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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 The *ECMWF Newsletter* is not peer-reviewed.

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New Director-General

On 1 July 2011 I took over from Dominique Marbouty as Director-General of ECMWF. Not least because of the research collaboration I had with ECMWF scientists some years ago, I am fully aware of its deserved reputation for being a world leader in numerical weather prediction (NWP). Indeed my research interests over many years have been related to weather systems, their dynamics and predictability.

My background is as a physicist and then for many years as a Professor of Meteorology at the University of Reading. In 1999 I became the Director of the Hadley Centre for climate prediction and research, and subsequently the founding Director of the UK's National Centre for Atmospheric Science. I took up the post of Chief Executive of the UK's Natural Environment Research Council in 2005, from which role I moved to ECMWF. As a leader I have experience of the many and varied issues that need to be managed effectively and efficiently for organisations both small and large.

As the new Director-General I am delighted to be joining such a successful and important organisation as ECMWF. I have greatly enjoyed learning about the activities of ECMWF, and my personal thanks go to Dominique, and others at ECMWF, for making my transition into the role such a smooth one. He involved me as Director-General-Elect in the most recent meetings of the Policy Advisory Committee and Council, as well as in the final stages of preparation of the ECMWF Strategy 2011-2020. ECMWF and the meteorological community owe Dominique a huge debt of gratitude for his outstanding contributions over many years and I wish him well in the future. The President of ECMWF Council, François Jacq, pays further tribute to Dominique on page 2 of this Newsletter.

As described in the Strategy, the vision is for ECMWF to be the acknowledged world leader in global medium-range NWP, in order to provide the best possible forecast products, particularly to the European national meteorological services, for the benefit of society. This is an inspirational as well as challenging vision and one that I am fully committed to it being achieved.

People all over the world rely on weather forecasts to help them in their daily lives whether it is to avoid problems associated with severe weather or whether it be an opportunity to develop their businesses. Indeed, the way we live has increased our sensitivity and vulnerability to the natural environment and in particular to weather. Being able to give as early foresight as possible of what weather conditions are to come is a huge benefit arising from ECMWF forecast products.

Our goal is to develop our core forecasting systems. This will mean that we can produce forecast products that enable people to receive early warnings of severe weather as many days in advance as possible and reliable predictions up to a few weeks ahead of the onset and decay of heat and cold spells as well as periods of drought. As a result national meteorological services (NMSs) will be able to use our forecast products to provide and develop services to sectors such as the energy supply industry, transport, commerce, agriculture, health and disaster relief. In addition, we will be producing forecasts that support the provision of air quality services, for example, for protection of health and developing environmental policies. A further goal is to produce reanalyses that provide the best possible description of the past weather and climate trends in the twentieth century. In all these areas the activities of ECMWF and NMSs will continue to be fully complementary.

As I start as Director-General I reflect on the fact that ECMWF is a user-driven organisation that is a significant part of the European Meteorological Infrastructure. As well as the crucial operational forecast products that it creates and disseminates, ECMWF is an important component of the meteorological research community that is focussed on advances to improve forecast skill and capabilities. We collaborate and partner with many individuals and organisations for mutual benefit.

During my period as Director-General I am committed to ensuring that ECMWF continues to focus on cost-efficiency and value-for-money whilst fully serving the needs of the Member and Co-operating States and acting as a beacon to the international meteorological community in the field of NWP.

Alan Thorpe

An appreciation of Dominique Marbouty

FRANÇOIS JACQ
(ECMWF PRESIDENT)

On 30 June Dominique Marbouty relinquished the post of Director-General of ECMWF. He will now take up a new job in Paris as an adviser in the French Ministry of Environment from 1 September. During his 12 years at ECMWF, with 7 of those years as its leader, Dominique has made major contributions to the enhancement of the status of ECMWF and the development of its activities to meet the needs of Member States.

Before joining ECMWF, Dominique had a long and fruitful career within Météo-France. He held a wide variety of positions: head of a research unit, head of a regional office, head of the regional network and deputy director general. His experience of both research and operations, along with an understanding of the political dimension, were put at the service of ECMWF.

Dominique was first recruited at ECMWF as Head of Operations, and then became Director and finally, a few months before leaving, Director-General.

ECMWF is without doubt the leading medium-range forecasting centre in the world. This is of course

the result of the effort and competence of the entire staff, but these need to be applied with a clear focus on what needs to be achieved. Dominique, along with his fellow Directors, was instrumental in defining the appropriate strategy for achieving and maintaining world-class status, and ensuring the implementation of that ambitious strategy. The strategy was clearly based on making significant and well-defined scientific progress, particularly aimed at enhancing the early warning of severe weather. But, to support the scientific strategy, it was important to develop ECMWF's infrastructure. This is why it was so important that Dominique was able to:

- Convince Member States to double the budget devoted to high-performance computing (HPC), which in turn triggered important developments.
- Complete the HPC procurement with great efficiency.

Research teams also need buildings and infrastructures. Dominique was able to build a new facility devoted to research without any increased funding from Member States, even after the collapse of the firm chosen to build it. This demonstrates his wide range of capabilities.

Dominique also had the vision that ECMWF should develop in other directions. For example he convinced Council that ECMWF should coordinate European efforts in global reanalysis. Indeed, the recent start of the ERA-CLIM project, funded by the European Commission, is a culmination of efforts in this area. Also the development of seasonal forecasts has been an important step in supporting the activities of Member States.

There is of course another important legacy from Dominique. After major efforts, he succeeded in bringing into force the amended convention - this is a major achievement. It provides a modernized instrument for supporting ECMWF's activities and will strongly facilitate the further expansion of ECMWF.

As impressive as it may be, a scientific centre could not be of world-class without a proper administration and a proper human resources policy. In this field also, Dominique has been a big influence. For example, he has been able to:

- Solve the issue of the pension scheme by convincing the Council to put in place a mechanism which does not threaten ECMWF's financial position.
- Considerably improve the situation of consultants; though it is still necessary to develop a proper policy on those matters, Dominique has set up the foundations.

Good management also means having good quality accounts - so Dominique started the implementation of IPSAS (International Public Sector Accounting Standards). He also had to face concerns of the Members States about the accuracy of the budget.

However (and otherwise it would not be fair on Alan Thorpe), there are still things to be solved. Dominique experienced hard times discussing the conditions under which ECMWF operates. These illustrate that in some cases, politics is even more complicated than understanding the physics of atmosphere. Dominique had been the source of wise guidance in those matters, showing both diplomacy and tenacity.

Finally, saying ECMWF is a European institution is not understating the situation, even if European in this case does not mean the European Union. Thanks to Dominique, ECMWF is a major component of the European Meteorological Infrastructure (EMI). For example, Dominique has been able to:

- Establish excellent relationships with EUMETNET, EUMETSAT and ESA.
- Ensure ECMWF is highly respected by the European Commission. In particular the contribution of ECMWF to the GMES (Global Monitoring for Environment and Security) programme is impressive.

What has been written only outlines Dominique's profound influence on all aspects of ECMWF's activities and his achievements during his highly successful period as its leader. He will be greatly missed, but I am sure that Dominique now has a very distinguished successor. I am convinced that Alan Thorpe will further enhance ECMWF's reputation and achievements by building upon Dominique's legacy.

Outcome of Council's 75th session

MANFRED KLÖPPEL

Raising of the Icelandic flag. To mark the participation of Iceland in the Council as a Member State the Icelandic flag was raised. From left to right: Árni Snorrason (Director General of the Icelandic Meteorological Office), Alan Thorpe (incoming ECMWF Director-General), Dominique Marbouty (outgoing ECMWF Director-General) and François Jacq (ECMWF President).

Under the chairmanship of its President, Francois Jacq (France), the Council held its 75th session on 16 and 17 June 2011. This session was the first chaired by Mr Jacq, the last for the outgoing Director-General, Dominique Marbouty, and the first for Iceland participating as a Member State.

During the first day of the session, the representative from Iceland, Árni Snorrason, raised the Icelandic flag.

The Council congratulated the Centre on the main achievements since its last session in December 2010, noting in particular that:

- A new cycle of the forecasting system had been implemented on 18 May 2011, introducing meteorological and technical changes.
- Several important projects, in particular the ERA-CLIM project funded by the European Union, were developing as expected.

The following main decisions were taken unanimously at this session:

- Member States agreed to vote by correspondence in August 2011 on the accession of the Republic of Croatia to the ECMWF Convention.
- The Council authorised the Director-General to start negotiations with the Republic of Moldova on becoming an ECMWF Co-operating State.
- A resolution on the Centre's contributions to Global Monitoring for Environment and Security (GMES) was adopted requesting the European Union to prepare a framework for the use of the Centre's facilities in the operational phase from 2014 onwards (see http://www.ecmwf.int/about/basic/volume-1/resolutions/index.html) and extending the already agreed data policy to cover the GMES preoperational phase.

In addition, the Council unanimously adopted the ECMWF Strategy for the period 2011-2020. The principal goal of ECMWF in the next ten years is to improve its global, medium-range weather forecasting systems, at the current rapid rates, in order to:

- Provide Member States' National Meteorological Services with reliable forecasts of severe weather across the medium-range.
- Meet Member States' requirements for high quality near-surface weather forecast products such as precipitation, wind and temperature.

Complementary goals are to:

- Improve the quality of monthly and seasonal-to-interannual forecasts.

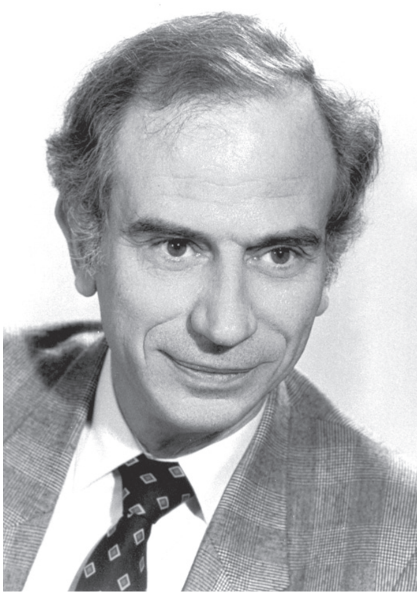
- Support climate monitoring with state-of-the-art reanalyses of the Earth-system.
- Contribute towards the optimisation of the Global Observing System.
- Enhance support to Member States' national forecasting activities by providing suitable boundary conditions for limited-area models.
- Deliver global analyses and forecasts of atmospheric composition

The strategy itself and a document describing the scientific and technical basis of the strategy can be found at:

- http://www.ecmwf.int/about/programmatic/strategy/index.html

Jean Labrousse

Jean Labrousse, the second Director at ECMWF, sadly passed away on Saturday 9 July 2011.



A French national, Jean played an important role during the early days of ECMWF. As Head of Operations, from June 1974 to 1979, he had the overall responsibility for the Centre's operational forecasting system and for the Centre's computer system. He was instrumental in establishing the operational facilities required for ECMWF to deliver its first operational global medium-range weather fore-cast to its Member States on 1 August 1979.

Jean Labrousse became ECMWF's second Director from 1 January 1980. After a short period of two years he returned to France, since he was appointed as Director of Météorologie Nationale (Météo-France) from 1 January 1982 by the French Conseil des Ministres. From 1987 to 1991, he was Director of the Research and Development Programme of the World Meteorological Organization.

Before he retired in November 1997, Jean Labrousse was Director of the Earth-Ocean-Space-Environment Department in the French Ministry of Research, Technology and Space (1991-1993), Scientific Secretary for Meteorology EEC/COST (1994-1997), and Head of the French Secretariat for Joint Implementation (United Nations Framework Convention on Climate Change).

Staff at ECMWF are enormously grateful for Jean's outstanding contributions in setting up ECMWF's first operational infrastructure and for his excellent leadership during his short period as Director of ECMWF.

ECMWF Annual Report for 2010

BOB RIDDAWAY

The ECMWF Annual Report 2010 has been published. It provides an over-view and a broad, non-technical description of ECMWF's main activities. There is also an indication of ECMWF's future plans.

The report draws attention to some of the key events of 2010 that are associated with operational activities and membership of ECMWF.

- ***Implementation of IFS Cycle 36r1.*** A new cycle of the ECMWF forecasting and analysis system, Cy36r1, was introduced in operations. This cycle includes major increases in horizontal resolution for the deterministic and the probabilistic forecasting systems. The higher-resolution wind fields are better at representing features such as tropical storms, fronts and land/sea transitions; this translates into better wave forecasts. *26 January*
- ***Headline measure of skill reached the forecast range of 10 days.*** ECMWF reached a landmark in the perform-ance of its deterministic forecasting system during a month. For the first time ever, the headline measure of skill in February reached the forecast range of 10 days. *February*
- ***ERA-CLIM project selected for funding.*** The ERA-CLIM project proposal, submitted to the European Commission in January, was selected for funding. This three-year project will be coordinated by ECMWF. The goal of ERA-CLIM is to prepare for the production of a next-generation global atmospheric reanalysis that spans the entire 20th century. *12 May*

● ***New products on the website.*** New products from the ECMWF Ensemble Prediction System (EPS) were made available on the website following Council's decision to extend the range of weather forecast products that are available freely and with no restrictions. *13 May*

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

● ***Implementation of IFS Cycle 36r2.*** A new cycle of the ECMWF forecasting and analysis system, Cy36r2, was implemented. This included a new method for providing initial-time perturbations for the EPS. In the new cycle, differences between members of an ensemble of data assimilations (EDA) were used. *22 June*

● ***Co-operation agreement with Bulgaria.*** The co-operation agreement between the Republic of Bulgaria and ECMWF entered into force. *12 July*

● ***Co-operation agreement with Israel.*** The co-operation agreement between Israel and ECMWF entered into force. *28 October*

● ***Implementation of IFS Cycle 36r4.*** The new model cycle 36r4 was implemented in operations. The new cycle includes a new cloud parametrization scheme and new surface analysis schemes introduced for snow and soil moisture. *9 November*

● ***Migration of data to the Automated Tape Libraries completed.*** The process of migrating data from the old silos to the new Automated Tape Libraries finished. *19 December*

In addition the *Annual Report* describes a wide range of activities and achievements in 2010 that are of benefit to the operational activities of Member and Co-operating States as well as supporting the endevours of the international meteorological community.

Dominique Marbouty, ECMWF Director-General, starts his foreword to the Annual Report by stating that: "The main event of 2010 was undoubtedly the entry into force of the amended Convention on 6 June. It concluded a process that started more than 10 years ago when the ECMWF Council decided that it wanted to allow new States to join ECMWF. This period was divided in two almost equal phases. The first one was dedicated to defining the necessary changes and resulted in the unanimous adoption of the proposed changes at an extraordinary session of the Council in April 2005. During the second one it was necessary for all Member States to adopt these amendments which, for most of them, required a decision by their Parliaments. By the end of 2010 two States had already officially applied to become ECMWF Member States."

As outgoing President of the Council, Wolfgang Kusch, states that: "ECMWF plays a significant role in complementing the activities of national institutions in Member and Co-operating States, particularly meteorological and hydrological services. During my presidency in 2010, the Centre once again provided very good early forecasts of various severe weather events several days or even weeks ahead, thereby allowing early warnings to the public." Wolfgang Kusch concluded his statement by stating that "I would like to congratulate the whole team working at ECMWF on the remarkable progress made in a variety of areas during 2010".

The *Annual Report* can be downloaded from:

- http://www.ecmwf.int/publications/annual_report

Forecast Products Users' Meeting, June 2011

DAVID RICHARDSON

The annual meeting for users of ECMWF forecast products was held at ECMWF on 8 to 10 June. The purposes of these meetings are to:

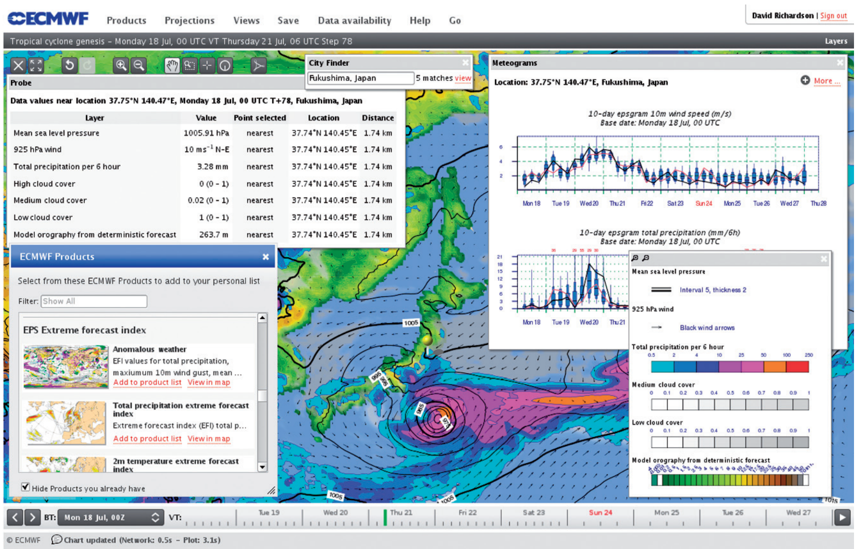
● Update users on recent and planned developments of the ECMWF operational forecasting system, especially the forecast products.

● Give users of ECMWF forecasts the opportunity to discuss their experience with the medium-range and extended-range products and to present feedback on their use and future requirements.

The meeting was attended by representatives from National Meteorological Services of 16 Member States and Co-operating States and from a number of commercial users of ECMWF weather forecast products.

Changes to the ECMWF forecasting system since the previous meeting, including the implementation of three new operational model cycles, were presented. Cycle 36r4 (November 2010) incorporated a large number of improvements, including a new cloud scheme and new surface analyses for soil moisture and snow depth. Cycle 37r2 (May 2011) included changes to the use of observations (reduced observation errors for AMSU-A satellite data) and use of flow-dependent background errors (from the EDA) in the data assimilation. A number of significant changes were made to the Ensemble Prediction System (EPS), including the use of the ensemble of data assimilations (EDA) to provide additional initial perturbations (Cycle 36r2, June 2010) and revised simulation of the model uncertainties in the EPS (Cycle 36r4).

ECMWF has introduced a number of new products during the last year. New parameters produced from the forecasts include height of lowest cloud base, height of 0°C level, surface and sub-surface runoff, total-sky and clear-sky direct solar radiation at the surface, and cloud rain and snow water content. Low, medium and high cloud covers are now available from the EPS members as well as for the deterministic



The new ecCharts interactive web facility for operational forecasters. Forecasters can easily zoom and pan to relocate the map to any geographical area of interest. Also they can display a wide range of fields from the deterministic and EPS forecasts. Timeseries and EPSgrams can be displayed by clicking on any point or using the city finder tool. The system has already proved valuable to forecasters, for example during the Fukushima crisis.

forecast. New products introduced during the last year include the new EPS clustering (described in detail *ECMWF Newsletter No. 127*), and information on tropical cyclone genesis and extra-tropical cyclone tracks on the ECMWF web site. Users commented positively on these recent additions, and several examples of their use were shown during the presentations from users.

The new interactive web facility aimed at forecasters (ecCharts, see *ECMWF Newsletter No. 126*) was presented and users had the opportunity to try out the features during the meeting. ecCharts has been available to operational forecasters in the Member States and Co-operating States for beta testing since the beginning of the year. Several of the participants reported that ecCharts has already proved to be a valuable tool; in particular it allowed forecasters to gain quick access to full-resolution data for the Japan region during the Fukushima crisis.

ECMWF is introducing a second weekly run of the monthly forecast, run every Monday (00 UTC), to provide an update to the current Thursday forecast. A new set of web pages has been prepared, showing the graphical products from both Thursday and Monday runs. Users confirmed that this reorganisation, which allows users to easily compare the latest forecast with the previous ones for the same verifying period, meets their requirements.

A new seasonal forecasting system is planned for implementation later in 2011. This uses a higher resolution and more recent version of the ECMWF atmospheric model coupled to the NEMO ocean model. The new System 4 has significantly lower overall model biases that the current System 3. The implementation schedule for System 4 was discussed, including the availability of the hindcast datasets for users. Further details, including updates on the implementation and performance of System 4 are available at

- http://www.ecmwf.int/products/changes/system4/

As usual, during the meeting participants made a number of requests for additional products. These focused on more weather element information and extension of some products further into the medium range.

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

- http://www.ecmwf.int/newsevents/meetings/forecast_products_user/Presentations2011/

IMO prize to first ECMWF Director

ALAN THORPE

WMO's most prestigious award, the IMO prize, originates from WMO's predecessor, the International Meteorological Organization. It is granted annually by the WMO Executive Council for outstanding work in the field of meteorology, climatology, hydrology and related science. The 56th IMO prize has been awarded to the late Aksel Wiin-Nielsen as a lifetime achievement award.

Prof Wiin-Nielsen, who passed away last year, was particularly renown for his leadership and success in setting up ECMWF. A Danish national, Prof Wiin-Nielsen was ECMWF's first Director from I January 1974 to 31 December 1979. He put ECMWF on track to become a world leader in global Numerical Weather Prediction (NWP).

Before joining ECMWF, Prof Wiin-Nielsen developed a scientific career that started in 1952 in the University of Copenhagen, and continued in Stockholm at the International Meteorological Institute set up by

Carl-Gustaf Rossby. Here he took part in setting up the first operational NWP system in the world.

Prof Wiin-Nielsen moved to the USA in 1959 where he worked at the Joint Numerical Weather Prediction Unit and NCAR. From 1963 he created the Department of Meteorology at the University of Michigan. When a decision was made to establish ECMWF, Prof Wiin-Nielsen was the natural choice as its first Director.

On leaving ECMWF he became WMO Secretary-General in 1980, and then Director of the Danish Meteorological Institute (DMI) in 1984. In that function, Prof Wiin-Nielsen returned to ECMWF to attend sessions of the ECMWF Council, representing Denmark. He served as President of the ECMWF Council in 1987.

Prof Wiin-Nielsen was one of the leading meteorologists of the second part of the twentieth century who contributed significantly to the development and understanding of NWP.

Extension of the ERA-Interim reanalysis to 1979

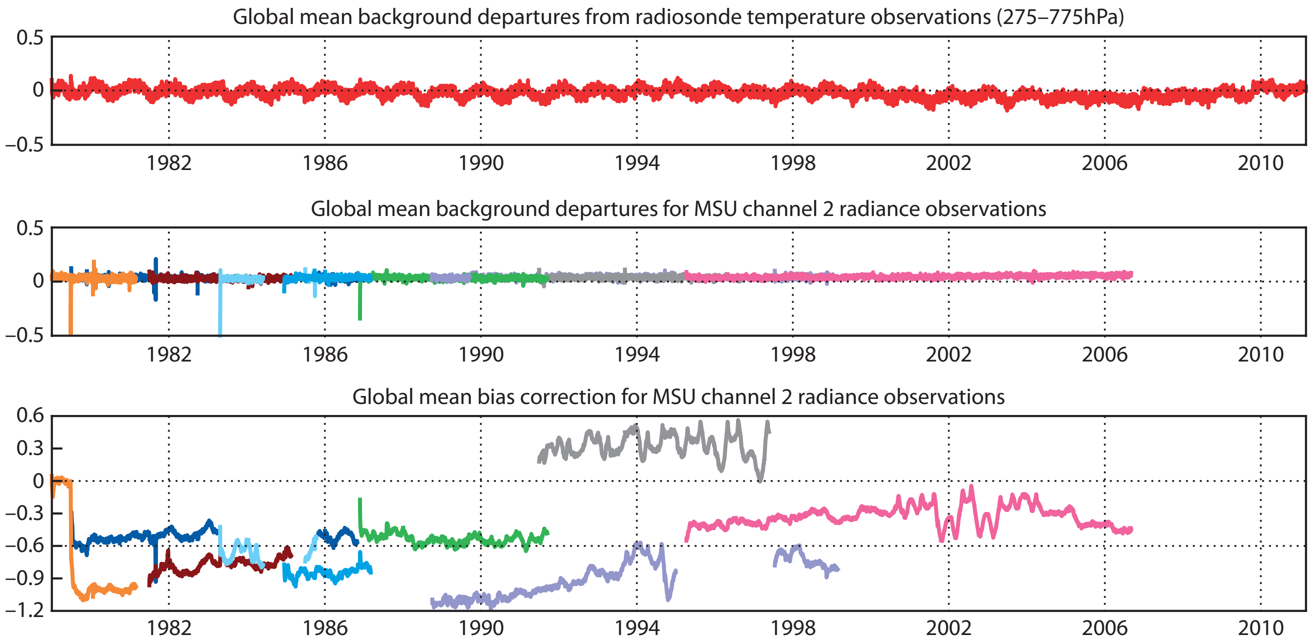
DICK DEE, PAUL POLI, ADRIAN SIMMONS

In response to demands from many users, the ERA-Interim reanalysis dataset has been extended by a decade and now includes data from 1 January 1979 to the present. This extension makes the dataset even more useful for climate-related studies and climate change monitoring, as it now covers a period exceeding three decades.

The 10-year extension was completed in just under 8 months with few technical interruptions.

Most importantly, the accuracy of the reanalysed fields is not very different in the first decade compared to the 1990s, and the temporal consistency of the extended reanalysis is remarkably good. This can be seen, for example, in time series of observation departures, and also in the bias corrections of satellite radiance data that are automatically generated during the reanalysis. Producing a long reanalysis in multiple streams has always been a challenge, but this (unplanned) exercise with ERA-Interim has demonstrated that it is possible to do so without introducing major jumps or shifts in the final product.

ERA-Interim data for 1979-1988 will shortly be available in MARS and on the ECMWF public data server. We will continue to extend the ERA-Interim reanalysis forward in time for at least several more years, until it can be replaced by a new version that uses an up-to-date IFS release and an improved set of input observations. This will be done in the framework of the ERA-CLIM project (see *ECMWF Newsletter No. 123*, p.6); current plans are to begin production of such a new reanalysis of the satellite era by the end of 2012.



Stability and temporal consistency of the extended ERA-Interim reanalysis. The three panels demonstrate the stability and temporal consistency of the extended ERA-Interim reanalysis, and the nearly seamless transition between the two production streams on 1 January 1989. Reanalysed temperatures in the mid-troposphere are largely consistent with radiosonde observations (top panel) and with bias-corrected radiance measurements from the Microwave Sounding Units (MSU) flown on successive NOAA satellites (centre panel; colours indicate different satellites). The bias corrections for the MSU data, produced by the variational analysis in ERA-Interim, account for calibration differences, orbital drifts and various other instrument errors (lower panel).

Improved exploitation of radio occultation observations

AXEL VON ENGELN (EUMETSAT, DARMSTADT, GERMANY),
DAVID R. ECTOR (NOAA, BOULDER, COLORADO, USA)

Radio occultation measurements (RO) are now an important component of the Global Observing System. In June 2008, the joint ECMWF/GRAS Satellite Application Facility (GRAS SAF) workshop on '*The Applications of GPS Radio Occultation Measurements*', recommended the formation of an International Radio Occultation Working Group (IROWG). In 2009, this was endorsed by the Coordinating Group for Meteorological Satellites (CGMS), and IROWG is now the fourth permanent working group of the CGMS.

The group's first meeting (IROWG-1) took place on 10-11 September, 2010, at the University of Graz, Austria. More than sixty scientists participated in IROWG-1, including representatives from the major centres providing and assimilating RO data. IROWG-1 was held together with the '*International Workshop on Occultations for Probing Atmosphere and Climate 2010*' (OPAC 2010) and the '*GRAS SAF Climate Workshop*', 6-10 September.

The RO technique itself uses observations of Global Positioning System (GPS) signals seen through the Earth's atmosphere from a space-based GPS receiver; it has been improving our understanding and prediction of the weather, climate and ionosphere over the last fifteen years. RO missions such as GPS-MET, CHAMP, SAC-C, Oersted, GRACE, GRAS, IOX, CORISS and the RO constellation, COSMIC, have been used as important observation sources for NWP models, climate benchmarking reference and ionospheric assimilation models. Several of the existing RO satellites have reached or are nearing the end of their useful lifetimes.

Recent missions are TerraSAR-X/TanDEM-X and ROSA on Oceansat-2; some follow-on RO satellite systems are being planned such as COSMIC-2, ROSA/SAC-D, and PAZ. However, it is clear that an international coordination of efforts is needed in order to:

- Understand and utilize more fully RO observations.
- Achieve better coverage.
- Avoid gaps in the observation systems.
- Ensure and sustain RO observations.

Furthermore, within the next two decades there will be a multiplicity of Global Navigation Satellite Systems (GNSS) constellations transmitting radio signals which can be used for RO, such as GPS (USA), Galileo (EU), GLONASS (Russian Federation), COMPASS (China), IRNSS (India), and QZSS (Japan). These GNSS will significantly increase the potential number of signal sources for RO to somewhere in the range of 87-125 transmitters, thus providing RO opportunities to increase substantially the spatial and temporal sampling densities of the atmosphere and the accuracy of the observations.

The main purposes of the IROWG-1 workshop were to exchange experi-

Working Groups of the Coordinating Group for Meteorological Satellites (CGMS)

The CGMS Working Groups are:

- International Radio Occultations Working Group (IROWG)
- International TOVS Working Group (ITWG) (meetings are known as International TOVS Study Conferences)
- International Winds Working Group (IWWG)
- International Precipitation Working Group (IPWG)

The working groups interact closely with the annual CGMS meetings by reporting to and taking actions and recommendations from CGMS. The regular and formal interaction provides a direct link with the operational agencies that operate the relevant satellite instruments.

Objectives of the IROWG

The overall objectives of IROWG are to:

- Make recommendations to national and international agencies and to the atmospheric sounding community regarding the utilisation of current RO data and the development of future RO systems.
- Suggest and promote studies aiming at the definition of future RO satellite constellations that fulfill the expected operational and research user requirements.
- Encourage cooperation on ground support infrastructure for RO systems.
- Promote standard operational procedures and common software to the scientific community for processing and assimilating radio occultation measurements from satellites.
- Stimulate increased international scientific research and development in this field and establish routine means of exchanging scientific studies and verification results.
- Support and stimulate the training and education of the scientific community at large for the exploitation of RO product information.
- Promote the exploitation of RO observations and their unique capability in the context of climate applications.
- Foster communication between the RO scientific community, space agencies and science policy institutions such as the IPCC.

ences in the exploitation of RO data and formulate common recommendations. To achieve this, the Workshop focused on five topics: NWP, climate, research to operations/payload technology, innovative occultation techniques, and space weather. Extensive recommendations and their rationale were developed for (a) each topic and (b) the entire IROWG and its participating agencies, institutions and providers and assimilators of RO data. Specific aspects regarding the operation and planning of satellite radio occultation instruments were formulated as recommendations to the CGMS. The IROWG-1 Workshop summary and the full recommendations are online at the Working Group site

● http://www.irowg.org.

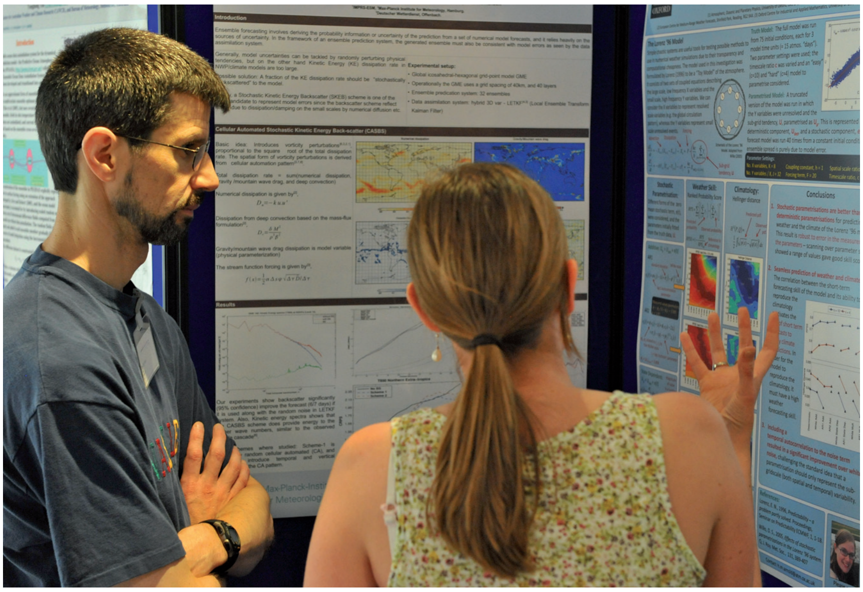
The next IROWG workshop is in Estes Park, Colorado, USA from 28 March to 3 April 2012. It will be held together with the UCAR/COSMIC Workshop on GPS RO Data Processing for Climate Applications. Further details can be found at the IROWG website.

The establishment of the IROWG and its contribution to the improved exploitation of radio occultation observations highlights the value of ECMWF's programme of workshops.

Representing model uncertainty and error in weather and climate prediction

TIM PALMER

Between 20 and 24 June, a workshop was held at ECMWF on '*Representing Model Uncertainty and Error in Weather and Climate Prediction*'. The workshop attracted almost 100 participants, from Europe and other parts of the world, such as Japan, North and South America and Australia, and was co-sponsored by WMO/WGNE, WMO/THORPEX, WCRP, and of course ECMWF. The organisers were Tim Palmer (ECMWF/Oxford), Christian Jacob (Monash University), Tom Hamill (NOAA/ESRL), Istvan Szunyogh (Texas A&M) and Ben Kirtman (University of Florida).



One of the key highlights of the new ECMWF strategy is provision of reliable medium-range forecasts of severe weather. However, severe weather events can also be some of the most unpredictable. Hence, in order to provide reliable forecasts of severe weather, ECMWF must provide accurate flow-dependent estimates of forecast uncertainty arising from the fact that neither the forecast initial conditions, nor the forecast model equations, are known precisely. This can be achieved within ensemble prediction systems, where both the initial conditions and the model equations are perturbed.

There are a number of techniques to represent model uncertainty in ensemble forecasts. These range from the multi-model techniques which feature prominently in IPCC assessment reports, to the stochastic parametrization approach pioneered at ECMWF, but now widely used at weather forecast centres around the world. The multi-model technique is now fairly mature for climate prediction, and clearly outperforms single model predictions. On the other hand, as the TIGGE (THORPEX Interactive Grand Global Ensemble) data shows, there is not much advantage to the multi-model ensemble over the ECMWF EPS (Ensemble Prediction System) in the medium range, especially when hindcast data is used for calibration.

The purpose of the meeting was partly to compare different methods for representing model uncertainty, and to discuss how to advance this area of research.

Amongst the talks, there were presentations from experts focussing on uncertainty in the representation of specific key processes: this included the dynamical core, cloud microphysics, radiation, convection, oceans and the land surface. There then followed some talks looking at model uncertainty from a mathematical and dynamical systems perspective, including mathematical issues related to the solution of stochastic differential equations. The various schemes used in weather and climate centres to represent uncertainty were reviewed, from the multi-model ensemble, the multi-parametrization ensemble, the perturbed parameter approach, the superparametrization approach, and finally the stochastic parametrization

approach. Work describing the use of simplified stochastic dynamical system models for the subgridscale, using lattice and cellular automaton dynamics, were presented.

It was recognised that in many areas, this is a relatively new and exciting area of research. A key outcome of the meeting was that the stochastic parametrization paradigm needs further development at the process level, and hence needs to be incorporated as part of general parametrization development. Key tools will include sophisticated analyses of observational datasets, output from cloud resolving models, and analyses from objective data assimilation. Data assimilation techniques themselves will benefit from better representations of model uncertainty.

The presentations delivered at the workshop, along with the posters, can be found at:

- http://www.ecmwf.int/newsevents/meetings/workshops/2011/Model_uncertainty/index.html

New model cycle 37r2

PETER BAUER, ERIK ANDERSSON

On 18 May 2011, a new cycle of the Integrated Forecasting System (IFS) was implemented that produced a remarkable improvement over the previous version (cycle 36r4 implemented on 9 November 2010). Cycle 37r2 combined a number of significant scientific contributions with the instalment of GRIB-2 that permits the encoding of data on a larger number of model levels as required by the increased vertical resolution planned for 2012 The scientific components of the Cy37r2 cycle enhanced the accuracy of both the analysis system and forecast model.

The ensemble of data assimilations (EDA, ECMWF Newsletter No. 123) produces short-range forecast error variances so that the 4D-Var analysis can better represent the background error dependence on the flow since the introduction of Cy37r2. Since Cy36r2 (implemented on 24 June 2010), the EDA spread has been contributing to the definition of initial perturbations for the EPS, and it is planned to exploit more of the entire EDA error covariance structures in 4D-Var in the near future.

The other major contribution to the cycle's forecast impact is the reduction of AMSU-A radiance observation errors. This followed a comprehensive investigation of spatial and spectral error covariances (see the article starting on page 14) aimed at revising the radiance data thinning to use more of the available data. Since reducing the degree of data thinning increases computational cost, observation errors were reduced instead with very similar effect as produced by less data thinning.

With Cy36r4, a new cloud scheme was introduced that added liquid and frozen precipitation as prognostic variables that greatly enhanced the realism and complexity of cloud and precipitation forming processes. This scheme was updated with Cy37r2 so that a condensation limiter was reactivated and several adjustments were made to auto-conversion and melting.

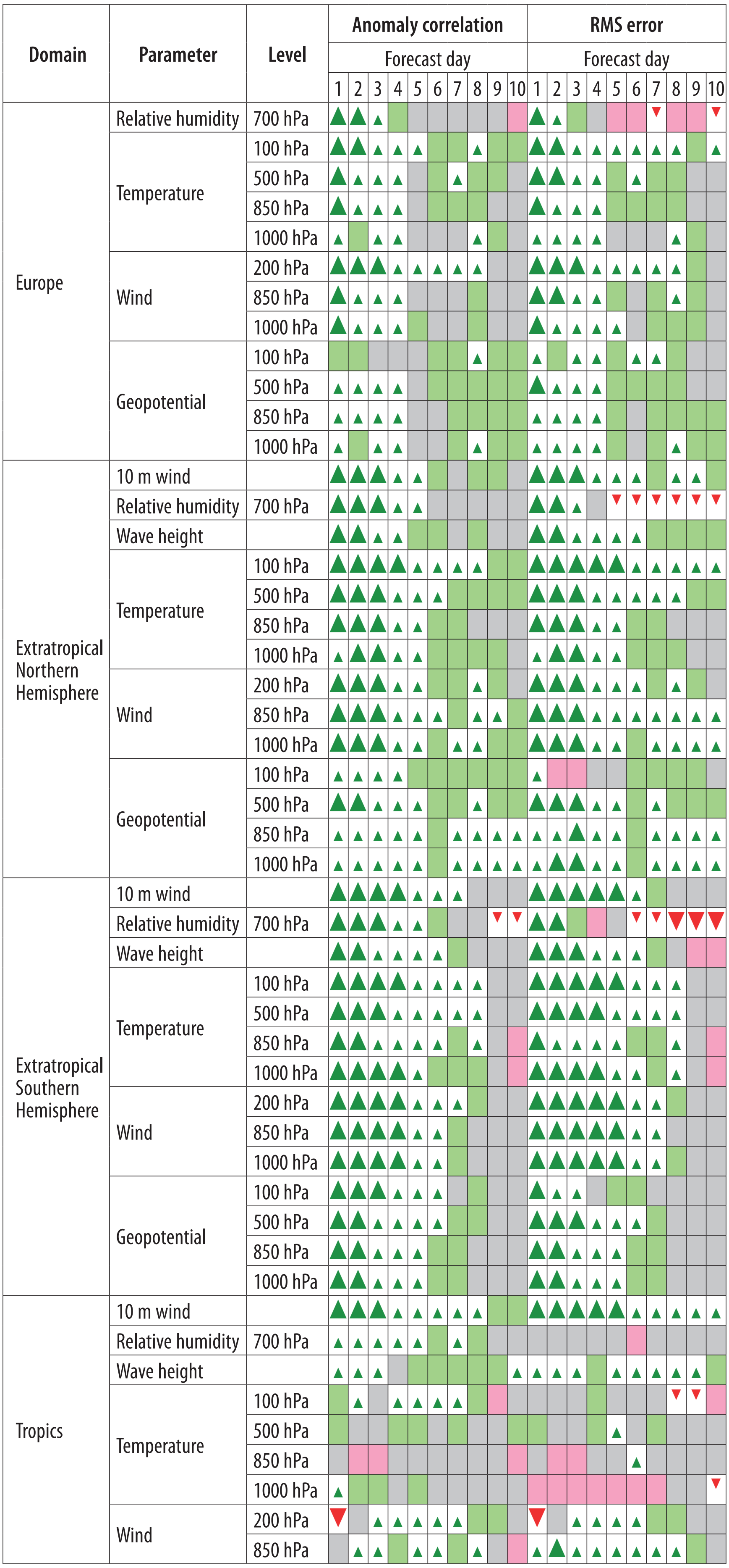
The figure shows the summary score card of the cycle. Symbols and colours indicate better (green) or worse (red) performance of Cy37r2 when compared to Cy36r4 as a function of forecast range, both verified with their own analyses. Information on statistical significance has been included as well.

The overall performance of Cy37r2 is very good and improvements are statistically significant well into the medium range and, to a different degree, valid at most levels. Satellite data generally dominates the analysis in the southern hemisphere because of the sparse conventional network. Thus, the impact of the new cycle is slightly larger in the southern hemisphere than in other areas due to the increased weight given to AMSU-A data in the analysis; this is a result of reduced observation errors as well as enhanced spatial detail through more flow-dependent background error variances. The apparently negative impact in terms of root-mean-square errors for relative humidity at 700 hPa are explained by the effect of the cloud parametrization change on mean state - anomaly correlation is not affected.

If verified against observations, geopotential height, temperature and wind scores of this cycle are equally positive over northern and southern hemispheres as well as Europe, while scores in the tropics are more neutral.

The cycle also contained a fair number of additional changes, for example, a more accurate co-location of radio occultation observations with model profiles and wave model updates. In addition there is preparatory work for developments such as the assimilation of ground-based radar data, model error cycling, observation-based forecast diagnostics and observational data monitoring.

Cy37r2 combined a strong forecast impact with fundamental technical changes due to the joint effort of many colleagues in the Operations and Research Departments; their contributions are acknowledged. We are also very grateful to all the colleagues in the national meteorological services and elsewhere that were involved with the introduction of GRIB-2 encoding of model level data.



Symbol legend: for a given forecast step ... (d: score difference, s: confidence interval width)

- Cy37r2 **far better** than Cy36r4 **statistically significant** (the confidence bar above zero by more than its height) (d/s>3)
- Cy37r2 **better** than Cy36r4 **statistically significant** (d/s≥1)
- Cy37r2 better than Cy36r4, yet not statistically significant (d/s≥0.5)
- not really any difference between Cy36r4 and Cy37r2
- Cy37r2 worse than Cy36r4 yet not statistically significant (d/s≤–0.5)
- Cy37r2 **worse** than Cy36r4 **statistically significant** (d/s≤–1)
- Cy37r2 **far worse** than Cy36r4 **statistically significant** (the confidence bar below zero by more than its height) (d/s<–3)

Summary score card for Cy37r2. Score card for Cy37r2 against Cy36r4 verified by the respective analyses at 00 and 12 UTC for 1 June 2010 to 17 May 2011. Thanks go to Martin Janousek for providing the figure.

Developments in precipitation verification

MARK J. RODWELL, THOMAS HAIDEN,
DAVID S. RICHARDSON

ECMWF's new strategy places more emphasis on the verification of weather parameters such as precipitation and near-surface wind. This change in emphasis is a result of user requirements and scientific developments. It led to the establishment of an ECMWF Technical Advisory Committee Sub-group on Verification Measures. The Sub-group recommended that some new headline scores be adopted to supplement our established primary headline scores (anomaly correlation of 500 hPa geopotential, and continuous ranked probability score of 850 hPa temperature, see e.g. *Richardson et al.*, 2010). Among these supplementary scores is the newly developed 'SEEPS' score (*Rodwell et al.*, 2010) used for the verification of deterministic precipitation forecasts.

Here we explain the SEEPS score, and present examples of how it is being used to monitor and compare deterministic forecast performance, guide development decisions, and assess the spread–error relationship within the Ensemble Prediction System. Finally, we discuss potential future developments.

The SEEPS score

The task of forecasting precipitation beyond a day-or-two in advance is very much a probabilistic one, which must take account of a range of uncertainties. The ECMWF Ensemble Prediction System (EPS) takes account of uncertainties in initial conditions and sub-grid scale processes. Appropriate scores to assess the overall performance of probabilistic forecasts are 'proper' scores for which there is no benefit in hedging. Examples of such scores are those derived from the Brier and Ignorance Scores (e.g. *Gneiting & Raftery*, 2007).

As well as making probability forecasts, there is also a need to make high-resolution deterministic precipitation forecasts. High resolution is beneficial, for example, within the data assimilation process in order to produce the best initial conditions for subsequent forecasts. At short ranges, high-resolution precipitation forecasts provide complementary information to that provided by the lower-resolution EPS (*Rodwell*, 2006). In addition, the diagnosis and improvement of high-resolution deterministic forecast error prepares the model for future use at a higher-resolution within the EPS (on next-generation computers).

A score is required that can be used to monitor the performance of deterministic precipitation forecasts. Although probabilistic scores can sometimes be applied to deterministic forecasts, they are generally not appropriate. For example, the Brier Score and Ranked Probability Score unduly reward deterministic forecasts for always predicting the category containing the median. Instead it is more appropriate, for deterministic forecasts, to use 'equitable' scores which heavily penalise constant and purely random forecasts (*Gandin & Murphy*, 1992).

A number of equitable scores have been used in the verification of deterministic precipitation forecasts. Amongst the most common is the True Skill Score (TSS), also known as the Peirce Skill Score (PSS). This is based on a 2-category contingency table (for the occurrence of a given event) of the form:

		Observed	
		Yes	No
Forecast	Yes	Hits	False-alarms
	No	Misses	Correct-nulls

1–PSS can be written as:

$$1\text{–PSS} = \text{Miss rate} + \text{False alarm rate}$$
$$= \frac{\text{Misses}}{\text{Total events}} + \frac{\text{False alarms}}{\text{Total non-events}}$$

However, this score, along with others that are commonly used, does not appear to possess all the attributes desirable for routine monitoring of the performance of deterministic precipitation forecasts. A simple example is that it is impossible to assess the prediction of dry weather and precipitation-amount with only two categories. Because of this, a new equitable score ('SEEPS') has recently been developed by *Rodwell et al.* (2010).

SEEPS (Stable Equitable Error in Probability Space) uses three categories: 'dry', 'light precipitation' and 'heavy precipitation'. Here 'dry' is defined, with reference to WMO guidelines for observation reporting, to be any accumulation (rounded to the nearest 0.1 mm) that is less than or equal to 0.2 mm. To ensure that the score is applicable for any climatic region, the 'light' and 'heavy' categories are defined by the local climatology so that 'light' precipitation occurs twice as often as 'heavy' precipitation. Here a global 30-year climatology of SYNOP station observations is used, and the resulting threshold between the 'light' and 'heavy' categories ($T_{L/H}$ in Figure 1) is generally between 3 and 15 mm for Europe, depending on location and month. This approach to defining categories was motivated by the 'Linear Error in Probability Space' methodology of *Ward & Folland* (1991).

SEEPS can be written as the mean of two 2-category scores that individually assess the dry/light and light/heavy thresholds. Each of these 2-category scores is rather like the 1–PSS but written as:

$$\frac{\text{Misses}}{\text{Expected events}} + \frac{\text{False alarms}}{\text{Expected non-events}}$$

where the word 'expected' implies a climatological-mean rather than a sample-mean. The result is that SEEPS permits

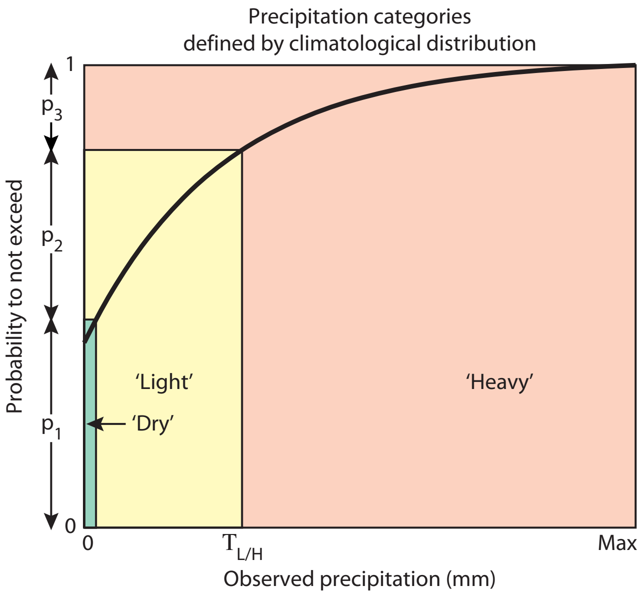


Figure 1 Schematic diagram showing how the probabilities and thresholds for the three SEEPS precipitation categories ('dry', 'light precipitation' and 'heavy precipitation') are determined from the climatological cumulative distribution (black curve).

the construction of daily error time series that can be augmented as new data become available. A summary of the main attributes of SEEPS is given in Box A. All these attributes are important for monitoring purposes.

Here, SEEPS is used to compare 24-hour accumulations derived from global SYNOP observations (exchanged over the Global Telecommunication System; GTS) with values at the nearest model grid-point. Sometimes 1-SEEPS is preferred for presentational purposes as this provides a positively-oriented skill score.

Case studies

The diagnosis of short-range forecast error is particularly useful for parametrization development. Figure 2 shows how SEEPS highlights precipitation errors in a short-range forecast (the first 24 hours of the deterministic forecast initiated from 12 UTC on 22 April 2010). Although the large-scale synoptic flow was well forecast at this short-range, errors are evident in the precipitation field. For example, with the exception of a few places such as southern Sweden, most of northern Europe was dry at this time (Figure 2a) while the forecast developed up to 5 mm of precipitation within a northerly flow over Scandinavia and into Germany (Figure 2b). The forecast also developed too much precipitation within a warm front that extended from southern France to Bulgaria. Notice also that there is too much precipitation predicted along the Italian west coast associated with a second warm frontal system. Other features are well predicted such as the heavy precipitation along the Moroccan coast associated with on-shore winds.

Through use of the 30-year climatology (the climatological probability of an April day being dry is shown in Figure 2c), the precipitation fields are converted into the dry, light and heavy precipitation categories. The precipitation discrepancies highlighted above are clearly evident in the category fields (Figures 2d and 2e) and reflected in relatively large SEEPS errors (Figure 2f). Other case studies, which concentrate on medium-range forecast errors, are discussed in *Rodwell et al.* (2010).

SEEPS has been defined so that scores can be averaged over different climatic regions. To ensure that all sub-regions are correctly represented in an area-mean, the local observation density is taken into account. For example, the areas of the (small) squares in Figure 2f are proportional to the weights given to each individual score within the overall European-mean. The monitoring of area-mean scores, in order to chart progress with performance and inform development decisions, is likely to be a key use of the SEEPS score.

The characteristics and benefits of SEEPS — A

Stable: SEEPS is designed to be as insensitive as possible to sampling uncertainty (for sufficiently skilful forecast systems). This allows more accurate trends to be extracted from noisy data.
Equitable Error: A perfect forecast has a SEEPS score of 0. The expected score increases linearly with the unskilled component of the forecast towards a maximum value of 1.
Probability Space: This is used to define precipitation categories; SEEPS adapts to the underlying climate to assess the pertinent aspects of local weather. It can be aggregated over heterogeneous climate regions.

Score decomposition

For practical applications and further model development, it is of interest to know which kind of error ('dry' when 'light' predicted, 'light' when 'heavy' predicted etc.) contributes most to the total SEEPS. The off-diagonal panels in Figure 3 show these contributions as a function of forecast day for Europe in winter 2009/10. Large contributions are due to missed heavy events. Observed 'heavy' events which were forecast as 'light' contribute even at day 1. Observed 'heavy' events which were forecast as 'dry' contribute almost as much at long lead times, but such errors are rarer at short lead times. An error which is nearly independent of lead time is the prediction of 'light' when 'dry' was observed. The over-prediction of light precipitation is a well-known problem which can also be seen in the comparison of observed and forecast frequencies (given in the panels on the diagonal in Figure 3). Improvements in the cloud scheme aimed at alleviating this problem are currently being tested.

Score trends

Figure 4 shows the evolution of 1-SEEPS (a positively-oriented skill score) since 1993 for the extra-tropics and the tropics (the boundary defined at 30° latitude). The increase in skill has been largely the same for days 2 and 6 of the forecast, both in the extra-tropics and the tropics. It amounts to a lead-time gain of about 2 days. The difference in forecast skill between the extra-tropics and the tropics is considerable. It is equivalent to about 4 forecast days and has slightly increased over the period shown.

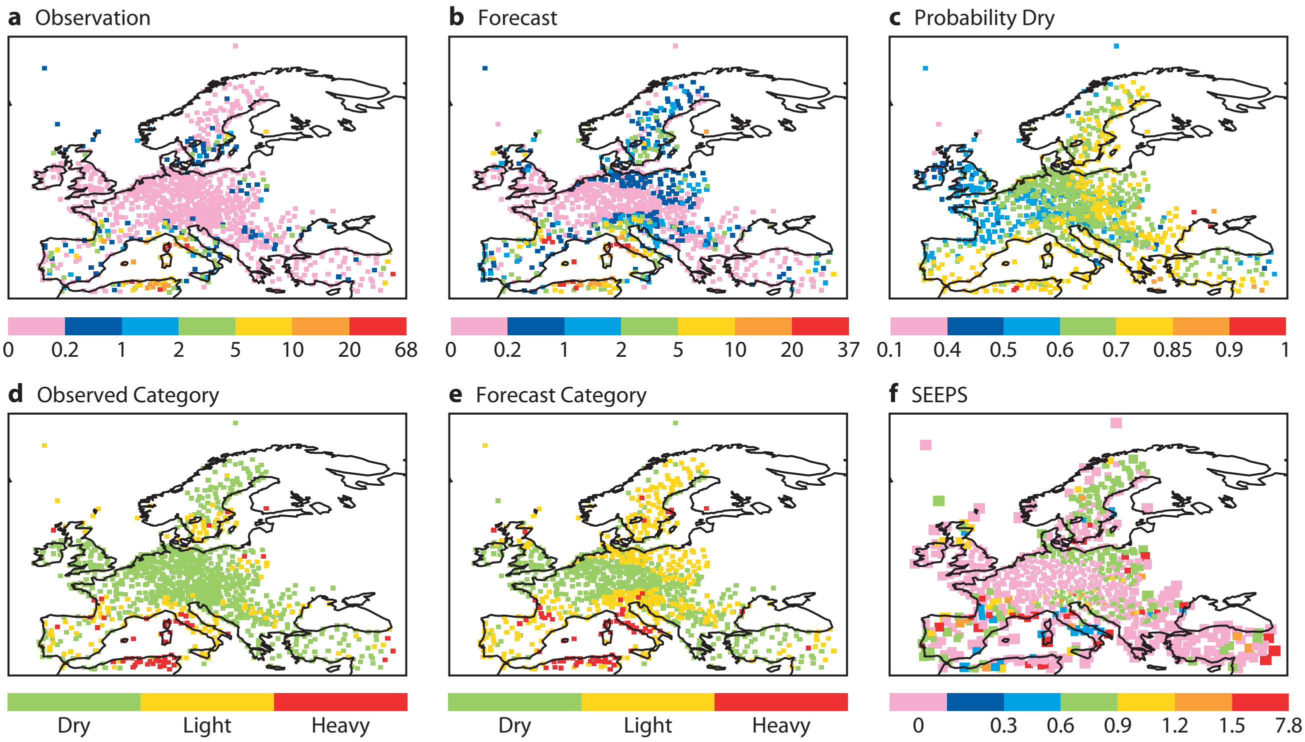


Figure 2 (a) Observed precipitation accumulated over the 24 hours to 12 UTC on 23 April 2010. (b) Forecast precipitation accumulated over lead-times 0 to 24 hours and valid for the same period as the observations. (c) Probability of a 'dry' day in April based on the 1980–2009 climatology. (d) Observed precipitation category. (e) Forecast precipitation category. (f) SEEPS. Units in (a) and (b) are mm. Squares in (f) are plotted at each observation point with areas proportional to the weight given to each station in the European area-mean score.

Since a one-year running mean filter has been applied in Figure 4, sudden improvements in skill associated with new model cycles appear as gradual ascents extending over one year, centred on the date of change. For example, the introduction of the prognostic cloud scheme in April 1995 (cycle Cy13r4) is apparent in the extra-tropics. Also major changes to the assimilation, cloud scheme and convective parametrization in January 2003 (cycle Cy25r4) are reflected in the curves of both the extra-tropics and the tropics.

Model inter-comparison

Model inter-comparisons provide important information for both users and developers, and are part of the operational verification at ECMWF. Since March 2010 comparisons have been made between the skill of precipitation forecasts from the global models of the Japan Meteorological Agency (JMA), National Centers for Environmental Prediction (NCEP), UK Met Office and ECMWF. Verification against observations offers a large number of possibilities with regard to the choice of score, interpolation method, spatio-temporal aggregation, verification period, verification domain, and observation quality control. As a consequence, results from different studies are rarely directly comparable (*Ebert et al.*, 2003). Here we use the same methodology with regard to data preprocessing, interpolation, and score computation for all available models, ensuring maximum compatibility of results.

Figure 5 shows a time-series of 1-SEEPS of the four models (NCEP data is available from June 2010 only) for forecast day 4 for the extra-tropics. Day-to-day variations are smoothed by the weekly averaging but strong variations are present also on the weekly to seasonal timescales and shared by all the models. The reduction of skill during the northern hemisphere convective season (May to August) is noticeable in the global score because there are many fewer SYNOP stations in the southern hemisphere (the weighting methodology does not completely compensate for this lack of observations). Skill differences between models are comparable in size to the weekly and monthly variations. The ECMWF model shows a robust and statistically significant lead.

Analysis of results for individual continents and for other lead times confirms the general ranking seen in Figure 5, although the differences are not always as large. In the shortest range (forecast days 1 and 2), the UK Met Office and ECMWF models exhibit very similar SEEPS values.

Evaluation of parallel suites

Before each change to the forecasting system, the proposed new model cycle is tested in parallel with the operational system. Cy36r4 (which became operational in November 2010) involved several changes that could have directly affected precipitation forecasts. It included a change to a five species prognostic microphysics scheme, with cloud rainwater content and cloud ice water content as new model variables. There was also a retuning and simplification of convective entrainment/detrainment and a land/sea dependent threshold for precipitation formation. Cy36r4 was tested over the period 1 July 2010 to 8 November 2010 in parallel with the operational cycle at the time (Cy36r2). Figure 6 shows the positive impact on 1-SEEPS scores. The most pronounced and highly statistically significant increase in skill was found for the extra-

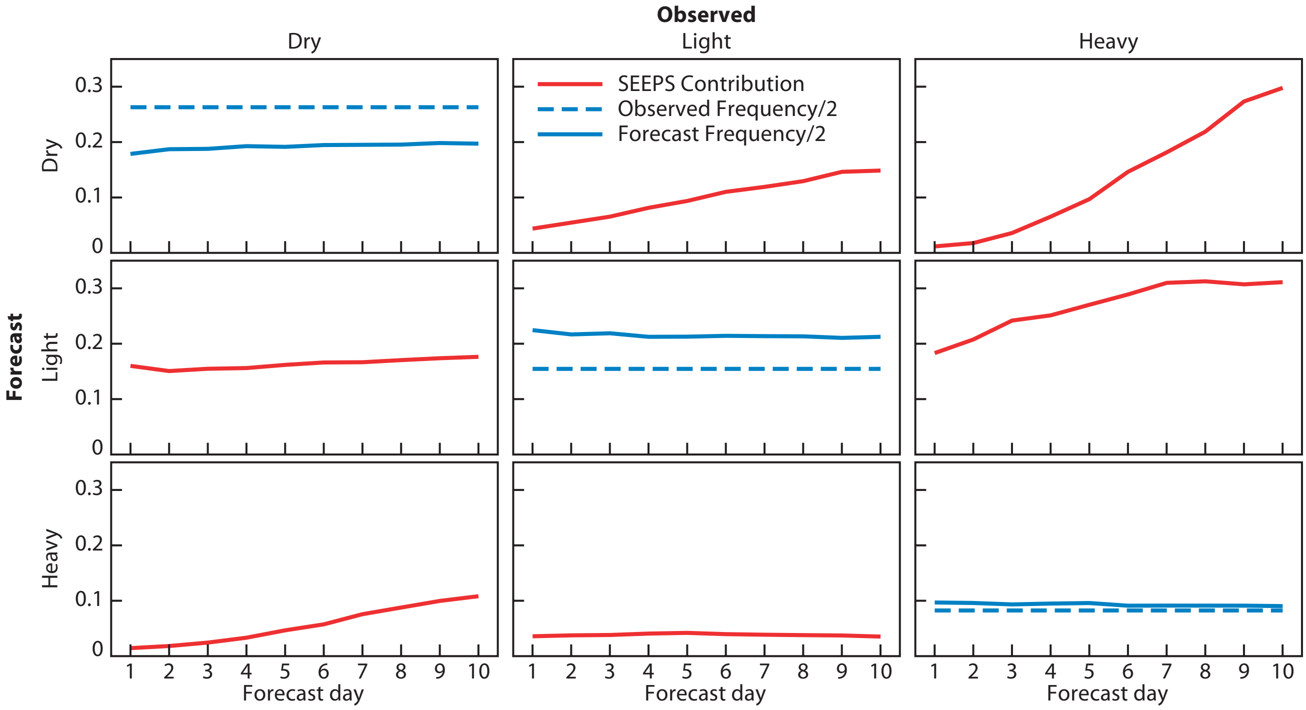


Figure 3 Off-diagonal panels show the contributions to SEEPS from each kind of forecast error as a function of forecast day. Panels on the diagonal show observed and forecast frequency of events. Results are for Europe during the period 1 December 2009 to 28 February 2010 (12 UTC forecasts).

tropics at short lead times. In the tropics the improvement was seen to persist to longer lead times, but not to reach the same level of statistical significance.

Spread–error relationship

The SEEPS score has also been tested with regard to its usefulness in the analysis of the spread–error relationship in the EPS. The approximate equivalence of long-term mean spread and error is usually established by tuning the specification of uncertainties in the initial conditions and sub-grid scale processes with regard to 500 hPa geopotential height and 850 hPa temperature. Consequently, it is of some interest to complement this by looking at the spread–error relationship for surface fields such as precipitation. SEEPS may be useful for this purpose because of the way it handles the

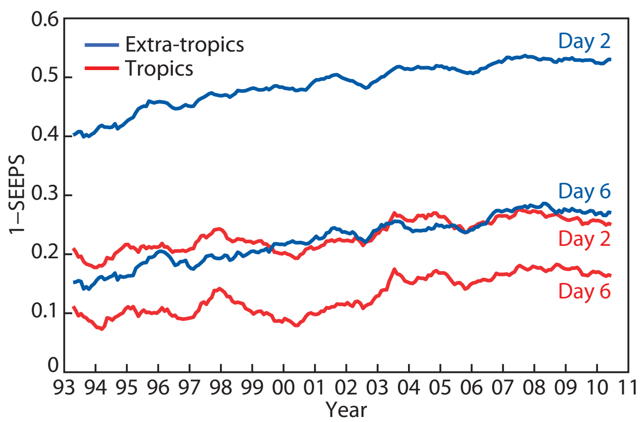


Figure 4 Long-term evolution of 1-SEEPS for the ECMWF model for forecast days 2 and 6 in the extra-tropics and the tropics with a one-year running-mean filter applied.

difficult distribution of precipitation and its normalizing characteristics with regard to climatology; also, importantly, SEEPS places emphasis on the dry/wet boundary. Ensemble error is calculated here as the mean of the SEEPS of each ensemble member against the observations. Ensemble spread is calculated as the mean of the SEEPS of each ensemble member against each other ensemble member.

Figure 7 shows the SEEPS spread–error relationship for Cy36r1 and Cy36r2. The difference between the two cycles is that Cy36r2 uses the Ensemble of Data Assimilations (EDA) as well as singular vectors to create the initial perturbations for the EPS. It became operational in June 2010. In the extra-tropics, there is reasonable correspondence between spread and error at Cy36r1 (blue lines). Interestingly the apparent under-dispersion at short lead times and over-dispersion at longer lead times is not seen in the upper-air fields. Further work is required to understand if SEEPS is indicating a true mismatch in spread and error. The EDA improves the spread-error relationship in the extra-tropics mostly on forecast day 1 (red lines). In the tropics the correspondence between spread and error at Cy36r1 is poorer (black lines). Although the increase of spread with lead time parallels that of the error, it does so at too low a level. This under-dispersion is also seen in the upper-air fields. The EDA (green lines) again helps to improve the spread at short ranges.

Future developments

To improve the coverage and robustness of global precipitation verification, it should be attempted to close remaining gaps in the areal distribution of precipitation observations obtained from the GTS. As model output frequency increases (currently 3-hourly for the ECMWF model), and with algorithm developments, it will be possible to verify against observations at times other than 0 and 12 UTC (such as from Finland, India, and Australia, for example).

The impact of observation uncertainty and representativeness on scores was quantified for 24-hour accumulations based on rain gauge data in Rodwell et al. (2010), but there are plans to extend this analysis. For example, high-resolution precipitation analyses combining rain gauge and radar data (*Haiden et al.*, 2011) will be used to better assess sub-grid scale variability and shorter accumulation periods. The hope being that the diurnal cycle can be partially resolved, and the spread–error relationship better assessed.

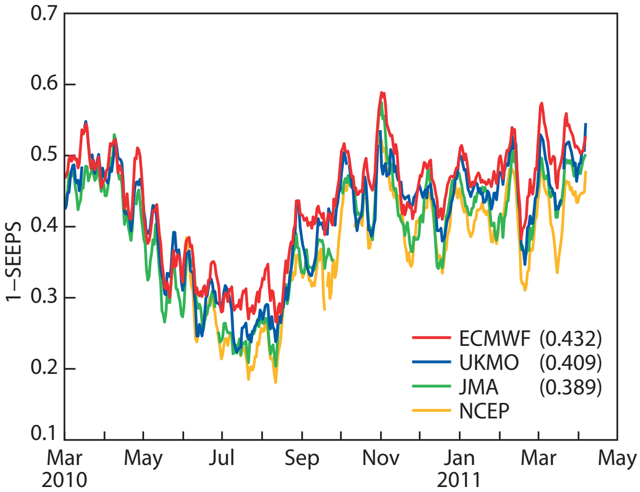


Figure 5 Precipitation forecast model inter-comparison for the extra-tropics for day 4 using 1-SEEPS. The verification period is 1 March 2010 to 5 April 2011 (12 UTC forecasts), with NCEP data available from 1 June 2010 onwards. Shown are running weekly averages of 1-SEEPS for the global models of ECMWF, UK Met Office (UKMO), Japan Meteorological Agency (JMA) and National Centers for Environmental Prediction (NCEP). Numbers in parentheses are period averages.

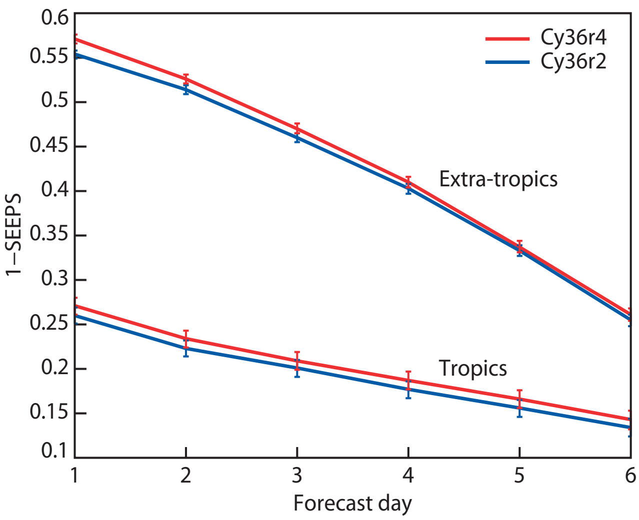


Figure 6 1-SEEPS scores for Cy36r4 (red) and Cy36r2 (blue) for the extra-tropics and the tropics as a function of lead time, averaged over the period 1 July to 9 November 2010 (12 UTC forecasts). Error bars show 95% confidence intervals calculated by re-sampling.

The SEEPS categories can also be used within a proper score (such as the Ranked Probability Score) for the probabilistic verification of the EPS. The combined approach provides a natural and 'seamless' way of applying the attributes of equitability and propriety to the entire Integrated Forecasting System. It also permits the assessment of the dry/wet boundary within the probabilistic system, and thus complements the frequently used Continuous Ranked Probability Score. Additional tests, sensitivity studies and theoretical work will be carried out to assess the utility of this approach.

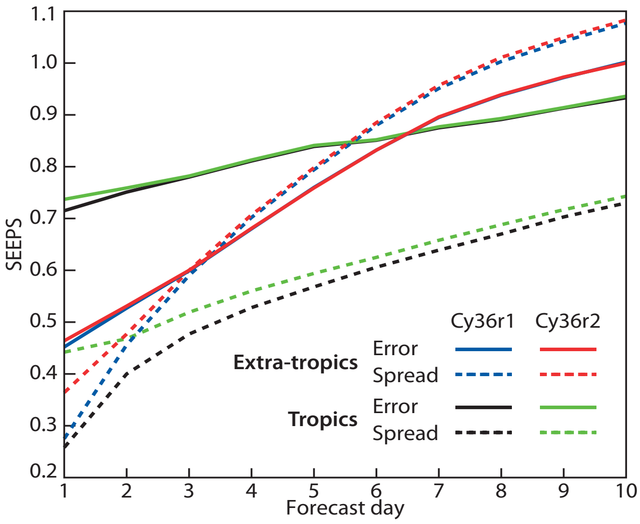


Figure 7 SEEPS error and spread of EPS precipitation forecasts from 00 UTC runs for a period of 56 days in the first half of 2010 for the extra-tropics and tropics. The operational suite at the time was Cy36r1 and the e-suite containing the EDA was Cy36r2.

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Observation errors and their correlations for satellite radiances

NIELS BORMANN, ANDREW COLLARD, PETER BAUER

The assumed observation errors for tropospheric channels from AMSU-A (Advanced Microwave Sounding Unit) have recently been reduced considerably in the ECMWF system, contributing to a significant positive forecast impact in Cy37r2 of the Integrated Forecasting System (IFS). With this change more weight is given to AMSU-A observations in the assimilation system. The rather simple adjustment has been prompted by a study into estimating observation errors and their correlations for most satellite radiances used in the ECMWF system. It was found that observation errors for AMSU-A show only weak correlations spatially or between channels, and the observation error is instead dominated by uncorrelated instrument noise. This suggested that the data could be used more aggressively than previously thought, even if we assume uncorrelated observation errors as is currently done in the ECMWF system.

For other instruments, such as IASI (Infrared Atmospheric Sounding Interferometer), the situation is more complex: while temperature-sounding channels mostly tend to behave in a similar way as those for AMSU-A, channels sensitive to water vapour or with strong surface contributions show considerable inter-channel or spatial error correlations.

This article summarises the observation error estimation and highlights some of the implications.

Observation errors – their role and how to estimate them

The assumed observation errors play an important role in the assimilation system, as together with the background errors they determine the weight given to an observation in the analysis. The observation errors should include an estimate of the error in the observation operator; this is the algorithm used to map the model fields to the observed quantity (i.e. for radiances a radiative transfer model).

For technical reasons, observation errors in today's assimilation systems are commonly assumed to be uncorrelated, so that the error in a radiance observation from one channel is assumed to be independent of (a) the error in a radiances observation from another channel on the same instrument and (b) the error in neighbouring observations. This assumption has long been questioned for satellite radiances, especially since the radiative transfer computations are expected to include errors that are similar between similar channels or neighbouring observations. For instance, the gas concentrations or channel characteristics assumed in the radiative transfer model might be slightly wrong, and this error will be the same between channels or neighbouring observations. To counteract some of the effects of neglecting observation error correlations, satellite radiances are commonly thinned spatially, and the assumed observation errors are inflated.

Estimating observation errors and their correlations is not straightforward. We do not know the 'truth' – we only have observations with measurement errors, radiative transfer models with radiative transfer errors, or forecasts and analyses with their associated errors. When we compare satellite radiances with model equivalents, the differences between the two quantities will be affected by all of these errors. However, over the years, several methods have been developed that allow us to estimate observation errors on the basis of differences between observations and first-guess

Error estimation methods — A

Below is a summary of the three estimation methods used in *Bormann & Bauer* (2010) – the paper describes the assumptions and limitations in more detail.

Hollingsworth/Lönnberg method: The method assumes that errors in the observations (and the observation operator) are spatially uncorrelated. It has been used in the past to estimate background errors from radiosonde networks (*Hollingsworth & Lönnberg*, 1986). Observation errors can be estimated by using spatial covariances of first-guess departures and assuming that the spatially correlated part is due to errors in the first-guess. The method can only be used to estimate inter-channel error correlations, and it will give misleading results in the presence of significant spatial observation error correlations.

Background error method: The method assumes that the spatial structure of the background errors used in the ECMWF system is correctly modelled. Observation error covariances are estimated from spatial covariances of first-guess departures by subtracting a spatial background error covariance matrix mapped into radiance space, possibly scaled to be consistent with the first-guess departure covariances at longer separation distances.

Desrozier diagnostic: The method is based on representing the assimilation system as a simple linear optimal estimation problem, and it assumes that the weights given to the observations in the assimilation system are consistent with true error covariances. In that case, simple equations for observation and background error covariances can be derived from covariances of first-guess and analysis departures (*Desroziers et al.*, 2005).

or analysis equivalents. The first guess is the short-term forecast used in cycling assimilation systems. Differences between observations and first guess or analysis equivalents are usually referred to as departures, and they are routinely produced in assimilation systems.

Based on a large sample of such departures, *Bormann & Bauer* (2010) estimated observation errors and their correlations for radiances used in the ECMWF system, employing three such error estimation methods (see Box A). None of the methods used is without flaws – all make some assumptions about the structure of the observation or background errors, and these assumptions are more or less valid depending on the observations in question. But it was found that the results were qualitatively quite similar for the three methods, giving additional confidence in the estimates. Here we highlight the results for AMSU-A and IASI, two of the most important satellite instruments currently in use.

AMSU-A

One of the flagship satellite instruments for numerical weather prediction is AMSU-A. It is a 15-channel microwave radiometer that has provided the backbone for temperature soundings from space for more than a decade. Currently five of these instruments are assimilated in the ECMWF system, from the NOAA, MetOp and Aqua satellites. These observations are not as strongly affected by clouds as data from infrared instruments; therefore they provide some temperature-sounding capability in weak cloudy conditions.

The observation error covariance estimates for AMSU-A show surprising results for the error correlations. The estimates for error correlations between different channels are rather small (Figure 1), and while there are some spatial error correlations between closely-spaced observations, they tend to tail off to below 0.2 as long as the observations are separated by more than ~50–75 km (Figure 2). This compares to a thinning scale of 125 km used in the ECMWF system for AMSU-A observations. Consistent with the error correlation estimates, the estimates for the observation errors for most channels are close to the estimated instrument noise, i.e. the estimate of the random error provided by the data producers (Figure 3). The estimates of the observation errors are also much smaller than what was assumed in the ECMWF assimilation system.

The findings are surprising, as they seem to suggest that the radiative transfer error with its inter-channel and spatial correlations is rather small. This may be due to the high quality of the radiative transfer computations. But another factor is that the remaining radiative transfer errors for AMSU-A are likely to lead to large-scale, air-mass dependent biases, and these appear to be successfully taken out by the bias corrections routinely applied to these observations.

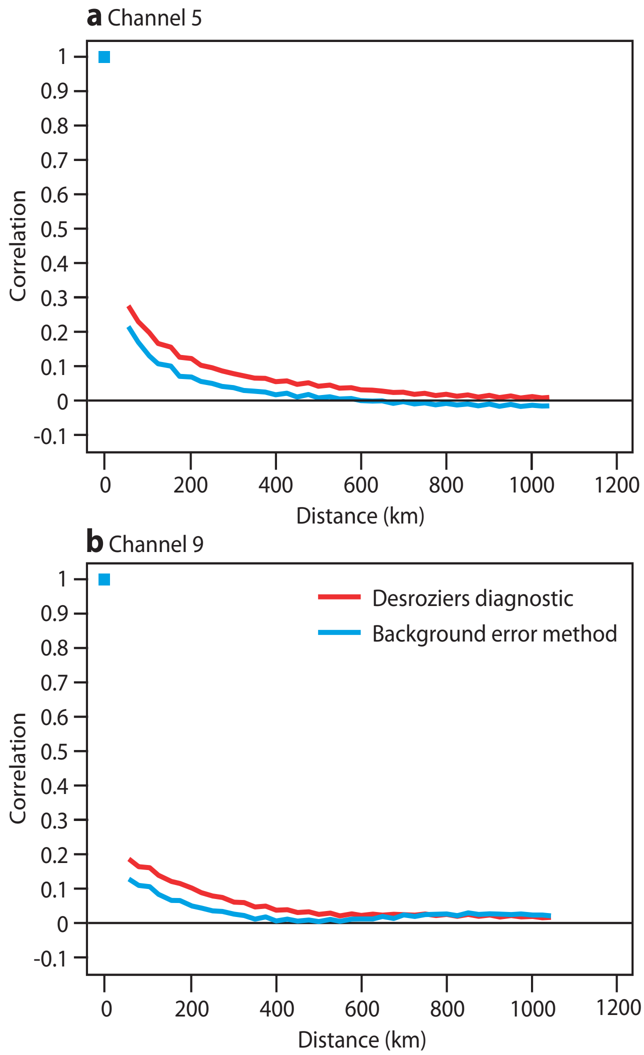

Figure 2 Estimates of the spatial error correlation matrix as a function of the separation distance between two observations for two typical AMSU-A channels: (a) channel 5 (peaking around 800 hPa) and (b) channel 9, peaking around 90 hPa. Results for two methods are shown: the Desroziers diagnostic and the background error method.

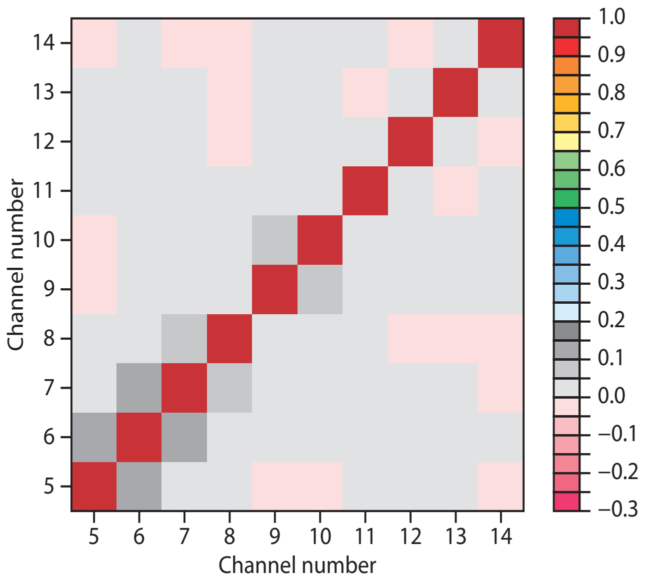

Figure 1 Estimates of the inter-channel error correlation matrix for the AMSU-A channels used at ECMWF. Channel 5 is the lowest sounding channel, peaking around 800 hPa, whereas other channels have their largest temperature sensitivity progressively higher in the atmosphere, with channel 14 peaking at around 2 hPa. The results were obtained with the Desroziers diagnostic.

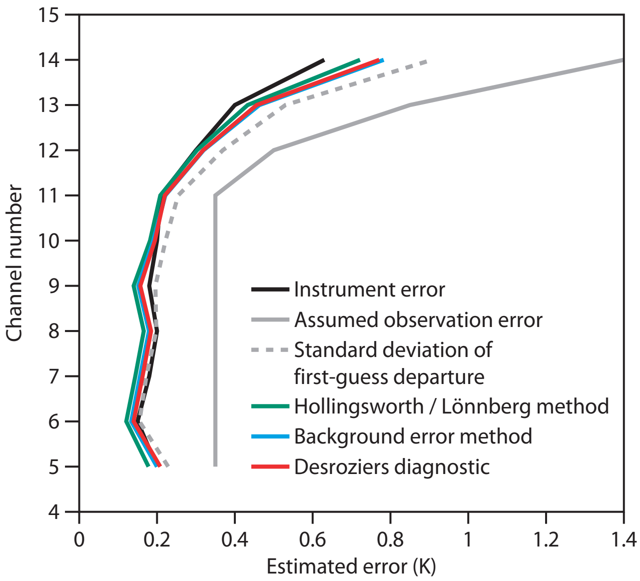

Figure 3 Estimates of the observation error (K) for the AMSU-A channels used in the ECMWF system. The coloured lines show the estimates from the three estimation methods used by *Bormann & Bauer* (2010) as indicated in the legend. Also shown are the instrument noise, the standard deviation of first-guess departures and observation error that has been assumed so far.

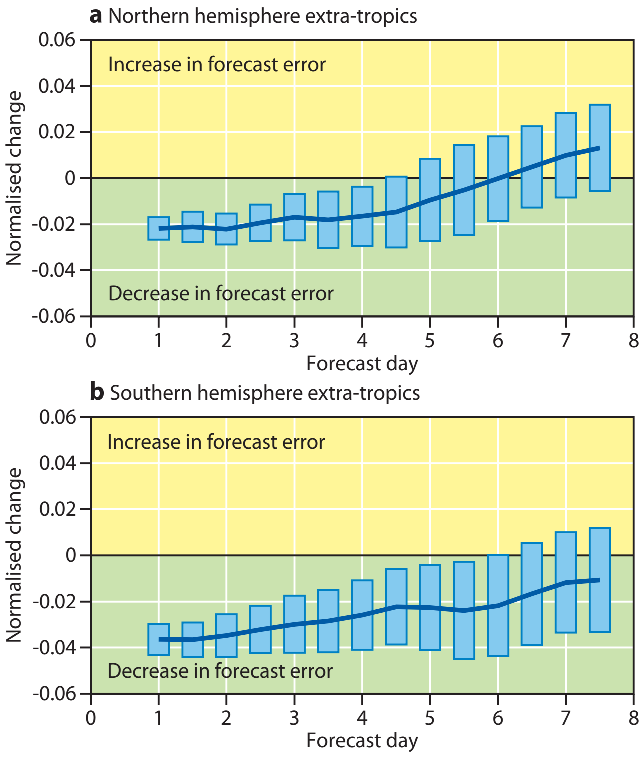

Figure 4 Forecast impact of reducing the observation error for AMSU-A observations for (a) northern hemisphere and (b) southern hemisphere extra-tropics. Shown is the normalised change to the root mean square of the forecast error of the 500 hPa geopotetial height as a function of forecast range. Negative values show a reduction of the forecast error as a result of the observation error reduction and hence a positive forecast impact. Error bars indicate statistical significance intervals. Results are from a trial with a total of 120 cases, for the periods 21 December 2009 to 31 January 2010 and 15 May 2010 to 31 July 2010.

The fairly weak error correlations suggested that AMSU-A could be used more aggressively in the ECMWF system, even with the assumption of uncorrelated observation errors. We therefore performed assimilation trials in which either (a) the thinning scale was reduced to 60 km for channels 5–10 or (b) the assumed observation error for channels 5–10 was reduced (from 0.35 K to 0.20 K for channels 6–10 and from 0.35 K to 0.28 for channel 5), the values being inspired by the estimates provided in Figure 3. In each case the thinning scale or observation errors for the upper stratospheric AMSU-A channels was left unchanged, as a reduction led to problems in the assimilation due to instabilities of the tangent linear model in the stratosphere for high-resolution experiments.

The forecast impact of changing either the thinning scale or assumed error observation is very positive, leading to significant improvements up to forecast day 5–6 for most parameters. A combination of both approaches was also tested, but this did not show further benefits.

Due to the lower computational cost, the reduction of the observation errors has been implemented operationally in the latest cycle (Cy37r2), rather than the more costly reduction in the thinning. The positive impact of this change is illustrated by Figure 4 – this shows the normalised change to the root mean square forecast error of the 500 hPa geopotential height.

IASI

Another important satellite sounding instrument is IASI, a hyperspectral infrared interferometer that provides measurements in 8,461 channels. At the time of writing, only one such instrument is flying in space, on the European MetOp-A platform, but further instruments are planned for the next few years. The ECMWF system uses up to 175 IASI channels, covering primarily the long-wave CO_2 temperature-sounding band. Infrared observations are much more affected by clouds than microwave ones, so only channels deemed clear from cloud, or totally overcast are currently assimilated in the ECMWF system.

The observation error covariance estimates for IASI tell a somewhat different story, as can be seen, for instance, in Figure 5. While the upper temperature sounding channels, displayed primarily in the lower left quarter of the figure, show similar characteristics as AMSU-A (i.e. with low inter-channel error correlations), other parts of the spectrum exhibit considerable inter-channel error correlations, as can be seen in the upper right quarter. These are channels affected by clouds, have a significant contribution from the surface ('window channels') or are sensitive to water vapour. For these channels, the observation error estimate is also considerably larger than the estimates for the instrument noise (Figure 6). It appears that either the radiative transfer error is larger or the bias correction less successful in compensating for it than for AMSU-A, or other aspects such as residual cloud contamination or representativeness play a role.

The error estimation study also highlighted other interesting aspects. For instance, neighbouring channels show

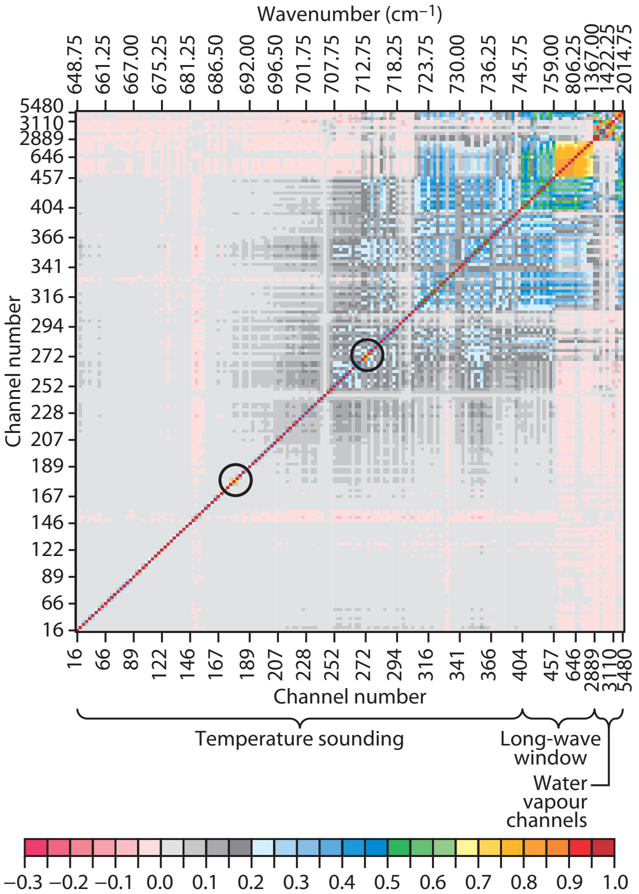

Figure 5 Estimates of the inter-channel error correlation matrix for the IASI channels used at ECMWF. The values are derived from spectra over sea for which all 175 channels used at ECMWF were diagnosed to be clear-sky. The lower axis gives the IASI channel number, whereas the upper axis gives the wavenumbers of the channels. The circles indicate two instances where neighbouring channels are selected, showing large error correlations arising from the apodisation.

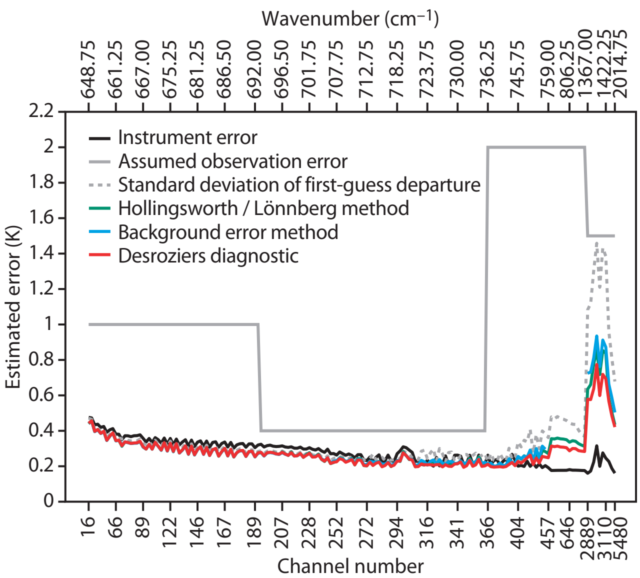

Figure 6 Estimates of the observation error (K) for the IASI channels used in the ECMWF system. The colour coding for the various lines is as described in Figure 3.

rather high error correlations of around 0.6 (see circles in Figure 5). This is a result of the effect of apodisation, a convolution applied to IASI data aimed at compensating for some of the effects introduced by measuring a truncated interferogram. Although this characteristic is well known, it is reassuring that it shows up clearly in these observation error estimates.

Other characteristics of IASI data are less well known, but are highlighted through a further analysis of the observation error characteristics. For instance, for some channels, we found very small spatial observation error correlations that displayed a chess-board like pattern when displayed as a function of scan-line and scan-position difference (Figure 7). IASI scans the atmosphere across the satellite track, providing data for four pixels at 30 scan-positions for each scan-line. Considering just one of the four pixels, the finding suggests that part of the error is common to several observations with the sign of the error alternating with scan-position. The current explanation is that this is linked to an instrument feature, the so-called ghost-effect, a result of micro-vibrations of parts of the instrument. Although the error is negligible and of no concern for the assimilation of the data, the analysis illustrates the power of data assimilation systems to highlight minute features of satellite data.

Other instruments

We performed the same analysis of observation errors for radiances from all main satellite instruments currently used in the ECMWF system, with consistent findings across all of them. Water vapour channels or channels with strong surface contributions show considerable inter-channel or spatial error correlations. We found the largest spatial error correlations for humidity-sensitive microwave radiances, for which spatial correlations can be larger than 0.2 for separations larger than 100 km. Microwave imager radiances in cloudy or rainy regions show particularly strong error correlations. However, for the humidity-sensitive radiances, the estimation of observation errors is also more difficult, as some of the assumptions made in the estimation methods are more stretched.

The effect of observation error correlations

Given the finding of significant error correlations for some of the radiance observations, the question arises: what does it mean for data assimilation if two observations have a significant error correlation?

Let us consider two observations that have a significant positive error correlation and the same observation error. This means that, compared to the case of uncorrelated errors, for a given situation it is statistically (a) more likely that the true errors for both observations are similar (e.g. they have the same sign and comparable magnitude) and (b) less likely that the true errors are different (e.g. they have the opposite sign, but comparable magnitude). Consequently, an assimilation system that takes these error correlations into account will respond differently to the presented observations, depending on the differences between the first guess and the observations.

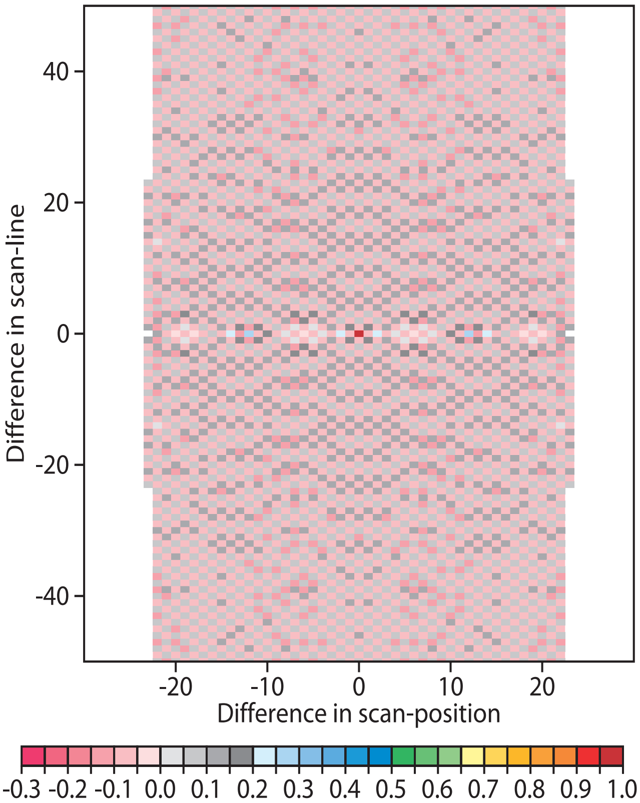

Figure 7 Estimates of the spatial observation error correlation for IASI channel 380, as a function of the difference in scan-lines and AMSU-A scan-position between the two observations.

- If the two observations differ in a similar way from the first guess, the assimilation system will put less weight on the observations compared to the system that ignores such error correlations. This is because similar differences are more likely for observations with correlated errors, so it is more likely that the error is due to an error in the observations.
- If the two observations differ in a different way from the first guess (e.g. opposite signs of departures), the assimilation system will put more weight on these observations compared to a system that ignores the observation error correlations. This is because different errors are less likely for the correlated observations, so the departures are more likely to indicate an error in the first guess.

This behaviour can also be demonstrated for IASI in a real assimilation system. To do so, we investigated what happens when a single IASI spectrum is included in an assimilation system that either ignores inter-channel error correlations or takes these into account. We investigated several selected cases in which all IASI channels that are usually considered for assimilation were diagnosed as cloud-free. In each of these experiments no other observations were assimilated, in order to study the influence of the observation error correlations for IASI in isolation. When error correlations are taken into account, the observation error correlation matrix used was the one shown in Figure 5, and the observation error (from the diagonal of the observation error covariance matrix) was kept the same as when uncorrelated errors are used. Results from two cases will now be presented.

Figure 8 shows the departures for the assimilated IASI channels for the first case. Here, most departures for the lower-peaking temperature sounding channels have the same sign. This suggests that the first-guess is too warm or that there may be residual cloud contamination even though the observations are assumed to be clear-sky.

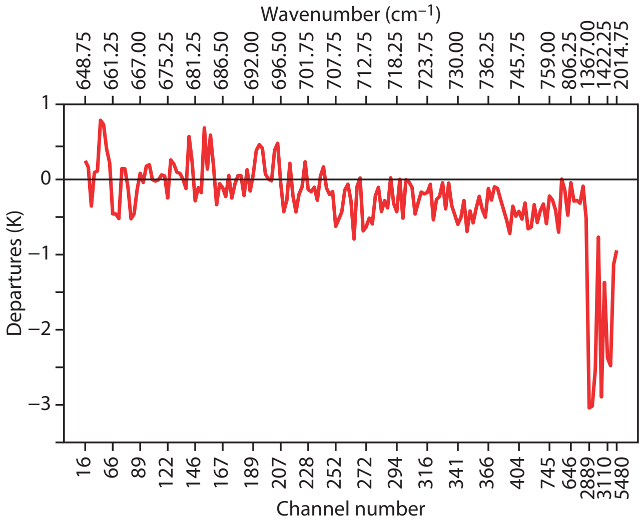

Figure 8 Departures (i.e. difference between observations and first guess) for the first case of single-IASI spectrum experiments.

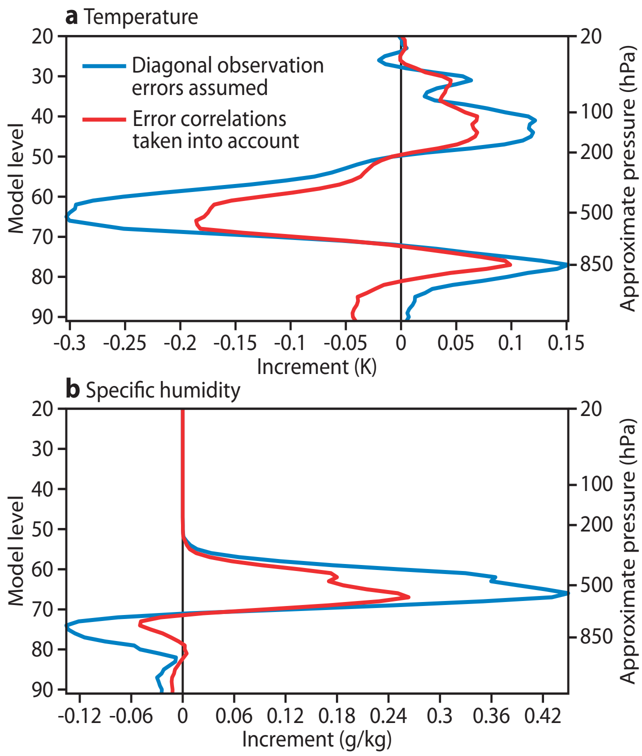

Figure 9 Profile of the increments (i.e. differences between the analysis and the first guess) of (a) temperature and (b) specific humidity at the location of the assimilated IASI spectrum for the first case of single-IASI spectrum experiments. The blue line shows results from the experiment that assumes diagonal observation errors, whereas the red line shows results from the experiment that takes the error correlations into account.

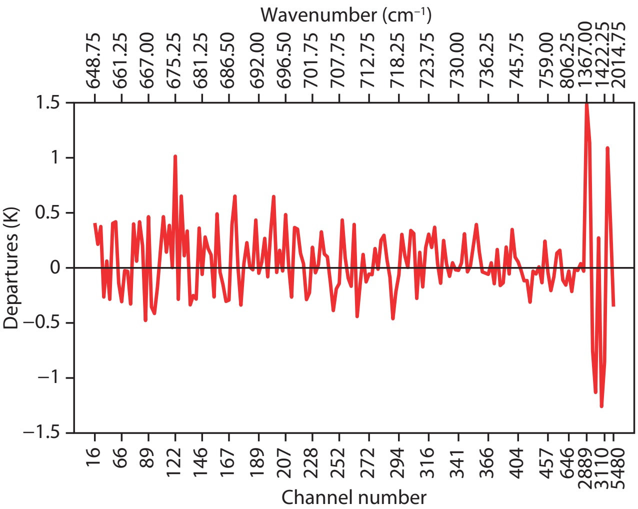

Figure 10 Departures (i.e. difference between observations and first guess) for the second case of single-IASI spectrum experiments.

Figure 9 shows profiles of the increments of temperature and specific humidity that result from assimilating this spectrum with or without taking error correlations into account. Increments are the adjustments made to the first guess as a result of assimilating the observations, and the size of the increments reflects the weight given to the observations in the assimilation. The figure shows that these adjustments are smaller when the inter-channel error correlations are taken into account for this case. The reason is that now the assimilation system knows that the errors in the observations are not independent, and the consistently negative departures are likely to be a reflection of such errors in the observations. As a result, the assimilation system puts less weight on the observations compared to when the observation errors are assumed to be independent.

But the opposite can happen as well: in the second case, the departures vary significantly around zero between channels (Figure 10). Here, the increments are actually larger when observation error correlations are taken into account (Figure 11), consistent with the considerations above for the two-observation case.

We can compare this behaviour with the commonly used approach of using inflated but uncorrelated observation errors. This approach will have a similar effect of reducing the increments as shown in the first case, as less weight is given to the observations. But it will also reduce the increments in the second case, and thus do the opposite of what is observed when error correlations are taken into account. So an error inflation will not have the same effect as taking the error correlation into account.

Future

Taking inter-channel or spatial error correlations into account in the assimilation system is an area of active research at ECMWF and elsewhere. While it is clear that neglecting error correlations may lead to a sub-optimal weighting of observations, it is less clear how well we need to model the observation error correlations in order to see a clear benefit over assuming diagonal, possibly inflated observation errors. In addition, observation errors and their correlations are likely to be partly situation-dependent, especially for instruments like IASI, where residual cloud-contamination is thought to be one of the reasons for the presence of inter-channel error correlations. Further work in this direction is required. As the experience with AMSU-A shows, an optimised weighting of observations can lead to rather significant forecast improvements.

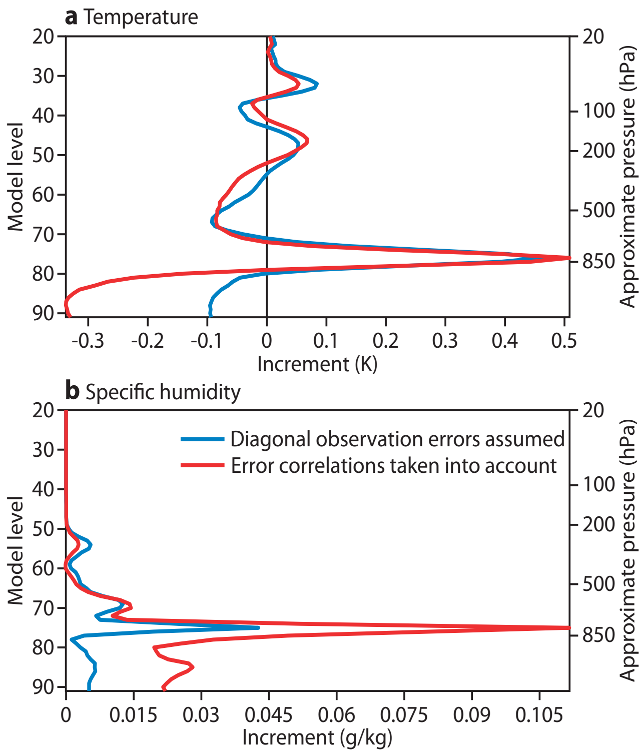

Figure 11 Profile of the increments (i.e. differences between the analysis and the first guess) of (a) temperature and (b) specific humidity at the location of the assimilated IASI spectrum for the second case of single-IASI spectrum experiments. The blue line shows results from the experiment that assumes diagonal observation errors, whereas the red line shows results from the experiment that takes the error correlations into account.

FURTHER READING

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Development of cloud condensate background errors

JIANDONG GONG, ELÍAS VALUR HÓLM

From the moment the first television pictures taken from space by the TIROS I satellite appeared on 1 April 1960, the public and meteorologists alike have been fascinated by the potential of cloud observations to help forecast the weather. For half a century these images have been employed extensively in the research and monitoring of weather phenomena such as hurricanes, as well as for predicting the weather, but meteorologists are still learning how to make full use of cloud affected observations in numerical weather forecasting.

The main cloud observations used by weather forecasting centres are indirect measurements; they are in the form of top of atmosphere outgoing infrared and microwave radiances which are affected by a whole column of the atmosphere and the surface. Much progress has been made at ECMWF to improve the use of microwave radiance observations in cloudy and precipitating areas in recent years (*Bauer et al.*, 2010; *Geer et al.*, 2010; *Geer & Bauer*, 2010) and currently there is a focus on extending the use of infrared observation into cloudy areas as well.

In this article we will concentrate on the development of cloud condensate background errors that are required for optimal use of cloud affected observations in data assimilation.

Use of cloud information in the analysis

The main difficulty in using radiance observations in a data assimilation system is that radiances are related to the model's state variables through a complex radiative transfer model. The radiative transfer model integrates the model fields in a column into a single number for comparison with the observed radiance – this process is called an observation operator. Conversely, when a radiance observation implies a change in the atmospheric state, a single number is distributed into updates to all those variables in the model column which affect the radiance.

How accurately each model variable is updated depends on the accuracy of the observation operator, the background state, and the estimated observation and background errors. In particular, if the background errors are not correctly estimated, then the signal can be attributed to the wrong variables. To give an example, specifying a humidity background error that is too large could cause radiance information on temperature and humidity to be excessively allocated to humidity. Accurate estimates of the background errors is thus essential to correctly attribute radiance observational information, in particular in cloudy and precipitating areas where the uncertainty is larger than in clear sky.

Currently the radiance observation operator RTTOV (Radiative Transfer for TOVS), developed by EUMETSAT's NWP Satellite Application Facility and used at ECMWF, takes prognostic temperature and humidity as input. It then diagnoses clouds and precipitation fluxes needed in the calculation of model equivalents of the observed radiances. With this approach, temperature and humidity are updated by the assimilation system, but the initial condition of cloud condensate is left unchanged. This approach has two significant limitations. First, errors in cloud condensate may be wrongly interpreted as errors in humidity and temperature, because the observation operator does not consider prognostic cloud condensate. Second, the forecast model may have to adjust the cloud condensate to the changes in temperature and humidity through a spin-up process.

A more accurate approach to the assimilation of cloud sensitive observations is to also include prognostic cloud condensate as input to the observation operator and update cloud condensate in the initial conditions along with humidity and temperature. This requires developments in three areas.

- Use of prognostic cloud condensate in cloud sensitive observation operators, in particular cloudy RTTOV.
- Inclusion of cloud condensate in the linear physics used by the data assimilation.
- Specification of background errors for cloud condensate.

At ECMWF developments in all three areas are taking place in a concerted effort to make better use of cloud sensitive observations, in particular radiances. With this work we want to be able to answer two related questions:

- Does the inclusion of prognostic cloud condensate as input to the observation operator make a difference to the impact of the data on the forecast?
- Does updating the initial conditions of cloud condensate make a difference to the forecast of clouds and precipitation?

Here we report on the development of background errors for cloud condensate and show some initial, idealised assimilation results.

Choice of variables for the cloud analysis

The current forecast model at ECMWF has six variables that together describe the evolution of water in the atmosphere:

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water vapour, cloud water, cloud ice, cloud fraction, rain and snow. In the data assimilation on the other hand, only water vapour is updated. This difference is mainly due to the difficulty of accurately describing the dependency of cloud sensitive observations on cloud processes. This difficulty has made it preferable to ignore changes to the initial conditions of all cloud and precipitation variables in the assimilation process and only update humidity.

With the increasing use of cloud sensitive observations we decided to revisit whether only updating humidity is still the best approach. As a starting point we consider the previous version of the ECMWF cloud scheme, where water vapour, cloud condensate and cloud cover were the prognostic variables. Cloud condensate is a more fundamental variable than cloud cover, because cloud cover can be diagnosed quite accurately from the cloud condensate. There is also a fairly accurate way to split cloud condensate into cloud liquid and cloud ice as a function of temperature only, which was also used in the previous ECMWF cloud scheme.

Another very practical reason to prefer cloud condensate over cloud cover in the analysis is that the processes governing the evolution of cloud cover are more nonlinear than those governing cloud condensate. Choosing cloud condensate makes it much easier to develop the linear physics needed for the four-dimensional variational data assimilation (4D-Var). In 4D-Var an analysis is produced by finding a forecast that gives close to optimal fit to a weighted average of the observations available over a time period (currently 12 hours at ECMWF) and the background fields available at the start of the time period.

Adding cloud condensate to the analysis makes a distinct change to the treatment of water in parts of the 4D-Var that are linear (i.e. the inner loops). In the current linear model, all water is lost from the system once it condenses, because there is no cloud condensate variable in the linear system. When cloud condensate is included in the linear system, the new frontier now becomes precipitation, where water is again lost whenever there is precipitation due to there not being any linear precipitation variable. So the boundary of the unknown is extended from condensation to precipitation by adding cloud condensate in the analysis. Future developments will doubtless include precipitation in the analysis as well.

Cloud condensate background errors

The cloud condensate background error is determined from a large sample of forecast differences produced by an ensemble of analyses. The analysis ensemble, which has ten members using observations that have been differently perturbed for each member, produces ten independent forecasts; these can be subtracted from each other to produce nine independent samples of forecast differences valid at the start of the following assimilation cycle. It can be shown that these forecast error differences are proportional to the background errors, with forecast difference variances twice the value of the background error variances.

The background error has three factors, which when multiplied together give the total background error.

- *'Balance operator'*. This describes the correlation of cloud condensate errors with errors in other analysis variables.
- *Background error variance*. This is a statistically determined function which describes how the error variance of the unbalanced cloud condensate depends on the background state.
- *Background error correlations*. These describe the vertical and horizontal correlations of the normalised unbalanced cloud condensate errors.

More details about these three factors are given in Box A.

A

Factors determining the total background error

The following three factors, when multiplied together, give the total background error.

- *'Balance operator'*. This describes the correlation of cloud condensate errors with errors in other analysis variables. For cloud condensate, the main correlation is with water vapour through the process of condensation. The balance relationship for cloud condensate that we use subtracts a statistically determined function of water vapour and relative humidity from the total cloud condensate to form 'unbalanced' cloud condensate with errors less correlated with those of other analysis variables.
- *Background error variance*. This is a statistically determined function which describes how the error variance of the unbalanced cloud condensate depends on the background state. The unbalanced cloud condensate is divided by the background error standard deviation in this step to form a normalised unbalanced cloud condensate. Due to the large variability in cloud condensate and its errors, it is necessary to have a flow dependent model of the error variances which adjust to the weather of the day. The variance model we have developed for this depends on model level as well as the relative humidity and the cloud condensate content of the background. One particular difficulty is what to do in case there is no cloud condensate present in the background. For this case, the background error is put to a value which is relatively small, but large enough to allow cloud sensitive observations to add clouds in case they are seen by the observations.
- *Background error correlations*. These describe the vertical and horizontal correlations of the normalised unbalanced cloud condensate errors. While also being statistically determined, the correlations remain constant in time. The correlations do however vary in space, with the horizontal and vertical correlations at each point on the globe reflecting the average conditions at that point.

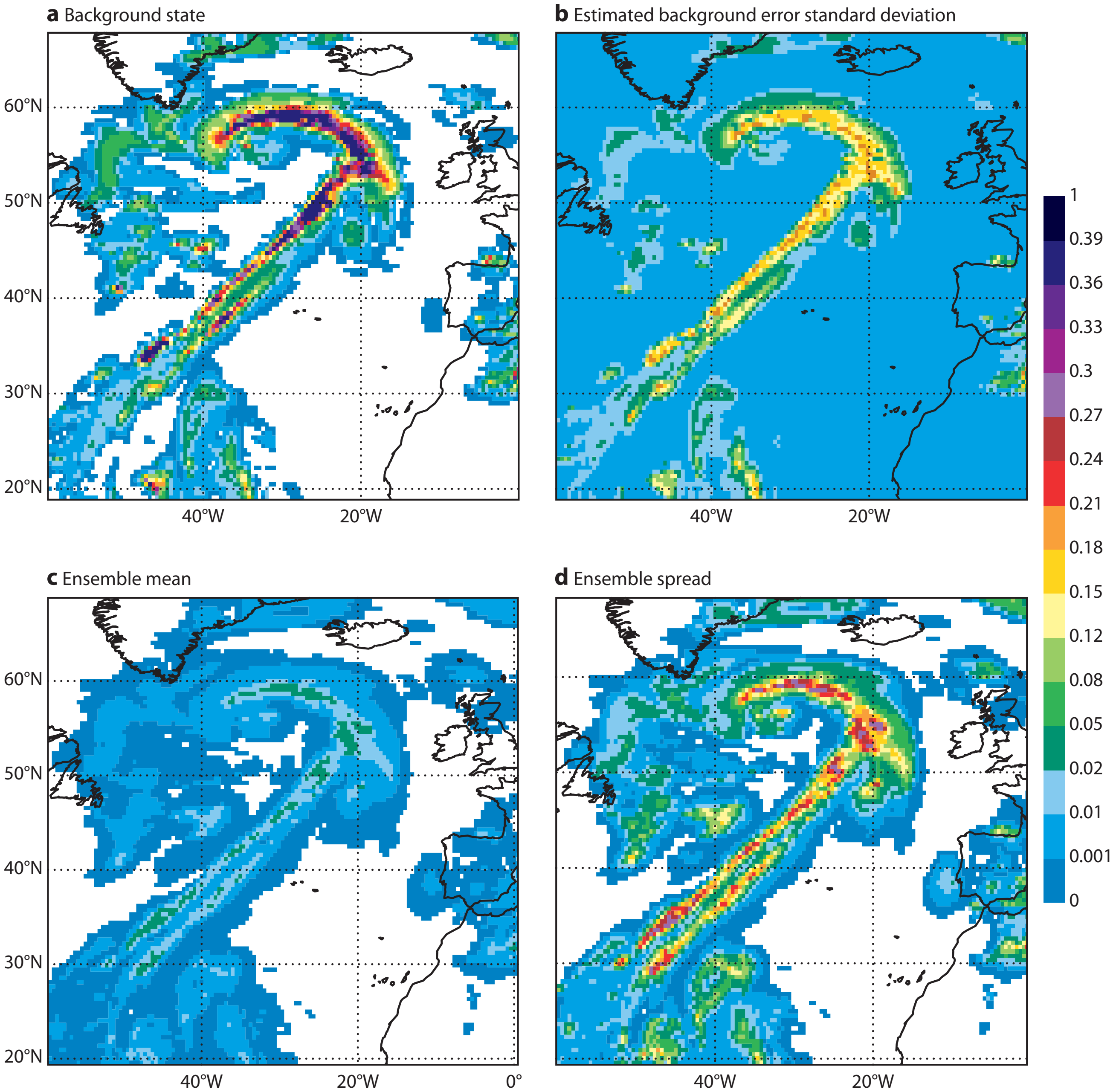

Figure 1 Cloud condensate background error standard deviation (at about 670 hPa) from a statistical model compared with the ensemble spread from ten ensemble forecast members valid at the same time: (a) background state, (b) statistically estimated background error standard deviation, (c) ensemble mean and (d) ensemble spread of the cloud condensate. Units are 1×10^{-3} kg/kg.

All three factors determining the background error contribute to its geographic and/or flow-dependent variation. The balance operator explains a part of the cloud condensate error variance in terms of water vapour errors, with the strength of the balance varying with relative humidity and model level. It is in lower to mid tropospheric cloudy regions where the strongest balance occurs – here up to one third of the variance is explained by water vapour.

The background error correlations vary mainly with the average cloudiness of a region. In predominantly clear regions there is very little vertical correlation, whereas in predominantly cloudy regions the vertical correlations stretch over several model levels to reflect the correlation brought on by convection and other cloud processes. The background error variance shows the strongest flow dependency and so we will now consider it in more detail.

The statistical model of the error variance is applied to the background state at every analysis cycle to give an estimate of the background error of the day. This estimate can be compared with the ensemble spread obtained from ensemble forecasts valid at the same time. If the statistical model is accurate, the results should be similar. Such a comparison is shown in Figure 1, where the background state of the cloud condensate and the ensemble mean are also shown.

It can be seen that the estimated background error standard deviations agree fairly with the ensemble spread, but there are also several differences. First, the ensemble

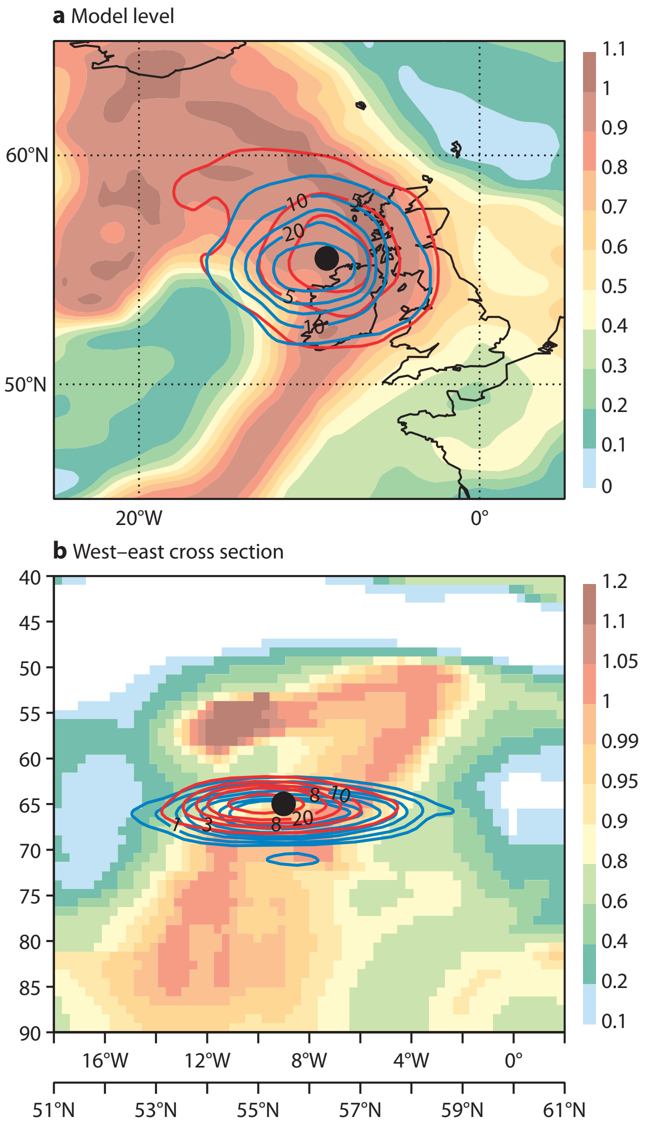

Figure 2 Single cloud liquid observation (black dot) in a nearly saturated area, at about 500 hPa, within a 3D-Var framework: cloud condensate analysis increments (blue isolines, units 1×10^{-6} kg/kg), specific humidity increments (red isolines, units 1×10^{-6} kg/kg) and background relative humidity (colour) for (a) model level and (b) west–east cross section at the observation location.

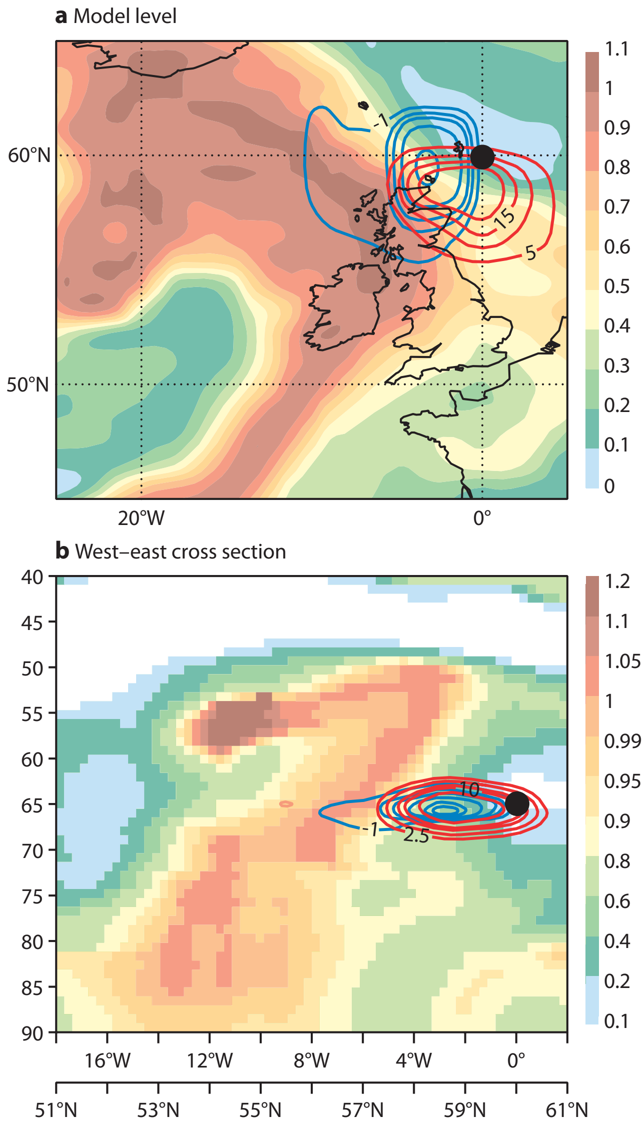

Figure 3 Single liquid observation (black dot) in very dry area with no background error condensate, at about 500 hPa, within a 3D-Var framework: cloud condensate analysis increments (blue isolines, units 1×10^{-6} kg/kg), specific humidity increments (red isolines, units 1×10^{-4} kg/kg), and background relative humidity (colour) for (a) model level and (b) west–east cross section at the observation location.

spread is zero where all ensemble members are cloud-free, whereas the estimated background error standard deviation defaults to a small value in cloud-free areas to allow observations to put clouds where the model background has none. Second, the largest values of the background error standard deviation are intentionally capped to allow for a smoother variation of the background error. This is because the exact location of the maximum error is fairly uncertain as can be seen by looking at how smooth the ensemble mean is compared with the background state. In this case the best policy is to be conservative and not commit to the error being very large at one particular location, which might be the wrong location.

One may ask why the ensemble spread itself is not used instead of a statistical model. The answer is that the ensemble spread will be used when available, but that there are many configurations of the Integrated Forecasting System (IFS), for example re-analyses, where no ensembles of analyses are available and it is necessary to default to a statistical model. The fact that the statistical model agrees fairly well with the ensemble spread shows that this is a viable strategy.

Single observation experiments

To investigate the behaviour of the cloud condensate background errors, data assimilation experiments were made with a single cloud liquid water observation in a single model layer. Although no such observations exist, they can be simulated and are useful in showing the response of the assimilation system. A few typical cases are shown in Figures 2, 3 and 4 where the observations are

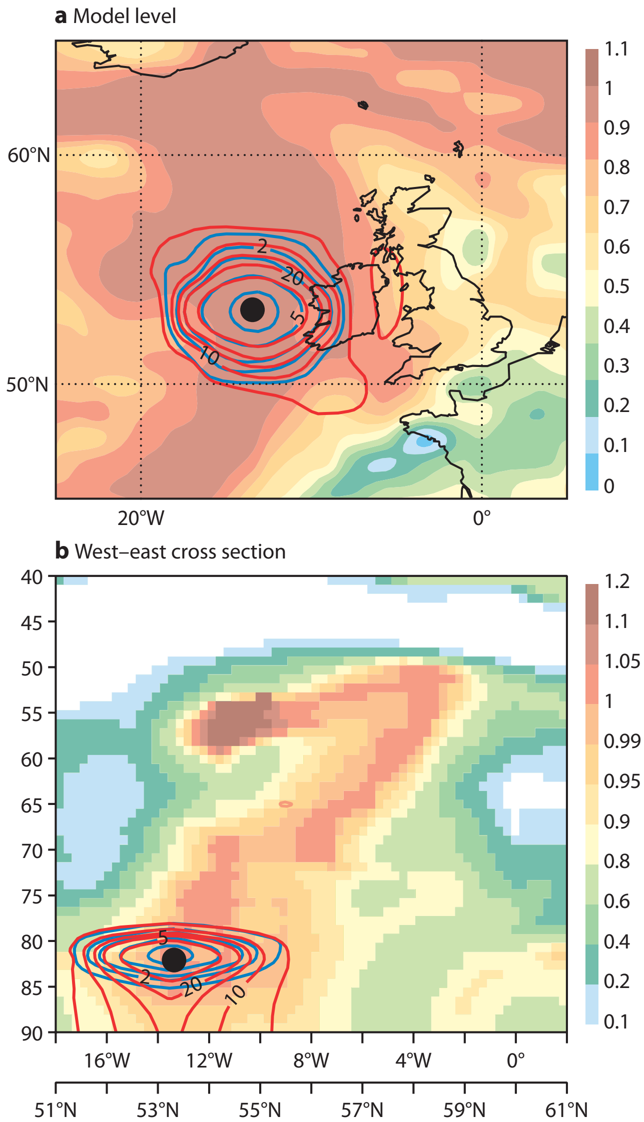

Figure 4 Single cloud liquid observation (black dot) in nearly saturated boundary layer, at about 960 hPa, within a 3D-Var framework: cloud condensate analysis increments (blue isolines, units 1×10^{-6} kg/kg), specific humidity increments (red isolines, units 1×10^{-4} kg/kg), and background relative humidity (colour) for (a) model level and (b) west–east cross section at the observation location.

placed at the start of the 4D-Var assimilation window, which allows the effect of the background errors on the analysis increments to be studied in isolation from the effects of other components the 4D-Var. This is important because we want to know that all components of the cloud condensate assimilation work well on their own before we couple them together in the 4D-Var framework.

In Figure 2 the cloud liquid water observation is in a nearly saturated area with a frontal cloud. The cloud condensate increment (blue isolines) follows the background cloud (high relative humidity) and is nearly isotropic. The specific humidity increment (red isolines) coming from the balance relationship between cloud condensate and humidity in the background error shows that the balance relationship gives realistic changes to humidity which are confined to cloudy areas.

In Figure 3 the cloud liquid observation is located in a very dry area adjacent to the front. Now the cloud condensate and humidity increments are not isotropic, and they are no longer centred on the observation. This is because the cloud condensate variance increases rapidly in cloudy regions, resulting in an increment which extends the existing cloud towards the observation. The cloud condensate and humidity background error variances each mainly follow their respective background error values, which accounts for them not overlapping in the dry-moist transition zone. The vertical correlations of cloud condensate background error are narrower than those of humidity, especially in the boundary layer. This is shown in Figure 4 where a cloud liquid observation placed in the boundary layer gives a humidity increment which extends to the surface, whereas the cloud condensate increment remains localised around the observation in vertical.

Current and future work on cloud condensate assimilation

The initial tests reported here show that we have a model of cloud condensate background errors which give realistic increments of cloud condensate within the data assimilation, as well as implying specific humidity increments through a background error balance relationship predominantly coming from condensation effects. Current work focuses on coupling the background errors together with recently developed linearised physics which include cloud condensate. This is done by placing a single cloud observation later in the assimilation window to see how the linear model translates the signal from the observation time to the initial time. Furthermore, we are testing the behaviour of single microwave and infrared radiance observations with and without prognostic cloud condensate as input.

Once we have verified that all the individual components needed for cloud assimilation work together, we can address the two main scientific questions we mentioned at the outset, namely whether adding prognostic cloud condensate as input to the observation operators makes a difference to the impact of the data on the forecast and whether updating the initial conditions of cloud condensate makes a difference to the forecast of clouds and precipitation.

FURTHER READING

Bauer, P., **A.J. Geer**, **P. Lopez** & **D. Salmond**, 2010: Direct 4D-Var assimilation of all-sky radiances. Part I: Implementation. *ECMWF Tech. Memo. No. 618*.

Geer, A.J., **P. Bauer** & **P. Lopez**, 2010: Direct 4D-Var assimilation of all-sky radiances. Part II: Assessment. *ECMWF Tech. Memo. No. 619*.

Geer, A.J. & **P. Bauer**, 2010: Enhanced use of all-sky microwave observations sensitive to water vapour, cloud and precipitation. *ECMWF Tech. Memo. No. 620*.

ECMWF Calendar 2011

October 3 – 5	Scientific Advisory Committee (*40th Session*)
October 6 – 7	Technical Advisory Committee (*43rd Session*)
October 10 – 14	Training Course – Use and interpretation of ECMWF products for WMO Members
October 10 – 11	Finance Committee (*89th Session*)
October 12 – 13	Policy Advisory Committee (*32nd Session*)
October 17	Advisory Committee of Co-operating States (*17th Session*)
October 19	RMetS/EMS meeting on 'Why aerosols matter: Advances in observations, modelling and understanding impacts'
October 25 – 26	Large Tape User Group
October 31 – November 4	13th Workshop on 'Meteorological operational systems'
November 8 – 10	Workshop on 'Diurnal cycles and the stable atmospheric boundary layer (GABLS)'
December 6 – 7	Council (*76th Session*)

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Technical Memoranda

647 **Lopez, P., G-H. Ryu, B.-J. Sohn, L. Davies, C. Jakob & P. Bauer:** Specification of rain guage representativity error for data assimilation. *June 2011*

643 **Peubey, C., W. Bell, P. Bauer & S. Di Michele:** A study on the spectral and radiometric specifications of a Post-EPS Microwave Imaging Mission. *May 2011*

ERA Report Series

12 **Berrisford, P., P. Kållberg, S. Kobayashi, D. Dee, S. Uppala, A.J. Simmons, P. Poli & H. Sato:** Atmospheric conservation properties in ERA-Interim. *June 2011*

Proceedings

ECMWF Workshop on Non-hydrostatic Modelling, *8–10 November 2010*

Index of newsletter articles

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