our ultimate goal of providing user-optimized forecast products.

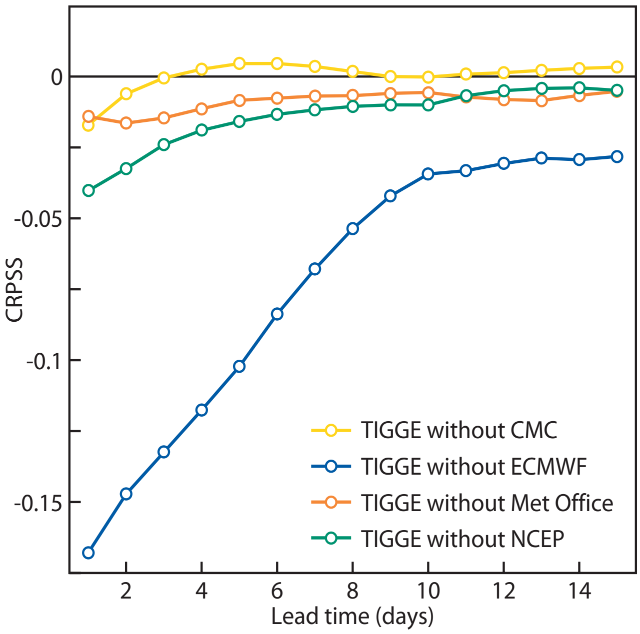


Figure 5 Illustration of gain or loss in skill of 2-metre temperature forecasts versus lead time using the Continuous Ranked Probability Skill Score (CRPSS) depending on which model has been removed from the TIGGE-4 multi-model containing all four single models (CMC, ECMWF, Met Office and NCEP). The CRPSS is defined as *CRPSS* = 1 – *CRPS(exp)*/*CRPS(ref)*, with *CRPS(ref)* being the CRPS (Continuous Ranked Probability Score) of the TIGGE-4 multi-model and *CRPS(exp)* the CRPS of the reduced multi-model respectively. Negative values indicate a worse performance of the reduced multi-model (i.e. a detrimental effect of removing a particular single model from the multi-model mix). All scores are for forecasts starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

Single-model contributions to the TIGGE multi-model

The computational and organizational overhead of collecting all individual model contributions and combining them into a consistent multi-model ensemble grows with the number of contributing models. Consequently it is worth investigating the added benefit each individual model can give to the multi-model system. For this purpose we constructed reduced multi-model versions with individual model components removed from the full multi-model mix and scored them against the full multi-model version containing all four models (Figure 5).

It is obvious that removing the ECMWF EPS from the multi-model ensemble has the biggest impact, whereas the other models contribute to a lesser extent to the multi-model success. It might be argued that one of reasons for this is that by removing the ECMWF EPS the multi-model ensemble loses 51 members, whereas removing the other models produces a loss of only 21 or 24 members. Since the CRPS (Continuous Ranked Probability Score) is expected to go down with increasing number of ensemble members (*Ferro et al.*, 2008), it is not straightforward to distinguish the effect of removing the forecast information that a single model adds to the multi-model from the effect of removing 51 instead of 21 or 24 members. However, there are two reasons why we believe that not explicitly accounting for the difference in the number of members is justified.

- The difference of number of members between the full multi-model ensemble containing 117 members and the most reduced multi-model ensemble containing 66 members would require only a moderate adjustment factor of about 1% CRPS reduction applied to the ensemble with the lower number of members. This is much lower than the difference indicated by a CRPSS between –0.15 and –0.05. Therefore, only 1% out of the 15% increase in the CRPS of the reduced multi-model ensemble is due to the lower number of members and the remaining 14% increase is caused by the withdrawal of the forecast information from that model.
- Suppose we want to compare the performance from an operational rather than theoretical point of view. That is we are not interested in theoretical questions such as “how would these models compare if they had the same number of members?”, but we want to answer questions like “how do the operational systems, as they are, compare?” In that case we should not adjust the scores to reflect a potential performance of a model with infinite number of members. Following these considerations, in none of the comparisons of this study are the scores adjusted according to their different numbers of ensemble members.

Apart from the question about which of the single models contributes most to the multi-model success, a further question in the context of the TIGGE project is whether the multi-model concept could lead to reduced costs but still keeping the same quality of forecasts. Assuming, for the

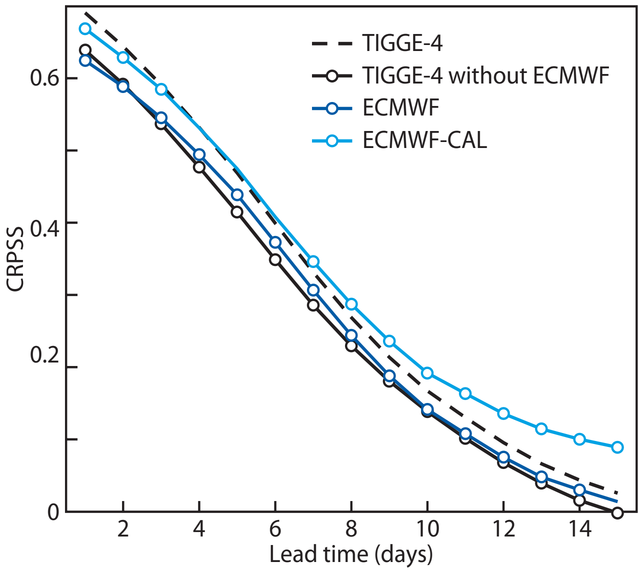


Figure 6 Continuous Ranked Probability Skill Score (CRPSS) versus lead time for 2-metre temperature forecasts. Results are shown for the TIGGE-4 multi-model containing CMC, ECMWF, Met Office, and NCEP forecasts, the TIGGE-4 multi-model without ECMWF forecasts (i.e. containing only CMC, Met Office, and NCEP forecasts), the simple bias-corrected ECMWF forecasts, and the re-forecast calibrated ECMWF forecasts (labelled ECMWF-CAL). Symbols are omitted for cases in which the score does not significantly differ from the TIGGE-4 multi-model score on a 1% significance level. All scores are for forecasts starting in DJF 2008/09 and averaged over the northern hemisphere (20°–90°N).

sake of argument, that ECMWF could no longer afford to provide its EPS forecasts, could a multi-model consisting of the remaining high-quality ensembles be as good as the ECMWF EPS on its own? Indeed, a TIGGE multi-model ensemble without ECMWF contribution is of comparable quality as the ECMWF EPS alone, i.e. combining the second-, third- and fourth-best global ensembles leads to forecasts which are as good as the best global ensemble (Figure 6). However, this is only true for the ECMWF EPS when it has not been reforecast-calibrated.

Running the complete ECMWF EPS, including its reforecasts, leads to a performance which cannot be achieved by any current multi-model version not containing ECMWF forecast information. These results are generally confirmed when considering other variables such as upper-air temperature or wind components, though small differences in the relative performance, also depending on the region, can be observed.

Overall costs and benefits

Coming back to the main aim of this article (i.e. comparing the costs and benefits of the multi-model and reforecast-calibration approaches) it is clear that the performance of the reforecast-calibrated ECMWF EPS forecasts is as good as the TIGGE multi-model system, if not better. When considering which post-processing approach leads to better forecast products or can give more useful information in a practical decision-making process, it has to be noted that the calibration procedure is particularly helpful at locations with clearly detectable systematic errors (e.g. areas with complex orography or coastal grid points). In such areas the calibration procedure can correct, for example, for unresolved scales and thus essentially performs a sort of downscaling of the forecasts. This ability is particularly important for all applications needing forecasts at specific locations like, for example, forecasting the wind power production at specific wind farms. The multi-model approach, on the contrary, might be advantageous in situations where it is able to suggest alternative solutions not predicted by the single model of choice.

Further investigations on the mechanisms behind the improvements achieved by the post-processing methods led to the conclusion that both approaches tend to correct similar deficiencies. That is, systematic error and spread deficiencies are improved to a similar extent by both approaches. Experiments assessing the contribution of the individual components of the multi-model system demonstrated that the ECMWF EPS is the single most important source of information for the success of the multi-model ensemble.

For a final assessment which of the two post-processing methods would be the most appropriate choice for a modelling centre, one also has to consider the technical overhead of producing multi-model or reforecast-calibrated single-model forecasts in an operational context. If, for example, a modelling centre has easy and reliable access to all components of the multi-model system, and if its users or operational forecasters ask for multiple solutions suggested by individual models, then the multi-model concept might be the method of choice. However, for a forecasting centre reluctant to take on the potential risks and technical overhead inherent in the increased complexity of a multi-model system, using the reforecast-calibrated ECMWF EPS forecasts rather than a logistically highly complex multi-model system seems to be a more appropriate choice.

Considering the performance improvements made possible by the availability of the ECMWF reforecast dataset, other modelling centres might start providing reforecasts for their model systems in the not too distant future. In that case it would be interesting to study the relative benefits achievable for reforecast-calibrated multi-model or single-model systems. Furthermore, we suggest exploring the relative merits of multi-model versus reforecast-calibrated predictions for other user-relevant variables like precipitation and wind speed, in particular in the context of extreme events.

FURTHER READING

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Surface pressure information derived from GPS radio occultation measurements

SEAN HEALY

THE POSSIBILITY of deriving useful surface pressure information from satellite measurements has potentially important implications for the future design of the global network of conventional observations. Profiles of GPS radio occultation (GPSRO) bending angle can provide surface pressure information when they are assimilated in the four-dimensional variational (4D-Var) system.

We have recently performed a set of forecast impact experiments to investigate the ability of GPSRO measurements to provide useful surface pressure information when all conventional, synoptic and drifting buoy surface pressure measurements are removed from the NWP analyses. Somewhat surprisingly, we have found that removing the conventional surface pressure observations has limited impact on the medium-range surface pressure and geopotential height forecast scores in the southern hemisphere when GPSRO measurements are assimilated. However, we have also found that the surface pressure analyses produced with GPSRO measurements are extremely sensitive to relatively small biases in the NWP system when no conventional surface pressure observations are assimilated.

Background

Bending angle profiles derived from GPSRO measurements have been assimilated operationally at ECMWF since 12 December 2006 (see Healy, *ECMWF Newsletter No. 111*). They differ from satellite radiance measurements because they have much higher vertical resolution, and they can be assimilated without bias correction. To date, the main impact of GPSRO measurements has been on upper-tropospheric and lower-stratospheric temperatures. However, it is well known that profiles of pressure as a function of geopotential height can be derived from GPSRO measurements, and in theory it should also be possible to derive useful surface pressure information from the measurements using variational assimilation techniques. Physically, this information content arises because the bending angles are assimilated as a function of a height variable, known as the 'impact parameter' (see Box A).

The assimilation of GPSRO measurements as a function of a height variable means that the integration of the hydrostatic equation is a component of the 'observation operator' (or 'forward model') used to simulate the bending angle measurements in the 4D-Var system. This introduces a clear, physically-based sensitivity of the simulated bending angle values with respect to the model surface pressure. Broadly

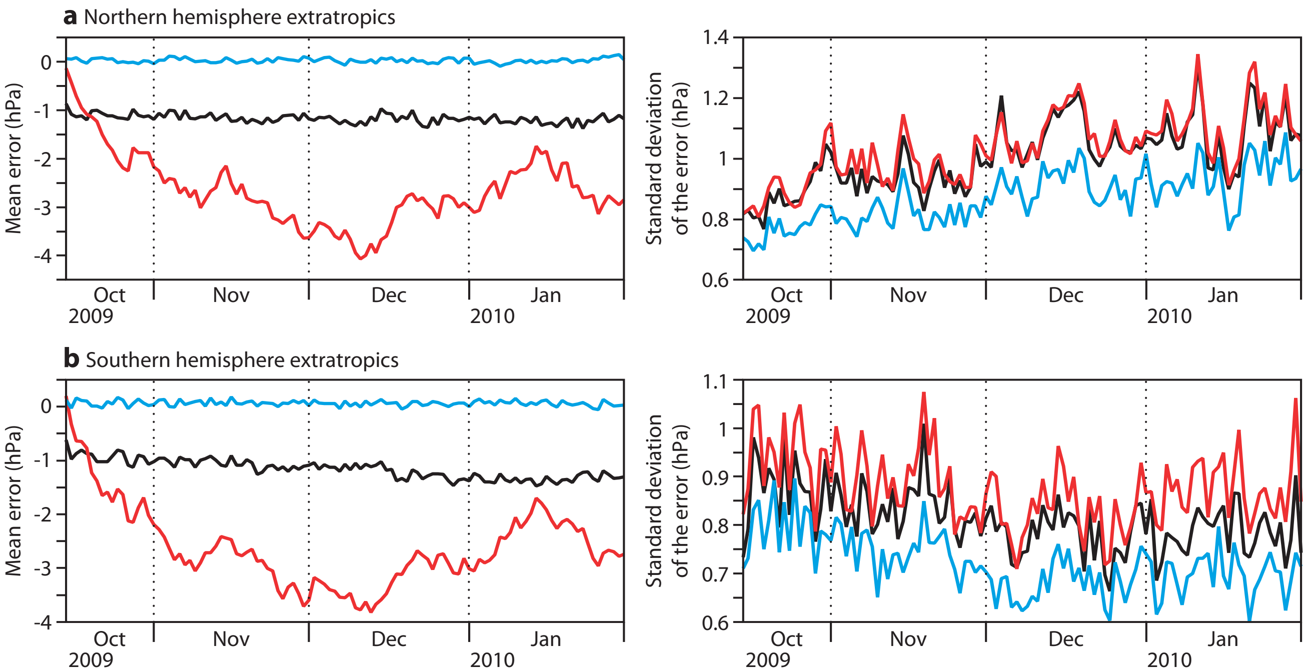


Figure 1 Time series of the mean error and standard deviation of the error of the 24-hour forecast of surface pressure, for the period 15 October 2009 to 31 January 2010, for (a) northern hemisphere and (b) southern hemisphere extratropics when conventional surface pressure observation measurements are removed (black line), both GPSRO and conventional surface pressure observation measurements are removed (red line), and for the full observing system (blue line). The verification is against the operational ECMWF analyses.

The GPSRO height coordinate

A

Deriving surface pressure information from GPSRO observations requires accurate mapping of the NWP model output to the height coordinates used for GPSRO observations. ECMWF assimilates GPSRO bending angles as a function of a height variable, known as the 'impact parameter'. This variable also arises in physics when describing the scattering of classical particles in a spherically symmetric potential, and there are strong similarities in the mathematics of this scattering problem and the calculation of the bending of radio waves in the atmosphere. Geometrically, the impact parameter is the radius of closest approach that a ray (or particle) would have had, in the absence of any bending (see box figure).

Physically, the impact parameter is analogous to the angular momentum of a particle, and it is a conserved quantity along the ray path if the atmosphere is spherically symmetric, rather like the conservation of angular momentum of a classical particle in a spherically symmetric potential. This conservation property means that the impact parameter provides information on the height of the 'tangent point', when the ray's path is tangent to the Earth's surface, and the bending is largest.

The assimilation with respect to a height variable introduces some subtle problems in the use of GPSRO data, which are not generally encountered with other measurements. The ECMWF forecast model – in common with all other operational NWP models – assumes a spherical Earth for computational purposes. The surface of this sphere is assumed to be Mean Sea Level (MSL), and the geopotential heights are then given relative to this MSL.

The details of the actual geometrical shape of the Earth's surface do not arise when assimilating other measurements. In contrast, GPS measurements are given relative to the 'World Geodetic System 1984' (WGS-84) reference ellipsoid, which itself is an approximation to the Earth's geoid. More specifically, in the processing of GPSRO measurements, we introduce another level of approximation with the use of a 'radius of curvature', which defines the best spherical fit to the WGS-84 ellipsoid in the region of the observation.

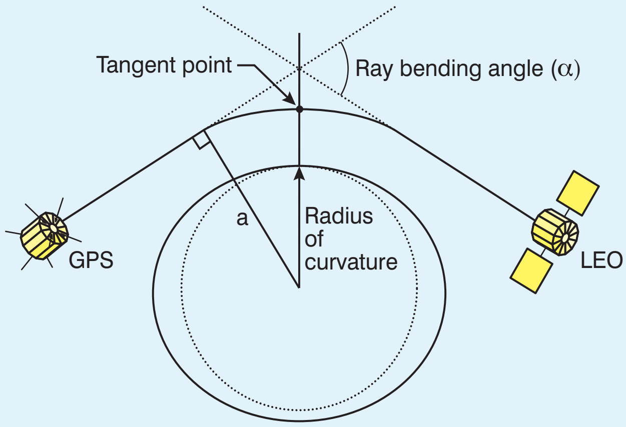


Illustration of the GPSRO geometry and the impact parameter 'a'.

Ultimately, when assimilating the GPSRO measurements, we have to interpret that ECMWF NWP model surface as if it was the geoid, and then in the forward operator use a correction factor known as the 'undulation', which is defined as the height of the geoid above the WGS-84 ellipsoid, in order to relate the NWP model output to the GPS observations. We also have to include the transformation between geopotential height and geometric height in the forward operator, to account for the fact the gravity varies as a function of height. Failure to include this transform introduces forward model banding angle biases that increase with the height of the tangent point. For example, at 30 km the forward modelled bending angle bias is around 2% if the transform is not included, and we typically assume an observation error of 1% at that level.

speaking, increasing the surface pressure increases the simulated bending angles and, conversely, reducing the surface pressure reduces the simulated values. Theoretical information content studies – which essentially estimate the surface pressure errors before and after making a GPSRO measurement – have suggested that the measurements should contain useful surface pressure information, but demonstrating this in a full NWP system has been more problematic. This is partly a result of the measurement numbers.

The combined number of synoptic, METAR and ship measurements assimilated per day is typically around 100,000, and there are also 13,000 drifting buoy surface pressure observations. In contrast, there are only around 2,500 globally distributed GPSRO bending angle profiles assimilated per day. Therefore, we have investigated the ability of GPSRO measurements to constrain the surface pressure field in a degraded NWP system, when all conventional surface pressure observations are removed.

Assimilation experiments

The surface pressure information content of GPSRO measurements has been investigated in a series of assimilation experiments, covering the period 15 October 2009 to 31 January 2010. The experiments using Cycle 36r1 of the Integrated Forecasting System (IFS) are run at T511 resolution and use incremental 4D-Var assimilation. They have been designed to illustrate the information content of GPSRO measurements by selectively removing (or 'blacklisting') different combinations of observations from 4D-Var system.

Figure 1 shows the time series of the mean and standard deviation of the 24-hour surface pressure forecast errors in the northern hemisphere extratropics (20°–90°N) and southern hemisphere extratropics (20°–90°S) for three experiments:

- The full observing system assimilated operationally at ECMWF.
- The full observing system minus all conventional surface pressure observations.

- The full observing system minus all conventional surface pressure observations and all GPSRO measurements.

In general, the results in the tropics (20°N–20°S) are very similar, and we will not discuss them further in this article.

The verification scores are against the operational ECMWF analyses. The time series results clearly demonstrate that the GPSRO measurements provide a useful constraint on the surface pressure when compared to experiment where both the GPSRO and conventional surface pressure observations are removed, with both the standard deviation and mean of the errors being reduced. In particular, the mean errors when the GPSRO data are assimilated are reasonably stable in time, at around the –1 hPa to –1.5 hPa level, whereas they can be as large as –4 hPa when these measurements are not assimilated.

The GPSRO measurements have greatest impact on the standard deviation of the errors in the southern hemisphere extratropics with a reduction of around 0.06 hPa. However, it is also clear that at the short range the GPSRO measurements are not able to fully compensate for the loss of all the conventional surface pressures observations, particularly in the northern hemisphere extratropics where the standard deviation of the error with the full observing system is about 0.15 hPa smaller. This is probably not

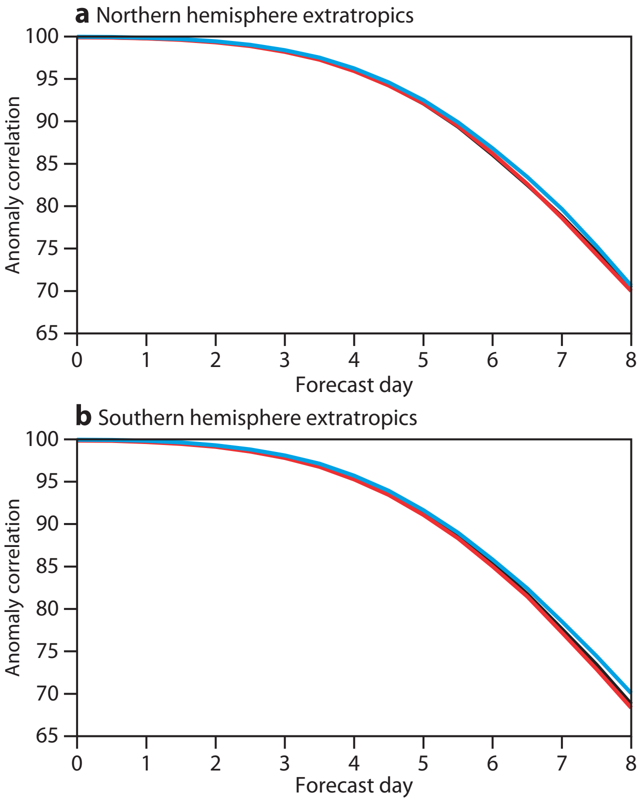


Figure 2 The 500 hPa geopotential height anomaly correlation scores for (a) northern hemisphere and (b) southern hemisphere extratropics when conventional surface pressure observation measurements are removed (black line), both GPSRO and conventional surface pressure observation measurements are removed (red line), and the full observing system (blue line). The statistics cover the period 1 November 2009 to 31 January 2010 and the verification is against operational ECMWF analyses.

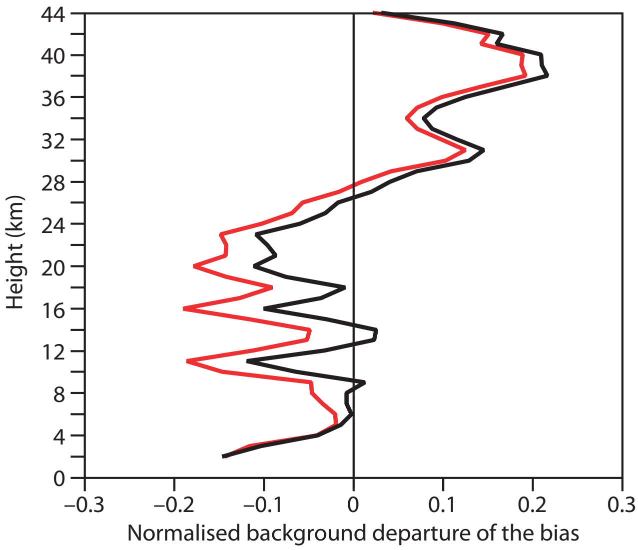


Figure 3 The noise normalised background departure of the bias for the COSMIC-4 satellite, when conventional surface pressure observations are blacklisted (black line) and for the full observing system (red line). The statistics cover the period 1 November 2009 to 31 January 2010.

surprising given the number and the spatial distribution of conventional surface pressure measurements that have been removed from the 4D-Var.

The impact on the geopotential height scores is shown in Figure 2. The scores for the northern hemisphere extratropics are degraded throughout the entire forecast range as a result of removing the surface pressure observations, and the GPSRO measurements have little impact. This degradation is statistically significant at the 95% level from day-1 to day-6. However, in the southern hemisphere extratropics – where the number of conventional surface pressure observations is lower – the GPSRO measurements clearly have some impact. The differences between the GPSRO experiment and the full system are small but slightly negative from around day-4, but they are not statistically significant at 95% level.

Although the GPSRO measurements are able to reduce the surface pressure biases, one question is what causes the –1 hPa to –1.5 hPa bias when they are assimilated? The bending angle departure statistics when surface pressure measurements are blacklisted provide some insight. Figure 3 shows the bending angle departure statistics for the COSMIC-4 satellite with the full observing system and when the conventional surface pressure measurements are removed, but the GPSRO observations are assimilated. There is a clear reduction in the mean bending angle departures above 10 km when the surface pressure measurements are removed. In fact, we have been able to show that the surface pressure bias is related to the bending angle departures above 10 km, because it is virtually unchanged in experiments where the GPSRO measurements are blacklisted below 10 km.

The bias in the mean bending angle departures between 10–30 km with the full observing system is now a robust feature with all GPSRO instruments, including GRAS and

COSMIC which are processed at different centres. This suggests that it originates from the NWP background rather than observations, and it is thought to be a combination of a warm temperature bias in the troposphere, combined with a cold bias in the stratosphere. When the conventional surface pressure observations are removed from the assimilation system, it appears that the biased bending angle departures are reduced by surface pressure increments. The surface pressure is almost being used as a 'sink variable', meaning it can be changed without degrading the fit to other observations. This transfer of biases is a common problem in satellite meteorology, when the assimilated quantities have a sensitivity to more than one atmospheric variable.

In addition to the surface pressure information that can be derived directly as a result of the hydrostatic integration in the GPSRO forward model, the 4D-Var system should also be able to derive some information indirectly from the measurements. This will arise as the result of assumed 4D-Var background error correlations between upper temperatures and the surface pressure, and the fact that the forecast model used to provide the 4D-Var trajectory is hydrostatic. This contribution can be isolated by switching off the surface pressure sensitivity in the GPSRO observation operator. We have found that removing the hydrostatic term in the forward operator leads primarily to an increase in the standard deviation of the surface pressure errors, with only a small change in the surface pressure biases.

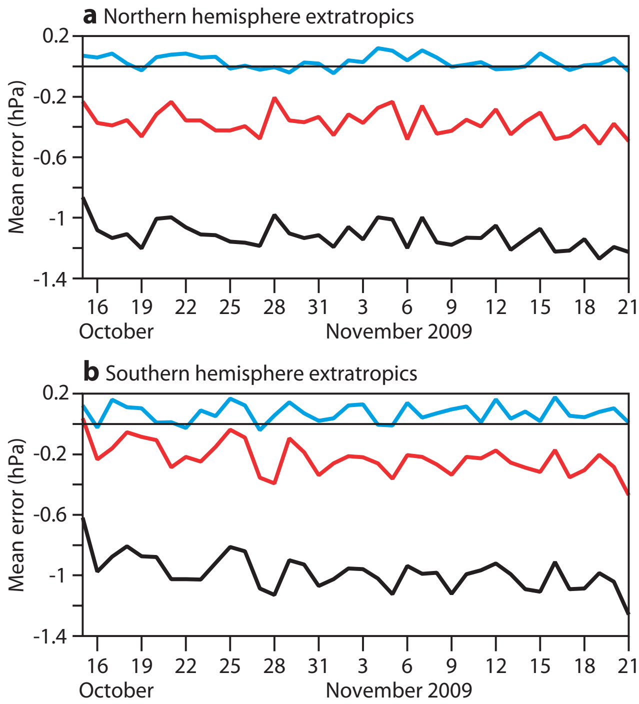


Figure 4 Time series of the mean error of the 24-hour forecast of surface pressure for (a) northern hemisphere and (b) southern hemisphere extratropics.when surface pressure measurements have been removed (black line), and when the forward modelled bending angles have been reduced by 0.1% (red line). The results with the full observing system are shown for reference (blue line).

Sensitivity to small biases

We can demonstrate the sensitivity of the surface pressure biases to relatively small changes in the assimilation of the GPSRO measurements, with an experiment where the GPSRO bending angles are effectively subjected to a bias correction of +0.1%. This has been achieved by reducing all the forward modelled bending angles by 0.1%. A perturbation of this amount in the bending angles corresponds approximately to shifting the height of the bending angle measurements by around 7 m in the vertical, because to first order the bending angles fall exponentially with height with a 7 km scale height. The impact on the surface pressure bias is shown in Figure 4, with the bias being reduced by around 0.7 hPa globally. Note that the smallest observation errors used in the assimilation of GPSRO measurements is 1% between 10–30 km, so the imposed perturbation is small when compared to the assumed observation errors used at ECMWF.

It must be emphasised that we are not advocating any bias correction of GPSRO measurements on the basis of these results, as the aim of this exercise is to highlight the observed sensitivity, but it is interesting to put a 0.1% perturbation in some context. It is not inconceivable that either processing of GPSRO bending angles from the raw phase and amplitude measurements, or the forward models used to assimilate the measurements, can introduce biases at the 0.1% level. In fact, recent operational processing changes at the University Corporation for Atmospheric Research (UCAR), introduced operationally on 12 October 2009, have shifted the stratospheric bending angles by around -0.2%. This has resulted in much better consistency with MetOP-A GRAS, but has increased the bias with respect to ECMWF short-range forecasts.

In relation to forward model accuracy, the empirical refractive index coefficients, which are used to convert pressure, temperature and water vapour information to refractive index values, have come under increasing scrutiny in recent years, and new laboratory measurements of the coefficients are probably required. In connection with this, Josep Aparicio at Environment Canada has also demonstrated that introducing non-ideal gas effects in GPSRO observation operators can introduce a systematic shift in the simulated observations which are of order 0.1%.

Another component of the observation operator that has been tested recently at ECMWF is the accuracy of the geopotential to geometric height transform. Our results suggest that the errors in this transform at 30 km are generally less than 1 m, although they can be as large as 5 m in isolated regions. Hence, there is no evidence of large-scale biases introduced by this transform which might translate into surface pressure biases of around -1.2 hPa.

Removal of aircraft temperature measurements

The warm mid- and upper-tropospheric bias in ECMWF forecasts and analyses is partly caused by aircraft temperature measurements which are biased warm. These measurements will be bias corrected at ECMWF in the near future. Given the

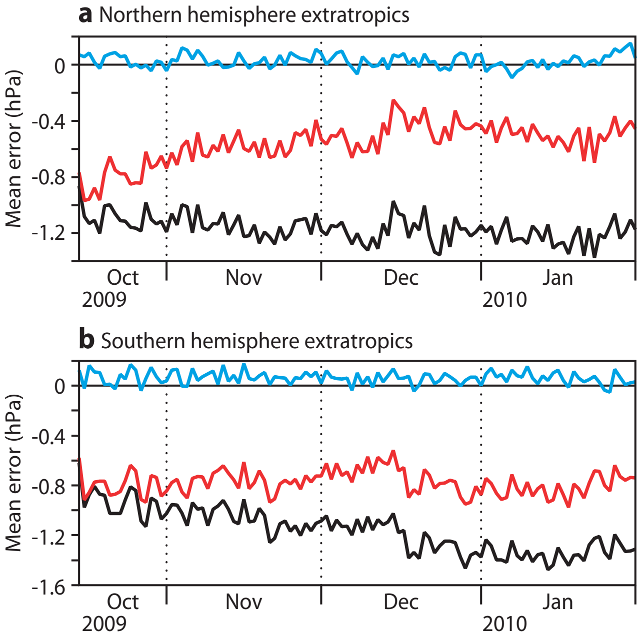


Figure 5 Time series of the mean error of the 24-hour forecast of surface pressure for (a) northern hemisphere and (b) southern hemisphere extratropics when aircraft temperature measurements and conventional surface pressure observations are removed from the assimilation system (red line). These are compared with the standard experiment where conventional surface pressure observations are removed but both GPSRO and aircraft temperature measurements are included (black line), and with the full observing system (blue line).

sensitivity of the GPSRO surface pressure biases to small changes in the assimilation system, we have investigated how they change in the GPSRO experiment when the aircraft temperature measurements are removed from the assimilation system.

Figure 5 shows the mean 24-hour surface pressure forecast errors when the aircraft measurements are removed. The impact is largest in the northern hemisphere extratropics, where the aircraft numbers are greatest. In the full system, when all observations are assimilated, GPSRO measurements tend to pull the analysis away from the aircraft temperatures,

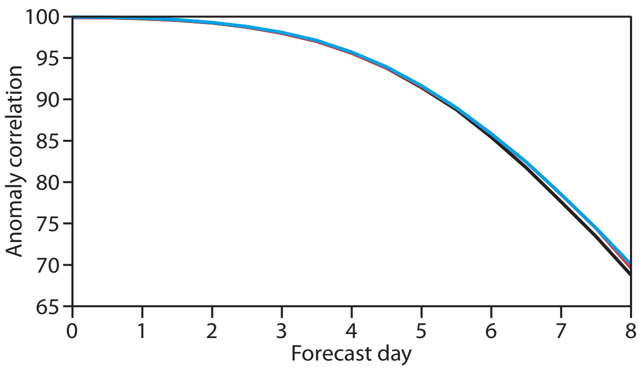


Figure 6 The 500 hPa geopotential height anomaly correlation scores for the southern hemisphere extratropics when aircraft temperature measurements and conventional surface pressure observations are removed (red line), conventional surface measurements are removed but both GPSRO and aircraft temperature measurements are included (black line), and for the full observing system (blue line).

and produce a closer fit to radiosonde temperature observations. However, when the surface pressure observations are removed, this is no longer the case. It appears that the GPSRO measurements reduce the surface pressure, rather than fight the aircraft measurements and correct the temperature bias.

Figure 6 shows the 500 hPa geopotential anomaly correlation score for the southern hemisphere extratropics when both the aircraft temperature measurements and conventional surface pressure measurements are removed. From around day-4 onwards the results are essentially neutral when compared with the full observing system. The scores in the northern hemisphere extratropics still show a clear, statistically significant degradation.

Summary and future work

GPSRO measurements are an important source of upper-troposheric and lower-tratospheric temperature information. In addition, we have now demonstrated that GPSRO measurements contain surface pressure information, and that they are able to stabilise global NWP surface pressure biases at around the –1.2 hPa to –1.5 hPa level when all conventional surface pressure observations are removed from the 4D-Var assimilation system.

GPSRO measurements are not able to fully compensate for the loss of all of the surface pressure observations in the northern hemisphere extratropics, and the geopotential forecasts are clearly degraded over the entire forecast range. The impact of removing surface pressure observations in the southern hemisphere extratropics is also clear in the short-range forecasts, but by around day-5 the impact of the conventional observations is quite small. In fact, when aircraft temperature measurements are also removed, there is no degradation in the height scores from around day-4 the southern hemisphere extratropics. It is also interesting to note that the bending angles above 10 km provide most of the surface pressure information.

Given the respective observation numbers, it is intriguing to speculate how an order of magnitude increase in the number of GPSRO data would change the impact of the measurements, relative to that of the current conventional network. It would be interesting to investigate this further with observing system simulation experiments, or using ensemble data assimilation techniques. However, the present study has demonstrated how sensitive the GPSRO surface pressure analysis biases are to small changes in the bias characteristics of the observations, NWP background or forward model. Furthermore, we have also shown that the GPSRO observation operator can map temperature biases introduced by other measurements into a surface pressure bias.

Overall, the results suggest that the combined bending angle departure biases need to be smaller than 0.1%, which is currently a very stringent requirement. Obviously, given this situation it would be wrong to be overly reliant on the GPSRO measurements to constrain the surface pressure information, and conventional observation will remain an important component of the observing system. Nevertheless, the GPSRO measurements are likely to become increasingly important in this area as the data numbers rise.

Quantifying the benefit of the advanced infrared sounders AIRS and IASI

TONY McNALLY

THE AIRS INSTRUMENT onboard the NASA-AQUA satellite and the IASI instrument onboard the EUMETSAT-MetOp satellite are arguably the two most sophisticated atmospheric sounders ever flown. Due to their very high-resolution sampling of the infrared spectrum they have the potential to provide more detailed and accurate information about atmospheric temperature and composition than has been possible with previous satellite sensors.

ECMWF, together with other NWP centres, assigned a very high priority (and devoted significant resources) to the successful exploitation of data from AIRS and IASI. Results quickly emerged that clearly demonstrated that the new information brought by these instruments was beneficial to NWP systems and improved forecast skill. On the basis of these results, first AIRS (in 2003) and subsequently IASI (in 2007) became important elements of the operational observing system.

The results of pre-operational trials of AIRS and IASI from a number of NWP centres have been published in the open literature, but more recent evaluations of their impact have been rather limited. In view of the prominent position occupied by these instruments and the fact that the planning process for the next generation infrared sounders is now under way, it was considered timely to perform an extensive and consolidated review of the NWP impact of advanced infrared sounders.

Experiments

The latest experiments have been run with version Cy35r2 of the ECMWF Integrated Forecasting System (IFS), run at T511 horizontal resolution (typically 40 km grid spacing) with 91 levels in the vertical. While this is not the most recent version of the analysis system, it was operational at the time the study began. In respect of the handling of data from AIRS and IASI this version is also rather similar to the current operational scheme – the only difference being that the latter additionally exploits overcast (cloudy) observations from

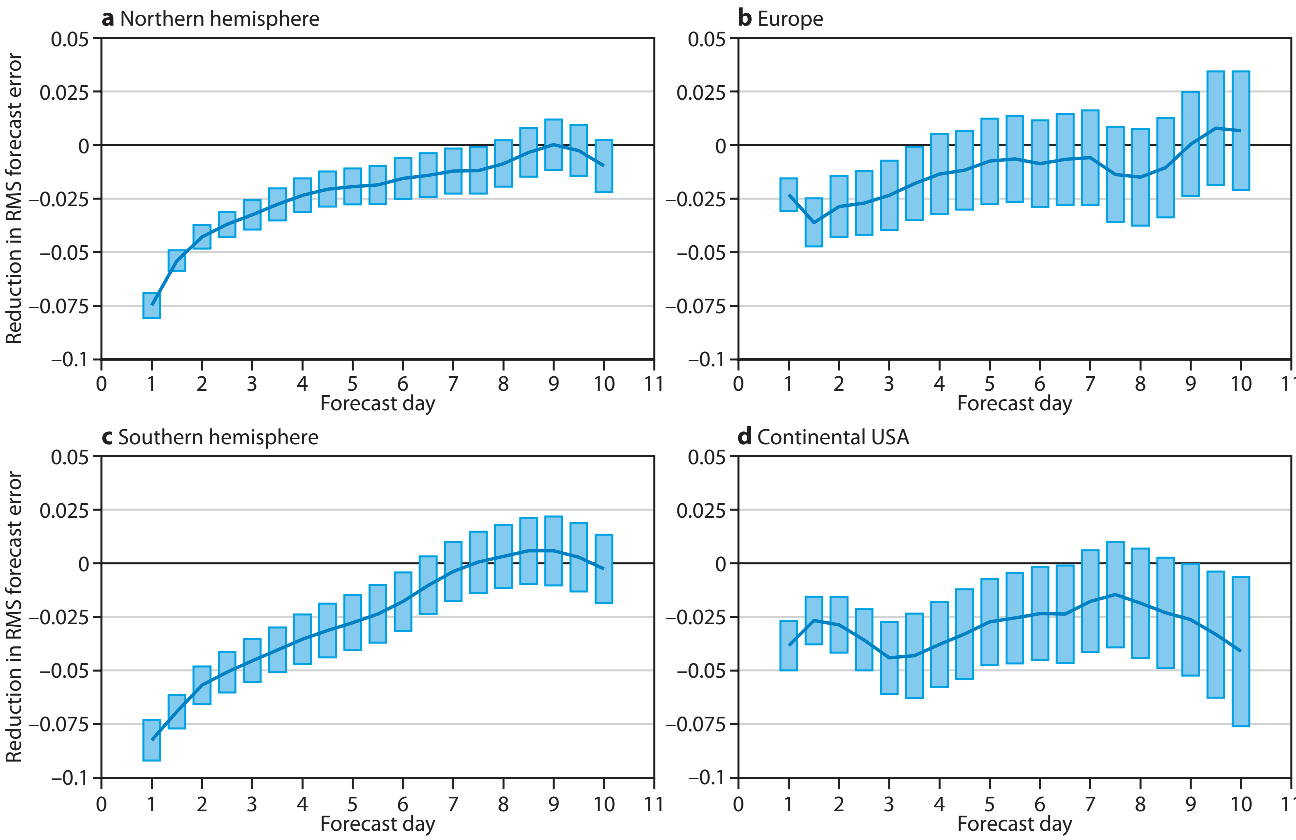


Figure 1 Reduction in the one-year average RMS forecast error for 500 hPa geopotential height when AIRS and IASI are added to a baseline system for the (a) northern hemisphere, (b) Europe, (c) southern hemisphere and (d) continental United States of America. The vertical grey bars indicate 95% confidence intervals on the normalized mean change.

AIRS and IASI. The test period considered is 7 August 2008 to 6 August 2009 and thus covers an unprecedented full continuous calendar year.

Two different types of impact experiment have been run:

- ***Addition experiments***. AIRS and IASI data are added separately and in tandem to a baseline that contains no advanced infrared sounder data (but does contain all other satellite and conventional observations). The primary aim of this is to quantify the benefits brought by the additional availability of these data.
- ***Denial experiments***. AIRS and IASI data are removed individually and together from a control system that otherwise exploits the full global observing system. The primary aim of this is to quantify the cost of losing data from one or both sounders. All forecasts have been verified against ECMWF operational analyses.

Results of adding AIRS and IASI to a baseline system

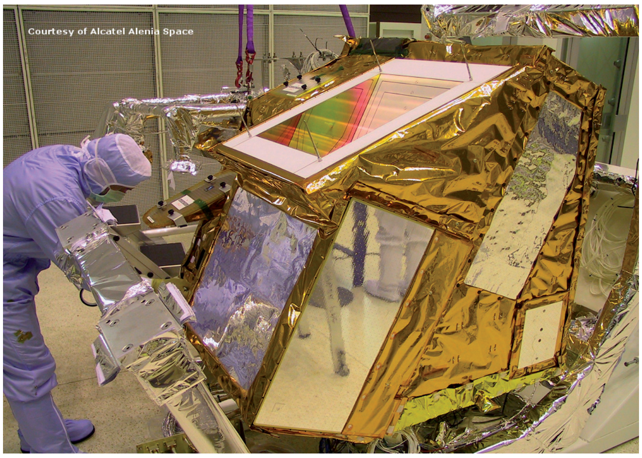
It has been found that the addition of either AIRS or IASI to the baseline both have a clear positive impact upon reducing root mean square (RMS) forecast error for geopotential and humidity. The large-scale hemispheric impact of AIRS is very similar to that of IASI. Both instruments show the largest reduction in the short-range, but there is a clear and statistically significant improvement signal out as far as day 6.

In the United States (US) and European regions the short-range forecast error impact from AIRS and IASI is smaller, but this is because conventional observations determine the local initial conditions very strongly in these data-dense areas and the influence of satellites is less. For the medium-range forecast errors for the US and European areas (where the initial conditions from satellite dominated remote ocean areas are important) there is again a statistically significant benefit when adding either instrument. One possible exception to this is the unexpected result that the addition of IASI appears to have a much weaker medium-range impact over the European region than that of AIRS.

In Figure 1 we see the effect on 500 hPa geopotential forecast scores of adding both AIRS and IASI in tandem to the baseline. In each case the quantity plotted is the reduction in RMS error, normalized by the RMS error of the baseline system. Together the two instruments generally produce a larger impact than that seen when either is used alone. This is an important result for future satellite planning as it suggests that there is a measurable benefit to forecast skill from flying two advanced infrared sounders compared to one.

Results of denying AIRS and IASI from a control system

Experiments where AIRS and IASI are denied from a control system (that contains all available observations) generally support the results of the addition experiments.



The Infrared Atmospheric Sounding Interferometer (IASI) instrument during construction. (Photograph © 2006 Alcatel Alenia Space)

For the hemispheric scores it has been found that the individual removal of either AIRS or IASI degrades the forecast skill and results in larger RMS errors. However, the increase in error from removing a single instrument is much smaller than the corresponding reduction in forecast error when the same single instrument is added to the baseline system (previous section). This indicates that the presence of one advanced infrared sounder is able to partially compensate for the loss of the other. The compensation is such that only the simultaneous removal of both instruments produces a measurable loss of skill in the medium-range for the European and US regions.

Overview of the impact of AIRS and IASI

The impact of AIRS and IASI used either separately or together is very clear over this extended one-year test period. Forecast accuracy improves when these data are added and degraded forecasts result when the instruments are withheld. Results also demonstrate that there is a measurable extra benefit of having two instruments in orbit compared to just one and that a single AIRS or IASI is partially able to compensate for a loss of the other.

Investigations to understand why IASI appears to have little medium-range impact over the local European region are ongoing – this result was unexpected in view of previous studies (*ECMWF Newsletter No. 120*) that have showed IASI producing a clearly positive impact on forecasts over Europe.

Although not discussed here, key diagnostics from the analysis system also highlight the importance of AIRS and IASI. Adding the instruments (separately and together) have been found to improve the fit of analyses to radiosonde observations of temperature, humidity and wind.

These studies generally confirm and consolidate other impact experiments (performed at ECMWF and other centres) which collectively demonstrate that the information brought by advanced infrared sounders is significant.

The Data Handling System

NEIL STORER

WEATHER FORECASTING makes use of, and generates, very large volumes of data: observations, analyses and the results of research experiments, all of which need to be stored for long periods of time. This data represents a valuable asset and an incomparable archive of meteorological information from the past 30 years. It is used worldwide by researchers in meteorological and environmental studies, and is also available for educational and commercial purposes.

ECMWF's Data Handling System (DHS)

For many years ECMWF has operated a dedicated Data Handling System (DHS) in which all ECMWF users can store and retrieve data needed to perform a wide variety of research and development activities. The ease with which data in the DHS can be accessed is regularly commented upon by visiting scientists and other users of the system.

IBM's High Performance Storage System (HPSS) is the underlying data management system in which all of the data in the DHS resides. However users do not use HPSS directly, they access the data via one of two applications, MARS and ECFS, that have been developed by ECMWF (Figure 1):

- MARS (Meteorological Archival and Retrieval System): a unique resource which allows users to access and retrieve a wealth of meteorological data via a meteorological interface.
- ECFS (ECMWF Common File System): a facility which allows users to store data that is not suitable for storing in MARS.

At the middle of 2010, 15 petabytes of primary data existed in the DHS (Figure 2), residing on approximately 18,000 IBM 3592 tape cartridges located in five STK powderhorn silos, along with one hundred IBM tape drives that processed almost 10,000 tape mounts per day. In addition, about 5 petabytes of secondary copies of the most important data were stored on LTO tapes in ECMWF's disaster recovery system. The DHS provides an excellent service to

MARS retrieval example (many of the parameters can be omitted, in which case they default to relevant values):

```
RETRIEVE,
  CLASS    = OD,
  TYPE     = AN,
  STREAM   = DA,
  EXPVER   = 0001,
  REPRES   = SH,
  LEVTYPE  = PL,
  LEVELIST = 1000/850/700/500/400/300,
  PARAM    = 129,
  DATE     = 20100218,
  TIME     = 1200,
  STEP     = 00,
  DOMAIN   = G,
  TARGET   = myfile,
  PROCESS  = LOCAL
```

ECFS retrieval example

```
ecp ec:archived_data mydata_file
```

Figure 1 Examples of the parameters and commands used for MARS and ECFS retrievals.

the users and equipment (such as servers, disk subsystems and tape drives) is added to the configuration each year to ensure that this high level of service is maintained.

New DHS hardware

In the first half of 2009, the evaluation of a competitive tender was carried out for the replacement of two core components of the DHS: the IBM enterprise class tape drives and the StorageTek silos, which, having been in service for nearly 20 years will cease to be maintained at the end of 2010. A contract was concluded with Sun Microsystems Ltd. (now Oracle Corporation) in June 2009.

The replacement system will be installed in yearly phases and will take over completely from the old system later in 2010. Two SL8500 automated tape libraries (ATLs), 90 Sun T10000B tape drives and 6,000 1 terabyte tape cartridges were installed in October 2009. A third ATL, cartridges and over 60 more tape drives were installed in January 2010 and more equipment will be added in the third phase

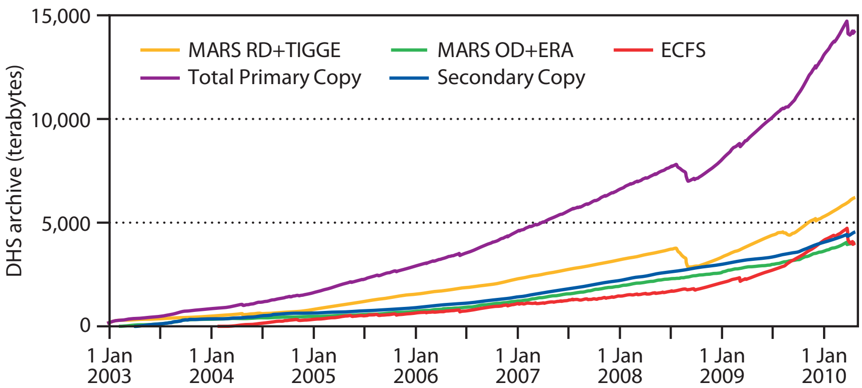


Figure 2 Historical growth in the data archive. MARS RD+TIGGE: Research Department and TIGGE data held on MARS. MARS OD+ERA: Operations Department and reanalysis data held on MARS. ECFS: Data held on ECFC. Total Primary Copy: Total primary data held on MARS and ECFS. Secondary Copy: Copy of Operations Department, reanalysis and e-suite data on MARS, and some ECFS data.

Figure 3 Inside one of the two corridors of an SL8500. Each ATL can house up to 10,000 tape cartridges.

during 2011. Each SL8500 can house up to 10,000 cartridges (Figures 3 and 4).

Within each ATL eight small robots, known as 'handbots', move cartridges between the slots in which they reside and the tape drives (Figure 5). There are four sets of rails running along the inside wall of the ATL and each rail has two independent handbots that move along it. The two corridors within the ATL are connected at the far end in a horseshoe shape, which allows a handbot in one corridor to move all the way along that corridor, past the tape drives that are located at the far end, then into the other corridor.

Handbots can only move horizontally, along the rails, not between them. Should a cartridge, retrieved by one handbot, need to be mounted on a drive serviced by

Figure 4 Construction of the Sun SL8500 ATLs.

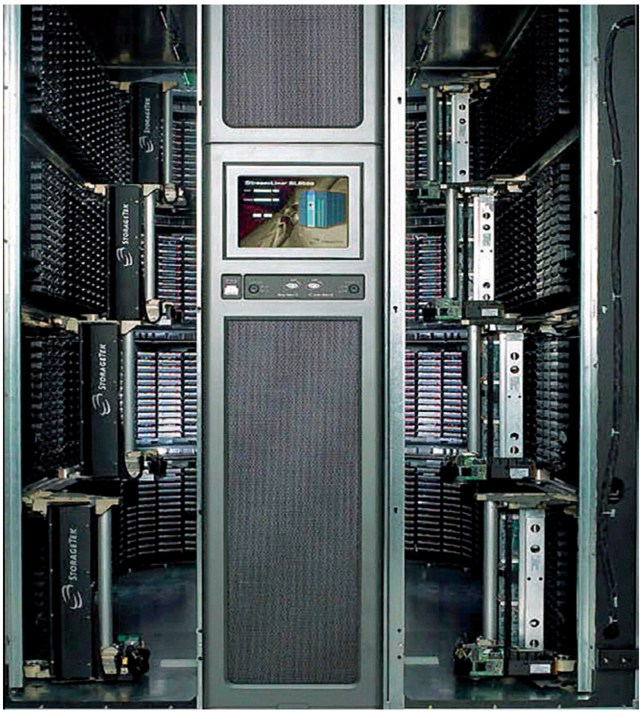


Figure 5 The eight 'handbots', four in each corridor and two on each rail.

another set of handbots then the one doing the retrieving must bring the cartridge to the end of the rail furthest from the tape drives, where an elevator system is used to move it vertically to the rail servicing the relevant tape-drive. A handbot on that second rail then can mount the tape on the drive. It is possible for cartridges in one ATL to be mounted on drives that reside in a different ATL via the use of 'pass-thru ports'. This helps to reduce queuing time when all of the drives in one ATL are in use but some are free in another one.

Migration of data to the new system

Throughout 2010 all of the data on the IBM 3592 tape cartridges residing in the old STK silos will be migrated into this new system. This will be a major exercise since it has to be done carefully, ensuring that the data is copied across correctly, without impacting unduly on the quality of service provided to the normal users of the DHS. Once the migration process has completed, the IBM tape drives and the STK silos in which they reside, will be decommissioned and removed from the site.

In January 2010, ECFS and that part of the MARS service that deals with operational data (MARS-OD) started to use replacement system. At the same time the old MARS-OD data started to be migrated across. This migration completed in March. The migration of ECFS data was delayed until version 7.3 of HPSS was put into production as this has a new file aggregation feature that greatly assists the migration of this type of data. By the end of April 2010 all of the MARS data was migrated.

The STK silos have stood ECMWF in good stead for twenty years. It is hoped that the new ATL complex will prove to be as reliable for the next twenty.

ECMWF Calendar 2010

October 4–6	Scientific Advisory Committee (*39th Session*)
October 6–8	Technical Advisory Committee (*42nd Session*)
October 11–15	Training Course – Use and interpretation of ECMWF products for WMO Members
October 11–13	Finance Committee (*87th Session*)
October 14	Advisory Committee of Co-operating States (*16th Session*)
October 18–19	Policy Advisory Committee (*30th Session*)
October 19–20	Working Group on 'Long-term building and refurbishment requirements'
October 18–27	NWP Training Course – Predictability, diagnostics and extended-range forecasting (originally scheduled for 19–28 April)
November 1–5	14th Workshop on 'Use of High Performance Computing in Meteorology'
November 8–10	Workshop on 'Non-hydrostatic modelling'
December 7–8	Council (*74th Session*)

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

Technical Memoranda

632 **Bonavita, M., L. Raynaud & L. Isaksen**: Esimating background-error variances with the ECMWF Ensemble of Data Assimilations system: the effect of ensemble size and day-to-day variability. *July 2010*

630 **Hersbach, H.**: Sea-surface roughness and drag coefficient as function of neutral wind speed. *July 2010*

629 **Hersbach, H.**: Assimilation of scatterometer data as equivalent-neutral wind. *July 2010*

628 **Heil, A., J.W. Kaiser, G.R. van der Werf, M.J. Wooster, M.G. Schultz & H.D. van der Gon**: Assessment of the real-time fire emissions (GFASv0) by MACC. *July 2010*

627 **Lopez, P.**: Direct 4D-Var assimilation of NCEP Stage IV radar and gauge precipitation data at ECMWF. *July 2010*

626 **Buizza, R.**: Horizontal resolution impact on short- and long-range forecast error. *April 2010*

622 **Takaya, Y., F. Vitart, G. Balsamo, M. Balmaseda, M. Leutbecher & F. Molteni**: Implementation of an ocean mixed layer model in IFS. *March 2010*

621 **Doblas-Reyes, F.J., A. Weisheimer, T.N. Palmer, J.M. Murphy & D. Smith**: Forecast quality assessment of the ENSEMBLES seasonal-to-decadal Stream 2 hindcasts. *April 2010*

ERA Report Series

3 **Dragani, R.**: On the quality of the ERA-Interim ozone reanalyses. Part II Comparisons with satellite data. *May 2010*

2 **Dragani, R.**: On the quality of the ERA-Interim ozone reanalyses. Part I Comparisons with in situ measurements. *May 2010*

Proceedings

ECMWF Workshop on Diagnostics of Data Assimilation System Performance, *15–17 June 2009*.

ECMWF Seminar on Diagnosis of Forecasting and Data Assimilation Systems, *7–10 September 2009*.

Index of past newsletter articles

This is a selection of articles published in the *ECMWF Newsletter* series during the last five years. Articles are arranged in date order within each subject category. Articles can be accessed on the ECMWF public website – www.ecmwf.int/publications/newsletter/index.html

NEWS

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METEOROLOGY

Observations & Assimilation

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

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