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PUBLICATION POLICY

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 The *ECMWF Newsletter* is not peer-reviewed.

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Guidance about submitting an article is available at www.ecmwf.int/publications/newsletter/guidance.pdf

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Realising the vision

In 1904 Vilhelm Bjerknes published a seven page scientific paper in the *Meteorologische Zeitung* entitled '*The Problem of Weather Forecasting from the Viewpoint of Mechanics and Physics*'. This paper presented his vision that weather should be treated as an initial value problem of mathematical physics. Future states should be determined by integrating the governing differential equations, starting from an observed initial state. At that time this was an amazing suggestion not least because then there were few routinely-made observations and, of course, computers had not been invented. If we roll forward to 1953 we find that the state-of-the-art in forecasting gave at best a 12-hour warning of the North Sea surge disaster that led to a large loss of life and extensive damage from flooding – the magnificent tapestry in the ECMWF Council Chamber reminds us of that extreme and disastrous weather event. In 1975 ECMWF was established at a time when the numerical weather predictions of the day might be trusted for at most two or maybe three days ahead.

Wind forward to today and we have recently had a vision of the on-going potential of numerical predictions by looking at the ECMWF forecast for Superstorm Sandy that made landfall at the end of October 2012 at and around New York City. This very successful forecast gave a clear indication of the event more than a week ahead and this is all the more amazing given that it was probably the only hurricane in 100 years to have turned westwards to make such a landfall. Vilhelm Bjerknes was indeed a true visionary and it is no surprise that he was nominated for the Nobel Prize in Physics no less than 54 times (but unfortunately was not awarded it). But it is testament to the power of his vision that when he gave a talk on the topic in the USA in 1905 the Carnegie Institution decided to award him a lifelong grant that funded his research team all through his active career!

Of course we know that many forecasts today are less successful than that for Sandy but it shows us the potential that exists. There is no doubt that people are extremely vulnerable to extreme weather and the related impacts. Being able to provide an outlook, even if rather imprecise, a month or even a season ahead, firming it up at the range of a week or two and then becoming rather certain a few days ahead allows the essential decision-support systems to be put in place to enable us to better cope with such disasters. This is what lies behind the Ready-Set-Go concept of preparedness. Superstorm Sandy shows us that we can add a further link in that chain – 'Now' – because people in New York and elsewhere used social media such as Twitter and Facebook to communicate about what was happening here and now as the storm struck. ECMWF is contributing to links in this chain and that is why the work to advance numerical weather prediction is so important. In this edition of the *ECMWF Newsletter* we summarise some of the detailed activities at ECMWF in 2013 by which we hope to advance even further.

Alan Thorpe

New items on the ECMWF website

ANDY BRADY

Four-year Programme of Activities 2013 – 2016

The Four-Year Programme of Activities provides an overview of the main activities that will be pursued to implement the ECMWF Strategy 2011-2020. It is updated annually and released every January.

- http://www.ecmwf.int/about/programmatic/

The OpenIFS Research Project

The OpenIFS project has the overall aim of promoting ECMWF and the IFS for academic research and teaching. See page 12 for an article about how the OpenIFS is being used.

- http://www.ecmwf.int/research/openIFS.html

Workshop on parametrization of clouds and precipitation across model resolutions

The ECMWF Workshop on '*Parametrization of clouds and precipitation across model resolutions*' was held from 5 to 8 November 2012. This workshop discussed the latest advances in understanding some of the key issues in parametrizing cloud and precipitation processes. See page 9 for a report about the workshop.

- http://www.ecmwf.int/newsevents/meetings/workshops/2012/Parametrization_clouds_precipitation/

Terminology changes for ECMWF's forecasts

As described in *ECMWF Newsletter No. 133*, the terminology that is used to describe ECMWF's forecasts and forecasting system is changing. In the future the medium-range (3–10 day) forecast will be described as comprising two component forecasts – the high-resolution and ensemble forecasts (HRES and ENS). Similarly, aligning with WMO, 'extended-range' will be used to describe forecasts in the range 10–30 days and 'long-range' to replace the use of 'seasonal'. The presentation of our forecasts (e.g. on our website) will be reviewed and, over time, the new terminology and an appropriate organisation will be applied.

- http://www.ecmwf.int/publications/newsletters/
- http://www.ecmwf.int/about/forecasts.html
- http://www.ecmwf.int/products/catalogue/

4th Workshop on the use of GIS/OGC standards in meteorology

ECMWF, the UK Met Office, Météo-France and Deutscher Wetterdienst (DWD) are jointly organising a dedicated 4th workshop on the use of GIS/OGC standards in meteorology. This will be held at ECMWF on 4 to 6 March 2013.

- http://www.ecmwf.int/newsevents/meetings/workshops/2013/GIS-OGC_standards/

Training course: ECMWF/EUMETSAT NWP-SAF Satellite Data Assimilation

The course from 1 to 4 July 2013 is aimed at providing a complete overview of the usage of meteorological satellite observations in operational NWP. It will include a series of lectures and practical sessions covering a range of topics - from fundamental theoretical concepts through to detailed practical implementations in modern state of the art data assimilation systems.

- http://www.ecmwf.int/newsevents/training/2013/nwp-saf/

ECMWF-WWRP/THORPEX workshop on polar prediction

Expansion of human activities in polar regions is leading to more demands for sustained, improved, and integrated observational and predictive weather, climate and water information in support of decision making. Meeting the demand for such services will require the resolution of important gaps in knowledge about polar regions. These issues are to be considered at the workshop which will be held from 24 to 27 June 2013.

- http://www.ecmwf.int/newsevents/meetings/workshops/2013/Polar_prediction/

14th Workshop on meteorological operational systems

The biennial Workshop on Meteorological Operational Systems will be the fourteenth in the series. The workshop, which will be held from 28 October to 1 November 2013, will review recent developments in the use and interpretation of medium and extended range weather forecasts and will address the data management and visualisation requirements.

- http://www.ecmwf.int/newsevents/meetings/workshops/2013/MOS14/

Workshop on efficient representation of hyperspectral infrared satellite observations

By making radiance measurements in many thousands of channels, hyperspectral infrared satellite observations provide comprehensive and highly detailed information on the atmospheric state and composition. This workshop will focus on optimizing dissemination practices to allow data compression with minimal information loss, together with the development of novel data assimilation techniques that can efficiently convey this information to the analysis. It will be held from 5 to 7 November 2013.

- http://www.ecmwf.int/newsevents/meetings/workshops/2013/NWP-SAF_satellite_observations/

ECMWF Web Site Redesign (Web2013 Project)

During 2012/2013, ECMWF is undertaking a significant redesign of its web site. If you would like to help us during this process, please register your interest.

- http://www.ecmwf.int/web2013/

ECMWF's plans for 2013

ALAN THORPE

After extensive discussion with its advisory committees and Council, each year ECMWF updates its four-year programme of activities and from that we produce a more detailed annual plan for the upcoming year; here we present aspects of the resulting Annual Plan 2013. The backdrop to these activities is the delivery of ECMWF's Strategy 2011-2020. In addition, during last year we developed a new integrated framework to describe ECMWF's activities. This framework involves eight key objectives that cover all aspects of the work of the Centre.

Here we present those aspects of the annual plan that will be of particular interest to external readers of the *ECMWF Newsletter*. In this brief article there is only space for some of the highlights to be described; the work of the Centre relies on the dedication and expertise of all of its staff.

ECMWF's eight key objectives

- ***Forecasting system development***: improve the forecasting system through development of model components and techniques to be introduced in upcoming new model versions.
- ***Science and innovation:*** carry out innovative research with a long term goal of improving and developing forecasting techniques.
- ***Data, products and services:*** develop state-of-the art forecast products, data services, evaluation tools and visualisation for users (including those for other aspects of the natural environment).
- ***High-performance computing:*** ensure provision of world-leading high performance computing and associated specialist facilities to meet ECMWF's and Member States' needs.
- ***Human resources and management:*** develop and implement the strategy, policies and processes necessary to ensure that ECMWF attracts, retains and motivates the staff necessary to achieve our goals.
- ***Infrastructure:*** provide the physical infrastructure, IT and business services needed to support its staff and the delivery of our goals.
- ***Finance and control:*** develop and utilise finance and management information systems to meet ECMWF's reporting obligations, provide an effective control environment and support informed decision-making.
- ***Partnership:*** develop effective partnerships with meteorological services, universities and other organisations that help ECMWF to deliver its goals.

Forecasting system development

In the early part of the summer of 2013, we expect to introduce a new model cycle with 137 vertical levels and some improvements to physical parametrizations. This will be followed up in the autumn with a new model cycle that increases the number of vertical levels, and couples the atmosphere and oceans from the start, in our ensemble forecasts; in addition the number of members in the Ensemble of Data Assimilations (EDA) will increase to 25. Finally work will begin in 2013 to prepare for the introduction of a new model cycle in 2014 that includes extending the period over which the data assimilation is carried out (the so-called window) to 24 hours from the current 12 hours.

Science and innovation

Making advances in NWP science is fundamental to improving the accuracy and reliability of ECMWF's forecasts. As part of our on-going programme designed to reduce the errors in the initial conditions, in 2013 we will focus on enhancing the EDA and 4DVAR so as to improve the use of conventional observations, including the ingestion of new ground-based and non-conventional observations. Another fundamental aspect is the quest to improve the representation of physical processes in our models. A focus in 2013 will be on improving surface and boundary layer processes, moist processes (particularly those associated with drizzle), aerosol effects on radiative fluxes, mass conservation and upper ocean processes (including waves, sea ice and dissipation).

To assess areas ripe for improvement our programme of diagnostic research on forecast quality will concentrate on extreme weather. We will also be investigating predictability by studying the impact of flow regimes, developing diagnostics of seasonal simulations, and examining the impact of resolution and using multi-models. Finally we will progress further with monitoring the climate by producing the 20th century reanalysis, preparing a new reanalysis of the satellite era (ERA-SAT) and developing the capability to produce a coupled ocean-atmosphere (including composition) reanalysis.

Data, products and services

ECMWF produces weather forecast information that is widely used by the national meteorological services as well as many other customers and stakeholders. Our user focus is a vital component of ECMWF's activities and we aim to develop aspects of the usability and utilisation of the forecasts. ECMWF will improve the flexibility and scalability of the way products are delivered to customers by developing a new version of the product generation software (ProdGen) that is ready for pre-operational testing. We will roll out a new licensing tool for use by Member States, redesign the user interface of the products catalogue and the underlying database, and prototype extra products that Member States would like to have available. Also we aim to augment data services by developing an interactive web application in support of Member States' licensing of ECMWF data, and by reviewing policies, systems and procedures for accessing the archive. The operational implementation of new pre-processing software on new hardware will be completed as will the validation of the new ecRegrid interpolation technique.

Partnerships

Collaboration and partnerships are fundamental ways in which ECMWF operates. In 2013 we aim to pursue many opportunities for possible new co-operation with meteorological services and organizations inside and outside of Europe. ECMWF is active in winning research grants from the European Union and elsewhere, and also it is becoming significantly involved in the EU Copernicus Services (Copernicus is the new name for what was previously called Global Monitoring for Environment and Security, GMES). These services involve operational global analyses and forecasts of, for example, atmospheric composition, the marine environment, climate change and land surface properties. This year we are preparing for the MACC-II project to transition to the operational Copernicus atmosphere monitoring service after July 2014.

Here are some additional examples of critical activities at ECMWF in 2013 contributing to the other four objectives that are of general interest.

- ***High-performance computing*** – procure and begin installation of a new High-Performance Computing Facility, enhance the Data Handling System, and implement a new Regional Meteorological Data Communication Network.
- ***Human resources and management*** – harmonise the terms and conditions of employee contracts, introduce a re-organisation of our departmental structure, and continue to implement our integrated human resources strategy.
- ***Infrastructure*** – establish ECMWF's requirements for relocation in the Reading area.
- ***Finance and control*** – develop management information reports and accrual accounting, and develop an integrated approach to business continuity planning.

This brief overview cannot describe all the exciting and important activities associated with each of the objectives. These include many on-going activities of the Centre that will continue to be vital to the success of ECMWF. I am confident that our innovative and challenging plans for 2013 will ensure that ECMWF continues to be the world leader in global medium-range weather forecasting.

Republic of Slovenia becomes ECMWF's twentieth Member State

MANFRED KLÖPPEL

On 1 December 2012, the Republic of Slovenia became ECMWF's 20th Member State. As a result, Slovenia was represented at the 78th session of the ECMWF Council which was held on 4 and 5 December.

As a Member State, Slovenia became a member of the pan-European partnership in numerical weather prediction at ECMWF. It has full voting rights at the Council, which is the top-level governing body of ECMWF. Also, a portion of the Centre's supercomputer and data archive resources will be allocated to Slovenia for its own use and Slovenia will have access to all ECMWF products and tools.

François Jacq, President of the ECMWF Council, said: "I am pleased to welcome the Republic of Slovenia as a new Member State and I am looking forward to working with representatives from Slovenia in future."

Klemen Bergant, Director of the Slovenian Meteorological Office and Permanent Representative of Slovenia with the World Meteorological Organization (WMO), said: "I would like to thank the ECMWF Council for having unanimously agreed on the accession of Slovenia to the ECMWF Convention. Being represented at this Council session for the first time is an important milestone for the Republic of Slovenia.

Establishing closer links to European centres of excellence, such as ECMWF, is one of the key strategic goals of the government of the Republic of Slovenia."

Alan Thorpe, Director-General of ECMWF, said: "I am proud that the Republic of Slovenia became ECMWF's twentieth Member State. The Centre will continue and even intensify the already existing close collaboration with our colleagues in Slovenia."

Raising the flag of the Republic of Slovenia. The meeting of the ECMWF Council in December 2012 provided a fitting occasion to raise the flag of the Republic of Slovenia at the Centre.

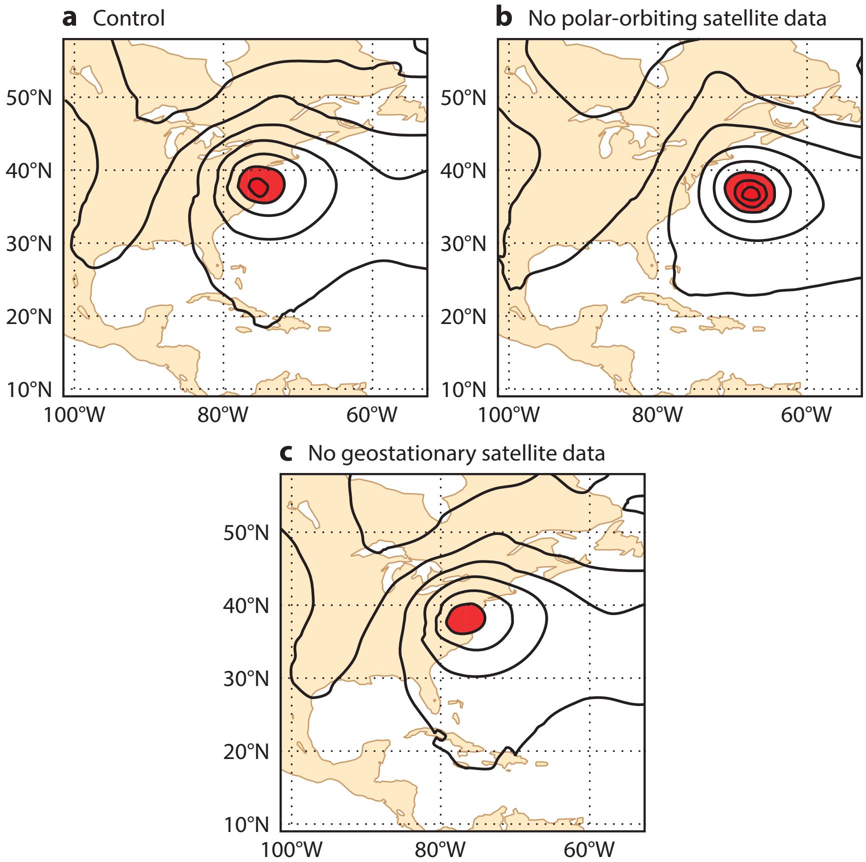
Polar-orbiting satellites crucial in successful Sandy forecasts

TONY MCNALLY

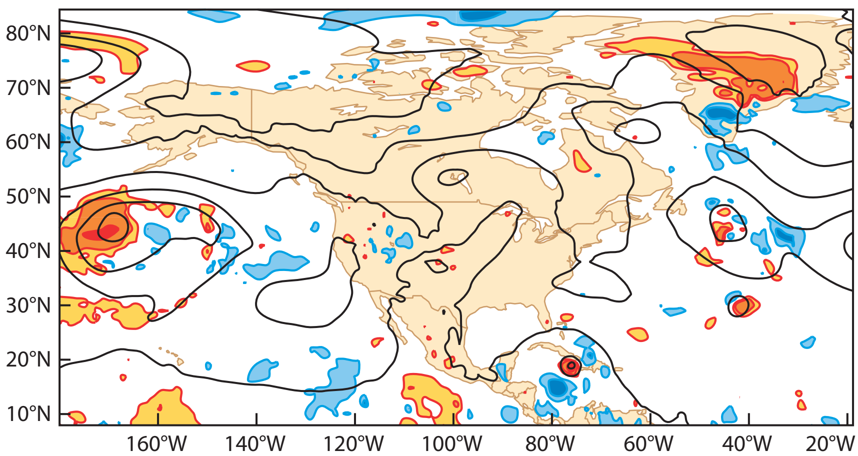
The excellent forecasts made by ECMWF predicting the devastating landfall of Hurricane Sandy attracted a great deal of publicity and praise in the immediate aftermath of the event. The almost unprecedented and sudden 'left hook' of the storm towards the coast of New Jersey was attributed to interactions with the large-scale atmospheric flow. This led to speculation that satellite observations may play an important role in the successful forecasting of this event.

To investigate the role of satellite data a number of experiments have been performed at ECMWF where different satellite observations are deliberately withheld and forecasts of the hurricane re-run. In each denial experiment the assimilation system cycles for five days without the withheld observations prior to re-launching the key forecast from 00 UTC on 25 October. All tests are performed at full operational resolution (T1279), but use a standard 12-hour 4DVAR system with long cut off rather than the 'early-delivery' suite.

The first figure shows five-day forecasts of mean sea level pressure valid at 00 UTC on 30 October for (a) the control (all operational data used), (b) a system where polar-orbiting satellite data is withheld and (c) where geostationary satellite data is withheld. We see the striking result that without polar-orbiting satellites the ECMWF system would have given no useful guidance five days ahead about the time that the storm would make landfall on the New Jersey coast. Instead the hurricane is predicted to stay well offshore in the Atlantic and actually goes on to hit the Nova Scotia coast 36 hours later. In contrast, without geostationary satellites the correct landfall of the storm is still reasonably well predicted albeit with a slight timing shift compared to the control forecast.



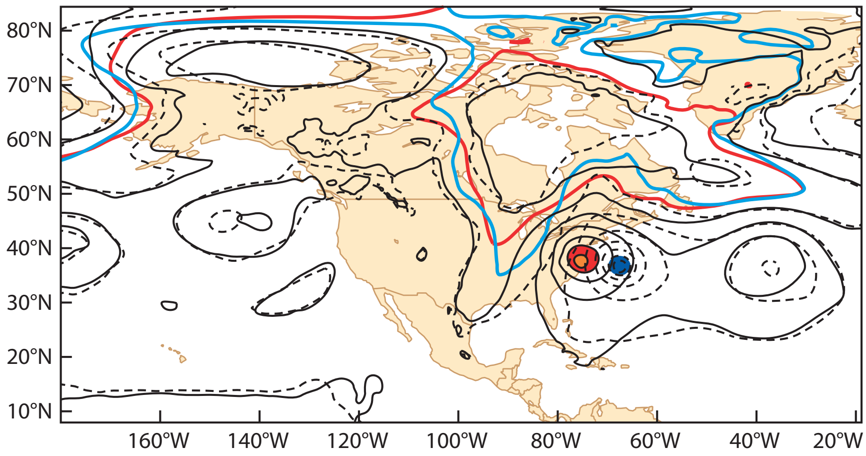
1: Forecasts of Hurricane Sandy. Five-day forecasts of surface pressure for Hurricane Sandy launched from 00 UTC on 25 October and valid at 00 UTC on 30 October for (a) the control system with all data, (b) the system where polar-orbiting satellite data is withheld and (c) the system where geostationary satellite data is withheld. Contours are at 10 hPa intervals and red shading indicates pressure less than 980 hPa.



2: Changes to the forecast initial conditions. Changes to the initial conditions at 00 UTC on 25 October (surface pressure) when polar-orbiting satellite data had been withheld from the assimilation system since 20 October overlaid with the surface pressure of the control (black contours). Red shading indicates a change (increase) of more than 2 hPa.

The changes to the forecast initial conditions that result from the denial of data from polar-orbiting satellites are shown in the second figure. Differences compared to the control in the immediate vicinity of the storm are rather modest - with just a 1 hPa to 2 hPa weakening of the original cyclone near Cuba. In the North Pacific the absence of this satellite data causes a weakening of an extra-tropical depression - again by just 1 to 2 hPa. However, this change in the North Pacific grows rapidly and five days later results in a significant amplification of the large-scale trough/ridge wave structure surrounding Hurricane Sandy as shown in the third figure. Under these modified conditions the forecast fails to predict the sudden westward turn of the storm.

Additional experiments show that the damage caused by the loss of the polar-orbiting satellite data can be mitigated by the use of informed background errors. Inflated background errors from an Ensemble of Data Assimilations (EDA) that better reflect the degraded observing system recovers some (but not all) of the skill of the control system. These results will be reported in a subsequent *Newsletter* article.



3: Impact of denial of polar-orbiting satellite data. Five-day forecasts of Hurricane Sandy for the control (black solid and red contours) and for the system with no polar-orbiting satellite data (black dash and blue contours). The 1026 hPa contour line has been highlighted to illustrate changes to the trough – ridge wave structure around the storm. Otherwise the contours are at 10 hPa intervals and red/blue shading indicates pressure less than 980 hPa.

The fact that the ECMWF forecast system would have failed to predict the course of Hurricane Sandy if polar-orbiting satellite data had not been available is a dramatic illustration that underlines the importance of these observations for accurate medium-range weather forecasting.

Satellite data provides unique information on the large-scale atmospheric conditions over areas that would otherwise be unobservable - information which in this case proved crucial.

ERA-20C production has started

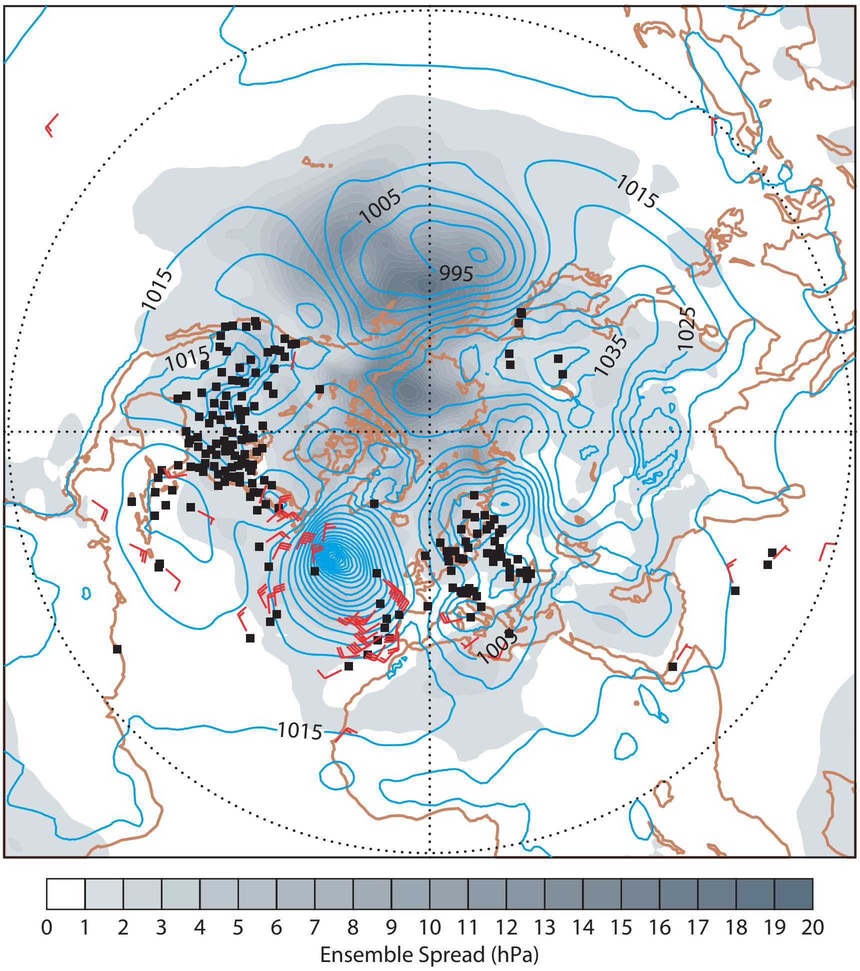
DICK DEE

Production of ERA-20C, a new reanalysis of the period 1900–2010, is progressing well on ECMWF's recently installed IBM Power7 clusters. ERA-20C uses a 10-member Ensemble of Data Assimilations (EDA) to generate 3-hourly global estimates of surface and upper-air parameters at a spatial resolution of approximately 125 km on 91 vertical levels (T159L91). The production uses six parallel computing streams, each covering a 20-year segment of the reanalysis period; the overlaps are needed to prevent discontinuities in the combined 111-year data set. The production streams have been optimised for efficiency and robustness; on a typical day, more than 2000 variational analyses must be completed in order to maintain the production schedule. The entire ERA-20C data set will occupy approximately 700 Terabytes, and should be available to users by the end of 2013.

ERA-20C uses the Integrated Forecasting System (IFS Cy38r1) supplied with model forcing and boundary conditions appropriate for climate integrations (see *ECMWF Newsletter No. 133*, p3). The reanalysis assimilates conventional observations of surface pressure and marine wind, obtained from well-established climate data collections (the International Surface Pressure Databank, ISPDv3.2.6, and the International Comprehensive Ocean-Atmosphere Data Set, ICOADSv2.5). The combined input dataset for ERA-20C contains approximately 1 billion observations from 2 million distinct ships, buoys, and land stations.

Prior to production, a comprehensive data analysis was carried out to detect possible break points and bias shifts in the data series for each identifiable platform. This information is used by the ERA-20C data assimilation system to develop meaningful bias adjustments for the observations.

The configuration of the EDA system used in ERA-20C differs from the ECMWF operational configuration in several respects. First, an ensemble of systematically different but equally plausible estimates of sea-surface temperature and sea-ice evolution, taken from the Met Office Hadley Centre's new HadISST2 product, are used to construct the EDA perturbations. This is intended to account for a key component of uncertainty in the observed 20th-century climate. Second, the EDA was modified to periodically recalculate the background error covariances needed for



The New York Times
Published: February 16, 1899
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TERRIFIC STORMS AT SEA

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of hurricane force, and seas swept her decks repeatedly. So fierce was the wind that the boat drifted before the gales and was barely able to keep steerage way. She anchored outside the bar late Sunday afternoon. The cable parted and she lost her anchor, together with 100 fathoms of chain. Then the great snowstorm drove her 150 miles off the shore. She succeeded in getting back late on Tuesday night.

The French liner La Bretagne, from Havre, came in a little before noon yesterday, with 58 cabin and 225 steerage passengers. She left Havre on Feb. 4, and two days later she encountered a fierce gale, which soon raised tremendous seas. This lasted until Feb. 12, and during this time the vessel had to be slowed down. The following day heavy head seas were encountered, but the steamship proved herself a stanch craft in heavy weather. She had hard work in breaking the ice while getting into her slip.

Weather situation on 3 February 1899. The map shows the locations of all available surface observations in the northern hemisphere during a 24-hour period, on 3 February 1899 (black dots: surface pressure; red vanes: 10-metre winds). Also shown are the 12 UTC surface pressure (hPa) analysis (ensemble mean: blue contours) and a measure of uncertainty (ensemble spread: grey shading). Note the very deep low-pressure system in the North Atlantic, reconstructed based on peripheral observations, and the large uncertainties in the active but poorly observed North Pacific.

the variational analysis. This change renders the data assimilation system fully self-sufficient and adaptive to the evolution of the observing system. Finally, the 4DVAR analysis window was extended to 24 hours in order to improve the performance of the data assimilation in sparsely observed situations.

To illustrate the system's ability to reconstruct interesting synoptic events, the figure shows a map of the available observations on 3 February 1899 with the corresponding reanalysis of surface pressure. The contours indicate the ensemble mean sea-level pressure analysed at 12 UTC on 3 February 1899, in a stereographic projection of the northern hemisphere. The spread of the ensemble is represented by grey shading. Observations of surface pressure and wind are mostly concentrated in North America and Europe.

The analysis is able to reproduce a large and very dangerous storm in the North Atlantic, which caused a great deal of damage and distress, as documented in newspaper articles at the time.

ecCharts service

SYLVIE LAMY-THÉPAUT, CIHAN SAHIN, BAUDOUIN RAOULT

ECMWF has developed a new suite of web applications called ecCharts to provide fast and easy access to its forecast data in graphical form. This new service has had 24/7 support since 10 October 2012. The service is becoming increasingly popular and has received good feedback.

The main purpose of ecCharts is to provide a web application giving access to ECMWF's medium-range forecast data in its native resolution as soon as it is available for dissemination. The rich web user interface offers an interactive set of tools to display and explore the current meteorological situation in far greater detail than has previously been possible on ECMWF's web site. Also ecCharts complements the Metview meteorological desktop application, which allows users to retrieve, manipulate and visualise any archived data on their own desktop.

ecCharts offers three applications:

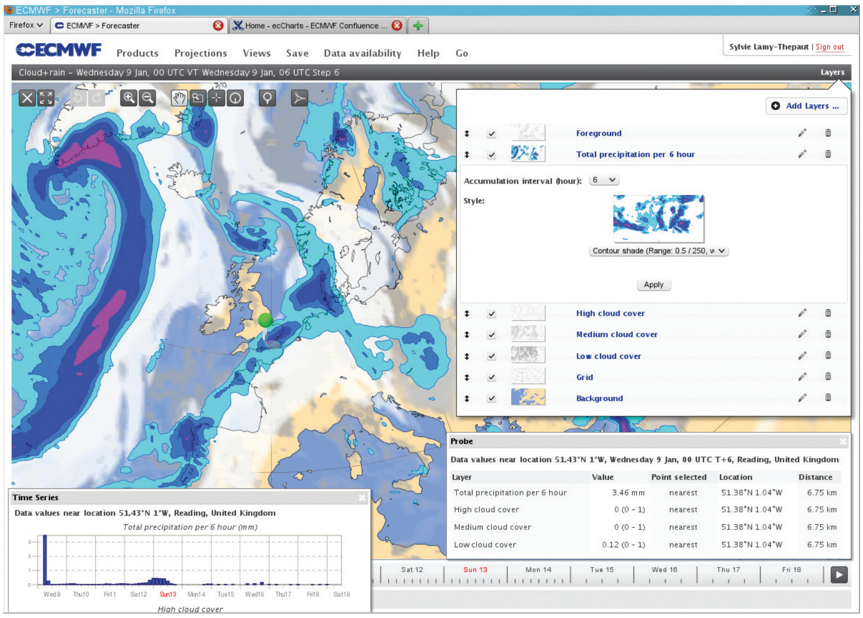
- ***ecCharts/forecaster*** provides an interactive web interface for exploring ECMWF forecast data.
- ***ecCharts/dashboard*** allows users to organise their favourite products.
- ***ecCharts/WMS*** implements the Open Geospatial Consortium (OGC) standard technological approach to allow ECMWF graphical products to be embedded in other meteorological workstations.

All these applications are based on the same service-oriented architecture, and give access to the same high-resolution data.

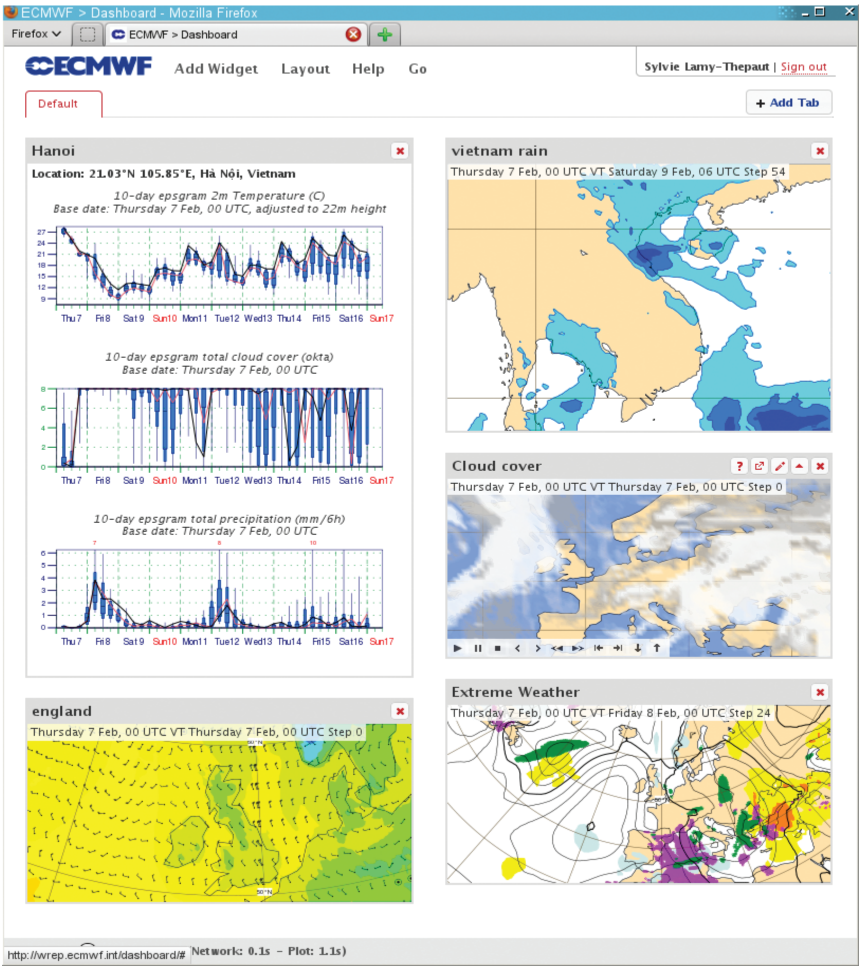
ecCharts offers users the possibility to browse the ECMWF products catalogue. A product is the ecCharts basic concept – it is made from layers. Each layer can be tailored using a dialogue to allow the user to change aspects such as the threshold for probabilities, or the accumulation interval for accumulated parameters such as precipitation. They can also choose a visual style from a pre-defined set. Once the user is satisfied, the result can be saved in the user's own catalogue, and it can be reused later in the ecCharts/forecaster or ecCharts/dashboard applications.

The user can navigate, zoom, pan and animate these two-dimensional high-resolution products without any restriction. Some tools are also available to help analyse the meteorological situation by probing the data for a given location such as time series, EPSgrams and extreme weather information.

One of the challenges is to offer a seamless web experience. This relies strongly on the response time of the service and the network quality. Each step of the product generation process has been carefully designed to optimise the response time of the application



The ecCharts/forecaster application. The maximum space is allocated to the graphics. The layer dialogue shows the configuration options for the displayed product. Floating windows show related information such as time series, EPSgrams or probe (i.e. data values at a specific point).



The ecCharts/dashboard application. The users can organise and configure their favourite products in a set of folders presented as tabs at the top of the user interface.

and minimise the network traffic without degrading the quality of the final product.

Each product layer requires access to high-resolution data, which is then used to perform computations and apply techniques for visualisation. To optimise the creation time, the layers are created in parallel, cached and put together to create the final product.

Each visual style has been carefully chosen to emphasize the feature presented in the layer without overhead. Some studies are also being carried out to improve the visualisation and the interpretation of the ensemble prediction data.

A lot of efforts have been put into our ECMWF Magics++ library to optimise the layer rendering and to extend the visualisation capabilities. The contouring algorithm has been optimised and multi-threaded to improve the speed and reduce the size of the output without losing the quality or degrading the data, or restricting the flexibility of the user interface. These efforts have allowed us to generate, render and deliver most of our products in less than four seconds, providing a smooth web experience.

Another challenge is to make the system easily extendable to add new products and integrate new requirements from forecasters. ecCharts's service-oriented architecture simplifies the product generation by separating data access, computation and visualisation processes. Each of these processes can be developed modularly. This enables the offering of more diverse and complex products (for example, the probability of combined events and spaghetti plots), the extension of some of our popular products (e.g. EPSgrams) and the integration of new visualisation methods (such as tephigrams).

ECMWF will collect requests for additions to the products catalogue and these will be reviewed annually at the Forecast Products Users' Meeting and the Technical Advisory Committee to help set priorities for development. ECMWF has created a support web page for this purpose. It is accessible by following the navigation in ecCharts user-interface: ecCharts>Help> EcCharts. Product updates are performed twice a year in June and November.

We would like to encourage the forecasters in our Member and Co-operating States to use ecCharts and provide us with feedback on the technical performance. Also we would appreciate receiving requests for product updates to ensure that ecCharts always stays relevant to forecasters' needs.

Visit us at:

- http://eccharts.ecmwf.int/forecaster/

Also and our documentation can be found at:

- http://software.ecmwf.int/wiki/display/ECCHARTS/Home

You can make a request for new products at:

- http://software.ecmwf.int/wiki/display/ECCHARTS/Request+new+product+or+feature

Improving cloud and precipitation parametrization

RICHARD FORBES,
ANTON BELJAARS

A workshop on the '*Parametrization of clouds and precipitation across model resolutions*' was held at ECMWF between 5 and 8 November 2012. The ECMWF strategy for the development of physical parametrizations over the next decade places particular emphasis on moist physics and it was timely for a workshop to discuss the latest advances in research and development on this topic. There are still many questions about how best to parametrize microphysical processes and represent the hydrological, radiative and dynamical impacts of cloud and precipitation across an increasing range of model resolutions, from the global to the convective scales.

The organisation of the workshop focussed on three themes:

- The appropriate level of complexity and numerical formulation of cloud and precipitation microphysics parametrizations.
- How to represent the impacts of sub-grid heterogeneity efficiently and consistently across a range of model resolutions.
- How to get the most benefit from observations with an emphasis on evaluating and constraining cloud and precipitation processes.

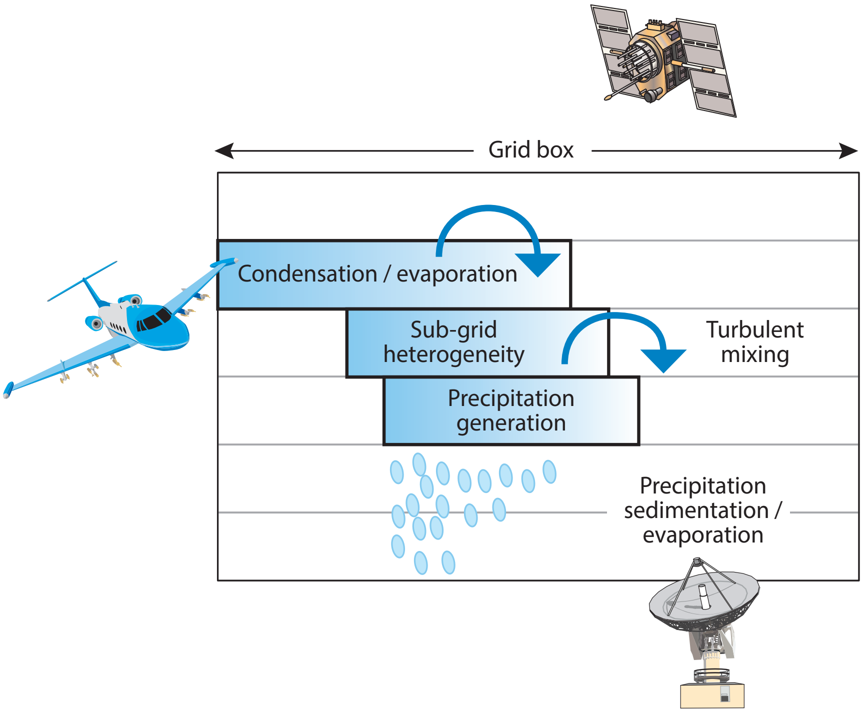
A series of presentations from leading experts in the field described the state-of the-art of cloud parametrization at a range of model resolutions as well as the use of new observational data sets and novel techniques for evaluating cloud prediction and process parametrization. This was followed by three working groups tasked with summarising the current status and formulating recommendations for each of the three workshop themes.

There were many recommendations from the working groups, but some of the key outcomes are as follows.

- The complexity of microphysics in the ECMWF operational NWP model is appropriate for global-scale NWP at the current time, although alternatives to the split ice/snow category representation of the ice phase should be considered given the uncertainties related to ice nucleation and ice autoconversion.
- For NWP the role of aerosol-cloud interactions in affecting the skill of precipitation forecasts has not yet reached a consensus and further research should be carried out in this area.
- There should be consistency of microphysical assumptions across the model parametrizations (clouds, radiation, assimilation), although this may require an increase in complexity.

Participants in the workshop on 'Parametrization of clouds and precipitation across model resolutions'. The workshop brought together more than 40 scientists from across Europe, North America and elsewhere to discuss progress, exchange ideas and provide recommendations for the direction of future cloud parametrization development at ECMWF and in the wider research community.

- Improved vertical resolution should be considered to better represent thin tropospheric and boundary layer clouds and melting layer processes.
- Sub-grid schemes that represent heterogeneity consistently with a defined probability density function (PDF) of, for example, total water have many attractions, but there are still uncertainties in how to represent the ice phase, mixed phase and precipitation processes. More research should be carried out in this area, but a hybrid approach targeting the benefits of both the current prognostic cloud fraction and PDF approaches could be the best way forward.
- High-resolution Cloud Resolving Models (CRMs)/Large Eddy Simulations (LES) combined with observations should be used more rigorously in order to provide information on sub-grid heterogeneity and help to formulate source and sink terms for cloud parametrization in lower resolution models.
- More should be made of the synergy of different observation types (radar, lidar and passive radiation), simultaneously evaluating cloud properties, radiative fluxes and precipitation to reduce compensating errors in models.
- Model evaluation should include a comparison of statistical relationships between different variables to focus on individual parametrizations (e.g. drizzle versus liquid water path to inform autoconversion and accretion parametrization).
- Skill metrics based on cloud (using radar and lidar) and atmospheric radiation fluxes should be routinely produced and may provide a more sensitive measure of improvements in skill than the traditional large-scale measures.



A schematic of some of the issues for cloud and precipitation parametrization. The workshop addressed three themes (a) representation of microphysical processes, (b) representation of sub-grid heterogeneity of cloud and precipitation and (c) evaluation of cloud parametrization with ground-based, satellite and in situ aircraft observations.

Presentations from the workshop, the working group reports and recommendations can be found at

- http://www.ecmwf.int/newsevents/meetings/workshops/2012/Parametrization_clouds_precipitation

Forecast performance 2012

ERIK ANDERSSON, DAVID RICHARDSON

Each year, comprehensive verification statistics are prepared to evaluate the accuracy of the forecasts. A summary of verification results is presented to ECMWF's Technical Advisory Committee. Their views about this year's performance of the operational forecasting system are given in Box A.

ECMWF has begun a routine comparison of the precipitation forecast skill of ECMWF and other centres for both the high-resolution forecast and the ensemble forecasts using the TIGGE data archived in the Meteorological Archival and Retrieval System (MARS). Results using ECMWF's headline scores for precipitation for the last 12 months show a consistent clear lead for ECMWF with respect to the other centres (Figure 1). The headline scores are SEEPS (Stable Equitable Error in Probability Space) for the high-resolution forecast and CRPSS (Continuous Ranked Probability Skill Score) for the ensemble.

Compared to other global models, the ECMWF precipitation forecast shows a relative weakness in the first day of the forecast. It is most visible in the scores for Europe but can also be seen in the extra-tropics in general (Figure 1a). While ECMWF has the best forecast from day 2 onwards, it drops behind the Met Office model at day 1 during the non-convective season. This does not occur in the tropics, where the lead of ECMWF relative to the other models is consistent throughout the six-day forecast range.

The relative weakness of extra-tropical ECMWF SEEPS scores at day 1 is related to an over-forecasting of light precipitation events when no precipitation was observed. The frequency distribution of ECMWF forecasts at day 2 is closer to the observed distribution than it is at day 1. Both the convective and the large-scale part of the precipitation forecast contribute to the problem. This behaviour (too often forecasting light precipitation at the short range) is not so apparent for the models from the UK Met Office or JMA (Japan Meteorological Agency). The model developers

Overall view of ECMWF's Technical Advisory Committee, 18–19 October 2012 **A**

With regard to its overall view of the operational forecasting system the Committee:

congratulated ECMWF on the very high performance level of its weather forecasting system and the reliability of its product delivery service;

i. took note of ECMWF's continued world leading position in medium-range forecasting and encouraged ECMWF to continue developments to maintain this lead;
ii. welcomed the introduction of the scorecard to summarise the impact of new cycles and publication of this together with additional information on a dedicated web page for each new model cycle, together with the provision of real-time test data;
iii. with respect to the assimilation system, noted with interest the improvements resulting from the introduction of new background error statistics and the increased quality of the snow analysis;
iv. welcomed the recent improvements to the model, in particular the modifications to convection and clouds which resulted in better precipitation forecasts, while noting that light precipitation still occurs too often in the model;
v. congratulated ECMWF for forecasting the genesis and accurately predicting the track and intensification of tropical storm Isaac into a category 1 hurricane just before the landfall near New Orleans in August 2012;
vi. acknowledged the improvement of the monthly forecasts while noting the challenge with capturing regime changes beyond two weeks ahead, and encouraged ECMWF to continue to develop its capability in regime change prediction;
vii. appreciated the extension of the EFI to include additional parameters and forecast steps and noted the high skill of the EFI in predicting severe weather events several days ahead, for instance heavy rainfall in western Europe in April 2012 or heat wave in south-east Europe in August 2012;
viii. expressed its appreciation with regard to the introduction of seasonal forecasting system 4;
ix. welcomed ECMWF's efforts to provide a better understanding of the performance in forecasting weather regimes as part of the new clustering scheme;
x. appreciated ECMWF's in-depth study of occasional poor forecasts over Europe ("busts");
xi. appreciated ECMWF responsiveness to Member State concerns, for instance the successful ECMWF efforts to improve the cloud scheme to correct 2 m temperature cold bias in winter over northern European countries, whilst noting that there are still some problems in the spring in Nordic regions;
xii. noted with satisfaction that the ecCharts interactive web-based service for forecasters is now supported 24 hours per day and 7 days per week and that several new parameters have been added to ecCharts in response to Member State requests;
xiii. encouraged ECMWF to continue to develop verification procedures that relate to weather impact (rainfall, wind, temperature) including for severe events, and to understand local variations in performance.

at ECMWF are working on a model upgrade to address this issue, scheduled for implementation later this year.

ECMWF Newsletter No. 128 contains an article about the SEEPS score used for the deterministic verification of the precipitation forecasts.

The complete set of annual results is available in *ECMWF Tech. Memo. No. 688* on '*Verification statistics and evaluations of ECMWF forecasts in 2011–2012*', downloadable from http://www.ecmwf.int/publications/library. This document presents recent verification statistics and evaluations of ECMWF forecasts (including weather, waves and severe weather events) along with information about changes to the data assimilation/forecasting and post-processing system. Also the performance of the monthly and seasonal forecasting systems is assessed.

FURTHER READING

Verification pages have been created on the ECMWF web server and are regularly updated. Currently they are accessible at the following addresses:

Medium range: http://www.ecmwf.int/products/forecasts/d/charts/medium/verification/

Monthly range: http://www.ecmwf.int/products/forecasts/d/charts/mofc/verification/

Seasonal range: http://www.ecmwf.int/products/forecasts/d/charts/seasonal/verification/

Note: All forecasting system cycle changes since 1985 are described and updated at:
http://www.ecmwf.int/products/data/operational_system/index.html

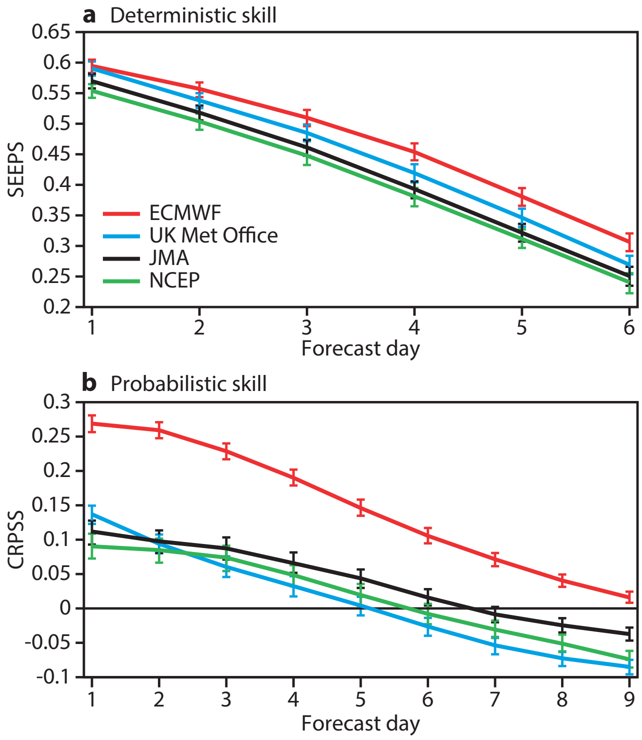


Figure 1 Comparison of precipitation forecast skill for ECMWF, UK Met Office, JMA (Japan Meteorological Agency) and NCEP (National Centers for Environmental Prediction) using the supplementary headline scores for precipitation: (a) deterministic skill (SEEPS) and (b) probabilistic skill (CRPSS). Curves show the skill computed over all available synoptic stations in the extra-tropics for forecasts from August 2011 to July 2012. Bars indicate 95% confidence intervals.

Teaching with OpenIFS at Stockholm University: leading the learning experience

ABDEL HANNACHI, JOAKIM KJELLSSON, MICHAEL TJERNSTRÖM, GLENN CARVER

The OpenIFS project (http://www.ecmwf.int/research/openIFS.html) at ECMWF started in December 2011. It provides for research and teaching at academic institutions an easy-to-use version of the model that is part of the operational IFS (Integrated Forecasting System). The OpenIFS model is based on IFS cycle Cy38r1and includes all of the forecast capability but without the data assimilation: the documentation of this cycle is at:

- http://www.ecmwf.int/research/ifsdocs/CY38r1/index.html.

Figure 1 shows the Arrhenius Laboratory hosting the Department of Meteorology, Stockholm University (MISU). In 1947 Carl-Gustaf Rossby arrived back in Sweden from the USA to strengthen research at the newly created MISU. Since then MISU has grown to become an international research environment with professors such as Bert Bolin, which continues to have a world-wide impact. Today MISU has an extensive research programme and offers undergraduate, Master's and PhD degrees. The OpenIFS initiative provides the opportunity for our students to get to know and 'familiarise' themselves with operational NWP models. The OpenIFS model was run for the first time outside ECMWF by our MSc students in November 2012 within the framework of our numerical weather prediction (NWP) course. The students' task was to simulate the Lothar storm that hit parts of Europe in December 1999. We undertook the adventure of running the OpenIFS on the high performance computer (HPC) Triolith, owned and operated by the Swedish National Supercomputer Center (NSC) at Linköping University campus, about 150 km south of Stockholm.

AFFILIATIONS

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Glenn Carver: ECMWF, Reading, UK

Figure 1 Department of Meteorology, Arrhenius Laboratory, Stockholm University (MISU), http://www.misu.su.se/.

To complement the theoretical part of the NWP module the students were given small projects using OpenIFS, which allowed them to put into practice some of what they have learned in the lectures. The various experiments performed by the students are described and the future outlook is discussed in the following sections.

Experiments

The topic of the projects for this year was to investigate the Lothar storm that swept across Europe during 24–26 December, 1999, and severely affected northern France, Switzerland and Germany (*Ulbrich et al.*, 2001). The main reason for selecting this storm is its severity and, most importantly, the fact that it was not well captured by the ECMWF forecasting system at the time. The students were asked to change some model parameters, run the model and then compare the forecasts. All forecasts in this experiment start at 12 UTC on 24 December and are run for five days. The model outputs are saved every six hours.

In principle, all model parameters such as those pertaining to the numerical scheme (e.g. time step and resolution), or physical parametrization (e.g. surface roughness or asymptotic mixing length) could be tweaked. In this particular project the students changed only four parameters, namely the horizontal resolution, gravity wave drag, surface momentum transfer and rain autoconversion rate. The students performed two runs for each parameter, with and without a change, and analyzed the resulting differences in the forecasts.

Discussion of the model runs

The first parameter the students changed was the spectral resolution. Two model runs were performed with the resolutions T511 (approx. 40 km) and T255 (approx. 80 km), both with 60 model levels.

Figure 2 shows the four-day forecast of mean-sea-level pressure (MSLP) and the 10-metre wind for 12 UTC on 28 December. There is a clear enhancement of the low pressure system over Switzerland and Germany with winds reaching 14–20 ms^{-1} at T511 but not at T255. The jet over the Atlantic west of Ireland is also significantly enhanced at the higher resolution as is the one to the east of Iceland. The values of the wind speed remain, however, significantly lower than those observed. *Wedi et al.* (2012) show how ultra-high horizontal resolution (T7999 ~2.5 km) is necessary to more accurately model the extraordinarily high wind speeds observed, particularly over mountainous regions of Europe.

The impact of changing the gravity wave drag was investigated by doubling and halving a parameter that determines its magnitude. The largest effect was obviously obtained when the gravity wave drag was doubled. Figure 3 shows an example of the difference in MSLP, gravity wave

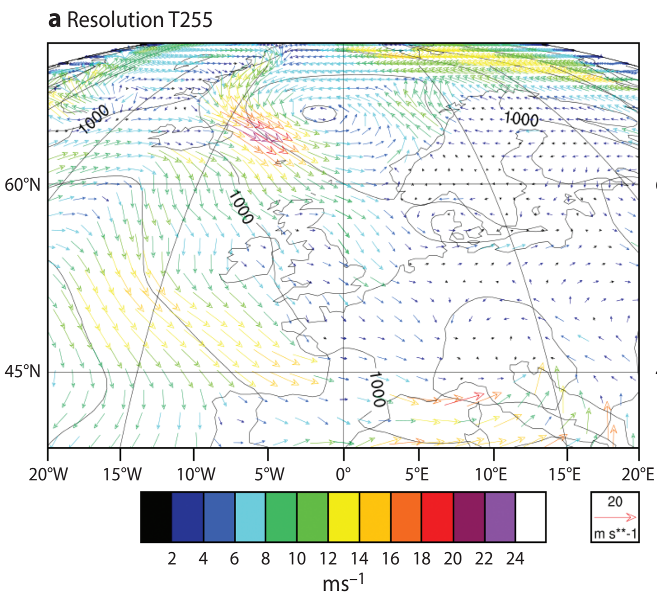

Figure 2 Four-day forecast of mean-sea-level pressure (contours) and 10-metre wind for 12 UTC on 28 December for (a) T255 and (b) T511. Contour interval 10 hPa. Figures supplied by Sara Broomé, Kristoffer Molarin and Nina Svensson (the MSc students).

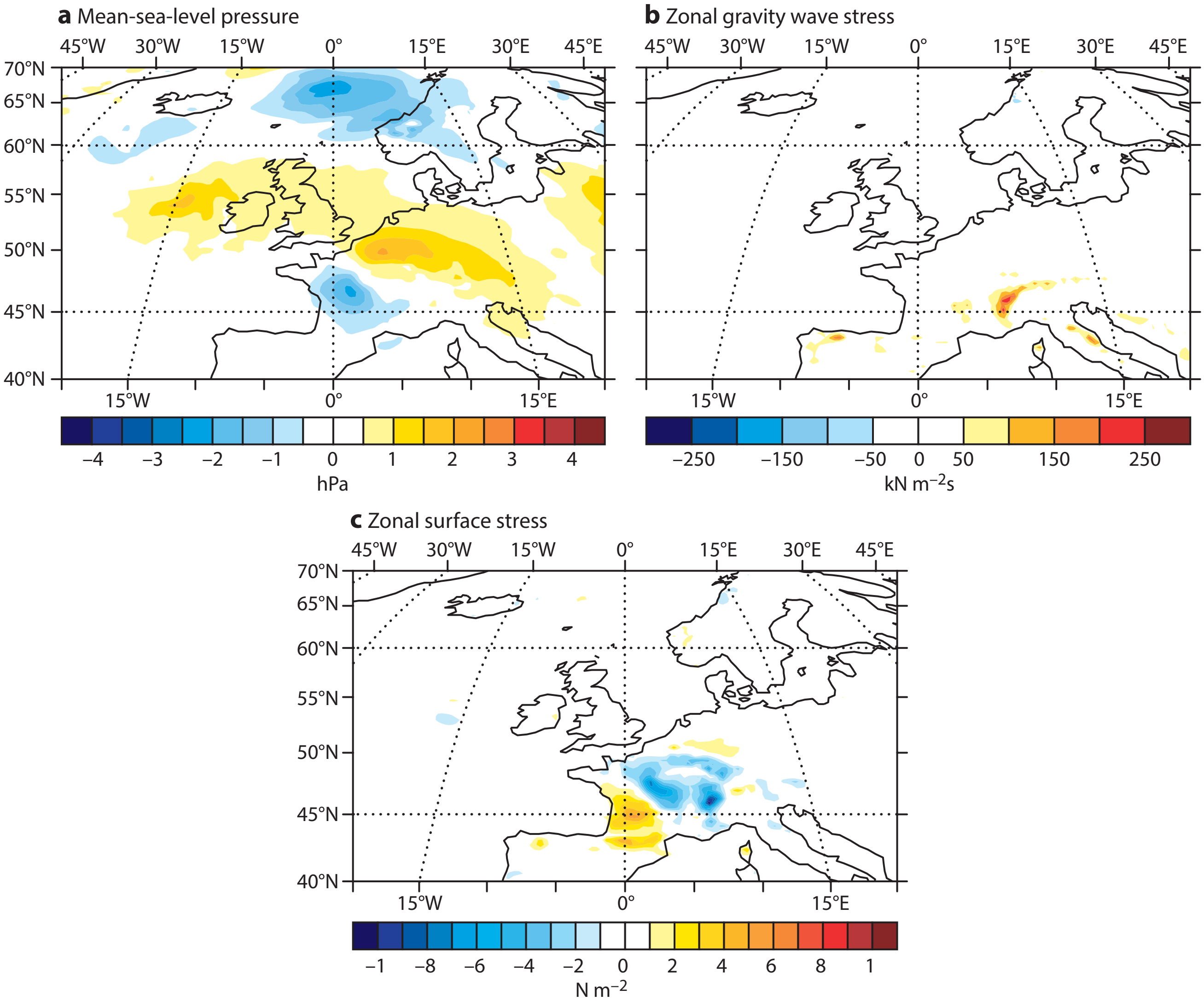

Figure 3 Difference in (a) mean-sea-level pressure, (b) zonal gravity wave stress and (c) instantaneous zonal surface stress between the 66-hour forecasts with a doubling of the gravity wave drag and the control at 06 UTC on 27 December.

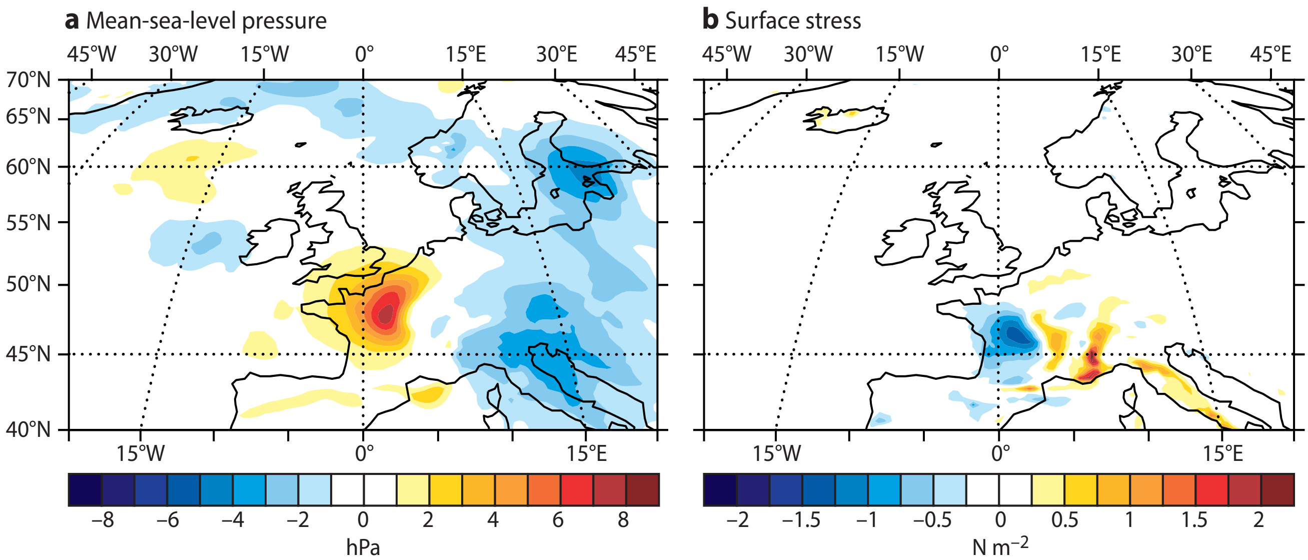

Figure 4 Difference in (a) mean-sea-level pressure and (b) surface stress between the 66-hour forecasts obtained with a reduced surface momentum transfer and the control at 06 UTC on 27 December.

stress and instantaneous zonal surface stress between the doubled and the control forecast experiments. The gravity wave stress is larger where expected – over the mountains. A modest increase in MSLP is also obtained over northeastern France and parts of Germany in agreement with the expected change due to the increased gravity wave drag. Perhaps the most interesting feature, and somewhat unexpected, is the rather large area with MSLP changes west of Norway, since this is not located downstream from major topography. It might not have had an impact on Lothar, but it is as large as anywhere else and illustrates the complex and chaotic behaviour of the atmosphere, where a local change can have remote effects.

Another physical parameter of importance in the dissipation of weather systems is the surface drag which is responsible for the momentum transfer from the atmosphere to the surface. This is dependent on the surface momentum transfer coefficient which in turn is a function of the surface roughness and static stability. In this experiment the transfer coefficient was reduced by 20% and results compared with the control simulation. Figure 4 shows an example of the difference, in MSLP and instantaneous zonal surface stress, between the reduced surface momentum transfer experiment and the control (original) forecasts for 06 UTC on 28 December.

A large effect of changing the surface stress is found over western France where a large increase of MSLP (7–9 hPa) is observed, with widespread changes in MSLP across most of Europe and the northern North Atlantic. However, there is some indication of a pressure decrease over some parts of southern and eastern Europe that could be an indication of an eastward shift of the low pressure system.

The students examined the effect of the rain conversion rate parameter on the low pressure system by doubling and halving the original value of the rain autoconversion rate coefficient. No noticeable change is obtained, however, in the forecasts between the two experiments.

OpenIFS technical aspects

A rapid turnaround in generating results is key to successful use of OpenIFS for teaching. For these experiments, the students installed and ran OpenIFS on the Triolith cluster at the National Supercomputer Centre (NSC), the largest supercomputer in Sweden consisting of 1200 compute nodes. Each node has two 8-core Intel SandyBridge processors, giving a total of 19,200 cores with a theoretical compute capacity of 338 TFlops placing it 83rd on the Top500 list (November 2012). We used the gfortran compiler suite with OpenMPI and the model was run in mixed MPI/OpenMP mode. At T255, a 5 day forecast on 16 cores took 25 minutes; T511 took 100 minutes on 32 cores. Figure 5 shows how the model scaled as the number of cores was increased.

Summary and outlook

Running the OpenIFS on our platform was a learning experience for both the students and the supervisors. The students, in particular, learned a great deal about weather

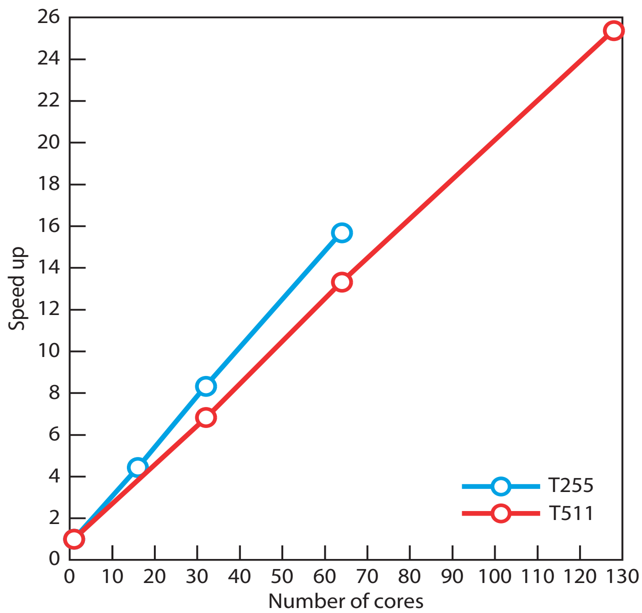

Figure 5 Speedup curves for the five-day forecasts for T255 and T511 with increasing cores on the Triolith cluster.

forecast models. They commented: "It was a great experience to work with the real thing". The simulations did not give a good indication of the timing or location of the storm, as the resolutions used in these runs were too low to capture the event accurately. It is hoped that in the future we will be able to run the model with its operational resolution (T1279L60).

Improving the model runs on Triolith is still in progress and some more work will be needed. In particular, it would be very useful to be able to change the initial conditions and choose different storms. One of our future objectives is to use ERA reanalyses to enable evaluation of the forecasts.

As well as teaching, another important objective for the future is to promote the use of OpenIFS as a research tool. Having easy access to a modern global NWP model provides an opportunity for researchers to, for example, use it as a test bench for process-related research, something that could feedback on model development at ECMWF. Using it first for a MSc course provided the leverage to get the infrastructure in place, and hopefully researchers will now take advantage of this.

These results are indicative of the good collaboration between ECMWF and MISU in establishing the first use of OpenIFS.

FURTHER READING

Wedi, **N.P.**, **M. Hamrud**, **G. Mozdzynski**, **G. Austad**, **S. Curic** & **J. Bidlot**, 2012, Global, non-hydrostatic, convection-permitting, medium-range forecasts: progress and challenges. *ECMWF Newsletter No. 133*. 17–22, Available from: http://www.ecmwf.int/publications/newsletters/

Ulbrich, **U.**, **A.H. Fink**, **M. Klawa** & **J.P. Pinto**, 2001: Three extreme storms over Europe in December 1999, *Weather*, **56**, 70–80.

20 years of ensemble prediction at ECMWF

CONTRIBUTORS

JAN BARKMEIJER, ROBERTO BUIZZA, ERLAND KÄLLÉN, FRANCO MOLTENI, ROBERT MUREAU, TIM PALMER, STEFANO TIBALDI, JOE TRIBBIA

Twenty years ago, on 24 November 1992, the first ensemble forecasts were produced at ECMWF. At that time, ensemble forecasts were issued three times a week, on Friday, Saturday, Sunday, with 33 members at a T63L19 resolution for up to 10 days. Today, the ensemble runs twice a day with 51 members at resolution T639L62 to day 10, and T319L62 from day 10 to 15, and is extended to 32 days twice weekly. It is coupled to a wave model from day 0, and to a dynamical ocean model from day 10 (work is in progress to move this coupling also to day 0). Worldwide, it is recognised as providing the best global, medium-range and monthly probability forecasts (Figure 1). 'Spaghetti' maps are now firmly on the table of most forecasters!

This article discusses some of the main points raised during an afternoon of presentations on 3 December 2012, organized to celebrate 20 years of operational ensemble production at ECMWF. The presentations were given by some of the people who contributed to its early design and implementation.

- *Erland Källén* (ECMWF) presents some historical background and an overall introduction to the articles.
- *Stefano Tibaldi* (ARPA Emilia Romagna) brings us back to the 1980s, when discussions started at ECMWF about how users could be provided with an estimate of forecast uncertainty.
- *Joe Tribbia* (NCAR) highlights the role that the singular vector strategy played in the development of the ECMWF ensemble and their continuing importance.
- *Tim Palmer* (University of Oxford & ECMWF) described how 'flaps of a butterfly wing' led to his involvement in ensemble prediction.
- *Robert Mureau* (MeteoGroup) considered the difficulties faced by professionals when trying to present probability forecasts.
- *Jan Barkmeijer* (KNMI) focuses on the role of linear models in data assimilation and predictability.
- *Franco Molteni* (ECMWF) deals with the monthly and seasonal forecast time range, and discusses ensemble methods applied to this forecast range.
- *Roberto Buizza* (ECMWF) presents on-going research work aimed at further improving the ECMWF ensemble system and providing more valuable products to ECMWF users.

Some biographical information about the contributors is given in Box A.

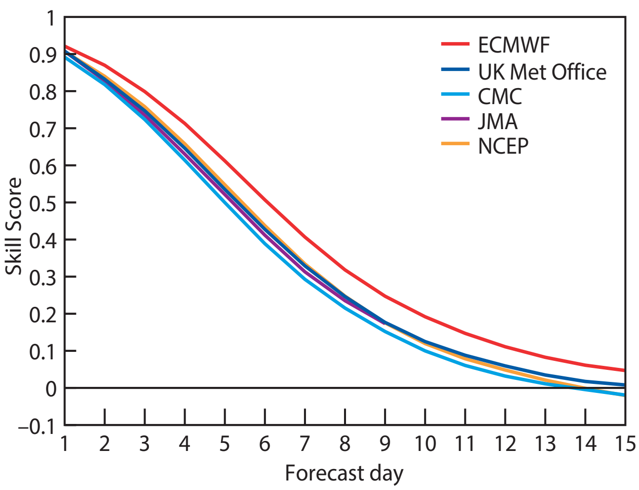

Figure 1 Three-month average continuous rank probability skill score for the probability forecast of the 500 hPa geopotential height over the northern hemisphere extra-tropics for August to October 2011 (dotted lines) and 2012 (solid lines) for the five leading ensembles available in the TIGGE archive: Canadian Meteorological Centre (CMC), Japan Meteorological Agency (JMA), National Centers for Environmental Prediction (NCEP) USA, UK Met Office and ECMWF. Each ensemble has been verified against its own analysis.

Erland Källén

20 years of ensemble prediction: an introduction

No weather forecast is complete without an estimate of its uncertainty – this has been a long standing truism in meteorology ever since the start of numerical weather prediction in the 1950s. Already *Thompson* (1957) argued that estimating prediction errors is an essential part of dynamic meteorology. He estimated the growth of prediction errors due to uncertainties in the initial state and came to the conclusion that a weather forecast can be no better than a random guess of the weather beyond about a week. *Lorenz* (1969) made a more elaborate analysis of the mechanisms that limit atmospheric predictability and arrived at a predictability estimate of about two weeks.

When ECMWF started with operational weather prediction in 1979 the forecasts did not include uncertainty estimates. It was however recognised that this would be very desirable and a workshop was organised in 1979 to discuss "*Stochastic Dynamic Forecasting*" (*ECMWF*, 1979). An early attempt to compute forecast uncertainties was made by *Hollingsworth* (1979), but the perturbation technique was not sufficiently developed to give useful uncertainty information. Following methods suggested by *Lorenz* (1965) a much improved technique to specify initial condition uncertainty was developed at ECMWF and Tim Palmer headed the team that would

Brief biographical information of the authors A

- **Erland Källén** worked at ECMWF between 1979 and1982 in the Research Department. After a period at Stockholm University, he returned to ECMWF in July 2009 as Director of Research, his current position.
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- **Stefano Tibaldi** worked in the Research Department of ECMWF between 1977 and 1987. He left as Head of Diagnostics and Predictability Research Section and was replaced in the position by Tim Palmer. Member of ECMWF SAC from 1990 to 1998, he is now the Director General of the Regional Protection Agency of Emilia-Romagna, Italy.
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- **Joe Tribbia** visited ECMWF for 6 months in 1991–92, and since then has been working closely with many ECMWF scientists. He is now the Head of the Climate Dynamics and Predictability (CDP) section in the Division of Climate and Global Dynamics (CGD) at the National Center for Atmospheric Research.
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- **Tim Palmer** worked at ECMWF between 1986 and 2011 (but continues as a part-time consultant). He is now a Royal Society Research Professor in Climate Physics at the Department of Physics of the University of Oxford.
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- **Robert Mureau** worked at ECMWF between 1987 and 1992, in the Research Department. He is now head of research and development at MeteoGroup.
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- **Jan Barkmeijer** worked at ECMWF between 1995 and 2002 in the Research Department. He is now group leader of the Model Section in the Weather Research Department at the Royal Netherlands Meteorological Institute
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  From January 2013 he was appointed Chair of the ECMWF Scientific Advisory Committee.
- **Franco Molteni** worked at ECMWF in different spells from 1984 to 1996. After a period in Italy, he returned to ECMWF in 2005. He is now the Head of the Probabilistic Forecasting Section.
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- **Roberto Buizza** has been working at ECMWF since 1991. He is now the Head of the Predictability Division of the Research Department.
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implement the first ECMWF ensemble prediction system, today called ENS. We are celebrating the twentieth anniversary of the first operationally-produced ensemble forecasts and the contributors to the commemoration event held at ECMWF gave both a historical account of the developments at ECMWF as well as a look into the future.

All contributors have played an important role in the development of the ECMWF ENS and we are very grateful for their efforts in helping to develop and maintain a world-leading ensemble prediction system as documented in *Hagedorn et al.* (2012). Stefano Tibaldi, Tim Palmer, Joe Tribbia, Robert Mureau and Franco Molteni were all members of the initial ensemble team at ECMWF, with Roberto Buizza and Jan Barkmeijer joining later. All were instrumental in developing the first ensemble system based on the idea that singular vectors (*Farrel*, 1982) can be used to efficiently represent the initial condition uncertainty. Later developments include model error representation through the use of stochastic physics tendencies and various resolution and model upgrades.

In recent years the initial state uncertainty representation has been enhanced through the addition of perturbations derived from Ensembles of Data Assimilations. Personal memories of the difficulties encountered and the successes accomplished can be found in the contributions included in this edition of the *ECMWF Newsletter*. Also included are discussions of how probabilistic forecasts have been received by the users, it is evident that still more work needs to be done in order to widen the acceptance of ensemble forecast information as an integral part of a weather forecast.

Today, 20 years after its operational implementation, the ECMWF ensemble forecasts are much more reliable and skilful than they were two decades ago. The skill has been improving at a rate which is more rapid than the improvement in high resolution, or deterministic, forecast skill. It is also clear that the ensemble skill improvement is dependent on a continued improvement of the accuracy of the high resolution model as well as the accuracy of the initial state. We are confident that continued work and collaboration within the scientific community will lead to further skill advances and an enhanced use of probabilistic forecasts. We are all grateful to the pioneers at ECMWF, please read and enjoy their stories.

Stefano Tibaldi
Why ensembles?

Why, twenty years ago, in 1992, did ECMWF decide to extend the operational production of the so-called ‘deterministic’ forecasts to ‘ensemble’ predictions? Or, more appropriately, why did ECMWF, almost fifteen years earlier in the very early 1980s, start a research project to explore the feasibility of producing probability forecasts and/or forecasts explicitly addressing the problem of forecast uncertainty which, in turn, led fifteen years later to a viable operation system, today a pillar of ECMWF’s operational forecasting system?

The early days

The seed for probability forecasts was planted very early at ECMWF by Tony Hollingsworth in a (failed, alas!) experimental attempt, back in 1979 (*Hollingsworth*, 1980). He followed *Leith* (1974) in applying straight Monte Carlo techniques to meteorological modelling by perturbing model variables with random perturbations with amplitudes of the order of the analysis error as estimated by the optimum interpolation (OI) technique. The gallant attempt turned out to be doomed because such random perturbations were not projecting enough on meteorological modes and were therefore rapidly wiped out by model dissipative mechanisms (mostly horizontal diffusion).

The idea remained somewhat dormant until Henk Tennekes raised the matter during discussions at ECMWF's Scientific Advisory Committee (SAC) at around 1986, discussions which are usually referred to by quoting his statement that "no forecast is complete without a forecast of forecast skill" (*Tennekes et al.*, 1987). My personal recollection is that his opinion, forcefully and convincingly stated, sufficiently influenced the rest of the SAC and the then Director (Lennart Bengtsson) and Head of Research (David Burridge) to set the ball rolling, at least at ECMWF (no need to convince Tony Hollingsworth, he was already convinced).

If you ask yourself where the scientific interest in probability forecasting was coming from, you have to recollect that the long-standing attempt of producing probability forecasts by solving the evolution equations for the pdfs (probability distribution functions) of atmospheric variables (the so-called classical stochastic-dynamic forecasting techniques, e.g. *Epstein*, 1969) had failed. In practice this was due, among other things, to the rapidly increasing complexity of the problem when moving away from the prediction of the mean mean toward that of the higher order moments.

But there were other reasons why the times were ripe. For example, the attempt of using the 12 or even 6 hour lagged-average forecasting technique (*Hoffmann & Kalnay*, 1983) to estimate forecast spread, hoping that it would provide an estimate of forecast skill, had also given somewhat disappointing results, see *Palmer & Tibaldi* (1988).

Additionally, no time can be truly ripe if the technical instruments are not ready (remember how long we had to wait for Richardson's NWP ideas to come to fruition). At that time (the second half of the 1980s) it had become technically possible to perform large-scale numerical experiments: the enormous growth of available computing power had made it possible to construct and operate at full steam that 'numerical laboratory' that Axel Wiin-Nielsen, Syukuro Manabe and others had started implementing 10–15 years earlier. In fact it was exactly in those years that a Numerical Experimentation Section was created in the ECMWF Research Department.

Why probability forecasting?

But again, why probability forecasting? There is nothing wrong with progressively improving single, 'deterministic' forecasts by increasing model accuracy and decreasing initial condition errors, is there? But the meteorological atmosphere is a chaotic system on time scales of a few days, maybe weeks, depending on the spatial scales of interest (and the climatic system is also chaotic, but on much longer timescales). Also the behaviour of our numerical simulations of the atmosphere would continue to be affected by the problems typical of model simulations of chaotic dynamical systems even if (a) we could have perfect initial conditions and (b) we could write perfectly accurate evolution equations and (c) solve them with perfect numerical schemes, only just because of the limited number of significant digits used by any computer (*Lorenz*, 1963).

Looking at the problem from a slightly more fundamental point of view, a forecast explicitly cast in probability terms is better not only because it provides the user with an estimate of the error 'of the day', but because it is more 'truthful'. So a probability forecast conveys a message which

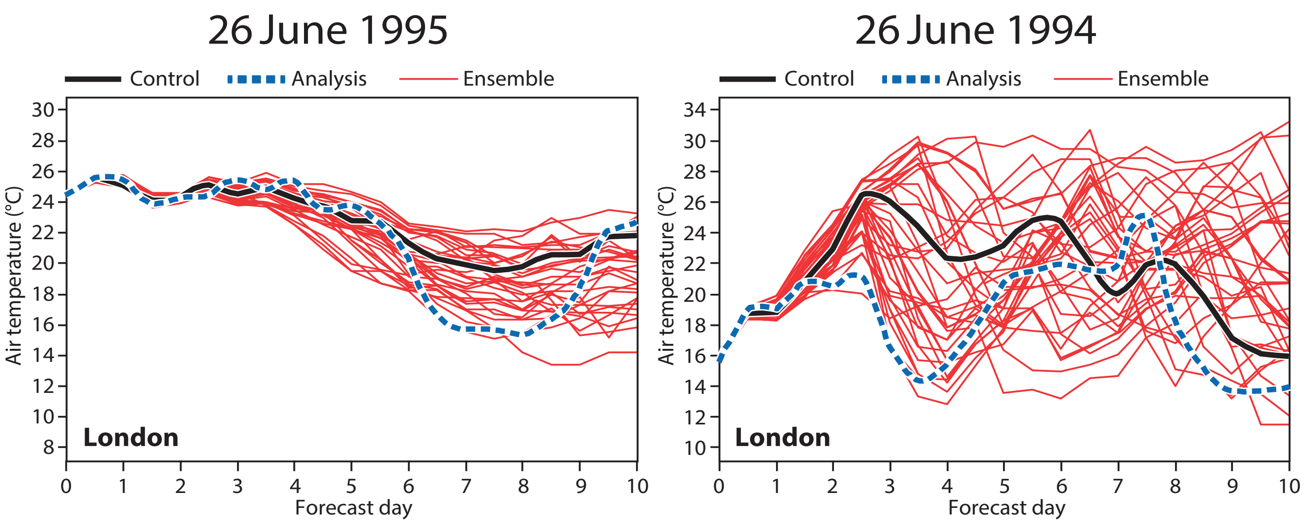

Figure 2 Two ensemble forecasts of air temperature on the same day of two different years at London illustrating the flow dependence of forecast errors (the errors 'of the day'). If the forecasts are coherent (small spread) the atmosphere is in a more predictable state than if the forecasts diverge (large spread).

explicitly reminds the user of the fact that associated to the forecast there is always a forecast uncertainty which should be considered, computed and taken into account when making any practical use of the forecast (see Figure 2). In fact even 'deterministic' forecasts are in reality probability forecasts in disguise, since an error bar (even if only an average error bar) can and should always be associated with it. That error bar implies a probability distribution of predicted future states around a central value.

Increasing the use of probability forecasts?

But, having said all that, do problems with spreading the use of ensemble forecasts or probability forecasts remain even today, after twenty years of operational production and dissemination? This would indeed appear to be the case, at least in some situations, as often the following problems are still outstanding.

- There are very poor statistics concerning the verification of rare events (e.g. extreme events) which are often the main target of ensemble forecasts.
- Some forecast users do not always interpret the concept of probability associated with ensemble forecasts in the correct way. It is sometimes difficult to explain that it is possible for two different forecasting systems produce different probabilities of occurrence of the same meteorological phenomenon because they have errors of different nature, size and structure and that this is perfectly legitimate and does not necessarily imply that one is wrong and the other one is right (they may in fact be both right, or wrong, for that matter!).
- The entire system of civil protection alerts, for example, is currently based (at least in some countries) on a conceptually deterministic use of meteorological and hydrological forecasts: will the river overflow the bank?

The answers "yes" or "no" are allowed but not "maybe"! Recall for a moment the experience of Charlie, Tim Palmer's golfing friend, the builder who laid concrete immediately before a frost on the basis of a (wrong) 'deterministic' forecast (*Palmer*, 2006). Had he used a probability forecast, he could have been much better off, but only after applying a quantitative cost/loss analysis to his concrete laying job. Was he ready at the time? Did he know all the necessary action/no action cost figures? And, even more importantly, would he be culturally ready even today?

Helping decision makers

A civil protection plan to evacuate thousands of citizens in view of a probable flood requires a bit more effort than costing the laying of three thousand square yards of concrete. So to modify a civil protection plan to make it consistent with weather and hydrological forecasts that are cast in probability terms requires a mix of cultural, scientific, technical and communication skills. Depending on the cost/loss ratio of every action to be taken as a consequence of the weather alert, different decisions might have to be taken, and the costing of some losses/damages (human life, population health, psychological consequences of loss of homes and property, etc.) might pose severe difficulties. Special development efforts might be needed before decision making and intervention procedures can be thought and formulated in probability terms.

The technical, economic and productive systems of some Central and Northern European countries might be already using probability ensemble predictions to their full value. Can we say the same of other public bodies and of operational meteorology, hydrology and civil protection of Mediterranean Europe, where objective and quantitative fact-based decision making has not yet completely penetrated minds and society?

Joe Tribbia

Singular vectors: are they still valuable?

Twenty-one years ago I had the good fortune to be an invited visitor to ECMWF and to work in the Predictability Section; this was in pre-launch stage of the ensemble forecasting system. It had been agreed in discussions with Tim Palmer that my tasks would be associated with the use of Singular Vectors (SVs) as a way of sampling the initial state uncertainty and thereby initialize the ensemble for the prediction of forecast reliability. Tim was not only the Section Head but also the intellectual leader who pushed hard for the development of ensemble forecasts based on SVs.

Leading the way with SVs

As is often the case, the Centre was leading the operational community into a new and challenging area of predictive science and the work I was doing during my visit would play a small part in the development of useful ensemble forecasts. Prior to my arrival almost all of the groundwork had been laid by two members of the Predictability Section, Franco Molteni and Robert Mureau. They had done some preliminary experiments using a quasi-geostrophic (QG) model to generate SVs that were interpolated onto the operational model's grid as a precursor to the self-consistent SVs generated using the numerical approximations of the forecast model (see Figure 3). These QG SVs appeared to be producing perturbed ensemble members that were dynamically active and held the promise of finally achieving rational spread–skill relationships. This was something many groups were seeking within the context of tackling dynamical extended-range forecasting, which was defined as numerical weather prediction beyond the deterministic range (in those days, week two to one month lead).

In addition to the foundation already in place due to the testing of QG ensemble perturbations, the Centre's Head of Research, Tony Hollingsworth, and Phillipe Courtier had seen to it that the ECMWF forecast model would have tangent forward versions of each subroutine along with their complementary adjoints, ensuring that my main tasks would be primarily to connect the components and insert an eigen-solver at the proper point to enable SV perturbations to be computed. At the end of my visit, I handed over this capability to a bright, young researcher the Centre had hired into the Predictability Section, Roberto Buizza, and the success of SV-based ensemble forecasts was assured.

The future for SVs

Twenty years later, the ECMWF ensemble forecasts are the best in the world due to the combination of having the most accurate model and data assimilation components, the use of stochastic physics, calibration of the forecast skill and the SV method of generating initial perturbations for the ensemble (c.f. *Hagedorn et al.*, 2012). However, the future use of the SV technique is in question as ECMWF moves forward. The most ominous threat, ironically, comes from the ensemble forecast itself which has been shown to be an effective and economical tool for the prediction of forecast reliability.

With the confidence gained from twenty years of ensemble prediction, ECMWF is experimenting with ensemble methods of data assimilation, like the Ensemble Kalman Filter (EnKF). If the current 4D-Var assimilation method is replaced with an EnKF-based assimilation scheme, the next logical step would be to use the ensemble members from the EnKF as the initial states for the ensemble members. (Preliminary experiments shown by Roberto Buizza indicate that not much, if any, skill would be lost in the ensemble forecasts in using such a strategy.) This would permit a self-consistent, statistically-optimal ensemble method of predicting both expected value of the forecast and its expected error covariance.

Even if SV initialization is eventually superseded by an alternative method of ensemble member generation at ECMWF, the Centre would be wise to continue to maintain the capability to generate SVs in their forecast system. The reason is simple: SVs are not only practically useful in generating ensemble members, they are also dynamically useful as an efficient basis for performing diagnostic analysis. This is clear from the dual nature of SVs which can be derived either as the most rapidly growing perturbations or the EOFs (Empirical Orthogonal Functions) at a future time of a distribution that is initially Gaussian. In the latter interpretation of SVs, these vectors are the most efficient that can be used to characterize the distribution. Also, while for the typical weather event ensemble filtering methods of generating initial states for ensemble members may be indistinguishable in a probability forecast from the SV method of initialization, in the atypical extreme event SV initialization may be a necessary ingredient for an early warning of a significant storm. This would be consistent with the fastest growing disturbance derivation of SVs and give a further rationale for their use.

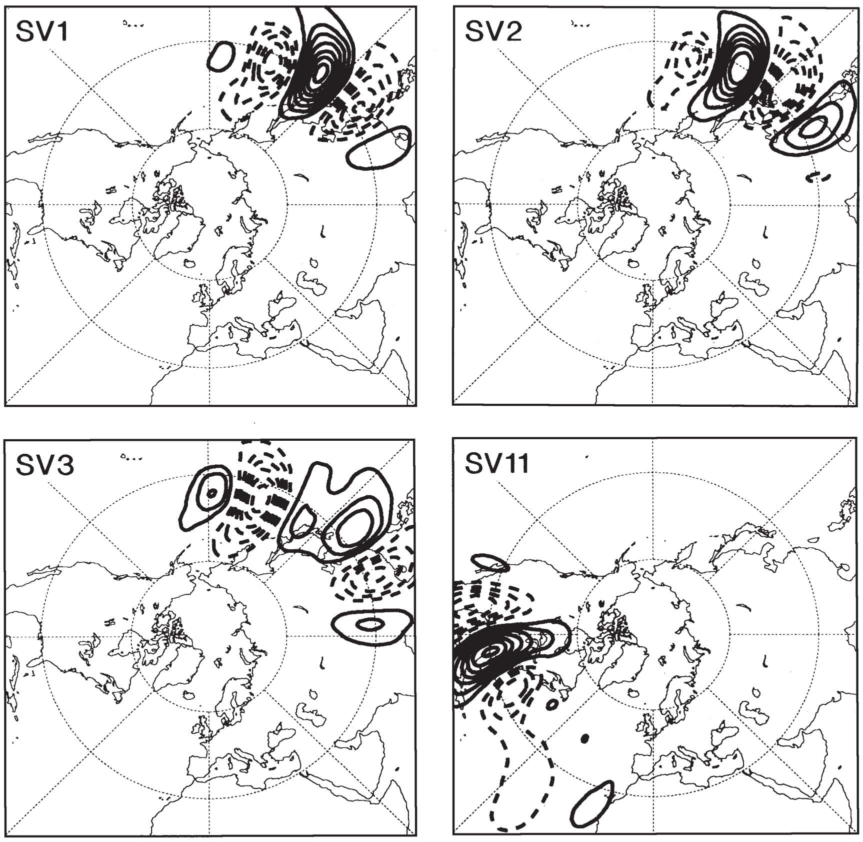

Figure 3 Until 1992, ECMWF did not have a tangent forward and adjoint version of its primitive equation model. Thus early experimentation on the use of dynamically conditioned, optimal perturbations was done by extrapolating to the T63L19 resolution of the ECMWF model singular vectors computed with a T21L3 quasi-geostrophic model. This figure shows one of the first examples of the T21L3 QG-SVs growing over a 12-hour optimisation time period from 12 UTC on 2 December 1988. The quasi-geostrophic SV perturbations numbers 1, 2, 3 and 11 are shown in terms of 500 hPa geopotential height (from *Mureau et al.*, 1991).

Whatever the future brings the history of SVs and their use at ECMWF has demonstrated that the efforts of the Predictability Section twenty years ago have benefited both the Atmospheric Sciences and Society.

Tim Palmer

Is the butterfly effect real? A practical example

Although I have spent much of my life developing and promoting the benefits of ensemble forecasting, this was not something I had planned to do, nor had I predicted that this is something I would do when I started my meteorological research. My entry into this field was an example of the 'butterfly effect' at work – see Figure 4.

At the Met Office

I joined the Met Office having completed a doctorate in theoretical physics in 1977. My initial research at the Met Office was in stratospheric dynamics. In the early 1980s I was lucky enough to spend a year at the University of Washington working with Jim Holton, and returned to the Office as an expert in stratospheric dynamics. This led me to being promoted to the rank of Principal Scientific Officer. The only problem was that I now had to head a group, and there was already a well-established stratospheric group leader who was a world leader in the field. And he wasn't going anywhere! The only group-leader vacancies were at the Office's Training College (then next door to ECMWF) and in the long-range forecasting branch.

The long-range forecasting branch, sometimes called the 'Synoptic Climatology' branch, was known for making long-range forecasts (typically a month ahead but sometimes longer) using statistical empirical models. Monthly forecasts using such techniques were made for a number of fee-paying customers; typically the utilities companies in the UK. My job, should I choose to accept it, was to introduce dynamical methods into long-range forecasting (Andrew Gilchrist was the driving force behind this project). For some time, I was not really sure what the better choice would be – Training College or Synoptic Climatology, and in any case I was rather baffled by the system that prevented me from being able to continue with the work which had established my name in the middle atmosphere field. In the end a few butterflies flapped their wings (or maybe did not) and I ended up choosing Synoptic Climatology.

The Met Office was already using a global climate model to study climate change. I had to adapt and test the model for use in monthly and seasonal forecasting. It was fairly obvious right from the start that it would be necessary to study these forecasts using ensembles of integrations, rather than single 'deterministic' forecasts, and there was already some literature on this, notably, by Kiku Miyakoda from GFDL. Doug Mansfield had already done some of the early work in this area in the Synoptic Climatology branch using a hemispheric model. Doug and I were then joined by James Murphy, who subsequently made a name for himself introducing ensemble techniques into the Hadley Centre's climate change forecast system.

After a year or two of research in this area, James and I finally introduced these ensemble techniques into the operational monthly forecast system, the one that produced forecasts issued to the utilities companies and others, producing dynamically based probabilities. Here we blended the

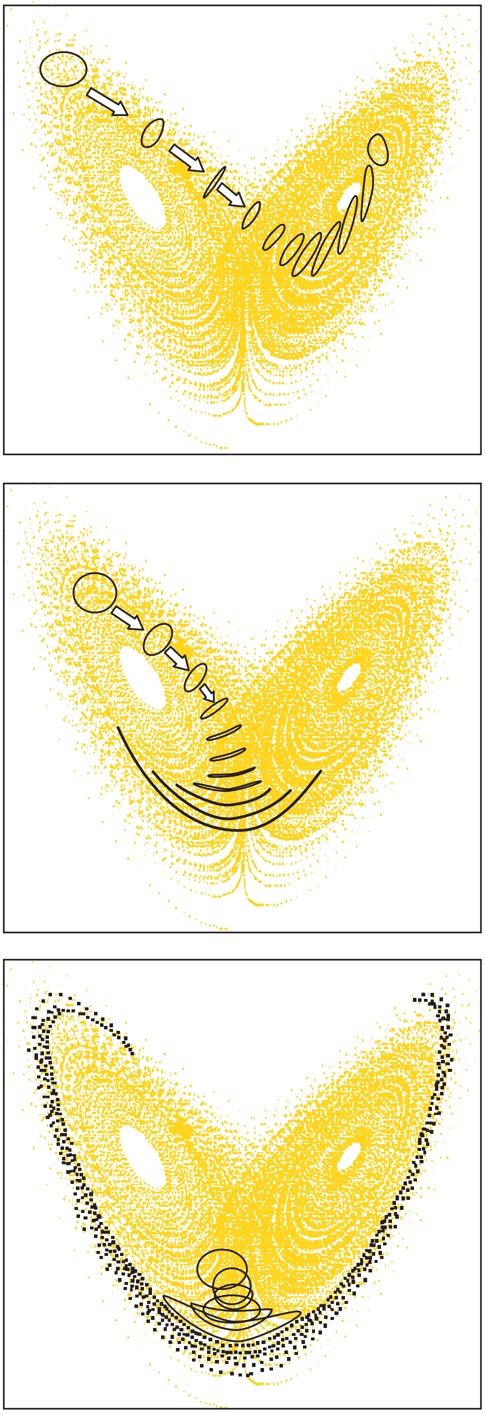

Figure 4 The rationale for ensemble forecasting can be demonstrated using the iconic Lorenz '63 model. In a nonlinear system predictability is a function of initial state. Ensemble predictions make it possible to forecast such flow-dependent predictability.

dynamical and empirical probability forecasts. The paper *Murphy & Palmer* (1986) documents what I believe was the first ever operational ensemble weather forecast. Unfortunately, these probabilities were not all that reliable, not least because the model had severe biases in its mid-latitude flow. This led me to think about parametrization of orographic gravity wave effects, but that is another story.

At ECMWF

It turned out that ECMWF was acquiring quite a reputation for innovative and exciting research, and, after a couple of years or so in the Synoptic Climatology branch, I applied for a job at ECMWF, working with Stefano Tibaldi. When I joined in 1986 there was interest at ECMWF in developing techniques to 'forecast the forecast skill' as it was then called (a phrase, coined, I believe, by Henk Tennekes). However, it seemed to me that what ECMWF really needed was an operational ensemble forecast system for producing completely probabilistic forecasts for the medium range, a bit like the one that had developed for the monthly forecast system at the Met Office. In fact Tony Hollingsworth had already started to think about Monte Carlo forecasting at ECMWF. However, he had rapidly found a problem that beset all attempts to use 'random' perturbations to create ensembles of initial conditions. In Tony's experiments the random perturbations were actually decaying as they were integrated away from the initial conditions, the complete opposite of what a chaotic system should do!

Before working actively on developing a medium-range ensemble forecasting system, Stefano Tibaldi and I looked empirically at what types of forecast flows were more predictable and what ones less so. Using a barotropic model developed by Adrian Simmons, I was able to show that the results of our empirical analysis could be explained in terms of the growth of small perturbations on barotropic basic states associated with the predictable or unpredictable composite forecast flows. To my initial surprise, however, I found that normal mode theory was utterly incapable of explaining how these small perturbations grew in the barotropic model; the basic states where initial perturbation growth was largest were more stable in the normal mode sense than the basic states where perturbations grew rapidly!

At this time, I recalled a talk by Brian Farrell from Harvard which I had heard whilst still at the Met Office. Brian said forcefully that normal mode growth was irrelevant for explaining baroclinic instability (Farrell, 1982). At the time I did not really understand why he was saying this, but I finally understood it when trying to understand results from the barotropic model. Essentially what Brian was saying is that the growth of small perturbations is governed by processes which relate to the fact that the linear evolution operators are not self adjoint. Together with Brian Hoskins and a PhD student, Zuojun Zhang, we were finally able to understand the results from the barotropic model.

This research had a strong impact on me as I began to think about ways to construct a medium-range ensemble forecast system which could overcome the problems found by Tony Hollingsworth. With Franco Molteni, it led us to formulate a strategy for perturbing the initial conditions for an ensemble forecast, based on singular vector perturbations. We still use this strategy today, although the Ensemble of Data Assimilations method (EDA) plays an increasingly important role for creating ensemble perturbations. However, since the IFS dynamics is rather dissipative at high wavenumbers (*Augier & Lindborg*, 2012), it is not completely clear to me how well EDA can adequately account for observation and initial model uncertainty at high wavenumbers (without artificially inflating the perturbations) and one should probably not drop the singular-vector perturbations too readily.

The flap of those butterflies wings in the early 1980s has had a profound effect on my career; one, I think, that was for the better!

Robert Mureau

Do people really want probability forecasts?

I worked at ECMWF between 1987 and 1992, and am proud to have been, from the very beginning, involved in ensemble forecasting. I have been and still am a firm believer in the use of ensembles for making probability forecasts. I fully agree with those who say that the probability distribution for a forecast parameter gives the most comprehensive information about the forecast. And, yet, when you ask me to answer the question in the title, I will have to take a deep breath and have to answer the question with a firm "no": people do not want probability forecasts. They should want it, but they do not. That is a frustrating answer, but it is reality. I think it is time we recognize and accept the hesitations of the user. Perhaps we should think of different strategies to persuade people to use probability forecasts.

Barbecue summers and hamburgers

Probability forecasting in meteorology and the attempts to promote probability forecasting go back to, at least, the 1960s when Allan Murphy and Ed Epstein started their pioneering work. That was tedious stuff, very theoretical and never very appealing to the simple user, despite the excellent examples that were provided (*Katz & Murphy*, 1997). When more computer power became available and we began to understand how to tackle the issue of generating perturbations that would survive the initialization (Hollingsworth, 1980) probability forecasting became much more transparent. We could now follow the effect of small errors and could literally see the forecasts diverge, just as Edward Lorenz had experienced in his very first modelling experiments.

At ECMWF, Horst Böttger, Bernard Strauss and Anders Persson realized from the very beginning that training forecasters in the use of the ensembles would be important and that it had to be part of the training courses run by the Met Ops Department at ECMWF. Those courses certainly did their job. An experienced (Dutch) forecaster once told me, slightly nervously, after attending the Training Course: "I go home now, but I don't dare to make a forecast anymore". He did go home, he did make many more forecasts, but as 'deterministic' as he ever had done before. That surprised me, but he explained that the daily operational routine expected you to fill in tables and present the forecast in numbers. And also, as he was trained in the traditional way, he saw it as his duty to show people the way in the dark world of uncertainty, and give into the wish of the users to make the decision for them.

There is a constant battle between on the one hand the professional (scientist, forecaster) and on the other hand the media and the decision makers. In the old days scientists were revered and well-respected members of society – people listened. Nowadays, they appear in popular talk shows and are constantly challenged to present their message in a way that everybody understands. That is good (out of the ivory tower), but accidents happen.

As mentioned above, people want straight answers. The well-prepared professional who goes to the studio with cautious arguments lined up and probabilities assessed, has to 'compete' with the talk show host and may get, after the extensive and thorough explanation has been given, still the question: "but is it going to rain?". Sometimes the professional caves in, sometimes the media simply misquote. In the late eighties you were given the impression that if, in Britain, you had eaten one hamburger in your life, you were doomed. Mexican flu, seasonal forecasting (barbecue summers), climate change... there are many examples. The public remembers all the above examples as false alarms. Of course these examples all support the case for probabilistic statements. But very often you do not get the chance: your interview would probably not be broadcast unless you make strong statements. A probability statement is seen as a weak statement, a 'cop out'. This is the world the professional lives in.

Still the same question after twenty years

The fact that the organizers of the event to mark twenty years of ensemble prediction at ECMWF asked me, explicitly, to give a talk with the above title illustrates the point. (I was particularly puzzled by the choice for the word "really" in the question). But it was justified to ask the question: most of us are still giving very similar presentations to twenty years ago, and, worse, are getting the same negative, sometimes outright cynical, responses. We must have done something wrong. We should try to understand better why people do not (want to) hear the message.

The most commonly quoted explanation is that people find statistics difficult to interpret. That is only true up to a point. If statistics can be linked to experience the problem does not seem to be too big. People understand that a horse with 12–1 odds to win is more likely to win than a horse with 30–1 odds. It is easy to relate odds to how many races a horse has won in the past. For the same reason it is somehow easy to grasp that a hurricane can make landfall in a relative wide coastal zone. People can go back into their memory for that. However, in general, if you tell someone that an event is to happen with a probability of 80%, that person will find it very difficult to accept that it is possible that the event might not happen. Intuitively most users will translate everything higher than 66% into a "yes". And vice versa, everything lower than 33% into a "no". Those of you who ever managed to 'sell' a probabilistic warning system, and asked for which threshold the user want to receive a warning mail, will know that the response will almost invariably be a request for the 66% threshold. Intuitively that is close to a decision conversion. You need many cost-loss discussions (and learning experiences) with the user to make him choose lower thresholds.

Also society has become more demanding. We want to manage the world as if it is our back garden. We have come to the point that natural disasters have become almost unacceptable. We want everything to be safe and guaranteed. We have insurances against almost anything. We build houses in low-lying areas (polders, flood plains), and expect the state to protect us 100% of the time. When it snows, we hardly accept warnings: we still want to go out and demand the civil authorities to keep the streets clear. We do not accept misses, and we hate false alarms. They are too disruptive in our precious time schedules. So, as a professional, you can hardly win. In Italy, recently, six seismologists who, in 2009, assured the public that there would be no earthquake in the region of L'Aquila (they made the mistake of converting a very low probability into a "no") were convicted in an official court of law for manslaughter.

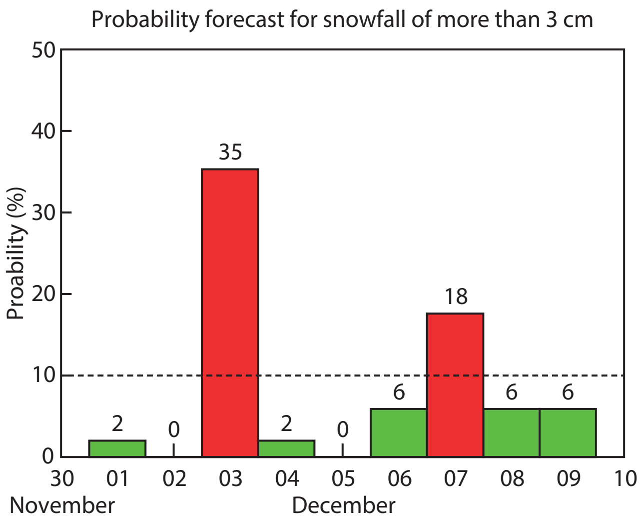

Figure 5 Example of a probability warning plot for Dutch Rail for snowfall in The Netherlands from the forecast starting at 00 UTC on 1 December 2012. Ensemble members are counted for snow for anywhere in the country, with the restriction that the temperature is below 1°C. The warning system indicated a risk of snowfall from 1 December onwards. On the 3rd light snow occurred and on the 7th there was serious snow in The Netherlands. Dutch Rail decides to contact MeteoGroup if there is a risk of snow in the forecast for 2 days ahead. On 3 December the train schedules were adjusted. Thanks to Etienne Weijers from Pro Rail for allowing this data to be presented.

The future

Am I pessimistic? No. At MeteoGroup we encounter many different types of customers and we always tell them about the many possibilities of the ensemble system. Sometimes with success, particularly with professional customers who have clear requirements and are able to formulate critical thresholds. The energy trading world is a good example of a community who understand the concept of risks. A probability forecast of wind power or solar power under or over certain thresholds has proven to be a useful product.

A good example of effectively using probability forecasts is the warning system which we have set up for Dutch Rail which gets warnings based on the 10% probability of snowfall of more than a certain amount (Figure 5). When the probability threshold is exceeded they will seriously consider adjusting the train schedule such that there will be fewer trains which will be easier to manage if there are snow problems A set of hindcasts has shown that such a system generates a number of false alarms. Dutch Rail appreciates the statistics and is prepared to explain to the public that it is a choice between waiting an extra half an hour for the train or getting stuck at a station for a large part of the day.

We have to continue further developing the ensemble system and improving the probability forecasts, particularly for the short range (convective systems, fog...). And we have to continue persuading the user to appreciate the value of probabilities. But we have to be more appreciative of the reluctance of people to use such a system. Maybe then we will be more successful.

Jan Barkmeijer

Is there a bright future for linear models?

Do linear models have a bright future? Without hesitation I would answer this question with an affirmative "yes". Between 1995 and 2002 I worked in the Predictability Section, which I consider as a highlight in my working career. During that time I got intensively involved in the application of linear models and was, and still am, impressed by what they can teach us. For sure there are areas where the role of linear models has changed or even diminished in recent years. In the context of probability forecasting at ECMWF this is illustrated by the increasing use of the Ensemble of Data Assimilations (EDA) to derive initial condition perturbations at the expense of singular vectors (SVs).

Despite the introduction of the EDA, it must be said however that SVs still play a role in tuning the spread–skill relation to a satisfactory level. At the same time it seems quite plausible that, with the increasing spatial resolution, linearized versions of forecast models will become too difficult to develop. Standard operational limited area models have now reached a grid resolution of a few kilometres and are equipped with highly complex and nonlinear physics packages, which, for example, describe the dynamics of various hydrometeors such as rain, snow, cloud ice and cloud water. To what extent SVs can probe dominant perturbations growth mechanism for such high-resolution models is still a matter of debate. Therefore it is intriguing that even for these mesoscale models the 4D-Var algorithm is still producing sensible results (e.g. in case of assimilating radar data). Another area where the use of linear models seems to be limited at first sight is climate predictions. After all the term 'linearity assumption' alone is already rather out of place here.

Yet, it is precisely these two topics, high-resolution modelling and climate predictions, which provide examples that support the view that linear models will remain useful for the coming years. The first example describes how linear models can be employed in climate predictions so that forecasts with increased amplitudes into a prescribed anomaly direction can be realized. The second example focuses on the definition of the linearization trajectory, which is required to execute linear models. Usually the linearization trajectory is produced by a nonlinear model run. If the perturbations become too large or nonlinearities too dominant, the 'linearity assumption' breaks down and this nonlinear trajectory becomes sub-optimal. Variational data-assimilation is an area where this approach may be of use.

Example A: Adding flavour to climate forecasts

Determining regional climate change is not straightforward as global change, variations in the atmospheric circulation and local feedback all contribute in an intricate interplay. For example, the increase of the global mean temperature cannot fully explain why more westerly winds than usual during winter will result in warmer winters in Western Europe. Since climate forecasts tend to disagree on changes in the large-scale atmospheric circulation this also implies that regional climate change comprises a less predictable component. Still, in order to produce time series of local climate variables for the future climate, one often relies on statistical techniques to obtain local climate information. A drawback of these approaches is that often the physical consistency between different meteorological variables is violated.

By using a minimization technique it is possible to adjust a climate run to produce, for example, an atmospheric circulation over the North Atlantic sector, which is characterized by a more persistent westerly circulation in winter. The method has already been applied in other studies (*Widmann et al.*, 2010, and references therein) for models of medium complexity. It has the advantage that the average atmospheric circulation is modified while at the same time synoptic-scale variability is able to adjust to these large-scale circulation adjustments.

Figure 6 presents the first results of this minimization method as obtained with the ECMWF IFS (Integrated Forecasting System). The method consists of two steps that are repeatedly performed during the model integration.

An optimal tendency perturbation is determined such that its linear response after a certain lead time, here 5 days, has a maximal contribution in the direction of a prescribed target pattern.

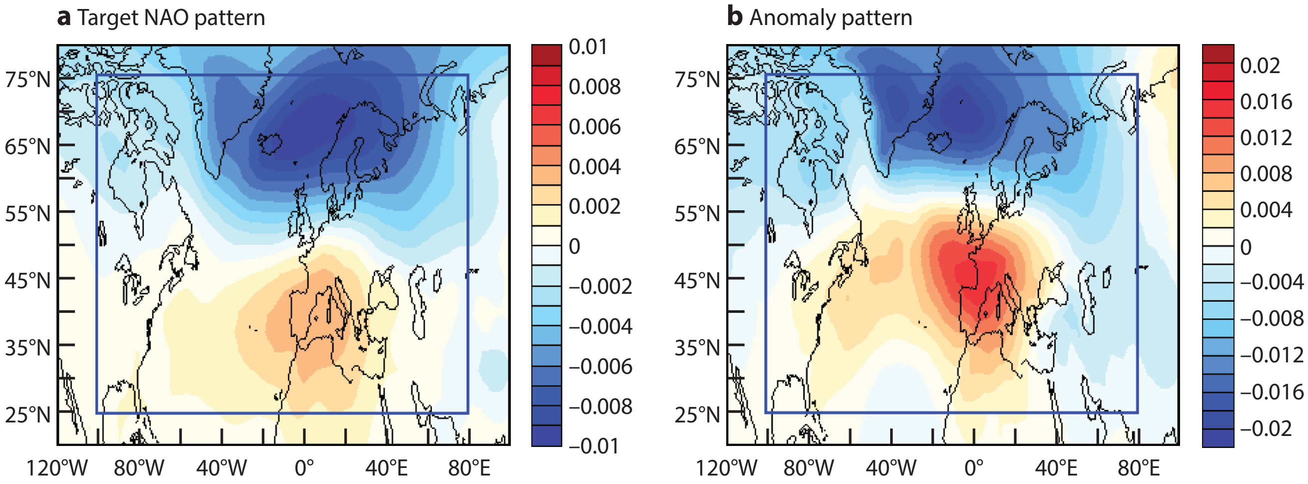

Figure 6 (a) Target NAO pattern used to determine 5-day forcings and (b) anomaly pattern given by a 3-monthly mean difference between the forced and unforced model run. The results are given in terms of the logarithm of surface pressure. Thanks to Lucinda Rasmijn for allowing this figure to be used.

The optimal tendency perturbation is subsequently applied in the climate run during the next 5 days.

Figure 6a shows the NAO (North Atlantic Oscillation) target pattern. The impact of using tendency perturbations in 5-day chunks during a 3-month run is given in Figure 6b in terms of the 3-monthly mean difference between perturbed and unperturbed run and again. Clearly, the tendency perturbations have resulted in a stronger projection onto the NAO target pattern. At the same time this model run has produced dynamically and physically consistent data which may help to identify and quantify feedback processes between atmospheric dynamics and boundary conditions.

Example B: Gaussian quadrature linearization trajectories

The use of linear models is limited for those time ranges for which the linear assumption is valid. By this we mean that the difference between two nonlinear model runs, and with an initial difference magnitude comparable to analysis increments, can be described by the associated linear version of the nonlinear model. Often to achieve this great effort is required to develop linearized models that capture as many features as possible of the full nonlinear model. Despite these efforts, the time window during which the linear assumption is valid ranges from around a day for models at the synoptic scale to only several hours for cloud resolving models at the kilometre scale. In order to be able to run a linear model a linearization trajectory is required. Usually such a trajectory is provided by a nonlinear model. By choosing, however, an optimal linearization trajectory it is possible to considerably extend the lead times for which the linear assumption holds. For example, in a quasi-geostrophic model an increase from a few days to over 200 days was realized.

In Figure 7 results are displayed for 10 cases. Around day 175 the initial numerical noise has reached such a level that the angle between the linearly and nonlinearly evolved perturbations starts to become non-zero. Around day 200 the differences have become too large to be neglected. While quasi-geostrophic models have only quadratic nonlinearities, higher order nonlinearities can easily be accounted for by introducing an ensemble of linearization trajectories with weights given by Gaussian quadrature points. For more details see *Stappers & Barkmeijer* (2012).

A natural application of this approach lies in 4D-Var. It is known that combining linear and nonlinear models in the 4D-Var algorithm can lead to instabilities caused by differences in phase speed of gravity waves. Using optimal linearization trajectories the distinction between inner and outer loops in 4D-Var is no longer necessary as the trajectory is already updated in the inner loop and with negligible additional computational costs. As the innovation vector is not modified in this approach it is also straightforward to derive exact equations for the adjoint-based observations impact.

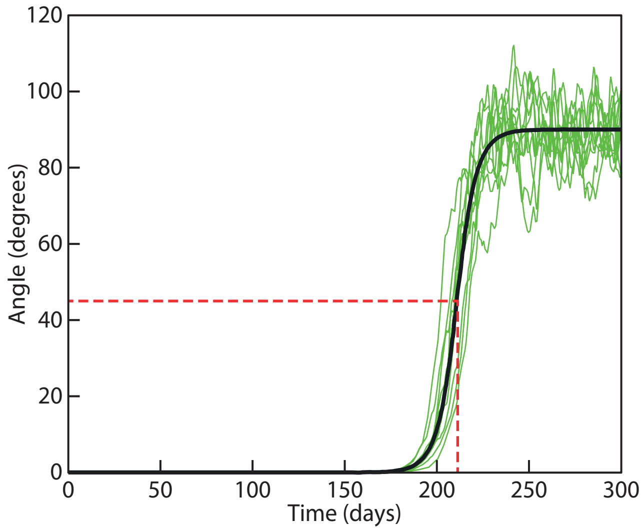

Figure 7 Angle between the nonlinearly and linearly evolved perturbation (10 cases) as a function of lead time and using the optimal linearization trajectory in the tangent linear model. Thanks to Roel Stappers for allowing this figure to be used.

Franco Molteni

What progress did we achieve with the ensemble approach to long-range predictions?

Ensemble prediction at ECMWF was born in the early 1980s with the goal of extending numerical prediction from the medium to the long range, and I was fortunate enough to get involved in the very early stages of such a research project. After my graduation, while working as a meteorological consultant for the Italian Electricity Board, I met Stefano Tibaldi (who at the time was the Head of the Numerical Experimentation Section at ECMWF), and asked him if ECMWF had any plan to use numerical models for long-range predictions. His answer, in short, was "we intend to do that, would you be interested in joining us?", and this is how my career was shaped!

I joined the Numerical Experimentation Section in January 1984 as a visiting scientist, and found that some 'deterministic' monthly range forecasts were already being run by Ulrich Cubasch. However, Stefano was keen to test the lagged-average ensemble approach advocated by *Hoffman & Kalnay* (1983); so, with Ulrich and Stefano, we ran four case studies of monthly forecasts with 9-member ensembles started from operational analyses lagged by 6 hours, using the ECMWF spectral model at T21 (yes, T21!) resolution. We soon realized that the model was drifting fast towards its own climatology, so we also ran the model from 10 earlier initial dates in order to get an estimate of the systematic error and subtract the model bias from the predicted anomalies. Thanks to a bit of 'beginner's luck', the results were sufficiently encouraging to convince the ECMWF management to invite me back in 1985 to repeat the experiments at T42 resolution. A summary of those experiments can be found in *Molteni et al.* (1987).

Research on extended-range predictability continued at ECMWF for more than a decade, using prescribed sea-surface temperature as a boundary condition for ensemble integrations of the atmospheric model. After 1987, under the leadership of Tim Palmer, the focus shifted from the monthly to the seasonal-scale, with a specific interest in the atmospheric response to the ENSO (El Niño–Southern Oscillation) phenomenon.

Seasonal predictions

In the mid 1990s, the time was ripe for starting experimental seasonal predictions using a coupled ocean-atmosphere model, and a new group was established under the leadership of David Anderson. This group managed to produce a remarkable prediction of the major El Niño event of 1997–98 (e.g. *Stockdale et al.*, 1998), and such a success was instrumental in moving seasonal prediction from a research project to an operational (albeit experimental) activity. The coupled system introduced in 1997 has been upgraded three times since then, with the latest configuration (referred to as System 4) having been implemented in November 2011 (*Molteni et al.*, 2012).

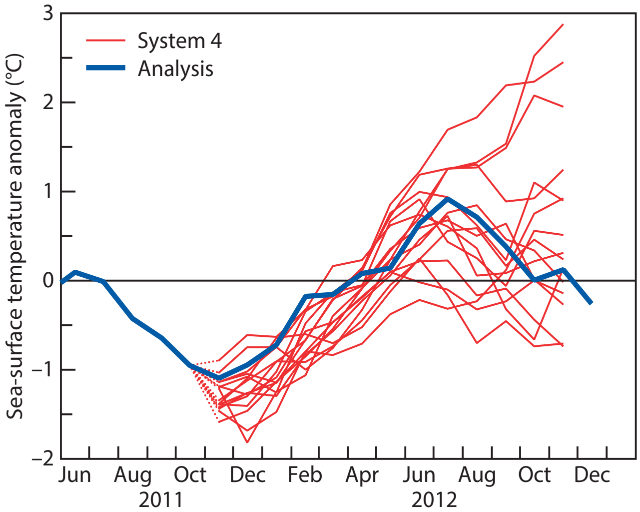

Figure 8 Predicted evolution of the monthly mean sea-surface temperature anomaly for NINO-3 SST anomaly from the 14-month forecast from System 4 started on 1 November 2011. Shown are the ensemble members and verifying analysis.

The ECMWF seasonal predictions have maintained a world-class standard in the last 15 years, especially with regard to the forecasts of ENSO events, as highlighted by the recent review by *Barnston et al.* (2012).

An example of an ENSO prediction is given in Figure 8, which shows the first 14-month prediction of SST anomaly in the NINO-3 region (150°W–100°W, 5°N–5°S) performed by System 4, superimposed to the actual evolution of the anomaly. Although predicting the impact of ENSO in some regions of the world remains problematic, ENSO prediction can be considered a success story for long-range ensemble forecasting at ECMWF and for the international scientific community in general.

Monthly predictions

But what about the monthly time scale? The early experiments of the 1980s showed some encouraging results, but also highlighted the limitations of the ensemble techniques and numerical models used at that time. ECMWF decided to go back to monthly forecasting with a coupled system in 2002, with products being released operationally in 2004. Since March 2008, monthly forecasts are run as a reduced-resolution extension of the medium-range ensemble (*Vitart et al.*, 2008). This allows monthly forecast to exploit the progress in ensemble perturbation strategy and model resolution which have been introduced in the medium-range ensemble configuration. Monthly-scale predictions are particularly challenging, because in the sub-seasonal time range the effects of internal atmospheric variability are often dominant over the 'forcing' from the surface conditions.

An important sub-seasonal phenomenon, the Madden-Julian Oscillation (MJO), has proved to be a particularly difficult and elusive target for numerical modellers. However, major development in convective parametrization occurred at ECMWF and other leading centres in the last few years have significantly improved the quality of MJO predictions.

Since the MJO generates teleconnections in both the northern and the southern extratropics, with important effects on Euro-Atlantic flow regimes (e.g. *Cassou*, 2008; *Vitart & Molteni*, 2010), one should expect improvements in MJO predictions to be reflected in the skill of monthly forecasts over the Euro-Atlantic region.

Improvements in MJO predictions are clearly shown in Figure 9, taken from a recent study by *Vitart* (2013). Here, the correlation between the ensemble-mean and the observed North Atlantic Oscillation (NAO) index is shown using re-forecasts run with the operational monthly forecast systems used from 2002 to 2012. Two curves are displayed: one for the skill in periods of no significant MJO activity, and one for periods when MJO amplitude exceed one standard deviation. Both curves show an increase of skill with time. However, in the earlier years, the inability of the ECMWF model to represent properly the MJO and its teleconnections produced a better NAO skill when the MJO was inactive. Viceversa, in the last 5 years, improvements in modelling the MJO-NAO connections resulted in a better NAO skill during active MJO periods, leading to a substantial increase in NAO predictability in the second half of the monthly forecast range. Again, this can be regarded as a major modelling success, but one that needs a well calibrated ensemble system to be fully exploited.

The remaining challenges

Looking ahead at the next generation of ECMWF long-range forecasting systems, we face a number of challenges. Some of them regard the formulation of the coupled model: for example, we are working to implement an ocean model with increased resolution (¼° grid, 75 vertical levels) and a dynamical sea-ice module, and we need to improve our representation of stratospheric and land-surface processes. Progress is also needed in ensemble perturbation strategies:

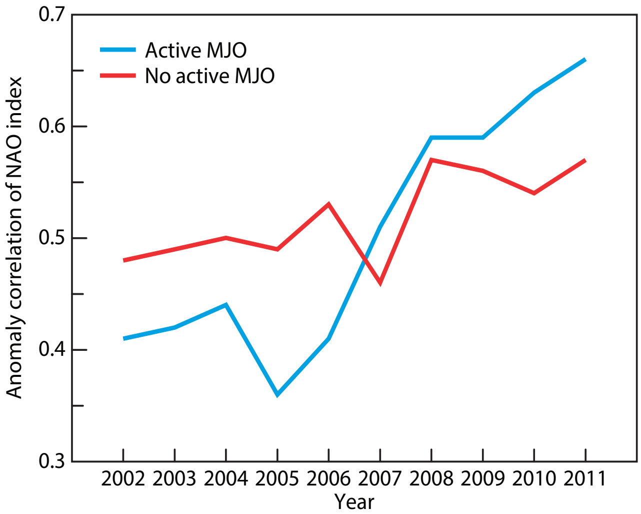

Figure 9 Anomaly correlation of ensemble mean forecasts of the NAO index for cases with no active Madden-Julian Oscillation (MJO) and those with an active MJO (amplitude > 1 standard deviation) in winters 1995 to 2001, from the re-forecasts performed to calibrate operational monthly forecasts in years 2002 to 2001.

we are moving towards a coupled ensemble data assimilation system, providing consistent initial perturbations in the atmosphere and the ocean, and a representation of model uncertainties closely connected with specific components of the physical parametrization package.

Finally, we should not forget that our understanding of the interactions between atmospheric flow regimes and ocean and land-surface conditions is still unsatisfactory. Dynamical understanding is no less important than model resolution and computer power in driving advances in long-range predictions.

Roberto Buizza
What next?

I joined ECMWF in October 1991, and started working on the development of the first version of the ECMWF ensemble prediction system under the supervision of Tim Palmer, with Franco Molteni, Robert Mureau and Joe Tribbia, who was visiting ECMWF for a six-month period. My first piece of work was computing singular vectors using the ECMWF tangent forward and adjoint dynamical model. I then developed the first linear and adjoint physical parametrization scheme, a vertical diffusion and surface drag scheme, which was required to compute meteorologically-sound singular vectors, and in the 3D-Var and 4D-Var assimilation schemes. This was followed by research on various predictability aspects, from adaptive targeting using singular vectors and model error simulation using stochastic methods, to applications of ensemble weather forecasts in the energy sector, in finance and flood prediction. I grew (older!!) as the ensemble evolved to become the recognized best medium-range probabilistic system.

In this contribution, I will discuss very briefly ECMWF's on-going research to improve the quality and reliability of its ensemble forecasts. I have grouped the work in four main areas.

- Model simulation of physical processes, taking model uncertainty into consideration.
- Data assimilation, including analysis uncertainty estimation.
- Ensemble forecast configuration.
- Ensemble products and calibration.

Box B summarizes the key characteristics of the current operational configuration, many of which will be referred to in the following discussion.

Model simulation of physical processes, taking uncertainty into consideration

Work to improve the simulation of physical processes also taking uncertainty into consideration will continue and is expected to lead to more realistic simulations of model uncertainties.

The fundamental role of past model improvements on ensemble prediction has been confirmed recently by a study of the time evolution of the performance of single and

Configuration of the ECMWF operational ensemble forecasts

B

The ECMWF global medium-range forecast comprises a high-resolution forecast (HRES) and an ensemble of lower-resolution forecasts (hereafter named ENS rather than EPS, following a recent revision of the terminology used at ECMWF, see *ECMWF Newsletter No. 133*, 1–13). The following provides some details about the configuration of the operational ensemble forecasts.

- *Membership*. 51 members, runs twice a day at 00 and 12 UTC with a 15 day forecast range; twice weekly it is extended to 32 days (on Mondays and Thursdays at 00 UTC).
- *Atmosphere resolution*. For the atmosphere, variable horizontal resolution, with a spectral triangular truncation T639 (about 32 km) up to day 10 and T319 (about 65 km) afterwards, with a spatial linear grid; in the vertical, ENS uses 62 levels up to 5 hPa.
- *Ocean wave resolution*. ENS is coupled to the WAM wave model with 55 km resolution, and 24 directions and 30 frequencies up to day 10, and 12 directions and 25 frequencies afterwards.
- *Ocean currents resolution*. ORCA100z42 grid, with a 1-degree horizontal resolution and 42 vertical layers.
- *Ocean currents coupling*. ENS runs with persisted sea-surface temperature (SST) anomalies up to day 10, and coupled to the NEMO ocean model afterwards.
- *Uncertainty simulation* – ENS has been designed to simulate initial and model uncertainties;
- *Initial uncertainties*. Atmosphere initial uncertainties are simulated by adding to the HRES-4DVAR T1279L91 (16 km) analysis two sets of perturbations generated using:
  – 50 forecast singular vectors computed at T42 resolution over different regions of the globe (NH, SH, tropics) with maximum total-energy growth over 48 hours.
  – 6-hour forecasts at T399 resolution started from the 11 perturbed members of the Ensemble of Data Assimilations (EDA).
- *Ocean currents uncertainties*. Ocean initial uncertainties are simulated by using the NEMOVAR ensemble of ocean analysis.
- *Model uncertainties in the atmosphere* – Model uncertainties are simulated only in the atmosphere using two stochastic schemes:
  – The stochastically perturbed parametrized tendency (SPPT) scheme is designed to simulate random model errors due to parametrized physical processes; the current version uses 3 spatial and time level perturbations.
  – The stochastic back-scatter (SKEB) scheme is designed to simulate the upscale energy transfer induced by the unresolved scales on the resolved scales.
- *Model climate and calibration*. Some of the ensemble products (e.g. the Extreme Forecast Index, or weekly-average anomaly maps) are constructed by comparing the most recent ensemble forecast with the model climate estimated using the re-forecast suite, which includes 500 forecasts. For each date (e.g. 14 December 2012), these 500 forecasts are defined by combining 5-member forecasts run for 5 initial dates centred on the current date (1, 7, 14, 21 and 28 December) of the past 20 years (these ensembles start from ERA-Interim central analysis, use singular vectors of the day but EDA-based perturbations computed for the current year since the EDA has been running only since 2010).

probability forecasts. Results provided by Martin Leutbecher have indicated that having an accurate simulation of the physical processes is essential to provide skilful medium- and long-range predictions.

A recent example of the role of model advances in improving the performance of long-range prediction is the positive impact that changes in the convection scheme had on the simulation of the Madden-Julian Oscillation (MJO), a major mode of intra-seasonal variability, which interacts with weather and climate systems on a near-global scale. Improvements introduced in January 2010 in the entrainment and detrainment, and the convection closure formulations has led to advances in the representation of atmospheric variability and in the propagation of the MJO signal through the entire integration period. Another recent example is given by the role of improvements in the land surface hydrology, convection and radiative parametrization in the prediction of the heat wave that affected the 2003 European summer. Finally, it is worth mentioning the on-going work to increase the number of vertical levels and revision of the model parametrizations in the stratosphere. Preliminary results indicate that the changes under testing are leading to a better simulation of the quasi-biennial oscillation. Tests have started to assess whether this improvement has any effect on the monthly time scale.

Work to improve the physical parametrizations will increasingly include the development of better approaches to improving the simulation of model uncertainties. The current operational ensemble uses a combination of two stochastic schemes, designed to simulate random model errors due to the parametrized physical processes and to the upscale energy transfer due to unresolved scales. The plan is to revisit the current formulations, and assess whether different approaches better linked to the physical schemes could lead to similar positive impacts. There are several promising lines of research.

One area under investigation in collaboration with the Finnish Meteorological Institute is based on an automatic estimation of the distribution (rather than one single value) of model parameters to be used to sample the parameters in each member of the ensemble.

Another area of research follows from the preliminary results obtained in collaboration with the UK and the Spanish Meteorological Institutes that suggested it is worth exploring whether tendency perturbations would be better computed separately for each single parametrization schemes than for the total tendency.

Data assimilation, including the estimation of analysis uncertainty

One of the crucial aspects of the design of ensemble prediction is the definition of the ensemble of initial states. In the current ensemble configuration, initial conditions are defined by adding perturbations generated using singular vectors and those based on the Ensemble of Data Assimilations (EDA) to a central analysis defined by the high-resolution four-dimensional analysis (interpolated to the ensemble resolution). Thus their quality depends on both the central (unperturbed) analysis and the initial perturbations.

With respect to the central analysis, results so far have indicated that centring the ensemble on the high-resolution analysis provides the best results. It is expected that this design will remain in place, at least until the EDA quality and resolution improves and its membership increases to 51 (from the current 11). Improvements in the data-assimilation algorithm (e.g. due to increased resolution, improvements in the statistical assumptions and extension of the assimilation time window) are expected to lead to improvements in the ensemble performance.

With respect to the initial perturbations, the introduction in 2010 of EDA-based perturbations addressed two known weaknesses of the old operational ensemble.

- Singular vectors are only marginally sensitive to observation characteristics (error in general, including coverage and representativeness).
- Singular vectors are too localized in space if compared to analysis error estimates, and poorly sample some areas of the world (e.g. the tropical band).

The plan for the future is to have an even closer coupling between the EDA and the ensemble, so that the forecasts benefit from planned EDA advances (e.g. in the planned

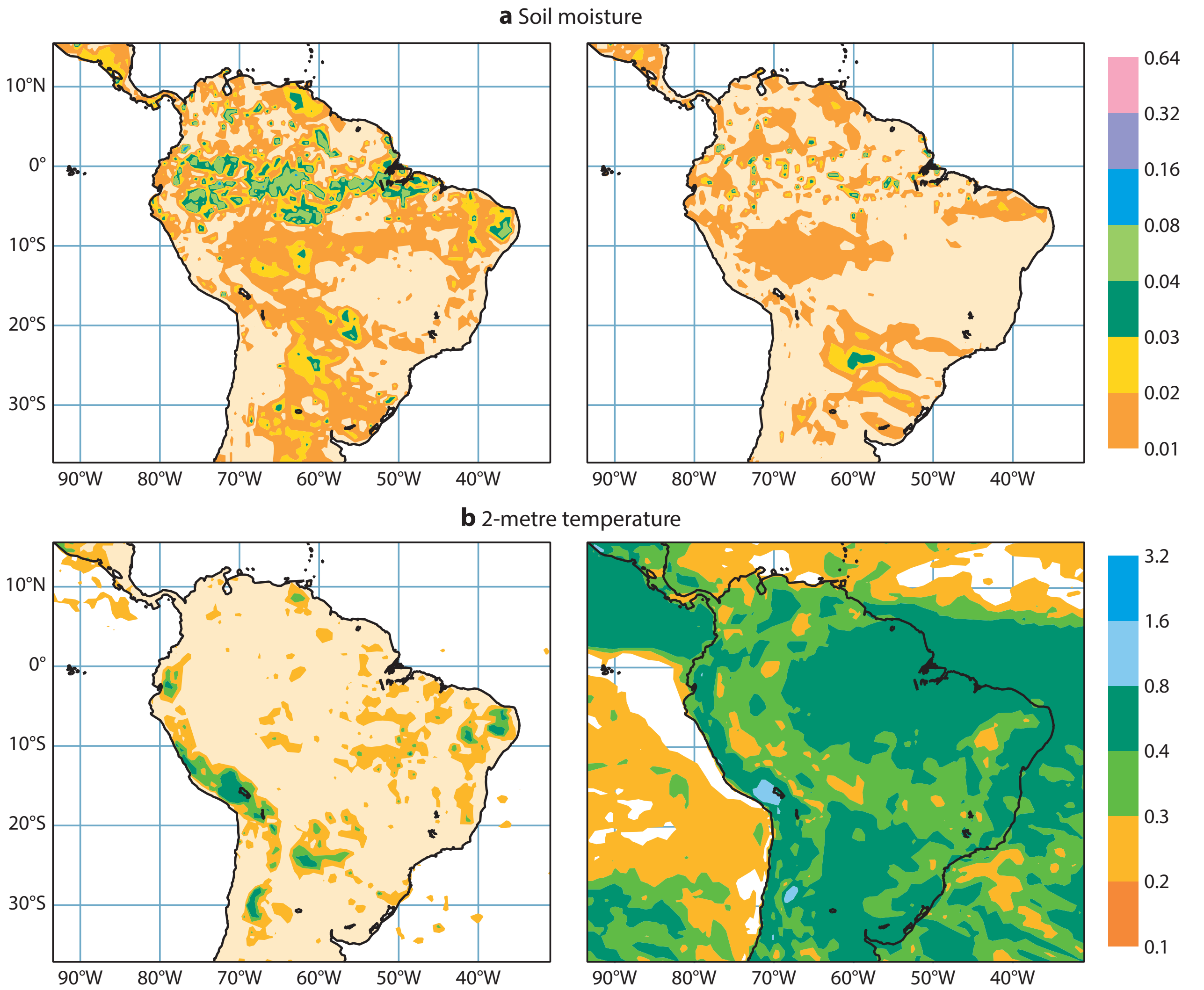

Figure 10 Average ensemble standard deviation at 24 hours from 8 cases for (a) soil-moisture and (b) 2-metre temperature of ensembles run in two different configurations: with only EDA-based land-surface perturbations (left panels) and with only EDA-based upper-level perturbations (right panels).

increase in the number of members, in the resolution of the outer and/or inner loops, in the specification of the observation errors used to perturbed the observations in the EDA members). A tighter coupling between the EDA and the ensemble will also be achieved by the addition of EDA-based land-surface perturbations. Preliminary results indicate that including soil moisture and soil temperature perturbations will lead to spread increases in regions where the forecast is under dispersive (e.g. in the early time range for variables close to the surface). As shown in Figure 10, after 24 hours, EDA-based land-surface perturbations would induce a larger soil-moisture spread than EDA-based upper-level perturbations over Brazil (top panels). This signal propagates to the free atmosphere and leads in some specific locations to 2-meter temperature spread of a comparable amplitude to the spread induced by the EDA-based upper-level perturbations (bottom panels).

Another area where work has started to improve the simulation of initial uncertainties is to include sea-surface temperature perturbations, mimicking what is currently done in the seasonal prediction System 4 using the ensemble of 5-member ocean analyses. The inclusion of EDA-based land-surface and sea-surface temperature perturbations can be seen as the first steps of a strategy that aims to improve the simulation of initial uncertainties of the coupled ocean-land-atmosphere ensemble.

The planned tighter coupling of the EDA and the ensemble will also imply implementing a consistent approach in the simulation of model uncertainty in both the EDA and the ensemble. Today, the EDA uses only one of the two model uncertainty schemes used in the ensemble, namely the SPPT (the stochastically perturbed parametrized tendency scheme is designed to simulate random model errors due to parametrized physical processes). The other scheme, which is based on SKEB (stochastic back-scatter scheme is designed to simulate the upscale energy transfer induced by the unresolved scales on the resolved scales), induces undesirable features when the EDA is used to compute background error statistics for the high-resolution 4D-Var. The aim is to develop a unified approach to the simulation of model uncertainties that can be used both in assimilation and prediction mode. This will be taken into considerations during the revision and upgrade of the current model error schemes.

Ensemble forecast configuration

Twenty years ago, ensembles were produced three times a week, at 12 UTC, and included 33 members run at T63L19 resolution. Since then, many changes in the ensemble configuration were introduced.

- Daily production started on 1 May 1994, still once a day.
- In 1998, each member was run with a coupled ocean wave model (WAM).
- From 2004 forecasts were issued twice a day, at 00 and 12 UTC.
- Between 1992 and today, membership increased from 33 to 51, and resolution from T63L19 to T639L62.

In 2008, the medium-range and monthly ensembles were joined, with the adoption of a variable-resolution strategy, forecasts were extended to 15 days every day and to 32 days once a week, and the coupling to the ocean current model was introduced (an example of a monthly forecast is given in Figure 11). At the same time, re-forecasts started been generated to allow the bias-correction and calibration of some products.

Since 2000, the ECMWF ensemble forecasts have been used to provide initial and boundary conditions to limited-area ensembles run by ECMWF Member States (among them, for example, the ones developed by the COSMO Consortium, Norway and France) and to drive ensemble flood forecasts (e.g. the European Flood Awareness System).

Is the current operational configuration the best for our users, or would they benefit more from a different set-up? For example, several global ensembles (e.g. the Canadian and the American ones) are now issued four times a day to provide users with a more frequent forecast updates. Should ECMWF follow their example?

Some of our Member States have informed us that the 00 UTC ensemble arrives too late on forecasting desks to be used early in the morning. We have also been informed that the 00 UTC ensemble is completed too late to be used to drive limited-area ensemble forecasts that have to generate forecasts by, say, 6 am local time. Should ECMWF at least also run an ensemble at 18 UTC to help the limited-area community?

To accommodate the users' requests while keeping the production cost to affordable levels, a possibility would be to move from symmetric 00 and 12 UTC production schedules, towards a four-times-a-day production, with each schedule not necessarily with the same membership, resolution and forecast length. For example, we could extend the 51 ensemble members to 15/32 days only at 00 UTC, but limit the 6, 12 and 18 UTC ensembles to 5–10 days, possibly with a smaller membership to reduce production costs. Possible changes to the operational configuration along these lines could be explored with the aim of making ECMWF ensemble forecasts of more value to our users.

Ensemble products and calibration

The last topical area in which further advances are expected is in the product generation, especially exploiting the re-forecast dataset to calibrate the ensemble forecasts.

Today, only a few products use the re-forecast dataset to either bias-correct some of the fields or to estimate the model climate. The latter is required to translate the ensemble probabilities into indices that highlight how far an ensemble forecast distribution is from the climatological one. An example of such a product is the extreme forecast index (EFI), which is routinely computed for surface variables such as total precipitation, 2-metre temperature and 10-metre wind speed.

As shown by *Hagedorn et al.* (2012), re-forecast calibrated ECMWF ensembles are more skilful than multi-model ensembles that include four of the best global ensembles.

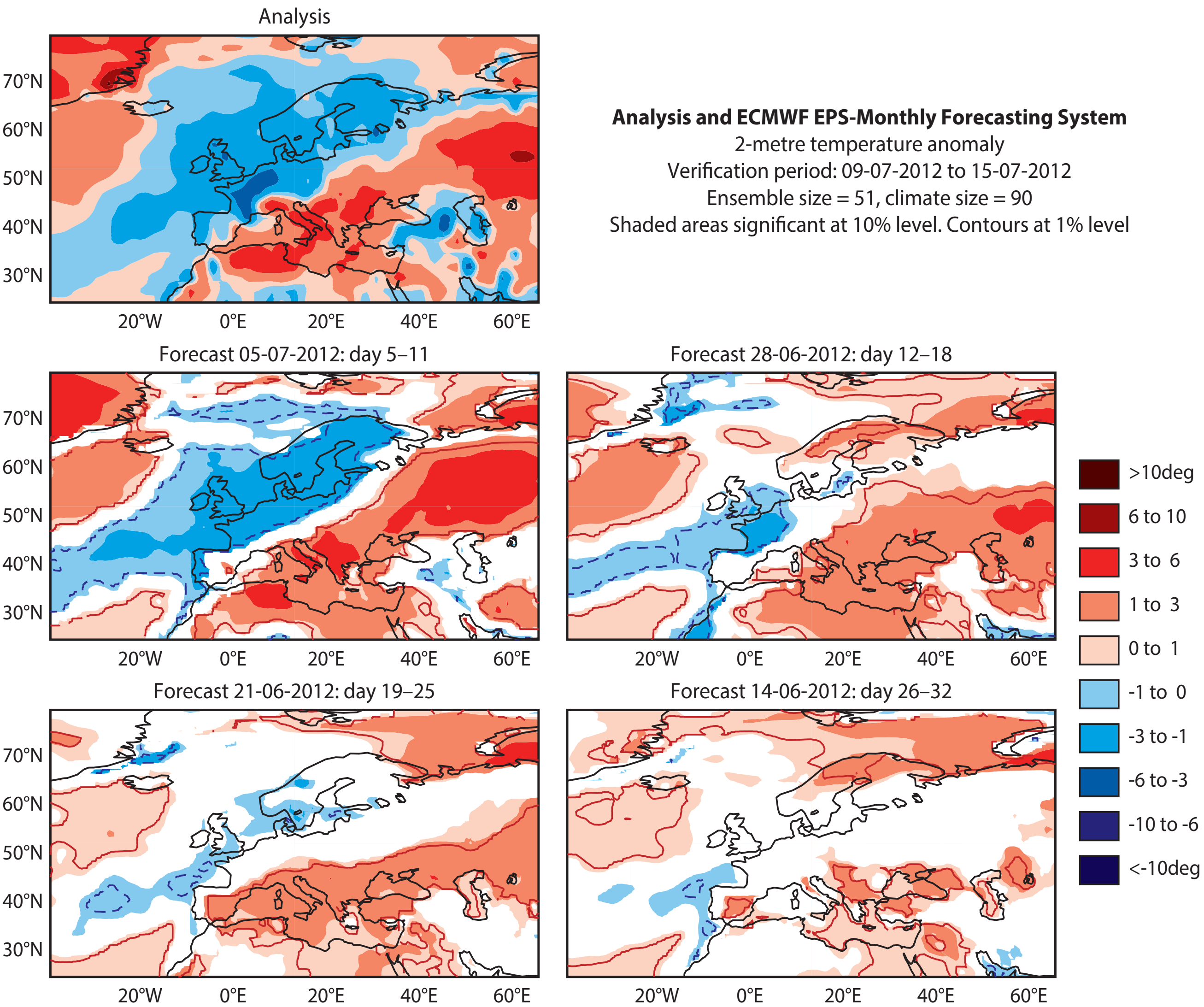

Figure 11 This is an example of a monthly forecast showing weekly-average 2-metre temperatures valid for the week 9–15 July 2012 (top panel), when Northwest Europe was experiencing cold anomalies and Southern Europe hot, summery weather! The other four panels show the weekly average forecasts issued on 5 July (5–11 days), 28 June (12–18 days), 21 June (19–25 days) and 14 June (26–32 days). The temperature anomalies are shaded when the ensemble forecast distribution is statistically significantly different from the climatological distribution. In some areas (e.g. UK and Italy) cold and warm conditions were correctly predicted up to three weeks in advance.

Following these results, a study has been initiated, in collaboration with the University of Heidelberg, to assess how we can further exploit the re-forecast data to generate a wider range of calibrated ensemble products. These could include, for example, meteograms at all grid points, and/or at specific locations, of calibrated ensemble distributions. This study will also look at which methodologies would be more appropriate to use for the different weather variables. It is expected that work in this area in collaboration with Academia and Member States could lead to more accurate, reliable and valuable ensemble forecasts.

1975, 1992, 2012, and beyond

We hope that this article has given an interesting historical overview on how ECMWF evolved its approach to numerical weather prediction. In 1975, in his article in the proceeding of the first '*ECMWF Seminar on the Scientific Foundation of Medium Range Weather Forecasts*', Cecil Leith stated that:

"Numerical weather prediction can never be exact owing to errors in the determination of the initial state and to external error sources arising from discrepancies between the dynamics of numerical models and that of the real atmosphere"

It took us until 1991 to develop and implement as part of ECMWF's forecasting suite the first ensemble prediction system that simulated the effect of 'initial state' error sources, and another decade to take 'external error sources' into account. Today, 20 years after operational implementation, the ECMWF medium-range ensemble forecasts are reliable and skilful up to one month ahead.

We are confident that continuous work and collaboration with the scientific community will lead to further advances and use of probabilistic forecasts.

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Uncertainty in tropical winds

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Analysing and forecasting the tropical circulations is a challenging task. In contrast to the mid-latitudes, balances are very subtle due to the smallness of the Coriolis force and the large Rossby radius of deformation that allows disturbances to affect the whole equatorial band. Furthermore, due to the thermal contrast between relatively warm surfaces and a troposphere that is continuously cooled by infrared radiative heat loss, widespread convection occurs in the tropics affecting a vast variety of space and time scales. These range from the individual convective cloud to the large-scale convectively coupled waves, the intra-seasonal oscillations, and the monsoon circulations.

A major difficulty in analysing tropical circulations resides in the sparseness of upper-air in situ data over tropical oceans, making satellite products the main source of observational information in these regions. The impact of conventional and satellite data on the analysis is determined by data density and the assigned observation errors. Thus, in areas with extended cloud coverage and convection, the analysis is more strongly driven by the forecast model than by observations, and is therefore more affected by model errors.

Recent international projects that focused on the intercomparison of global analyses from the main meteorological centres demonstrated that analyses agree fairly well for the mid-latitudes but surprisingly large systematic and regional differences persist in the tropical regions. As discussed in *De Szoeke & Xie* (2008), large differences in tropical winds, in particular over the Eastern Pacific, also exist between the different global seasonal-range forecast systems. Assessing the uncertainties and errors in tropical circulations in the ECMWF forecasting system is the challenge that will now be discussed.

Analysis increments

In regions with sufficient and 'accurate' observations, model errors can be quantified by analysis increments which are the corrections added to the background forecast by the 4D-Var analysis due to information from observations. These increments naturally have a seasonal cycle in the tropics. We decided to focus on the autumn season in 2011 where all the areas with large errors are apparent.

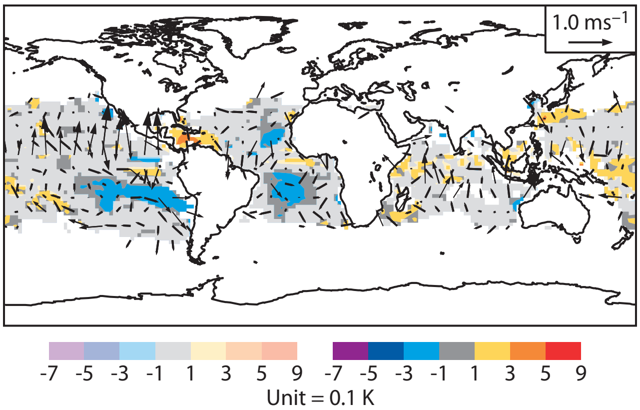
The seasonal mean of analysis increments for temperature and vector wind at 1000 hPa are shown in Figure 1a with Figure 1b showing the corresponding standard deviation of the wind speed analysis increments. A characteristic increment pattern emerges at 1000 hPa where high values of the standard deviation of wind speed closely follow the Inter Tropical Convergence Zone (ITCZ). But, at the same time, the vector wind increments increase the convergence in the ITCZ, particularly along its southern flank (situated northward of the equator) in the Eastern Pacific. Mean wind increments and standard deviation are both of order 1 ms^{-1}. The observations responsible for the low-level wind increments are mainly near-surface winds over the ocean from the ASCAT scatterometer.

At 850 hPa (Figure 2a) the increments still tend to increase the convergence near the equator, but now indicate a marked lack of cross-equatorial flow in the model in the East Pacific with a mean error of order 2 ms^{-1}. At 700 hPa (Figure 2b) the East Pacific stands out again with mean cross-equatorial wind increments of order 2 ms^{-1}.

Differences with UK Met Office analysis

So far the findings can be summarized as follows: near the surface along the ITCZ the observations tend to increase the convergence, and at 200 hPa there is a consistent divergent signal (not shown). Mid-tropospheric increments show large-scale structures which are consistent with the findings by

a Temperature and wind analysis increments at 1000 hPa



b Standard deviation of wind speed analysis increments at 1000 hPa

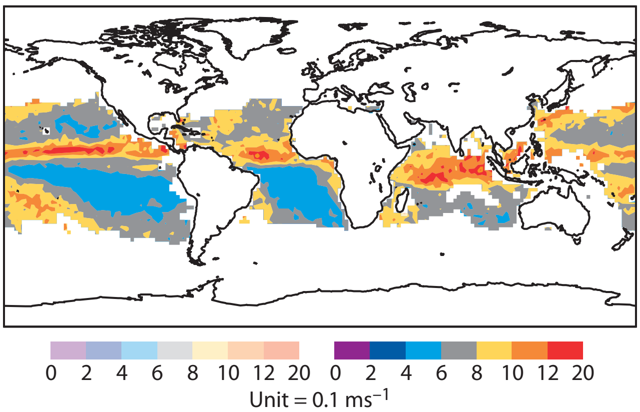


Figure 1 (a) Mean analysis increments for temperature and wind vector and (b) standard deviation of wind speed analysis increments at 1000 hPa for October–December 2011. Statistical significance at the 95% level is denoted by intense colours, pale colours are employed otherwise.

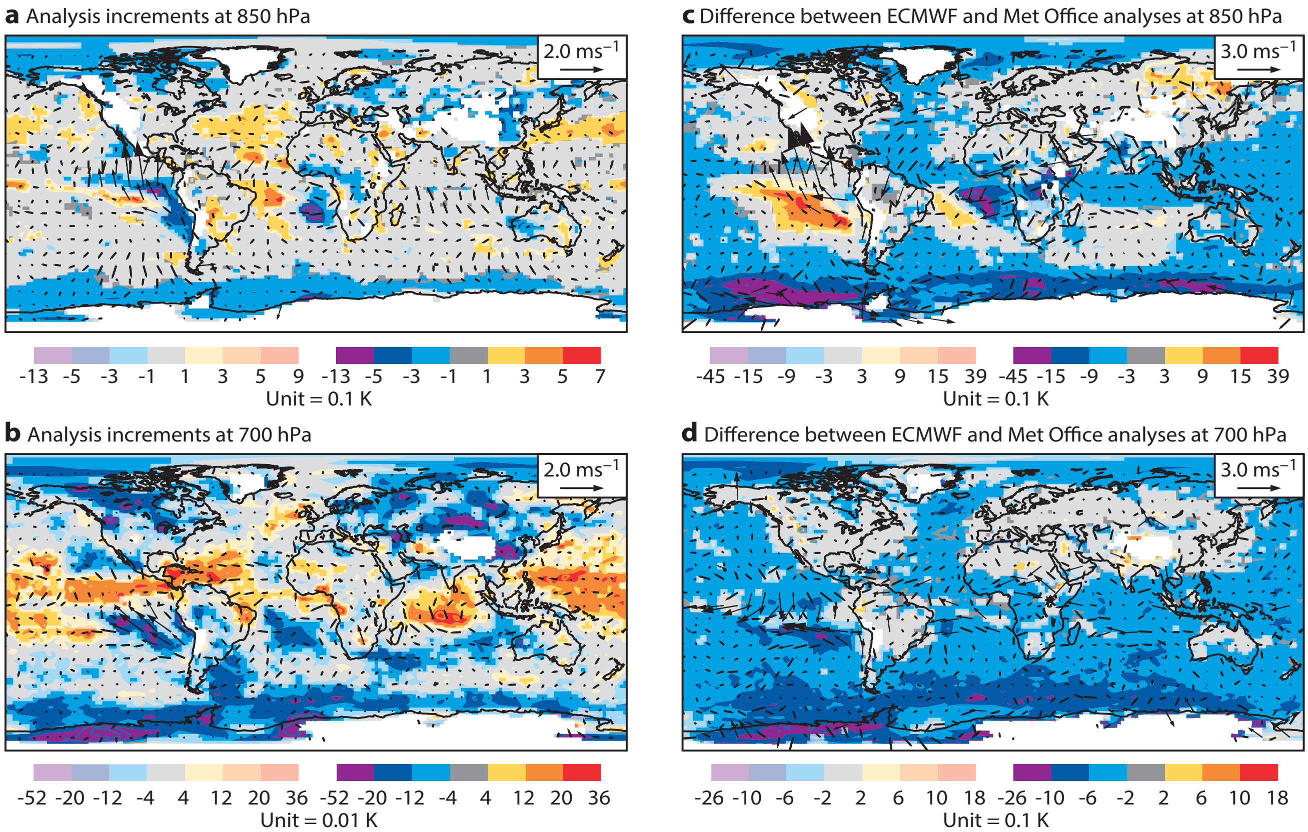


Figure 2 Mean analysis increments for temperature and wind vector for (a) 850 hPa and (b) 700 hPa for October–December 2011. Also shown is the mean difference between ECMWF and Met Office analyses at (c) 850 and (d) 700 hPa for the same period.

De & Chakraborty (2004). Also they are consistent with the results from *Žagar et al.* (2012) who showed that systematic model errors in the tropics occur at wavenumbers 1–3, whereas random errors occur in wavenumbers 4–7. However, the signals that stand out from Figures 2a and 2c are the strong wind increments at 850 and 700 hPa in the East Pacific.

Figures 2c and 2d show the differences between the ECMWF and the UK Met Office analyses at 850 and 700 hPa for autumn 2011. Broadly, the ECMWF analyses in the tropical troposphere are about 0.5 K colder than the Met Office analyses. Interestingly, however, these analysis differences appear to have many similarities with Figures 2a and 2b which are analysis increments that form proxies for ECMWF short-range forecast errors. The largest differences between the ECMWF and Met Office analyses occur over Central Africa and in particular in the East Pacific where at 850 hPa the ECMWF winds are more south-southeasterly, while at 700 hPa they correspond to a more north-northeasterly cross-equatorial flow. The question to then be addressed is which analysis is more realistic, or even better what observation types enforce the stronger cross-equatorial flow in the ECMWF analyses? Before doing so, it is useful to assess the model behaviour at longer ranges for ECMWF's high-resolution (HRES) and ensemble (ENS) forecasts.

Day 5 forecast errors

Figure 3 shows the day-5 forecast errors against their own analysis at 1000 and 850 hPa for the HRES forecasts. The tropical troposphere cools by about 0.5 K during the first 5 days. The wind patterns show a divergent signal at 1000 hPa along the ITCZ (Figure 3a), and large wind errors in the East Pacific at 850 hPa (Figure 3b). The results for the ENS forecasts (not shown) are similar to those for HRES. Two important findings can be deduced from these results. Firstly, the similarity in the errors between the HRES and ENS forecasts suggests that essential information on systematic tropical model errors can be obtained by only evaluating the HRES system. Secondly, comparing Figure 3 to the wind increments at 1000 and 850 hPa (Figures 1 and 2), one can readily see that wind increments (analysis minus short-range forecast difference) and day-5 forecast errors have a similar structure but opposite sign. This means that the observations tend to correct a model drift towards a weaker Hadley cell (less convergence in the ITCZ) and increase the low-level cross-equatorial flow in the East Pacific.

Observational data

Over the tropics, wind data is a very important source of observational information. The two main wind products with global coverage originate from the ASCAT scatterometer and the Atmospheric Motion Vectors (AMVs) that are derived by tracking the cloud and moisture fields. However, observations sensitive to temperature (e.g. infrared/microwave sounders) and moisture (e.g. microwave imagers, selected microwave and infrared sounder channels) can also produce wind increments through the dynamic

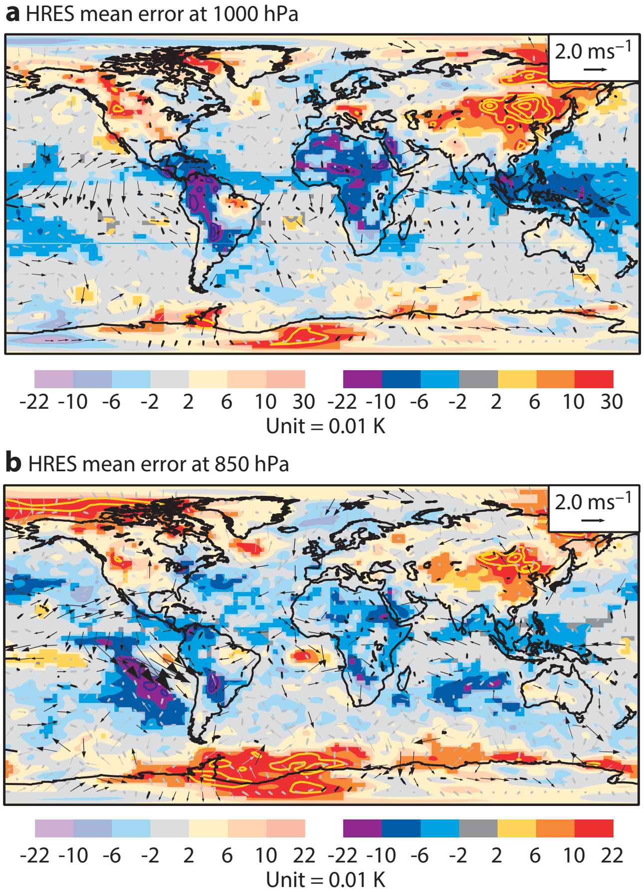


Figure 3 Day-5 mean forecast errors from HRES for temperature and wind at (a) 1000 and (b) 850 hPa for October–November 2011.

response to temperature and moisture increments in 4D-Var. These more indirect wind increments are usually broader in scale and thus less specific in height and location.

The East Pacific

Focusing on the tropical East Pacific, Figure 4 shows the mean temperature and wind analysis at 700, 850 and 1000 hPa for October–November 2011. The convergence pattern, which crosses the equator and intensifies towards the east where it intersects with the north-easterly flow from the Caribbean, is particularly strong at lower levels and the position of the ITCZ is easily identified near 10°N. Between 850 and 700 hPa the wind direction changes drastically from south/southwest to north/northwest at the equator, while intensities are fairly similar. These strongly sheared flow patterns intersecting with Central America over areas with large sea surface temperature gradients are difficult to represent correctly in the model.

The East Pacific is the only tropical region where all year-round, apart from spring, low-level south-southeasterly cross-equatorial flow dominates. Also during autumn and winter a reverse cross-equatorial flow prevails at 700 hPa that further enhances the vertical wind shear. As discussed in *De Szoeke & Xie* (2008), general circulation models tend to produce large errors in these regions. *Philander & Pacanowski* (1981) and *Okajima et al.* (2003) explain the particular Pacific wind pattern by the position of the ITCZ north of the equator, the northwest–southeast slant of the American coast, and the Andes orography that breaks the symmetry. On the other hand, *Rodwell & Hoskins* (2001) interpret the anticyclonic flow pattern as a Rossby wave response to the Central and South American monsoon to the east.

Data denial experiment

To assess the specific impact of wind information derived from observations, experiments can be conducted in which selected data is withdrawn. Figure 5 shows the mean 850 hPa analysis differences (colours denote temperatures and arrows

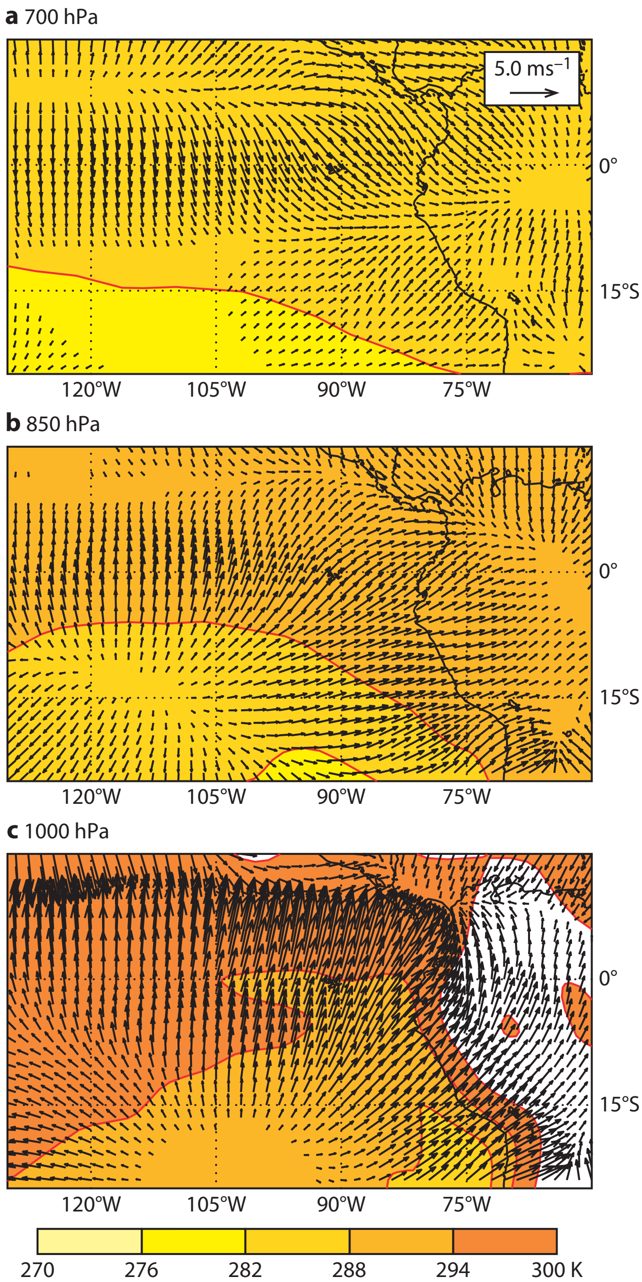


Figure 4 Mean wind and temperature analysis over the East Pacific at (a) 700, (b) 850 and (c) 1000 hPa for October–November 2011.

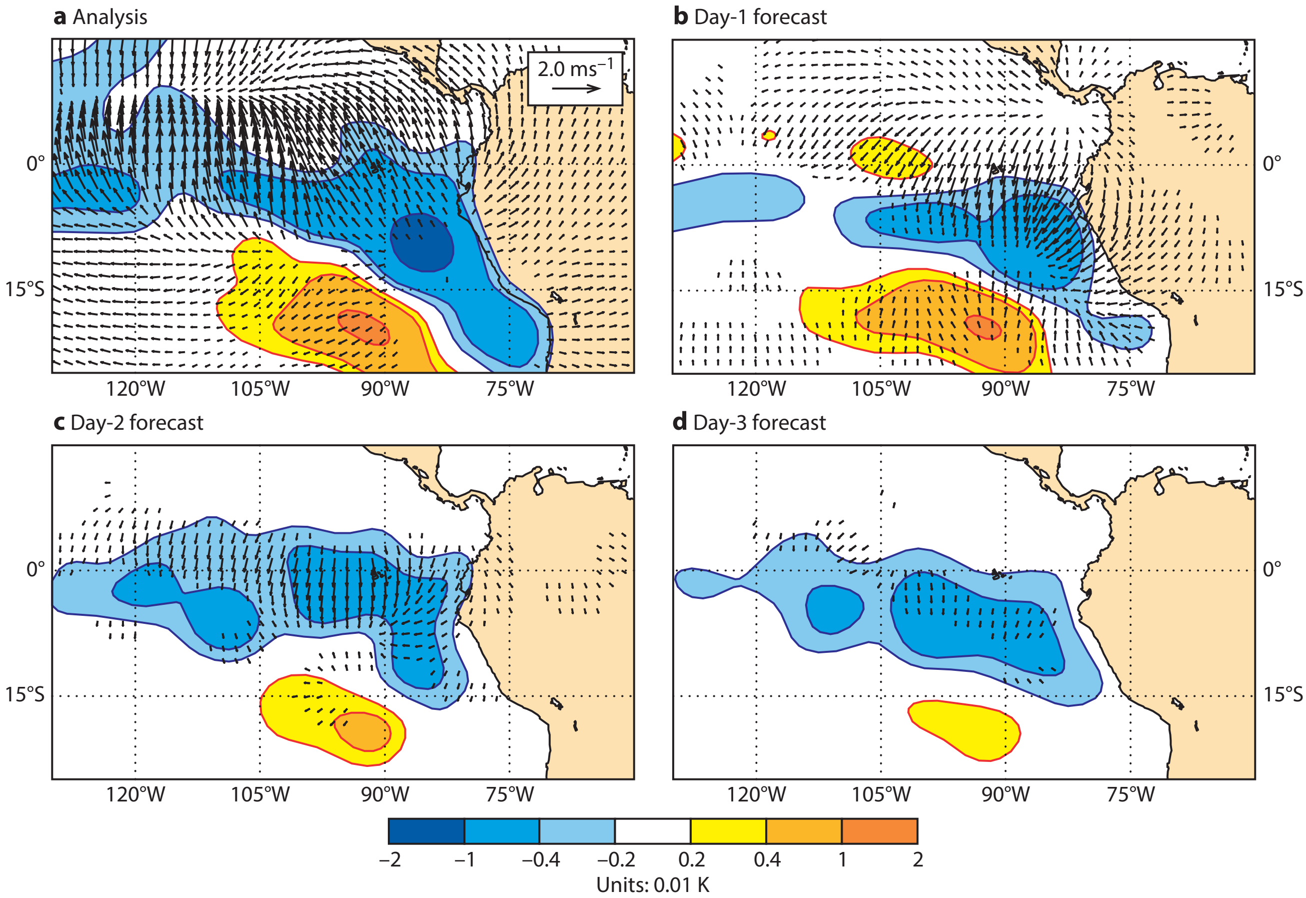


Figure 5 Mean analysis difference between control and the GOES-13 AMV denial experiment for wind (arrows) and temperature (colour scale) at 850 hPa for (a) analysis time, (b) day 1, (c) day 2 and (d) day 3 for October–November 2011.

wind) between the operational analysis and an experiment in which GOES-13 AMV data has been withdrawn in the area 30°S–0°/120°–150°W for October–November 2011. The analysis increments given in Figures 1, 2a and 2c are well reproduced in this data denial experiment and show a similar maximum of wind increments of order 2 ms-1 near 850 hPa (Figure 5a). The broad wind impact across the equator overlaps with a cooling by about 1 K through advection of cooler and drier air masses from the south. The observations therefore amplify low-level convergence across the equator and thus intensify the Hadley circulation in this area. The observations also move the centre of 850 hPa divergence from 15°S/110°W towards the continent.

Into the forecast, the areas with significant temperature increments remain rather stable until day 3. However, in the first 24 hours the enhancement of the cross-equator convergence changes sign (i.e. the model overshoots in response to the large analysis increments). The result of this strong dynamical adjustment process is that beyond day 2 there is barely any difference in the wind fields between the operational analysis using the GOES-13 AMVs and the experiment without that data.

Observation sensitivity techniques

Recently, adjoint-based techniques to assess observation sensitivity have been used to measure the observation contribution to the forecast error (*Cardinali & Healy*, 2012). It is interesting to assess whether the impact of AMV observations is generally beneficial for the 24-hour forecasts by means of the observation diagnostic known as Forecast Error Contribution (FEC). Here results are presented for the impact of u-component (Figure 6a) and v-component (Figure 6b) observations.

It is found that the v-component impact is generally positive (i.e. negative FEC) in the East Pacific, especially in the area where the amplification of the lower-level cross-equatorial flow at 850 hPa was noted. Most of the GOES-13 AMV observations provide wind information at 850 hPa (5 times more than at levels below and 10 times more than at 700 hPa). However, the negative impact of u-component observations (i.e. positive FEC) further to the southeast coincides with the area of lower-level divergence at 15°S/110°W. Here, wind speeds are very low and it is suspected that the AMV tracking algorithm may produce questionable retrievals in the presence of weak and divergent winds.

While the investigation described here focused on AMV observations, other wind-related data also impact the analysis as mentioned earlier. For example, ASCAT wind observations most strongly constrain 10-metre winds. Over the East Pacific, they show a more detailed pattern of first-guess departures (Figure 1) that is in contradiction to AMVs just south of the equator. Despite these differences, ASCAT winds also enhance lower-level convergence but along a smaller strip south of the ITCZ.

Concluding remarks

The task of quantifying analysis uncertainty and 'forecast error' is particularly challenging in the tropics due to the sparseness of in-situ data over the tropical oceans. The analyses from the various modelling centres can also have large differences.

Overall, one can say that the IFS presents a systematic trend to reduce the intensity of the meridional Hadley cell. The impact of ASCAT and AMV data on the analysis is similar in that both increase the convergence in the ITCZ and the low-level cross-equatorial flow, therefore pointing to a model bias in these regions. The model, however, overestimates the strength of the zonal Walker cell (i.e. a deep east-west overturning in the atmosphere normally confined to within about 20° of the equator) in that it overestimates precipitation and convergence over the Maritime Continent and the West Pacific (not shown). Interestingly, this is in agreement with a study by Oort & Yienger (1996) who demonstrated that an increase in the intensity of the Walker cell is associated with a decrease in the intensity of the Hadley cell and vice versa.

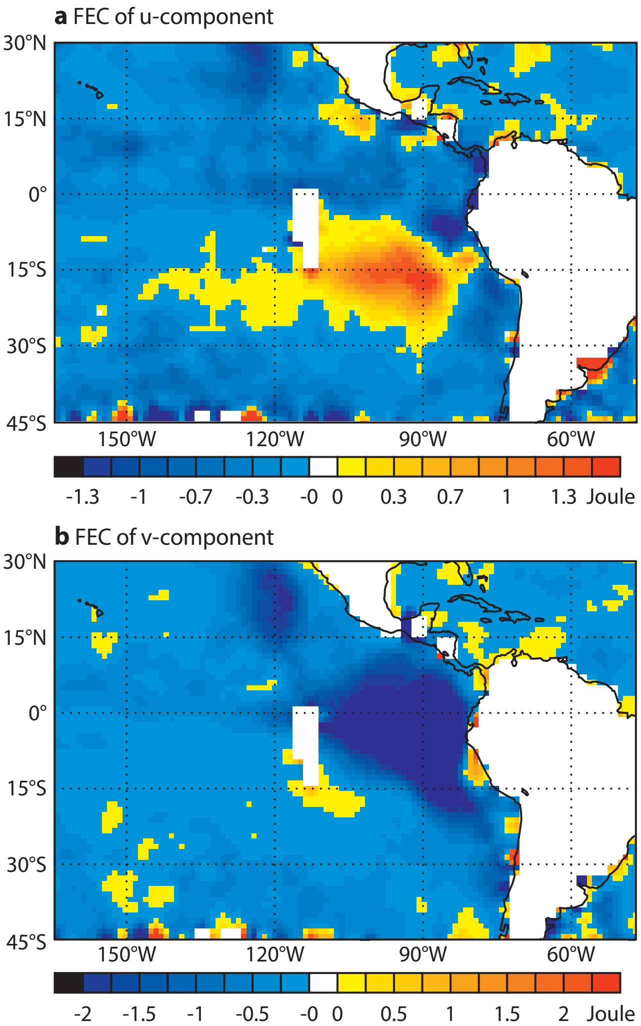


Figure 6 Mean Forecast Error Contribution (FEC) of (a) u-component and (b) v-component AMV observations in the atmosphere between 700 and 1000 hPa for October–November 2011 in the East Pacific. Positive (negative) values denote that the assimilated observations increased (decreased) the global 24-hour forecast error.

The area that stands out in terms of low-level wind errors and large differences in the analysis compared to that from the Met Office is the East Pacific. Data denial experiments further show that model forecasts at lead times beyond day 3 have largely 'forgotten' about the AMV analysis increments, and that the forecast adjustment processes between day 0 and day 3 produce a temporary flow reversal. Comparison with independent buoy data in this region confirms that the ECMWF analysis is indeed realistic but that a low-level flow bias persists in the forecasts. However, given the larger vertical wind-shear and likely larger observation errors of the AMVs in the East Pacific, the flow errors compared to analysis and increments are more uncertain, especially at 850 hPa.

We think that further improvements in tropical analysis will be achieved through improvements in the background error formulation (*Bonavita et al.*, 2012) as already achieved in the most recent operational cycle Cy38r1, the treatment of all-sky radiances, and in particular through the assimilation of tropical wind data from the ADM-Aeolus wind lidar that is expected in the 2015 time frame.

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RMDCN – Next Generation

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The Regional Meteorological Data Communication Network (RMDCN) is currently undergoing modernisation in order to meet the future requirements of ECMWF's Member States and the wider meteorological community. A recent procurement exercise identified that these requirements could be met most cost-effectively by migrating to a new state-of-the-art network operated by a new service provider – Interoute Communications Limited. This article describes the work that has been done, particularly over the last year, and the migration plans for the coming 12 to 15 months.

Background

During the 1990s Regional Association VI (RA VI) of the World Meteorological Organization (WMO) started a project to investigate the possibilities of using a Managed Data Communication Network for the provision of the Global Telecommunication System (GTS) in their region. With ECMWF participation this resulted in the creation of the RMDCN. Following an open procurement in 1998 the RMDCN started its operational service in March 2000 with 31 sites participating. The original service provider was Equant UK Ltd, which subsequently merged with Orange and France Telecom to create Orange Business Services (OBS).

The RMDCN provides a network infrastructure for the connections between ECMWF and its Member States and Co-operating States. In addition it has most of the connections for WMO Regional Association VI (RA VI) that are part of the WMO's Global Telecommunication System. The RMDCN is used for dissemination of ECMWF's forecast products and exchange of meteorological data (e.g. observations and radar data) between the connected sites. ECMWF manages the RMDCN and monitors the network on behalf of the connected user sites following an agreement with WMO.

Over time the demand for membership of the RMDCN began to grow. Supporting a further limited expansion of the RMDCN while keeping the number of user sites to a manageable level, the ECMWF Council agreed in 2008 to consider the following four categories of countries as potential future members of the RMDCN.

- ECMWF Member States and Co-operating States.
- RA VI countries not currently connected to the RMDCN.
- Countries operating Main Telecommunications Network (MTN) centres, including future Global Information System Centres (GISCs) of the WMO Information System (WIS).
- Countries outside RA VI connected to a RA VI country as part of the GTS, upon request by the RA VI country concerned.

Further details may be found on the ECMWF website at

- http://www.ecmwf.int/services/computing/rmdcn/.

As of early 2013, the number of RMDCN members now stands at 50 and includes National Meteorological Centres in countries such as Japan, China, India, United Arab Emirates, South Korea, Australia, USA, Canada and South Africa, as well as two EUMETSAT sites and one disaster recovery site in the Netherlands (see Figure 1).

The network has also evolved technically as well as geographically. A major change occurred in 2006 when the RMDCN was migrated from the Frame Relay architecture to a more modern one based on Multiprotocol Label Switching (MPLS). This provided several advantages, including improved availability levels, any-to-any connectivity and the provision of Class of Service (CoS) to allow traffic prioritization. Throughout its lifetime the RMDCN has also seen a steady increase in the speed of the connection of the sites, with the bandwidth of the ECMWF Member States Basic Package configuration typically doubling around every three years.

As the resolution of ECMWF's operational models continues to increase, so does the size of files that must be sent to its Member States. One of ECMWF's objectives is to provide the network infrastructure for the dissemination of products so it is vital to periodically verify that the RMDCN is fit for purpose and provides value for money. Therefore, in October 2010 the ECMWF Technical Advisory Committee (TAC) supported a plan presented by ECMWF to initiate a procurement process for the next generation of the network and established a TAC Subgroup on the RMDCN to assist with the definition of requirements and to review the outcome of the procurement.

The procurement process

As described above, the membership of RMDCN extends beyond ECMWF Member States and Co-operating States.

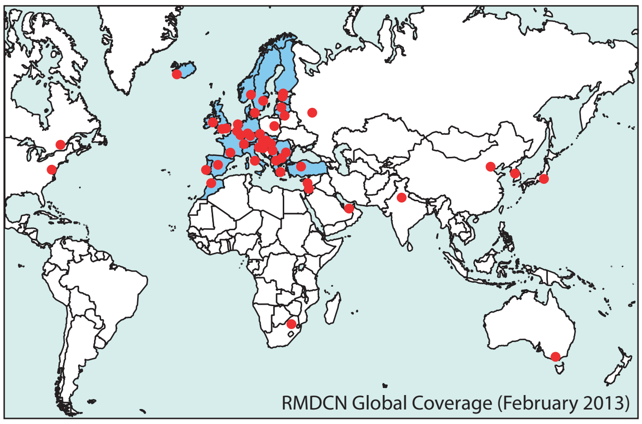

Figure 1 There are 50 sites (46 National Meteorological Centres, ECMWF, 2 EUMETSAT sites and one disaster recovery site in the Netherlands) connected to the network. The shaded countries indicate ECMWF Member States and Co-operating States.

Figure 2 Alan Thorpe, ECMWF's Director-General, signing the contract with Lee Myall, UK Regional Director at Interoute Communications Limited, for the provision of the Next Generation of the RMDCN.

Indeed the WMO intends to use the RMDCN as part of the core network for the new Weather Information Service (WIS), so the involvement of WMO was sought throughout the procurement process.

In preparation for the procurement, the TAC Subgroup on the RMDCN and the WMO Task Team on the RMDCN held meetings in 2011 to discuss requirements for the future RMDCN service. Early in 2012 these were finalized and consolidated to form the technical specification of requirements and the draft contract for publication in the Invitation To Tender (ITT).

After the closing date for replies to the ITT there followed several months of comprehensive assessment of the tenders. The evaluation clearly showed that the offer from Interoute Communications Limited (they proposed a network based on MPLS technology offering any-to-any connectivity) provided significantly better overall value for money, even when taking into account the cost of migration to a new provider.

Members of the WMO Task Team on the RMDCN and two other WMO observers attended the TAC Subgroup on the RMDCN and also gave their support to ECMWF's decision to select Interoute as the future supplier for RMDCN Next Generation. The nine-year contract (with a break point after six years) was then signed by the ECMWF Director-General and Interoute on 11 December 2012 (see Figure 2).

Features of the new contract

The discussions of the TAC Subgroup on the RMDCN and the WMO Task Team on the RMDCN resulted in a number of recommendations that have been implemented in the contract.

Contract term and technical/commercial refresh (TCR)

The contract duration for managed data networks is generally around three to five years. However the situation of the RMDCN is very different compared with other companies contracting for network services; the processes that need to be followed to procure a new network make it less flexible to change provider at short notice. The Subgroup noted that there are several reasons in favour of a three-year cycle.

- The lead time for a change of provider is around three years (this includes the whole procurement process and migration of the network).
- Evolution in the market has lead in the past to significant cost reductions and chances for technology upgrades around every three years.
- During the life-cycle of the current RMDCN the ECMWF-funded basic package has been upgraded around every three years.

The Subgroup then assessed the various advantages and disadvantages of longer initial contract terms and recommended the following scheme, based on a three-year cycle:

- Full contract term of nine years with a break clause at the end of the sixth year, to allow its potential termination in the case of persistent breaches of the Service Level Agreement.
- Technical/commercial refresh (TCR) with a guaranteed set of technology and/or cost benefits to the RMDCN after three years and six years (if the break clause is not used).

The TCR should ensure value for money over the duration of the contract, in recognition of the fact that the cost of networking technology has historically reduced over time. Individual countries will be able to decide whether to save money by paying less for their connection, or to upgrade their connection within the existing budget envelope.

The contract was successfully negotiated on the above terms.

For ECMWF Member States: the Basic Package configuration

As discussed earlier, ECMWF provides the network infrastructure for the dissemination of its products to its Member States. The configuration, known as the 'Basic Package', is the same for each ECMWF Member State and is based on a high availability requirement with sufficient bandwidth to guarantee on-time delivery for a critical set of ECMWF products. Migration to the new service provider will have a beneficial impact on Member States as the bandwidth of the Basic Package agreed with Interoute (4 Mbps) will be double the current speed. All sites will have the option to be connected at higher speeds (at their own additional cost) if they wish to do so.

Site types

In the current network with OBS effectively the only distinction made between the user sites is whether they are 'mission critical' or not. Mission critical implies a higher level of resilience, typically with an automatic failover to a backup circuit of the same speed.

One of the key requirements identified by the TAC Subgroup on the RMDCN was for a larger choice of configuration options (predefined 'site types'), allowing users a better opportunity to choose the solution that is most cost-effective for their particular needs. The Subgroup also considered that more flexibility in defining the site types would be beneficial.

In particular it proposed that lower grade access lines might be considered when costs would be prohibitively high in certain geographical areas. ECMWF has agreed with Interoute six site types: Platinum (most resilient and most expensive), Gold, Silver, Bronze, Copper and Iron.

The site types are differentiated by a number of factors, for example, the level of resilience, the quality and speed of backup, the level of service availability and the expected elapsed time for technical problems to be fixed.

Many sites will require the highly resilient Platinum site configuration, allowing a fully resilient mission critical setup with transparent backup arrangements.

At the lower end of the scale, the Iron site type allows a very cost effective option for some countries to connect to the RMDCN. It uses the Internet as a means to access the MPLS core network, using either a dedicated Internet access provided by Interoute (Iron A) or the available Internet access on the site (Iron B).

The site availability service levels vary for the site types, starting at a very high 99.97% for Platinum sites reducing to 99.8% for Copper sites. Iron A sites have much lower service level (95.3%) while for Iron B sites there is no contracted service level due to the fact that Interoute has no control at all over the access to the network.

Future technologies

The contract allows for various upgrades for the network service; for example, to introduce new technologies such as the IPv6 protocol and multicast traffic as they mature during the term of the contract.

Migration

Migration of an operational network of this size is not a straightforward exercise so planning work began immediately after the contract was signed. Before migration can take place, all sites have to select their site configurations and access speeds. The network will then be implemented in stages (in parallel to the still-operational OBS network) and its suitability for operational use will have to be tested thoroughly before letting go of the existing network.

The first step is to deploy a Pilot Network in the first half of 2013 in order to check out the new provider's capabilities. In cooperation with Interoute, we have selected sites considered to be representative for the whole community (ECMWF Member States, RA VI sites and sites outside Europe). The sites participating in the Pilot Network are: Austria, Belgium, Sweden, Bulgaria, Japan and ECMWF.

Following acceptance of the Pilot Network, orders will be submitted on 1 July 2013 for all other sites that have agreed their configuration, signed the order and the Accession Agreement (if they need to). This is the cut-off date for sites to be part of the so-called Initial Deployment.

Acceptance testing forms an important part of the move to a new network. There are four types of testing that will take place during the migration; two of these focus on the individual site installation, while the other two focus on the performance of the network as a whole.

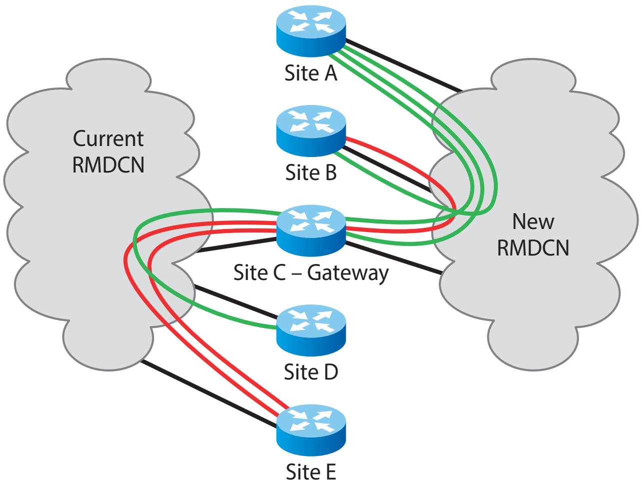

Figure 3 A graphical representation of a point during the migration from the current RMDCN to the new RMDCN. A 'gateway site' (planned to be ECMWF) will allow communication between sites that have already been migrated to the new network and those which are still operating on the old network.

Event	Due date (latest)
Contract Signature	11 December 2012
Pilot network phase	
ECMWF submits order forms for all Pilot Sites	4 February 2013
Interoute hands over all Pilot Sites	26 May 2013
Successful completion of Pilot Network Reliability Acceptance Test Formal acceptance of Pilot Network	30 June 2013
Initial deployment phase	
Order forms for a minimum of sixteen sites to be submitted, comprising at least the remaining ECMWF Member States. All these User Sites plus the six Pilot Sites are part of the Initial Deployment	1 July 2013
Start of Site and Network Reliability Acceptance Tests	20 November 2013
Successful completion of Global Network Reliability Acceptance Test Formally acceptance of new network	20 December 2013
Network Migration starts (for all sites part of the Initial Deployment)	6 January 2014
Network Migration finishes	6 February 2014

Table 1 Planned timeline of the migration to RMDCN – Next Generation.

Once the new network equipment has been installed and handed over to the site, the RMDCN team at ECMWF will carry out the *Site Functional Acceptance Test* to ensure that the equipment is functioning as it should. Some of the areas to check are router configuration, access line speed, the ability to 'talk' to other RMDCN user sites and backup functionality.

The *Site Reliability Acceptance Test* will follow the successful completion of the functional acceptance test and will check whether the service at an individual site meets the conditions of the Service Level Agreement (SLA) over a seven-day period.

The *Pilot Network Reliability Acceptance Test* will check, over a seven-day period, whether the service for the network of pilot sites meets the SLA. The Pilot Network Reliability Acceptance Test must be successfully completed within 35 calendar days of handover of all pilot sites.

Finally, the *Global Network Reliability Acceptance Test* will determine whether the new network as a whole performs to the required standard. It is again performed over a seven-day period. If the network fails to pass the test within the 30-day period then ECMWF has the right to terminate the contract.

Due to the fact that the primary consideration is to ensure that connectivity is maintained between all sites at all times, it was decided that a 'big-bang' approach – i.e. an instantaneous switch-over from the old network to the new – would be far too risky. Instead there will be a designated period of one month, during which all sites will be switched over.

During this period, ECMWF will act as a gateway between the current OBS network and the new Interoute network, thus enabling all RMDCN sites to continue to inter-communicate during the migration, whether they are on the OBS network or have already migrated to Interoute (see Figure 3). However, in order to minimise the overhead of running parallel networks, ECMWF will cease its connection to OBS in early May 2014. All currently connected sites are therefore being strongly advised to order their connections before 1 July 2013, so that they can be part of the Initial Deployment. Sites not part of the Initial Deployment will not be connected to the new RMDCN network until after the end of the one-month migration window (February 2014), on a business-as-usual basis.

Table 1 provides an overview of the migration plan timetable.

Preparing for the future

As the requirements on the RMDCN continue to grow, whether due to higher data volumes, increasing bandwidths or a continuing demand for membership from the wider WMO community, the next generation network will be in an excellent position to meet those requirements readily and cost-effectively.

ECMWF Calendar 2013

Apr 15–Jun 7	Training Course – Numerical Weather Prediction
Apr 15–19	Numerical methods, adiabatic formulation of models and ocean wave forecasting
Apr 22–May 2	Parametrization of subgrid physical processes
May 8–17	Predictability, diagnostics and extended-range forecasting
Jun 3–12	Data assimilation and use of satellite data
Apr 18–19	Advisory Committee for Data Policy (14th Session)
Apr 22–23	Finance Committee (92nd Session)
Apr 24	Policy Advisory Committee (35th Session)
Jun 5–7	Forecast Products Users' meeting
Jun 12	Joint session of the Technical Advisory Committee and Finance Committee
Jun 19–20	Council (79th Session)
Jun 24–27	ECMWF-WWRP/THORPEX Workshop on 'Polar prediction'
Jul 1–4	Training Course – ECMWF/EUMETSAT NWP-SAF satellite data assimilation
Sep 2–6	Annual Seminar on 'Recent developments in numerical methods for atmosphere and ocean modelling"
Oct 7–11	Training Course – Use and interpretation of ECMWF products for WMO Members
Oct 14–16	Scientific Advisory Committee (42nd Session)
Oct 17–18	Technical Advisory Committee (45th Session)
Oct 21–22	Finance Committee (93rd Session)
Oct 22–24	Workshop on 'Parameter estimation and inverse modelling for atmospheric composition'
Oct 25	Advisory Committee of Co-operating States (19th Session)
Oct 28	Policy Advisory Committee (36th Session)
Oct 28–30	14th Workshop on 'Meteorological operational systems'
Nov 4–7	EUMETSAT NWP-SAF Workshop on 'Efficient representation of hyperspectral infrared satellite observations for assimilation and dissemination'
Nov 13–14	Security Representatives' meeting
Nov 14–16	Computer Representatives' meeting
Dec 4–5	Council (80th Session)

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

Technical Memoranda

691 **Flemming, J. & A. Inness:** Volcanic sulphur dioxide plume forecasts based on UV-satellite retrievals for the 2011 Grímsvötn and the 2010 Eyjafjallajökull eruption. *December 2012*

690 **Matricardi, M. & A.P. McNally:** The direct assimilation of Principal Components of IASI spectra in the ECMWF 4D-Var. *December 2012*

689 **Bormann, N., A. Fouilloux & W. Bell:** Evaluation and assimilation of ATMS data in the ECMWF system. *December 2012*

688 **Richardson, D.S., J. Bidlot, L. Ferranti, A .Ghelli, T. Haiden, T. Hewson, M. Janousek, F. Prates & F. Vitart:** Verification statistics and evaluations of ECMWF forecasts in 2011-2012. *November 2012*

687 **Dee, D., M. Balmaseda, G. Balsamo, R. Engelen & A. Simmons:** Toward a consistent reanalysis of the climate system. *November 2012*

680 **Hólm, E. & T. Kral:** Flow-dependent, geographically varying background error covariances for 1D-VAR applications in MTG-IRS L2 Processing. *December 2012*

ESA Contract Report

Dragani, *R.*: Validation of the reprocessed MIPAS and SCIAMACHY retreivals using ERA-Interim, and one-year assimilation of MIPAS ozone profiles at ECMWF. *January 2012*

EUMETSAT/ECMWF Fellowship Programme Research Report

28 **Salonen, K. & N. Bormann:** Atmospheric Motion Vector observations in the ECMWF system; second year report. *November 2012*

27 **Baordo, F., A.J. Geer & S. English:** SSMI/S radiances over land in the all-sky framework: one year report. *November 2012*

Proceedings

ECMWF Workshop on Ocean Waves, *25–27 June 2012*

Items moved from the winter to spring edition

The winter newsletter usually contains information about:

- Special Project computer allocations.
- TAC Representatives, Computing Reprsentatives and Meteorological Contact Points.
- ECMWF Council and its committees.

Due to lack of space in this edition of the newsletter, these three items will now be included in the spring edition.

Index of newsletter articles

This is a selection of articles published in the *ECMWF Newsletter* series during recent 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

VIEWPOINT

COMPUTING

METEOROLOGY

Observations & Assimilation

Forecast Model

Useful names and telephone numbers within ECMWF

Telephone

Telephone number of an individual at the Centre is:

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

e.g. the Director-General's number:
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For double-barrelled names use a hyphen
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