ECMWF Newsletter

Number 149 – Autumn 2016

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

www.ecmwf.int/en/about/news-centre/media-resources

CONTENTS

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 The *ECMWF Newsletter* is not peer-reviewed.

Editor: Georg Lentze

Typesetting and Graphics: Anabel Bowen with the assistance of Simon Witter

Cover image: Artist's impression of Jason-3 satellite (© EUMETSAT)

Any queries about the content or distribution of the *ECMWF Newsletter* should be sent to Georg.Lentze@ecmwf.int

Guidance about submitting an article is available at www.ecmwf.int/en/about/news-centre/media-resources

CONTACTING ECMWF

Shinfield Park, Reading, Berkshire RG2 9AX, UK

Fax:		+44 118 986 9450
Telephone:	National	0118 949 9000
	International	+44 118 949 9000
ECMWF website:		www.ecmwf.int

Observing the planet

On 12 September, ECMWF used the opportunity provided by the Annual Meeting of the European Meteorological Society (EMS) in Trieste, Italy, to launch its next ten-year Strategy among colleagues from the weather community. The Centre's strategic goals now include ensemble forecasts at a horizontal resolution of 5 km and a better representation of Earth system processes both in modelling and in data assimilation. High-quality observations of the atmosphere, the land, the ocean, sea ice and atmospheric composition will be critical to achieving these goals.

First and foremost, observations are the main ingredient of data assimilation, the process of combining observational data with dynamical and physical information contained in our numerical models. The resulting analysis is then used to initialise our weather forecasts, the wave and ocean forecasts associated with them, and, as part of the EU-funded Copernicus programme, our flood and atmospheric composition forecasts. But the role and impact of observations does not stop there. They are also used in our reanalysis of the atmosphere over the past few decades, and they form the basis of verification and diagnostic work. As such, they help to document the model's quality and its deficiencies. They are therefore also at the heart of model improvement.

Over the life of our Strategy, we expect to see exciting developments, including the first hyperspectral instruments in geostationary orbit and EUMETSAT's Second Generation Polar System in Low Earth Orbit. They will bring new and improved instruments and will strengthen the core microwave sounding capability. These programmes as well as the next-generation US system, JPSS, and the evolving Chinese programme, Feng Yun, together with exciting technology and science demonstration missions such as ADM-Aeolus and EarthCARE, will all support the implementation of our new Strategy.

A very large part of our observations comes from satellites, and ECMWF greatly benefits from its close relationship with EUMETSAT and other space agencies, such as the European Space Agency (ESA) and the China Meteorological Administration (CMA). However, conventional observations also play a key role at ECMWF. The Centre is heavily involved in monitoring the Global Observing System (GOS), in particular through WMO and EUMETNET activities. Monitoring the GOS enables us to understand the role of the various components of this system in the analysis and in forecast quality. It also helps us to detect possible deteriorations, which enables us to give feedback to observation providers for the benefit of the community.

As we look ahead to the future of observations and how they will help us improve our predictions, we cannot ignore the present: the ten years in orbit of EUMETSAT's MetOp-A satellite, which has brought critical improvements to meteorology, well deserve to be celebrated!

A very exciting decade lies ahead of us, in which we expect to see a further deepening of the close partnership between ECMWF and the various actors involved in the Global Observing System.

Florence Rabier
Director-General

Météo-France hosts OpenIFS workshop

GLENN CARVER, SÁNDOR KERTÉSZ, FILIP VÁŇA (all ECMWF) FRÉDÉRIC FERRY, ETIENNE CHABOT (both École Nationale de la Météorologie)

An OpenIFS workshop dedicated to interpreting ensemble forecasts took place at Météo-France's École Nationale de la Météorologie (ENM) in the city of Toulouse from 7 to 9 June 2016. The OpenIFS programme at ECMWF provides a supported version of the operational Integrated Forecasting System (IFS) under licence to national meteorological and hydrological services, research institutes and universities. OpenIFS encourages and promotes research, teaching and training on numerical weather prediction (NWP) and NWP-related topics. An important part of this activity is scientific outreach represented by the annual workshop held in institutions of ECMWF Member States. In previous years, the workshop has been organised by the universities of Helsinki, Stockholm and Oxford and has been open to all users of OpenIFS. This year the workshop was held solely for ENM students at the invitation of ENM staff.

OpenIFS workshop 2016. Twenty-two postgraduate students from Météo-France's École Nationale de la Météorologie took part in the workshop. *(Photo: Sébastien Laflorencie)*

École Nationale de la Météorologie

L'École Nationale de la Météorologie is a department of the French national meteorological service, Météo-France, dedicated to providing higher education and professional training in meteorology, climate and related sciences. It delivers undergraduate, graduate and postgraduate courses. ENM is part of a larger campus in Toulouse, unique in Europe, which brings together the Météo-France operational branches of forecasting, observation, IT, business, climatology, research and training, together with the European Centre for Advanced Research and Training in Scientific Computing (CERFACS) and the French National Centre for Hydrometeorology and Support for Flood Forecasting (SCHAPI). There are 30 to 40 masters students per year and they follow a three-year course in atmospheric physics, dynamic meteorology, climate dynamics, hydrology and oceanography, numerical weather prediction, computer science, statistics and data processing.

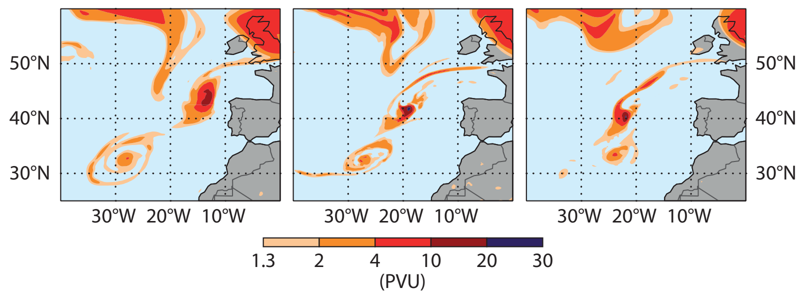
The approach taken for this year's OpenIFS workshop was to work exclusively with ENM staff and develop a case study for their students to analyse using the same pedagogical approach and tools successfully used in previous workshops.

Hurricane Nadine during HyMeX

The topic for this workshop was the use of operational ECMWF ensemble forecasts during the HyMeX (Hydrological cycle in Mediterranean experiment) observational campaign in September 2012. As discussed in an article by *Pantillon et al.* in *Q.J.R. Meteorol. Soc.* 142 (2016), the presence of Hurricane Nadine in the Atlantic at this time caused high uncertainty for ensemble forecasts at medium range for the north-western Mediterranean. This presented the opportunity to create an interesting case for the students to study by applying ensemble products to the real-world task of forecasting for flight planning during the campaign.

The workshop started with keynote presentations to introduce the topic: Véronique Ducrocq, as chair of the Executive Committee for Implementation and Science Coordination of HyMeX and head of the Groupe de Météorologie de Moyenne Echelle (GMME) at the CNRM (Météo-France's National Centre for Meteorological Research), spoke about the HyMeX field campaign; Jean-Pierre Chaboureau (Laboratoire d'Aérologie, University of Toulouse/ French National Centre for Scientific Research) described the impact of Hurricane Nadine; François Bouttier (CNRM/GMME) talked about the new pre-operational ensemble prediction system at convective scale based on the AROME-France model (2.5 km horizontal resolution, 12 members).

The ECMWF operational ensemble forecast of 20 September produced a bifurcation in the ensemble spread downstream of Nadine, causing difficulties in planning flights to intercept precipitation events for the first special observation period (SOP1) during HyMeX. Key to understanding the ensemble spread was the predicted separation between Nadine and an Atlantic cutoff at their closest point; distances above 1,000 km produced the observed case of weak interaction between the vortices, resulting in strong precipitation over the Cevennes, France; below 1,000 km produced strong interaction in the forecast and little or no precipitation over southern France.



Potential vorticity plots. Charts of potential vorticity at 320 K showing a single forecast from the ensemble representing the observed weak interaction case between Hurricane Nadine and the Atlantic cut-off low (left), a single forecast representing the strong interaction case (right), and the verifying analysis (middle).

The forecast of 20 September was just three days before IOP6 (Intensive Observation Period number 6) during HyMeX SOP1. A strong mesoscale convective system crossed south-eastern France during the night from 23 to 24 September, then northern Italy during 24 September 2012 in the morning and afternoon.

Case study exercises

Hands-on exercises were created using ECMWF analyses and forecasts from 20 September. To make the workshop more interesting, the event was reforecast using the 2016 operational ensemble system, a resolution improvement of 18 km from the 36 km of the operational ensemble in 2012 (but using the original analysis and members of the Ensemble of Data Assimilations). The students were given a series of tasks to first understand the synoptic situation by looking at the analyses, then the HRES deterministic forecast of the event from September 2012, followed by studying the ensembles from 2012 and then the 2016 reforecast. Specially written Metview macros allowed the students to explore the datasets by animating their choice of parameters, plotting ensemble products such as ensemble spread, stamp maps and so on. A gallery of the various plotting tasks can be found at https://software.ecmwf.int/wiki/display/OIFS/Workshop+gallery.

The students could also construct clusters of the ensemble members from the 2012 and 2016 ensemble forecasts. The aim of clustering is to identify the two (or more) main forecast scenarios, in this case intense precipitation or no intense precipitation over south-eastern France. With clustering, the bifurcation in the forecast becomes more evident by plotting, for example, ensemble spread separately for each cluster. The students were first asked to choose and plot their own clusters by manually selecting the most appropriate members from their choice of parameter. They then used Metview to compute a principal component analysis (PCA) on the 500 hPa ensemble output at 00 UTC on 24 September and compare their own derived clusters with those from the PCA. The exercises and Metview macros were designed so that the students could choose different parameters and dates to create the clusters, allowing them to see how the bifurcation in the forecast was related to the time of the closest approach between Nadine and the cut-off low.

The forecasting instructor Etienne Chabot (ENM), who was the forecaster on duty for HyMeX SOP1 at the time, challenged the students to realise the same forecast that he personally made for the IOP6. Using the forecast products (convection-parametrized models only) they could understand the difficulty of helping a scientific manager to take a binary decision on whether or not to give the go-ahead for an aircraft research flight. The students had to assess statistical ensemble products such as quantiles, probabilities, ‘spaghettis’, stamp maps, and using clustering, to try to estimate the uncertainty of their forecast in terms of intensity, localisation and chronology. The students were asked to explore and compare the 2012 and 2016 operational ensembles to look at the improvements the new ensemble made and how decisions for flight planning for the HyMeX SOP1 would have been impacted.

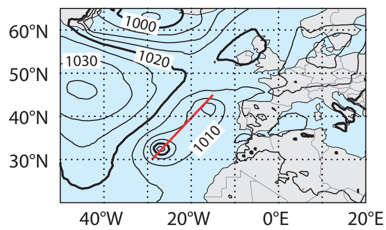
A novel aspect of the OpenIFS workshops is the use of the Metview/OpenIFS virtual machine (VM). It incorporates a fully functional Linux desktop that will run on any host operating system and includes all the required software and forecast data used in the workshop. The VM is ideal for workshops run remotely from ECMWF, as all the development and testing can be done in-house at ECMWF, knowing the students will be using the same system in their classroom.

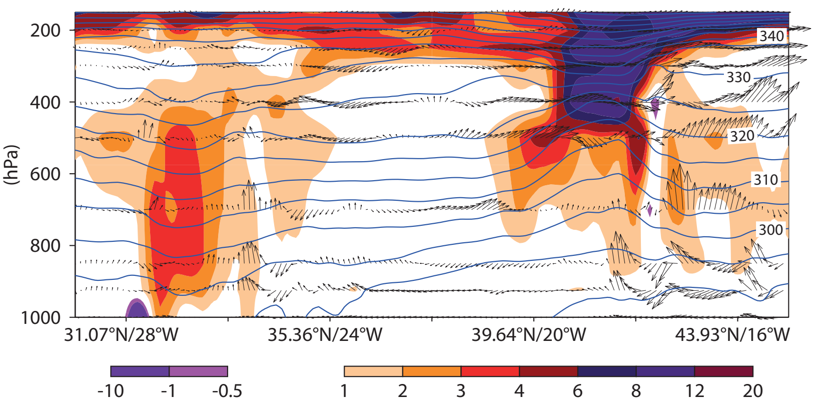
Feedback and outlook

The workshop was a great success and both the students and the tutors enjoyed it. The students were completing a course on ensemble forecasting, and this workshop complemented and increased their understanding of the use of ensembles in real-world forecasting. Some found using OpenIFS ensemble forecasts for a ‘real-world’ case study more useful than the ‘traditional’ courses! The students liked the ease of exploring ideas with the datasets using Metview. Another enjoyable aspect was the mix of French and English teaching. ENM staff have expressed a desire to repeat this workshop in collaboration with ECMWF for their students in the future.

The success of the workshop was due to the contributions and support of many people, including in particular Linus Magnusson at ECMWF and Thierry Barthet and David Pollack at ENM.

We look forward to the next OpenIFS general user meeting in Trieste, Italy, in June 2017.





Cross-sectional view. Cross-section through the approximate centres of Hurricane Nadine and the cut-off low, showing potential temperature (in Kelvin – contours), potential vorticity (shading), and three-dimensional wind projected onto the plane of the cross-section (arrows). The chart illustrates the different nature of the two weather systems: the warm core of Hurricane Nadine (left) and the cold tilted core of the Atlantic cut-off low (right). The red line in the small map of mean sea level pressure shows the position of the cross-section in the analysis of 22 September 2012 00 UTC.

Predicting heavy rainfall in China

LINUS MAGNUSSON,
THOMAS HAIDEN

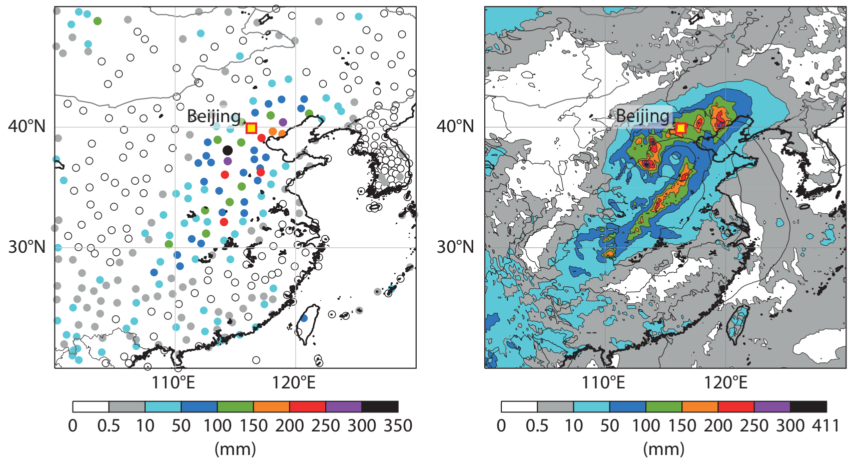
On 19 and 20 July, severe rainfall hit central and north-eastern China. ECMWF's forecasts three to five days ahead of the event performed reasonably well, but the quality of earlier forecasts was geographically uneven.

The rainfall was connected to a low pressure system that formed over southern China and moved northward. The cyclone generally resulted in more than 50 mm of rain in 48 hours along its way, with some stations in central China receiving more than 200 mm. Further north, the precipitation in Beijing reached almost 300 mm over the two days, but local variations were large. ECMWF's high-resolution forecast (HRES) from 19 July 00 UTC predicted rainfall in excess of 300 mm locally south-west of Beijing in the first two forecast days, which shows that the forecast system is capable of simulating such extreme rainfall, although one should not expect it to capture the exact location of the extremes.

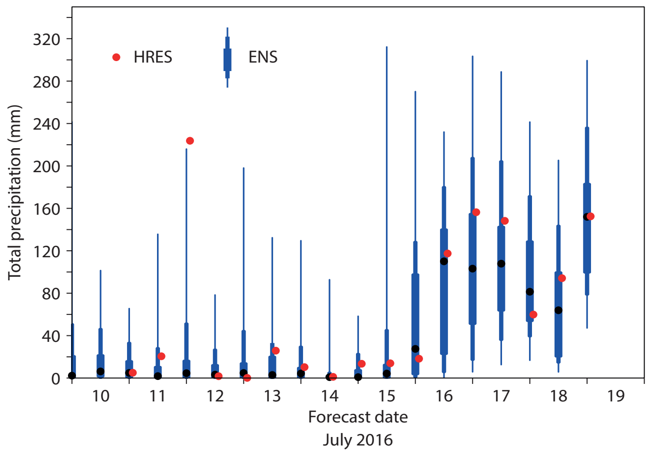
In the last forecast before the start of the accumulation period, the HRES and ensemble forecast (ENS) median gave around 150 mm for a grid point in Beijing. Ensemble members ranged from 50 to 300 mm, which indicates a large uncertainty in the local severity even in the shortest forecasts. Looking at earlier forecasts, a risk of 25% or higher for more than 100 mm was predicted by ENS from 16 July onwards, which corresponds to a forecast range of 3–5 days.

In forecasts produced before 16 July, the southern part of the rainfall was captured well, but the extension to the north, where the most severe rainfall occurred, was missed. This is apparent when we compare EFI (Extreme Forecast Index) and SOT (Shift of Tails) values for 3-day accumulated rainfall (19–21 July) in the forecasts from 15 and 19 July.

This event was one of several episodes of extreme rainfall in China this summer. At the beginning of July, central China was hit by severe rainfall that resulted in flooding of the Yangtze River. In this case, the short-range (1–2 days) ECMWF forecasts placed the rainfall somewhat too far north. Although the location error was only in the order of 100 km, it was big enough to have presented a substantial challenge to forecasters trying to predict rainfall levels for specific river catchments.



Observations and short-range forecasts. Forty-eight-hour observed precipitation 19 July 00 UTC to 21 July 00 UTC from SYNOP observations (left) and predicted 48-hour precipitation from the HRES issued 19 July 00 UTC (shading) together with mean sea-level pressure (contours) valid 20 July 00 UTC (right).

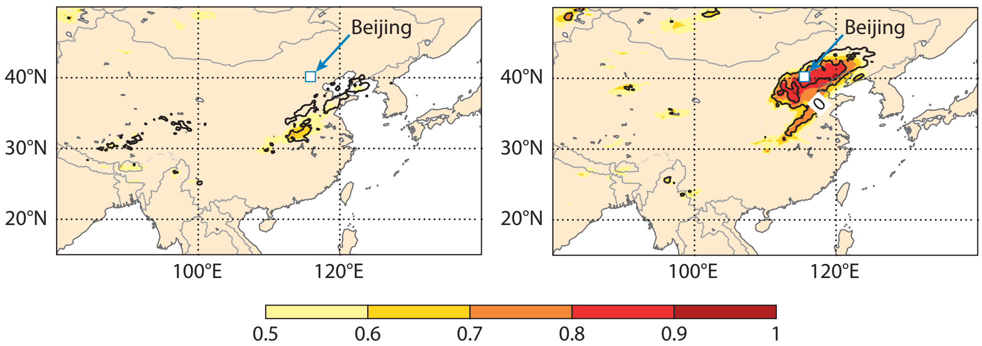


Ensemble and high-resolution forecasts. ENS and HRES 48-hour precipitation at a grid point in Beijing valid 19 July 00 UTC to 21 July 00 UTC for a range of starting dates. Black dots in the box-and-whisker plot represent the ENS median, the wide boxes represent the 25th and 75th percentile, the narrower boxes represent the 10th and 90th percentile, and the vertical lines show minimum and maximum values.

Cooperation agreement

In 2014 ECMWF concluded a cooperation agreement with the China Meteorological Administration (CMA). Their local knowledge and the availability of high-density observations will help us to better assess and understand the performance of our forecasts. One of the areas of cooperation will be the evaluation of ECMWF's forecasts in China using high-density observational datasets. This will enable ECMWF to obtain more detailed results on model performance in this area.

If insights gained from these studies lead to improved forecasts in the region, then that will not only be of importance for forecasters in China but may also be beneficial for Europe. Forecast errors can propagate with the group velocity of Rossby waves, so that initial and short-range errors



Extreme Forecast Index and Shift of Tails. EFI (shading) and SOT (contours) for 3-day precipitation (19–22 July) from 15 July (left) and 19 July (right).

originating in the area of China could reach Europe eight to ten days into the forecast. Therefore, one of many ingredients for achieving ECMWF's strategic goal of predicting risks of extreme weather over Europe two weeks in advance may be improved analysis and forecast performance over South-East Asia.

Other recent events

On 6 August, Skopje, the capital of the former Yugoslav Republic of Macedonia, was hit by severe flash floods that killed at least 21 people. The location of this event was not well predicted by ECMWF's forecasts.

In the second week of August, the US state of Louisiana was hit by severe rainfall over a period of three to four days. The large-scale features of this event were well predicted around a week in advance, while capturing the local details was a challenge even in the shortest-range forecasts due to its convective nature.

Evaluations of all the events mentioned in this article can be found in the ECMWF Severe Event Catalogue at https://software.ecmwf.int/wiki/display/FCST/Severe+Event+Catalogue.

ECMWF makes S2S forecast charts available

LAURA FERRANTI, FRÉDÉRIC VITART, SYLVIE LAMY-THÉPAUT, MANUEL FUENTES

ECMWF has begun to make a new range of forecast charts based on the Sub-seasonal to Seasonal predictions (S2S) database available to the public, at www.ecmwf.int/en/research/projects/s2s/charts/s2s/.

The charts can be used to monitor the S2S data and assess the quality of the forecasts. They can also serve as a testbed for the development of new products, for example by helping to identify signals for extreme events at the sub-seasonal timescale. The charts include ensemble mean anomalies for a range of meteorological parameters, the Extreme Forecast Index (EFI) for 2-metre temperature, and forecasts of the Madden–Julian Oscillation (MJO). Since S2S is a research project, the forecasts are available with a three-week delay. They are not intended for operational use.

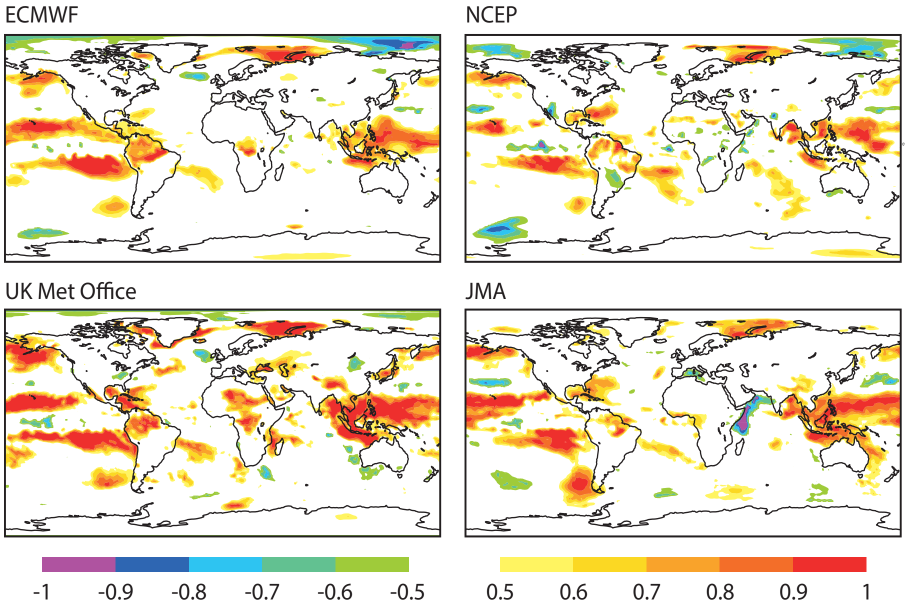
Currently the S2S charts are limited to six models. In future all 11 S2S models will be included and the range of products will be extended. Some centres produce their sub-seasonal forecasts on a daily basis while others produce theirs on a weekly basis. The horizontal and vertical resolution of the models and the ensemble size also vary greatly from one centre to another, and the forecasts cover a different number of years. Constructing products from very different forecasting systems is a challenge.

In order to make the products comparable, we use the largest common period available (1999–2010) to estimate the model climate. Forecast products are issued once a week (every Thursday) to keep the number of charts to a minimum. Forecasts produced on a daily basis typically have a small ensemble size, but it is possible to construct a larger ensemble by pulling together forecast ensembles initiated on a number of subsequent days. How many daily ensembles should be included in one larger ensemble depends mainly on the forecast application. In order to keep product generation simple, we consider only the ensemble initiated on Thursdays.

The S2S chart web page contains charts for all forecasts since January 2016. Every week new forecasts are added to the list. With this forecast history it is possible to evaluate forecast performance for specific events (e.g. heat waves and wet spells); analyse consistency between different models; and test the benefits of a multi-model approach.

The S2S project

The Sub-seasonal to Seasonal prediction project (S2S), launched by the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP), aims to improve forecast skill and understanding of the sub-seasonal to seasonal timescale and to promote its uptake by operational centres and its exploitation by the applications community. As part of this project, ECMWF is hosting a data portal for S2S forecasts containing near-real-time ensemble forecasts and re-forecasts up to 60 days from ten forecasting centres (11 by the end of 2016). Most of the forecasts are created by a coupled system (an atmospheric model coupled to an ocean model), and some include an active sea-ice model. For more information, visit http://www.s2sprediction.net.



Extreme Forecast Index charts. The charts show the Extreme Forecast Index (EFI) for 2-metre temperature from 28 July 2016 for the week starting 8 August, from ECMWF, the US National Centers for Environmental Prediction (NCEP), the UK Met Office, and the Japan Meteorological Agency (JMA). The EFI is an integral measure of the difference between the ensemble forecast distribution and the model climate distribution. The forecasts shown here broadly agree on warm temperature extremes over parts of the Pacific, the Maritime Continent, the Caribbean, the Amazon basin and the Barents Sea, while there is less of a consensus on extremes over Africa and the Indian Ocean.

Graduate trainees enjoyed their time at ECMWF

Two scientists who completed their two-year graduate traineeships at ECMWF in September say they thoroughly enjoyed the experience. Sinéad Duffy, who was based in the Forecast Department, has now returned to the Irish National Meteorological Service, Met Éireann, while Jacky Goddard has taken on a new role in the Research Department. Here are their accounts of their time as graduate trainees.

Jacky Goddard and Sinéad Duffy. Jacky (left) and Sinéad liked the interaction with scientists from many different nations during their traineeships.

SINÉAD DUFFY

I joined the Forecast Department in September 2014 to work on the verification of surface weather parameters using high-density observations from ECMWF's Member and Co-operating States. I came from Met Éireann, where I worked as a meteorological officer after completing an MSc in Meteorology at University College Dublin. However, I had never worked in the area of forecast verification before.

Over the past two years, my experience with ECMWF has been very positive. It has been wonderful to work with people from so many nations. Colleagues have been extremely helpful and generous with both their time and knowledge. In-house courses familiarised me with ECMWF models, the MARS meteorological archive, computing facilities and tools.

Throughout my time here, I have attended numerous workshops, seminars and lectures given by ECMWF scientists or visiting speakers. The Friday weather discussions open to all staff have been a wonderful weekly overview of the performance of ECMWF's forecasts and issues reported by Member and Co-operating States, and they have provided informative analysis of interesting weather across the world.

Whilst at ECMWF, I have presented my work at a European conference and contributed to Newsletter articles. I will return to Met Éireann in Dublin with much broader knowledge of ECMWF's models, forecast verification and weather in Europe and around the globe.

JACKY GODDARD

I joined the Data Assimilation Methodology team at ECMWF in October 2014 immediately after completing a PhD in Numerical Methods at Exeter University. Having had no previous experience in data assimilation, I had a steep learning curve initially.

Fortunately I was able to benefit from ECMWF's training programme in numerical weather prediction, which includes courses on Data Assimilation and ECMWF/EUMETSAT NWP-SAF Satellite Data Assimilation.

I have thoroughly enjoyed working with a very experienced and talented team of scientists, who were always happy to sit down and discuss my work or help with any problem, however basic or time consuming. The lecture series 'An Introduction to Meteorology' was also of great use to me, having come from a mathematical background.

During my time here, I have given talks at international workshops, contributed to special topic papers presented to ECMWF's Scientific Advisory Committee, and helped to make a contribution to the next operational cycle. The training and experience provided to me at ECMWF has also enabled me to apply and be selected for a new position in the Earth System Assimilation Section. I have really enjoyed and benefited from working at ECMWF with colleagues from very diverse backgrounds, both academically and culturally.

ECMWF's Graduate Training Programme

The goal of ECMWF's Graduate Training Programme is to provide training at an advanced level for recent graduates at a leading research and operational organisation in an international environment. The idea is to contribute to the European pool of well-qualified young professionals in modelling and data assimilation for numerical weather prediction, meteorological operations and large-scale computing support.

Applicants must be a national of a Member or Co-operating State and should normally come from national meteorological services, universities or research institutes in Member or Co-operating States. They must have the support of their national meteorological service. Traineeships are normally awarded for an initial period of one year with the possibility of an extension for a further year.

Copernicus Climate Change Service tracks record global temperatures

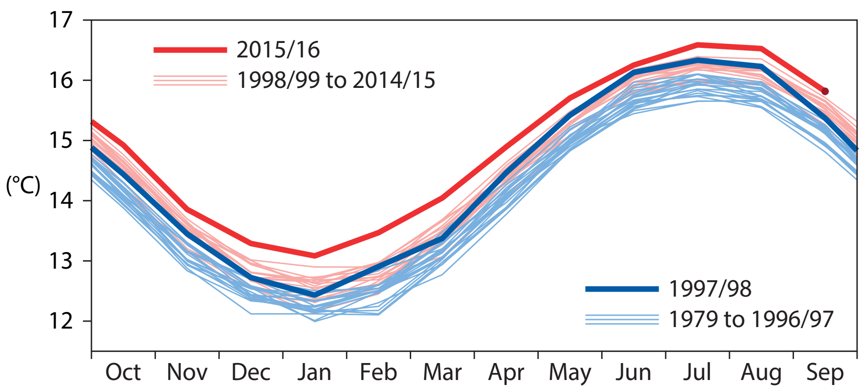
ADRIAN SIMMONS

The Copernicus Climate Change Service that is being implemented by ECMWF on behalf of the European Commission has tracked a period of record global warmth in the temperature summaries it has published monthly since August 2015.

The globally averaged surface air temperature usually peaks in July, when the land masses of the northern hemisphere are generally at their warmest. It varies by more than 3°C over the course of each year. The largest recent deviation from this annual cycle occurred in February 2016, when the global temperature was more than 0.8°C higher than the 1981–2010 average for February. The differences have since narrowed, but July 2016 was still more than 0.5°C warmer than the corresponding average for July. This was sufficient to make July 2016 the warmest month on record in absolute terms. August 2016 was not quite as warm as July 2016 but still ended up as the second warmest month on record.

The global temperature for each of the twelve months from October 2015 to September 2016 exceeded the highest value previously recorded for that particular month. This came close to happening earlier, for the months from October 1997 to September 1998. Both twelve-month periods were characterised by pronounced El Niño events. The earlier event was for the most part a little stronger over the tropical Pacific Ocean, but air temperatures were generally higher during the latest event because of the overall progression of global warming. Lower Arctic sea-ice extent in 2016 was also a factor behind the larger temperature differences seen during the northern winter months.

The values published by the Copernicus Climate Change Service are based on ECMWF's ERA-Interim reanalysis, which runs from 1979 onwards. They are in essence confirmed by values derived from the Japan Meteorological Agency's JRA-55 reanalysis. Early results from ERA5, a new ECMWF/Copernicus reanalysis that is currently in production, show local improvements over ERA-Interim but similar global averages. Longer-term context is provided by conventional analyses such as HadCRUT4, produced collaboratively by the Met Office and the Climatic Research Unit of the University of East Anglia. Extending back to 1850, HadCRUT4 shows no month prior to 1979 that was as anomalously warm globally as the months from 1997 onwards.



Global temperatures. Monthly global-mean surface air temperature from January 1979 to September 2016. The 12-month periods ending in September 1998 and September 2016, represented by the bold blue and red curves, coincided with strong El Niño events. Based on ERA-Interim data processed as described at http://climate.copernicus.eu.

Experts discuss role of drag processes in NWP and climate models

IRINA SANDU, AYRTON ZADRA
(Environment Canada)

The workshop on 'Drag processes and their links to the large-scale circulation', organised jointly by ECMWF, the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP), was held at ECMWF from 12 to 15 September. Despite their importance for the large-scale circulation, to date the representation of drag processes remains a major source of uncertainty in global models. 'Drag' refers to the effects of friction on atmospheric flow caused by elements of the land surface, ocean waves, orography and the breaking of mountain-induced gravity waves.

The workshop aimed to assess the current state of our understanding of drag processes and their impact on the large-scale circulation on timescales from synoptic to seasonal and climate timescales. The workshop also aimed to review how these processes are represented in global models; discuss and sharpen the research challenges to be overcome in order to achieve substantial advances in this area; foster collaborations; and stimulate further research. The idea of organising this workshop partially stemmed from the WGNE (WMO Working Group on Numerical Experimentation) 'Drag project', which demonstrated that the main NWP and climate models differ significantly both in the representation of total surface stress (or friction), particularly in regions with orography, and in the partitioning of surface stress among various physical processes.

The workshop attracted about 50 participants from the main numerical weather prediction (NWP) and climate centres in Canada, France, Germany, Japan, the Netherlands, the UK and the US as well as from several universities. The participants included well-established scientists and early-career scientists, six of whom were partially supported by WMO.

Outcomes

A broad range of scientific questions were discussed through invited talks, a poster session and working group discussions. Three main themes were covered: (i) theoretical aspects of drag processes and impacts of uncertainty associated with drag processes in NWP and climate models, (ii) the representation of drag in global models (parametrizations, ancillary fields such as mean and subgrid orography etc.), and (iii) constraining drag processes through observations, reanalysis and fine-scale modelling. The working groups made numerous recommendations for further research in these areas. These include:

- Consolidate knowledge regarding the impacts of drag processes on the large-scale circulation, e.g. by reproducing results in different models, and develop a more quantitative understanding of effects of drag on aspects of circulation, such as the mean state, stationary waves, synoptic systems. Understand what level of parametrization is required to reproduce given phenomena and whether there are processes that are currently not represented in global models.
- Seek to further understand inter-model differences in surface stress, for example through the following activities: a survey regarding the ancillary files, in which all centres would provide details on corresponding databases and methods as well as samples of ancillary fields; numerical experiments aiming to better define the appropriate sub-grid scales for orographic fields as a function of the model's (effective) resolution; extending the WGNE Drag project by comparing the tendencies given by the various parametrizations in regions of maximum uncertainty, and by using relevant single-column model experiments.
- Explore the use of high-resolution simulations, which can now be performed at resolutions of a few hundred metres over large regions, to help understand the underlying processes contributing to orographic drag and to constrain the parametrizations. As surface drag

Workshop participants. The workshop was organised by Irina Sandu (ECMWF), Felix Pithan (AWI), Julio Bacmeister (NCAR), Andreas Dörnbrack (DLR), Ted Shepherd (University of Reading), Gunilla Svensson (MISU) and Ayrton Zadra (Environment Canada). It attracted about 50 participants from NWP and climate centres as well as universities across the world.

cannot be observed on large scales, this type of simulation could provide a reference estimate of surface drag that would be extremely valuable for improving the parametrizations used in global models.

- Explore new methods to identify the parametrizations responsible for model errors and devise ways of optimising poorly constrained parameters that go beyond empirical tuning. These can include initial tendency diagnostics, nudging techniques, data assimilation methods, but also a more process-level-based evaluation of the phenomena represented by the parametrizations (e.g. waves vs turbulence) or the evaluation of theoretically understood far-field responses to changes in drag.
- Make more extensive use of existing direct or indirect observations to evaluate the representation of drag processes in models. Here examples include emerging observations of momentum fluxes, gathered either in observational campaigns or at permanent supersites, and scatterometer wind data or bulk measures of drag impacts on the circulation, such as the change in wind direction throughout the boundary layer.

The workshop presentations are available on ECMWF's website at www.ecmwf.int/en/learning/workshops-and-seminars/drag-processes-and-their-links-large-scale-circulation.

ECMWF hosts Year of Polar Prediction meeting

PETER BAUER, THOMAS JUNG (AWI), KIRSTIN WERNER (AWI)

ECMWF hosted a YOPP (Year of Polar Prediction) planning meeting from 5 to 9 September 2016 with international invitees from operational centres, research institutes and universities. The meeting covered numerous national and international efforts to provide additional observations in the Arctic and to perform numerical experiments towards a concerted YOPP observation and modelling plan.

The Year of Polar Prediction is one of the highlight deliverables of the Polar Prediction Project (PPP), which is one of three projects within the World Meteorological Organization's World Weather Research Programme (WWRP). The core phase of YOPP covers two years, from mid-2017 to mid-2019. By coordinating a period of intensive observing, modelling, verification, user engagement and education activities, YOPP will enable a significant improvement in environmental prediction capabilities for the polar regions and beyond. YOPP will contribute to the knowledge base needed to manage the opportunities and risks that come with polar climate change.

As a member of the PPP steering committee, ECMWF has been strongly involved in defining the science and implementation plans of the project. With the successful APPLICATE (Advanced Prediction in Polar regions and beyond: Modelling, observing system design and LInkages associated with ArctiC ClimATE change, coordinated by Thomas Jung, Alfred Wegener Institute, Germany) research proposal to the European Commission, ECMWF will be able to support model development, impact diagnostics and observing system assessments with a particular focus on the Arctic.

The two-year YOPP time frame will include special observing periods focusing on enhancing conventional observation coverage throughout the Arctic for evaluating the impact of sustainable networks on predictability (e.g. increased frequency of radiosonde launches). YOPP field campaigns will focus on process studies that help to improve models. In particular the process coupling at the ocean–sea-ice–atmosphere interface will be tackled. Numerous field campaigns will contribute airborne, shipborne, surface and satellite datasets from a wide range of national agencies in the US, Canada, Europe, Russia and Asia, and from international institutions.

PPP, YOPP and APPLICATE aim to bring model improvements into operational systems. ECMWF's involvement through the provision of dedicated global datasets, prototype reanalyses and planning support is therefore a good investment into the future.

Additional information is available on the Polar Prediction Project website at http://www.polarprediction.net/.

YOPP meeting participants. The YOPP planning meeting brought together more than 50 people from operational centres, research institutes and universities.

ECMWF releases software for observational data

PIOTR KUCHTA

After many years of development and the successful use in operations at ECMWF and other meteorological centres, ODB API, ECMWF's software for the efficient processing of observational data, is being released to the general public under the open source licence Apache 2.0.

ODB (Observational Database) API, which has been developed with support from the UK Met Office, includes an SQL (Structured Query Language) filtering and statistics engine, command line tools and an API (application programming interface) for C/C++, Fortran and Python. It has been designed for the efficient processing of observational data archived in MARS, ECMWF's meteorological data archive system.

The ODB software developed between 1998 and 2004 proved to be highly efficient as an observational data store for the Integrated Forecasting System (IFS). An important novelty was the introduction of ODB/SQL, a subset of SQL, for observational data processing. However, the early ODB file format was not well suited for archiving.

In 2008, an Observation Handling and Monitoring Taskforce was set up in order to improve the archiving, monitoring, visualisation and diagnostics of observations. Its outcome was the design of a MARS extension for archiving observational feedback, including data layout and indexing. In addition, a data format was designed for the observational feedback archive, with unique features that make it especially useful for archiving but also for stream processing. A new implementation of the SQL processor was integrated with the library, and thus ODB API was born. Since November 2011, ODB feedback data has been archived operationally in MARS as OFB (ODB feedback) and MFB (Monitoring feedback).

Main features of ODB API

The software has been written in portable C++. It provides public APIs for C/C++, Fortran and Python. The package also contains various command line tools for working with ODB API files, including executing SQL queries to filter data or calculate statistics, examining ODB API files as well as importing and converting to other formats. The file format ODB API works with fulfils the following requirements:

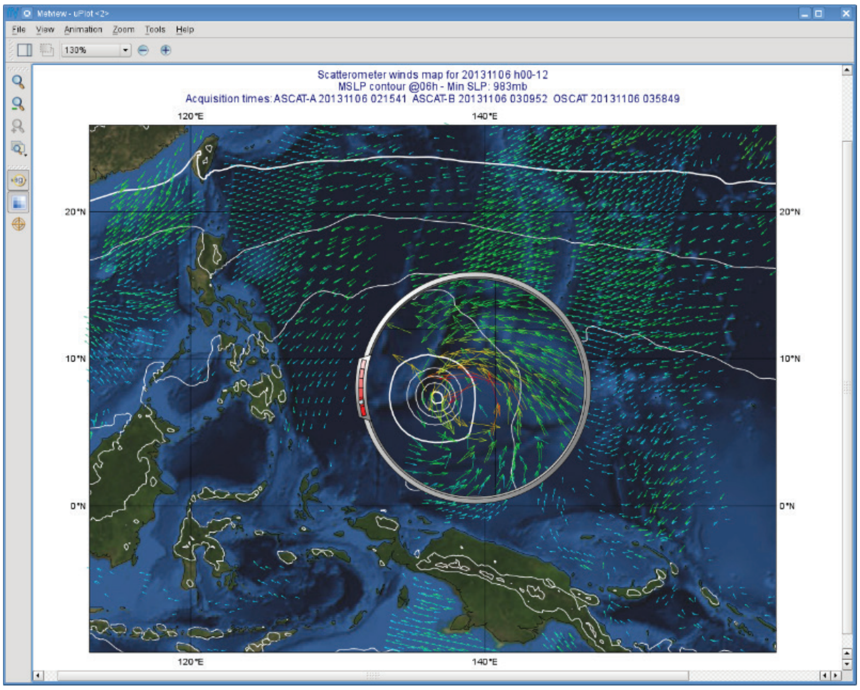
- simple, well defined, portable and machine independent
- self-described: metadata stored in files along with the data itself
- extendable: new compression algorithms and data types can be added in form of codecs
- new data can be appended to existing files
- data can be decoded in a streaming fashion to facilitate efficient processing of long times series.

Documentation and examples of using Python, Fortran and C APIs are available on the ODB API website at https://software.ecmwf.int/wiki/display/ODBAPI/ODB+API+Home.

Main uses of ODB API

ODB API is an essential tool for many scientists working at ECMWF and beyond:

- ODB feedback produced by experiments at ECMWF is archived in MARS in the ODB API format, so researchers working on scientific studies based on observations need to work with this data.
- Scientists working on reanalysis have been early adopters of ODB API, and their requirements were one of the main drivers of the ODB API design.
- ECMWF's Monitoring (OBSTAT) and Alarm system uses ODB API to calculate statistical information on the quality of observations used or monitored by ECMWF, primarily in order to improve the usage of observations within ECMWF's data assimilation system.
- The Metview desktop and the Magics data visualisation package developed at ECMWF can both read and plot observational data encoded in the ODB API format. Additionally, Metview has extensive support for examining metadata of ODB API datasets, can retrieve data directly from MARS or the ODB Server, and can execute SQL to filter datasets before plotting them.



Metview screenshot. This screenshot shows how Metview can plot observation feedback data stored in MARS, thanks to ODB API.

Survey shows MARS users broadly satisfied

CARSTEN MAASS

A recent survey shows high user satisfaction with MARS, ECMWF's Meteorological Archival and Retrieval System, while also highlighting opportunities for improvement.

MARS has been serving meteorological data to internal and external users for 30 years. To retrieve data from the archive, users primarily use the MARS client by calling the 'mars' command on an ECMWF system, e.g. the Member State server ecgate or ECMWF's high-performance computing facility. A remote version of the MARS client had been installed at some national meteorological services (NMSs), which allowed registered users to retrieve data directly to their local system. Additional web applications, such as the MARS Catalogue, an interactive browser of the entire archive content, and an online database of meteorological parameters, are available to help users to explore the archive more efficiently.

The remote MARS client has recently been replaced by a new service to retrieve and list archived MARS data via a Web API (web-based application programming interface). The Web API client is easy to install and can be used by many more external users, including fully registered computer users, self-registered web-only users from Member State NMSs, other web-only users registered by a Member State, and commercial customers.

Collecting feedback and measuring satisfaction is an ongoing activity at ECMWF. We issued the first survey of our computer users in 1999, then still on paper and distributed by post. In 2005 we conducted our first web-based user survey, which covered all computing services. Since then, we have issued further surveys, usually linked to major upgrades of computing systems or services, e.g. the migration to a new supercomputer.

Consequently, the introduction of the Web API offered a good opportunity to invite all our 7,600 external users with access to MARS to answer 38 questions about their use of and satisfaction with MARS and related services. To assess satisfaction and other aspects, we mostly asked users for a rating on a five-level scale, for example ranging from 'very satisfied' to 'very dissatisfied'. The majority of questions offered additional text boxes and a choice to answer 'N/A' (not applicable). We found that the most useful feedback came from the text boxes, where users could freely express their views and make suggestions.

Summary of results

Although the users who took part in the survey have qualifications in more than 13 disciplines and work in over eight types of organisation in 50 countries, a typical respondent can probably be characterised as a meteorologist with a permanent position at an NMS, who has been an ECMWF user for more than three years, uses MARS occasionally or as needed, enjoys access to the Member State server ecgate, and has access to real-time data.

Overall, 84% of respondents are either satisfied or very satisfied with the archive content. Historical operational data are most important to them, followed by the ERA-Interim climate reanalysis and real-time operational data. The established WMO formats GRIB and BUFR are their preferred formats for fields and observations. Users who prefer fields in NetCDF format seem happy to convert the data themselves. A few users would like to see all fields offered in GRIB 2 format.

Over 90% of active users are satisfied or very satisfied with the MARS client. They appreciate in particular its high availability, functionality, and user support. The client's data handling and computing capabilities make it the most used tool on ECMWF platforms to manipulate already retrieved data.

ECMWF's MARS team receives EMS Technology Achievement Award

The team in charge of MARS received the European Meteorological Society (EMS) Technology Achievement Award 2016 in the Italian city of Trieste on 13 September.

The award seeks to recognise influential technological achievements in meteorology and related areas.

EMS President Horst Böttger presented the certificate to the MARS team's senior members Manuel Fuentes (left) and Baudouin Raoult (right) during the Society's Annual Meeting.

"MARS constitutes a unique approach to meteorological data storage and retrieval technology that has had and still has a huge impact on developments in many organisations by making vast quantities of meteorological data accessible to thousands of organisations and individuals," Dr Böttger said in the award letter.

ECMWF's MARS team emphasised that developing the system has been and continues to be a collaborative enterprise.

"It is an honour for us to collect this award on behalf of the many colleagues who have helped to make MARS such a successful system," Manuel Fuentes said.

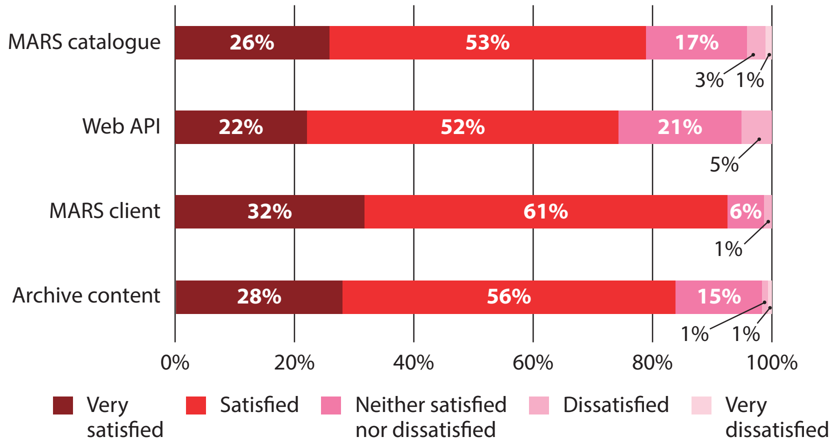
MARS is the first project to receive the award, together with the Distributed 'real-time' Environmental Measuring System developed at the Slovenian Environment Agency.

The satisfaction of active users with the Web API client is somewhat lower, with 74% being satisfied or very satisfied. Further analysis indicates that many users with access to both clients rate the functionality and speed of the MARS client higher compared to the Web API. Of course, when interpreting the results one needs to take into account the wide variety of respondents and the limited experience they could gain with the Web API, as this service is still fairly new.

Some users are not fully satisfied with the web-based MARS catalogue, parameter database, and documentation, reporting difficulties in finding data, descriptions of parameters, and information on the availability of parameters. This can partly be interpreted as a result of web usability issues with the migration to our current websites.

We would like to thank all users who participated in this survey. The feedback given provides us with valuable guidance on how to address our users' needs and further improve the services offered to them.

Full survey results and more details on this and other surveys can be found in our Confluence wiki at http://software.ecmwf.int/wiki/display/UDOC/User+Surveys.



Survey results. Rating distribution of overall user satisfaction with different MARS services and the archive content.

Supercomputing project reviews performance analysis tools

ANTONINO BONANNI, TIAGO QUINTINO, SIMON SMART

ECMWF hosted a Performance Analysis Workshop organised as part of the NEXTGenIO supercomputing project on 19 and 20 September 2016. Developers from Allinea and Technische Universität Dresden (TUD) reviewed fundamental concepts of software performance analysis and presented their tools and the latest features developed within the project. Real-life applications were used to demonstrate multiple techniques for finding and resolving performance issues.

The participants came from other project partner organisations, such as Intel, Fujitsu, the Edinburgh Supercomputing Centre (EPCC) and ECMWF.

The NEXTGenIO project is an EU-funded Horizon 2020 project, coordinated by EPCC, which will run until 2018 and will feed into ECMWF's Scalability Programme. It aims to develop innovative solutions to tackle the I/O bottlenecks that will become limiting as high-performance computing moves towards the exascale. The use of performance analysis tools, and the extension of these tools to provide better feedback about I/O behaviour, is a critical component of this process.

Group photo. Participants at the Performance Analysis Workshop.

The participants were able to review the main concepts of performance analysis and best practice for code debugging and optimisation. Allinea began by presenting the main features of their debugger DDT and their profiling tool MAP. TUD followed up with presentations on their toolset, including Score-P, Vampir and Cube. A hands-on session followed in the afternoon, where all participants had an opportunity to apply these tools to realistic scenarios.

The second day of the workshop focused on how Allinea's and TUD's tools can be used for workload characterisation, and was more specifically focussed on the needs of the NEXTGenIO project. Both Allinea and TUD presented pre-release functionality that is under development as part of the project. This provided a valuable opportunity to discuss these novel features in person, and share ideas for addressing NEXTGenIO challenges.

ANYWHERE and IMPREX hold general assemblies

DAVID LAVERS, FLORIAN PAPPENBERGER, PAUL SMITH, DAVID RICHARDSON, LINUS MAGNUSSON, LOUISE ARNAL, ESTIBALIZ GASCON

In September 2016, two EU Horizon 2020-funded projects in which ECMWF is a partner held their annual general assemblies. The first ANYWHERE (EnhANcing emergencY management and response to extreme WeatHER and climate Events) general assembly took place from 5 to 7 September in Genoa, Italy; and the IMPREX (IMproving PRedictions and management of hydrological EXtremes) general assembly was held in Chania on the Greek island of Crete from 26 to 28 September.

The main objective of ANYWHERE is to implement a pan-European multi-hazard platform and associated decision support tools. These are intended to provide emergency responders and managers of sites at risk with better identification and awareness, in time and space, of expected weather-induced impacts and potential mitigations.

IMPREX's aim is to improve society's ability to anticipate and respond to future hydrological extreme events (such as floods and droughts) in Europe. It will enhance the forecast quality of extreme hydro-meteorological conditions and their impacts. ANYWHERE and IMPREX are complementary projects. Both aim to improve the skill and operational uptake of forecasts of high-impact weather or climate events to facilitate better risk management in exposed communities.

The ANYWHERE meeting was held in the Palazzo Ducale in Genoa and brought together about 75 scientists and users from across the 31 partner institutions. A mixture of presentations and round-table sessions helped stimulate ideas and discussions on the best approaches to transferring and presenting environmental forecast information on a multi-hazard decision support platform. Project partners from the civil protection and commercial spheres will test the platform in operational conditions in five sites across Europe that experience multiple natural hazards (e.g. the Liguria region of Italy). These hazards include wildfires, drought, flash and coastal flooding and extreme meteorological events.

ANYWHERE general assembly. The meeting took place in the Palazzo Ducale in Genoa.

IMPREX general assembly. ECMWF scientist Linus Magnusson (front left) discussed data management at the IMPREX meeting.

IMPREX's general assembly was attended by 60 scientists from 23 partner institutions across Europe. IMPREX has a number of case study regions, such as the Jucar and Segura river basins in Spain and the Messara region in Greece, where the stakeholders tasked with managing water resources are exploring the use of ECMWF seasonal forecasts. Further presentations and discussions centred on the European hydrological risk outlook, data flow amongst project partners, and progress in each of the 13 work packages.

ECMWF's role

A key responsibility of ECMWF in these projects is to provide the project partners with relevant forecast output from ECMWF and the Copernicus Emergency Management Service. This output includes medium-range forecasts and re-forecasts and seasonal forecasts.

In IMPREX, ECMWF's role also includes developing and maintaining the project data management plan, thus facilitating the dissemination process between all data providers and users. In addition, ECMWF is contributing to the seasonal hydrological risk outlooks; verification practices including those of the European Flood Awareness System (EFAS); and seasonal hydrological forecasts. It is also investigating ways to improve medium-range and sub-seasonal predictions of extreme hydrological events in Europe.

ECMWF will benefit from these projects since they are likely to open up future opportunities for research and the exploitation of its forecasts. ECMWF will host the next ANYWHERE and IMPREX project meetings planned for March 2017 and May/June 2017, respectively.

More information can be found on the project websites at http://www.anywhere-h2020.eu/ and http://www.imprex.eu/.

doi:10.21957/m2cx1w

The use of radar altimeter products at ECMWF

SALEH ABDALLA, HAO ZUO

Radar altimeters are satellite instruments which probe the Earth's surface by emitting a series of electromagnetic pulses and measuring their reflections. The measurements are used to derive information on near-surface wind speed over the oceans, mean sea level, and ocean wave height. Observation capabilities have recently been boosted by the launch of two new satellites carrying radar altimeters: Jason-3 (January 2016) and Sentinel-3A (February 2016).

ECMWF uses radar altimeter products both to help initialise forecasts and to monitor the performance of its Integrated Forecasting System (IFS). Experiments carried out at the Centre show that assimilating altimeter observations brings significant benefits for ocean reanalyses of sea level changes and for monthly and seasonal atmospheric forecasts as well as for wave height forecasts.

Altimeter products

For the time being, all radar altimeter products used at ECMWF are ocean products. The Centre's use of these products can be summarised as follows:

- Data assimilation, the process of using observations to help initialise forecasts, is the most important application of altimeter observations. Sea-level anomaly (SLA) and significant wave height (SWH) products are used for this purpose. A detailed description of these products and of the impact of assimilating them is given below.
- SLA, SWH and wind speed products are used to monitor the performance of the IFS and to assess model changes.
- SWH and wind speed products have been used to estimate the absolute random model error.
- Altimeter wind speed has been used to estimate the effective model resolution (*Abdalla et al.*, 2013).
- Altimeter products are also used for climate studies. In particular, the assimilation of SLA and SWH data is used in atmospheric and ocean reanalyses produced at ECMWF.

An explanation of how altimeter measurements are used to derive information on sea-level height, significant wave height and wind speed is given in Box A.

Most altimetry missions accommodate a microwave radiometer instrument to measure atmospheric humidity. The main purpose is to determine the impact of atmospheric humidity on altimeter measurements (delay and attenuation of the radar signal). A total column water vapour (TCWV) product is also derived from those measurements and is used at ECMWF to monitor the IFS's performance.

Sea-level anomaly

Radar altimeter sea-level anomaly (SLA) observations have been assimilated in ECMWF's ocean data assimilation system using a variational data assimilation scheme developed in collaboration with CERFACS, the UK Met Office and Inria for the NEMO ocean model (NEMOVAR). SLA data is used in the production of the latest ocean conditions in the form of real-time analysis, and in the reconstruction of the history of the global ocean state in the form of ocean reanalysis products, such as ORAS4 (Ocean ReAnalysis System 4) and ORAP5 (Ocean ReAnalysis Pilot 5) (see *Zuo et al.*, 2015). The assimilation of SLA data improves the initialisation of the IFS, which has a positive impact on extended-range (monthly to seasonal) forecasts. The data used are along-track multi-mission altimeter SLA products from AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) and include observations from ERS-1, ERS-2, ENVISAT, TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, GFO, CryoSat-2, SARAL and HY-2A (Box B). Altimeter-derived global mean sea level (GMSL) variations

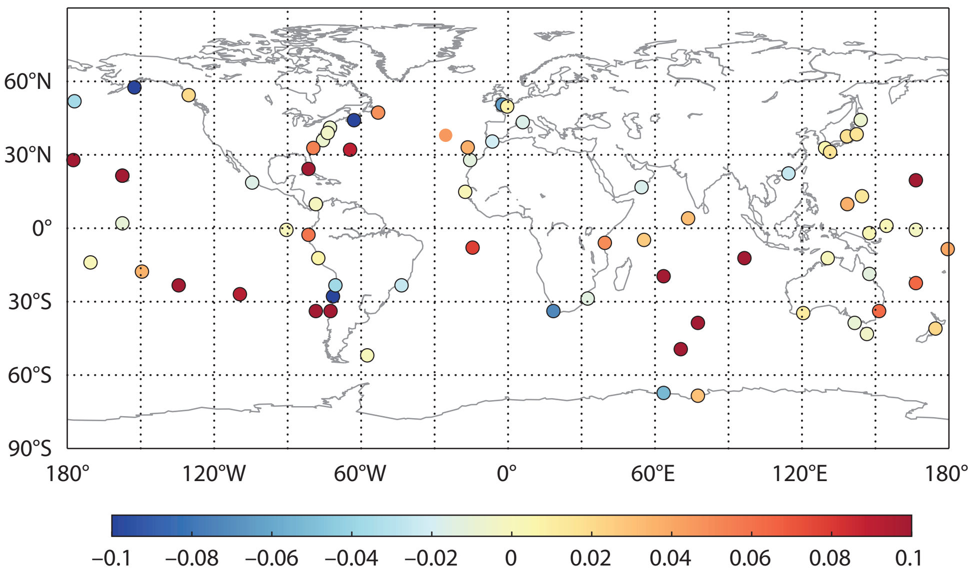


Figure 1 Differences in the correlation of the ORAP5 and CTRL SLA reanalysis with observations from 72 BADOMAR tide-gauge stations. Positive values indicate that ORAP5 is correlated better with the BADOMAR observations than the CTRL produced without the assimilation of SLA data. Statistics were computed using the monthly mean sea-level analysis from ORAP5 at the nearest model point to each tide gauge station between 1993 and 2011.

are also assimilated in ECMWF's ocean analysis system to constrain the global freshwater budget and global mean sea-level trends.

To enable comparisons between the model and the SLA observations, a reference mean dynamic topography (MDT) is required. This MDT can be calculated as the mean sea-surface height (SSH) from an assimilation of only temperature and salinity, for an arbitrary period (for example between 2000 and 2009, when the world's oceans were adequately sampled by Argo float measurements). A spatially dependent correction factor is then added to take into account the different reference periods used by the model and AVISO SLA observations. A super-observation scheme, described by *Mogensen et al.* (2012), is used to reduce the correlation of the SLA observation error and to avoid oversampling of the satellite observations. In this scheme, a super-observation grid is constructed with a resolution comparable to that of the model. Altimeter observations are then binned in time and space to create super-observations. An alternative solution is to thin the SLA observations using a stratified random sampling method, which also accounts for representativeness error from observations and can be used for ensemble member generation.

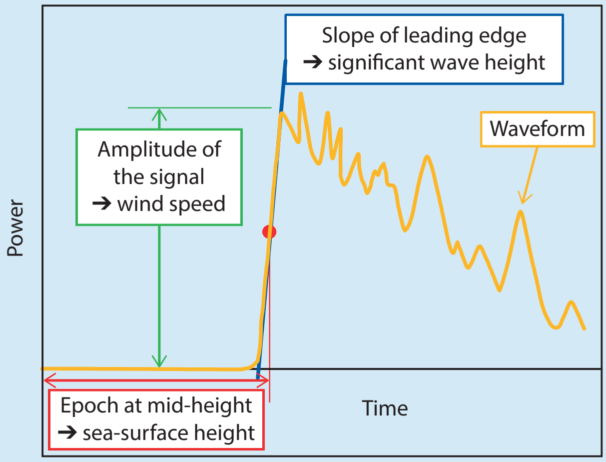
Impact on ocean reanalysis

Altimeter sea-level data has much more uniform spatial coverage than in-situ data. It is a unique dataset for the analysis of large and small scales. In assimilation, careful treatment of the altimeter data and careful specification of background and observation error covariance parameters are required. Experiments carried out at ECMWF show that, as a result of assimilating satellite sea-level data, ocean (re)analyses provide much-improved estimates of seasonal and inter-annual variability of sea-level changes. Compared to a contol run (CTRL) in which SLA data were not assimilated, ORAP5 shows higher correlation with AVISO gridded data, particularly in the tropical regions. ORAP5 is also in general in closer agreement with BADOMAR tide-gauge measurements than CTRL (Figure 1). The

Reading the signal

A

Space-borne radar altimeters measure the radar echo reflected from the surface of the ocean. This is called the ocean waveform. Usually 100 waveforms within 50 milliseconds are averaged on-board, i.e. averaging takes place at a rate of 20 Hz. The figure schematically shows a typical altimeter ocean waveform of such an average. The mean waveforms are transmitted to ground stations where they are processed to retrieve geophysical observations. The 20 observations per second are averaged to produce the 1 Hz products which are usually used for practical applications, such as data assimilation. Typically, this corresponds to about 6 to 7 km along the satellite ground track.



Information extracted from a radar echo reflected from the ocean surface after averaging about 100 individual waveforms within 1/20 of a second.

The time lapse between emitting the signal and receiving the midpoint of the leading edge of the waveform is used to determine the distance between the altimeter and the ocean surface (also called the range) after correcting for the signal delay due to various environmental factors, such as dry air ('dry tropospheric correction'), humidity ('wet tropospheric correction') and the electron content in the atmosphere ('ionospheric correction'). The impact of fluctuations in the range measurements due to tides, atmospheric pressure and ocean waves is then filtered out to determine the sea-surface height (SSH). The deviation of SSH from its mean over a few decades, which is known as the sea-level anomaly (SLA), is an important indicator of climate change.

The slope of the leading edge can be used to compute significant wave height (SWH), which is an important measure for the ocean sea state. If the ocean surface has no waves, the reflection from the surface is specular and the waveform leading edge is vertical (change from no reception to full reception of the echo in a very short period of time). The existence of ocean waves causes the waveform leading edge to tilt. The part of the signal that is reflected from the wave crests reaches the altimeter before the part that is reflected from the wave trough, with a whole spectrum in between. The higher the waves, the smaller the slope of the waveform leading edge is. This slope is translated into SWH. These observations are very important for ECMWF as they are the only ones that are currently assimilated in the ocean wave model (ECWAM).

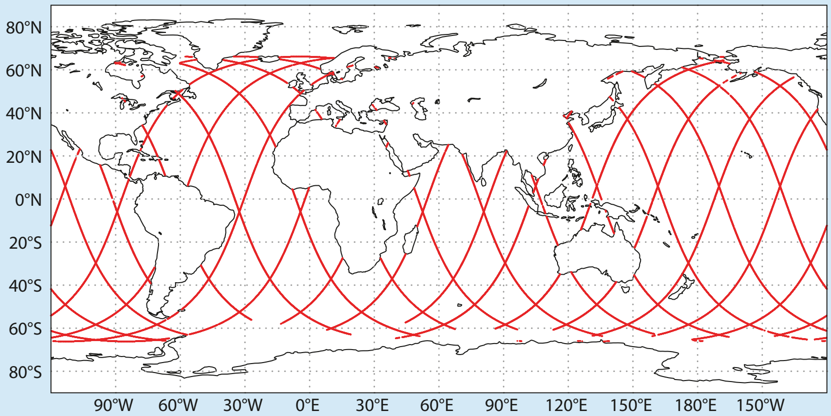
The amplitude of the waveform can be used to estimate the wind speed over the water surface. In the absence of surface wind (and assuming there are no other surface disturbances), the water surface is undisturbed, the radar signal is specular, and the maximum intensity is echoed back to the altimeter. The wind roughens the surface causing the scattering of the echo into different directions, and only part of the echo is received by the altimeter. The stronger the wind is, the rougher the surface is and the less signal is received back by the altimeter.

The altimetry observing system

B

The radar altimeter instrument is part of the payload of a number of past and current polar-orbiting satellites, as shown in the table. For operational models, the observations need to be available in near real time, i.e. typically within three hours for ocean waves. Currently Jason-2/3, CryoSat-2, SARAL and Sentinel-3A provide these fast-delivery products. In general, two polar-orbiting satellites give good global coverage in the form of a mesh in about 6 hours, as shown below for Jason-3. However, having more operational altimeters not only improves model predictions but also adds resilience to the altimetry observing system.

One of the main recent advancements in radar altimetry is the use of the synthetic aperture radar principle, known as SAR altimetry, to make altimeter measurements. The backscattered echoes are collected coherently by making use of the Doppler information in the along-track direction, forming a synthetic aperture which results in higher-resolution data. This type of altimetry provides higher-precision measurements, which are useful for measurements in the cryosphere, for example in the presence of sea ice and ice sheets, and in coastal zones. SAR altimetry was first used in the pioneering CryoSat mission. This type of instrument has started to become the norm, as can be seen with Sentinel-3A as well as future altimeters on Sentinel satellites.



Coverage of Jason-3 on a typical day, showing the locations of ocean observations which have passed quality control.

The main electromagnetic frequency implemented for radar altimeters is between 13.5 and 14 GHz (Ku-band). This corresponds to a wavelength of about 2.5 cm. The only exception is SARAL, which operates at the electromagnetic frequency of 35.75 GHz (Ka-band), corresponding to a wavelength of about 0.8 cm. Most modern radar altimetry missions carry dual frequency altimeters to estimate the impact of the atmosphere on the radar signal (ionospheric impact). The C-band with a wavelength of about 5.5 cm is the most commonly used second frequency.

Missions providing operational radar altimeter products

Mission	Near real time	Organisation	Repeat Cycle (days)	1-Hz Product sampling (km)	Launch	End of operations
ERS-1	Yes	ESA	3, 35, 168	7	Jul 1991	Mar 2000
TOPEX/ Poseidon	No	CNES, NASA	10	6	Aug 1992	Oct 2005
ERS-2	Yes	ESA	35	7	Apr 1994	Sep 2011
GFO	No	US Navy	17	7	Feb 1998	Sep 2008
Jason-1	Yes	CNES, NASA	10	6	Dec 2001	Jul 2013
ENVISAT	Yes	ESA	35	7	Mar 2002	Apr 2012
Jason-2	Yes	CNES, NASA, NOAA, EUMETSAT	10	6	Jun 2008	current
CryoSat-2	Yes	ESA	369	7	Apr 2010	current
HY-2A	No	CNSA	14, 168	7	Aug 2011	current
SARAL	Yes	ISRO, CNES	35	7	Feb 2013	current
Jason-3	Yes	CNES, NASA, NOAA, EUMETSAT	10	6	Jan 2016	current
Sentinel-3A	Yes	EC, ESA, EUMETSAT	27	7	Feb 2016	current

CNES: Centre National d'Études Spatiales
CNSA: China National Space Administration
EC: European Commission
ESA: European Space Agency
EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites
ISRO: Indian Space Research Organization
NASA: National Aeronautics and Space Administration
NOAA: National Oceanic and Atmospheric Administration

assimilation of SLA data also improves the fit to subsurface temperature observations from buoys in the tropical ocean (Figure 2). In the future, improvements are expected from using absolute sea level together with the recently improved geoid (the hypothetical shape of the surface of the oceans under the influence of the Earth's rotation and gravitation alone) based on the GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite missions, instead of using relative SLA defined with respect to an external MDT. The availability of additional high-resolution satellite altimetry data, from Sentinel-3 for example, will be beneficial for the assimilation of SLA near the coasts.

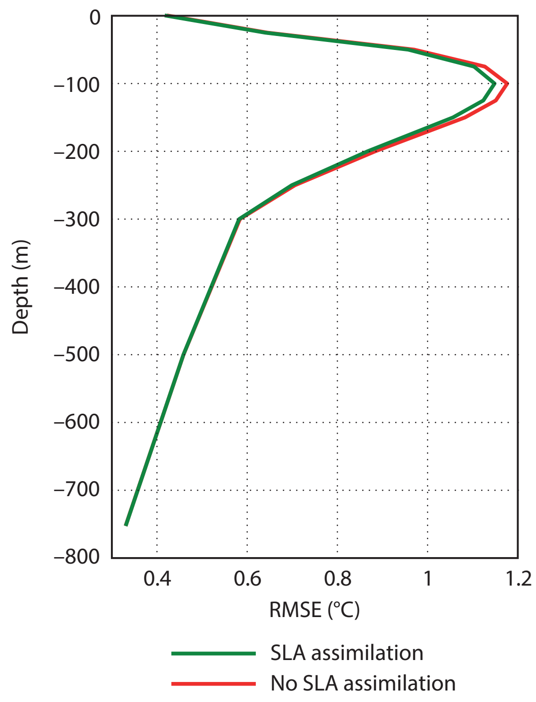


Figure 2 Root-mean-square ocean temperature error of ORAP5 reanalysis runs with and without SLA assimilation, compared to observations from buoys, averaged between 1993 and 2012, in tropical oceans (defined as oceans between 30°S and 30°N).

Significant wave height

Unlike atmospheric data assimilation, which started in the 1960s, ocean wave data assimilation emerged only in the 1980s, mainly as a result of the availability of altimeter ocean wave data. Satellite wave data are assimilated to improve the initial sea state for the wave forecast. Significant wave height (SWH), a parameter widely used to describe the ocean sea state, is defined as four times the square root of the integral of the wave spectrum. It closely corresponds to the average height of the highest one third of waves. The first operational implementation of altimeter SWH assimilation in ECMWF's global ECWAM wave model was realised on 15 August 1993. The SWH products that have been assimilated over the years are shown in Figure 3.

ECWAM uses the optimal interpolation (OI) technique for the assimilation of satellite ocean wave data. However, information on the full wave energy spectrum is not available from the altimeter since it only provides SWH, which represents the total wave energy.

On the other hand, the wave energy spectrum is the prognostic variable in the wave model, while SWH is a diagnostic variable that is computed from the wave spectrum. In the OI assimilation, the model SWH values (the background) are combined with altimeter SWH measurements to create the SWH analysis increments.

The main challenge in ocean wave data assimilation is to distribute the SWH analysis increments across the whole wave spectrum. This is done by classifying the sea state as wind-sea dominated (with mainly active wave generation) or swell-dominated (mainly waves that are no longer under the influence of their generating wind).

In wind-sea dominated conditions, the analysis increment is distributed over the whole background spectrum by adjusting its shape based on the model wave growth curves. In swell-dominated conditions, the increment is distributed over the background spectrum in a way that maintains wave steepness.

The assimilation procedure can be summarised as follows:

- The 1 Hz altimeter SWH data within 6-hour windows centred on major synoptic times are gathered and sorted by time.
- The data go through a quality control process: duplicate, wrong, noisy or questionable measurements are discarded.
- Super-observations of SWH are formed by averaging 11–13 consecutive measurements along the satellite ground track. Each super-observation represents data segments with a length of about 75 km.

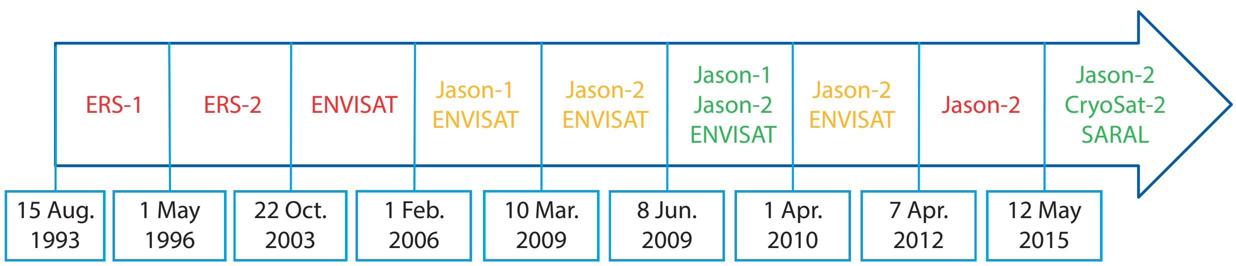


Figure 3 Timeline of altimeter SWH assimilation at ECMWF. There is currently good resilience in altimeter SWH observations as data are being provided by three satellites. Jason-3 and Sentinel-3A data are expected to be added in 2017. The colour coding indicates the degree of resilience.

- Bias correction is applied to harmonise the altimeter SWH data with the model counterpart.
- The OI scheme is applied to analyse the SWH.
- The wave spectrum is adjusted to incorporate the SWH increments as described above.

Finally, 10–15 day forecasts are calculated from the analyses at 00 and 12 UTC.

Impact on forecasts

The impact of altimeter SWH data assimilation can be assessed through comparison with independent in-situ data, the model's own analysis, and wave and atmospheric data from other instruments.

Figure 4 shows the mean difference between the SWH analysis when Jason-3, CryoSat-2 and SARAL observations are assimilated and the SWH analysis from a model run without any SWH data assimilation. Both are stand-alone wave model runs uncoupled with the atmosphere. Altimeter SWH data assimilation clearly affects the analysis, and detailed evaluation shows that it improves it. For example, the model is known to overestimate the SWH in the area in the Eastern Pacific off Central America. The data assimilation corrects this overestimation by reducing the wave height.

In-situ wave data are not assimilated and can therefore be used as independent data for data assimilation impact assessment. Figure 5 shows the percentage by which SWH random errors are reduced at analysis time and at various forecast ranges compared to in-situ measurements from buoys and platforms. The assimilation of one satellite alone (Jason-2) reduces the error by about 3.5% (about 5% in the tropics) at analysis time, while assimilating SWH from three altimeters (Jason-2, CryoSat-2 and SARAL) reduces the error by 6.5% (about 9% in the tropics). The impact of data assimilation decreases with forecast range and

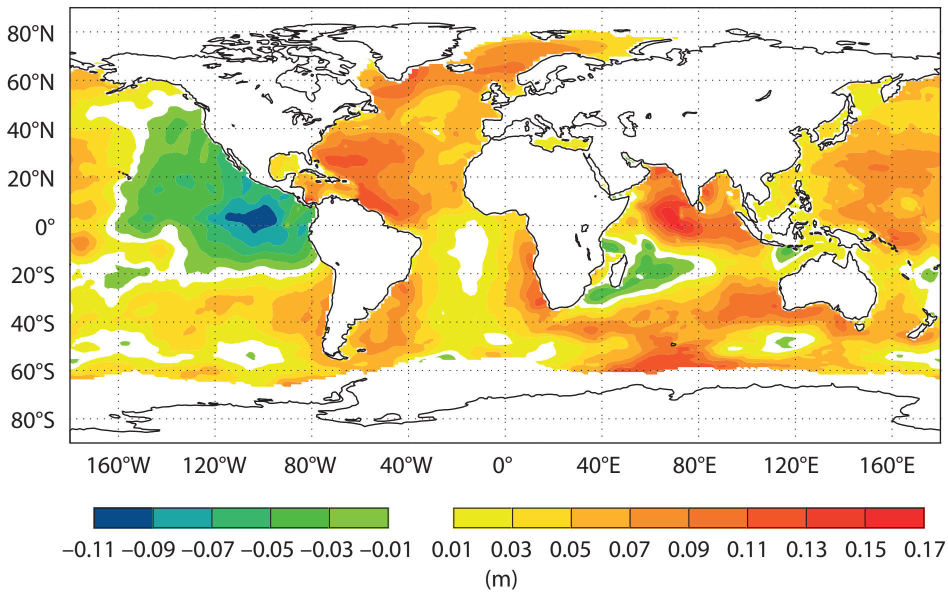


Figure 4 Mean impact, in June and July 2016, of assimilating Jason-3, CryoSat-2 and SARAL SWH data on the SWH analysis, expressed as the difference in SWH between an ECWAM stand-alone model run at a resolution of 0.25° (IFS Cycle 42r1) assimilating data from the three satellites and another model run without any data assimilation.

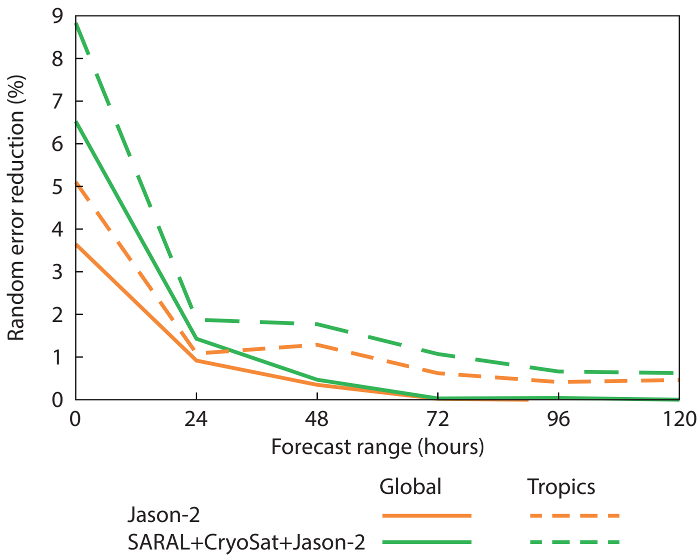


Figure 5 Impact of assimilating altimeter data on reducing the SWH random error in an ECWAM stand-alone model run at a resolution of 0.25° (IFS Cycle 40r1) as verified against in-situ buoy data, averaged over the period 14 February to 30 April 2013.

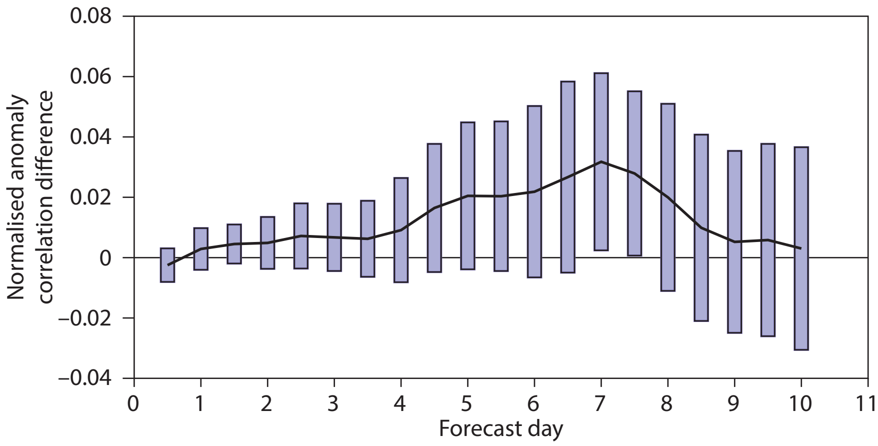


Figure 6 Mean impact of assimilating SARAL SWH on the geopotential anomaly correlation at 500 hPa in the extratropical northern hemisphere, for forecasts produced by IFS Cycle 40r1 (atmosphere and waves) at the resolution TL511 (corresponding to a grid spacing of about 40 km) between 14 February 2014 and 1 April 2014. Vertical bars show 95% confidence intervals.

vanishes after about two days in the extratropics (latitudes higher than 20°), which is usually dominated by active wave generation. In the tropics, which is dominated by swell, the impact is larger and longer lasting.

In general, the assimilation of altimeter SWH also has a positive impact on the predicted wave spectrum. This translates into better agreement between model and measured sea-state-describing parameters derived from the wave spectrum, such as mean wave period (not shown).

The tight two-way coupling between the atmospheric and ocean wave models in the IFS means that any wave model change, including data assimilation, affects the atmospheric fields. In another assimilation experiment, the results from a full IFS run (coupled wave-atmospheric model runs) using Jason-2, CryoSat-2 and SARAL SWH measurements were compared with the results of only assimilating Jason-2 SWH measurements. The experiment showed a positive impact on sea-state predictions in agreement with the results from the stand-alone wave model runs (not shown).

Furthermore, the additional altimeter SWH data from CryoSat-2 and SARAL have a small positive impact on some atmospheric fields. For example, Figure 6 shows the mean impact of assimilating SARAL SWH in addition to that of Jason-2 on the anomaly correlation of the 500 hPa geopotential height forecast in the northern hemispheric extratropics (latitudes higher than 20°) with respect to the operational analysis. The chart shows a generally positive impact although on most days the effect is not statistically significant at a confidence level of 95%.

Concluding remarks

Satellite altimetry provides a wealth of high-quality data for a wide range of marine applications. SLA, SWH and surface wind speed are of particular interest to ECMWF. The ECMWF ocean analysis system, which is part of the IFS, is initialised with SLA. The SWH is assimilated in the ocean wave model ECWAM, which is also part of the IFS. The assimilation of both SLA and SWH improves medium- to long-range forecasts. All altimeter measurements are also used for the verification of IFS predictions.

FURTHER READING

Abdalla, **S.**, 2015: SARAL/AltiKa wind and wave products: Monitoring, validation and assimilation, *Mar. Geod.*, **38**, 365–380.

Abdalla, **S.**, **L. Isaksen**, **P.A.E.M. Janssen** & **N. Wedi**, 2013: Effective spectral resolution of ECMWF atmospheric forecast models, *ECMWF Newsletter* **No. 137**, 19–22.

Chelton, **D.E.**, **J.C. Ries**, **B.J. Haines**, **L.-L. Fu**, & **P.S. Callahan**, 2001: Satellite altimetry. In: Fu, L.-L., Cazenave A. (eds.). *Satellite Altimetry and Earth Sciences*. Academic Press, 1–131.

Janssen, **P. A. E. M.**, **S. Abdalla**, **L. Aouf**, **J.-R. Bidlot**, **P. Challenor**, **D. Hauser**, **H. Hersbach**, **J.-M. Lefevre**, **D. Vandemark**, **P. Queffeulou** & **Y. Quilfen**, 2008: 15 years using altimeter sea state products, *ECMWF Technical Memorandum* **No. 552**.

Mogensen, **K.**, **M.A. Balmaseda** & **A.T. Weaver**, 2012: The NEMOVAR ocean data assimilation system as implemented in the ECMWF ocean analysis for system 4. *ECMWF Technical Memorandum* **No. 668**.

Zuo, **H.**, **M.A. Balmaseda** & **K. Mogensen**, 2015: The new eddy-permitting ORAP5 ocean reanalysis: description, evaluation and uncertainties in climate signals. *Clim. Dyn.*, doi:10.1007/s00382-015-2675-1.

doi:10.21957/q6pibt

Joint project trials new way to exploit satellite retrievals

ROSSANA DRAGANI

ECMWF is participating in the EU-funded AURORA (Advanced Ultraviolet Radiation and Ozone Retrieval for Applications) project, which is exploring new ways of exploiting the high-resolution data that will be provided with unprecedented accuracy by the Copernicus Sentinel-4 (S4), -5 (S5) and -5P (S5P) satellites.

AURORA will trial the use of data fusion of ozone retrievals from measurements in different spectral regions made by different sensors to reduce the amounts of data users need to handle, e.g. within data assimilation systems. Data fusion analytically combines atmospheric retrievals from different sources into a single, fused product characterised by greater quality than the individual retrievals. It will work with ad-hoc generated radiances that simulate measurements from the S4 and S5 satellites, which are scheduled to launch after the end of the project, and possibly with measurements from S5P, depending on its availability.

The project, which is funded under the European Commission's Horizon 2020 programme, started in February 2016 and will run for three years. ECMWF is making a major contribution to the project as one of the nine project partners (Box A). It also stands to benefit from it as AURORA offers an opportunity to refine the ozone assimilation while trialling it with fused ozone products. If successful, this approach could be exported to all applications that use ECMWF's Integrated Forecasting System, including the EU-funded, ECMWF-run Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S).

Objectives

The project's objectives include:

- scientific objectives concerned with reducing the complexity of the high volume of Copernicus S4 and S5 data through a combination of data fusion and data assimilation
- the development of a technological platform for easy-to-use, efficient and quick data access
- the development of two operational, application-oriented services based on innovative mobile apps for UV dosimetry and tropospheric ozone monitoring.

Achieving these objectives, in particular the scientific ones, could make it easier for CAMS and C3S to exploit Sentinel data.

Core elements

The AURORA system revolves around two core elements: data fusion (DF) and the data assimilation system (DAS).

DF is an algorithm that analytically combines together atmospheric retrievals originating from different sources to produce a single, fused product characterised by greater quality than the individual retrievals. The fused product is fully characterised in terms of retrieval error, information gain, averaging kernels and number of degrees of freedom. A brief description of some of these concepts is provided in Box B.

Data assimilation is the process by which observations are incorporated into a numerical model and combined with prior knowledge in a way that is consistent with their uncertainties. It is also a way to blend different observations together, but unlike data fusion, it exploits the physical and dynamical coherence imposed by the laws of physics and ensures consistency between different physical properties.

DF makes it possible to substantially reduce the number of observations to pass to the DAS whilst representing a computationally more affordable alternative to producing simultaneous retrievals. The latter technique provides the best estimate of the observed atmospheric species because simultaneous retrievals take into account all the available

The AURORA consortium

A

The consortium is led and coordinated by the N. Carrara Institute of Applied Physics, which is part of the Italian National Research Council, CNR-IFAC. It comprises nine partners, listed in the table, five of which are research organisations and four small and medium-sized enterprises (SMEs). The consortium also benefits from the support provided by the sub-contractor Resolvo s.r.l (Italy) for monitoring and communication. Airbus Defence and Space (Netherlands) acts as a third-party organisation, closely following progress on the opportunities explored by the project to exploit Copernicus data.

	AURORA partners		Country
Research Centres	CNR-IFAC	Consiglio Nazionale delle Ricerche – Istituto di Fisica Applicata Nello Carrara	Italy
Research Centres	BIRA-IASB	Belgian Institute for Space Aeronomy	Belgium
Research Centres	ECMWF	European Centre for Medium-Range Weather Forecasts	UK
Research Centres	FMI	Finnish Meteorological Institute	Finland
Research Centres	KNMI	Royal Netherlands Meteorological Institute	Netherlands
SME	DATACRAFT	DATACRAFT	Netherlands
SME	EPSILON	EPSILON International SA	Greece
SME	Flyby	Flyby SRL	Italy
SME	S&T	Science And Technology B.V.	Netherlands

Generating a satellite retrieval product

B

Satellite instruments do not directly measure the geophysical variables used in models (e.g. temperature or ozone). Instead, they measure the radiation at the top of the atmosphere at given frequencies. These measured radiances are related to the state of the Earth system, which is represented by the geophysical variables and hereafter simply referred to as 'the system', through the radiative transfer equation (RTE).

A radiative transfer model (RTM) aims to solve the RTE, i.e. to determine the model equivalent of the measured radiances given the state of the system. This is referred to as the **forward problem**. The process of determining the state of the system given the measured radiances is referred to as the **inverse problem**.

The retrieval process and its elements are schematically illustrated below, where panel a) represents the truth.

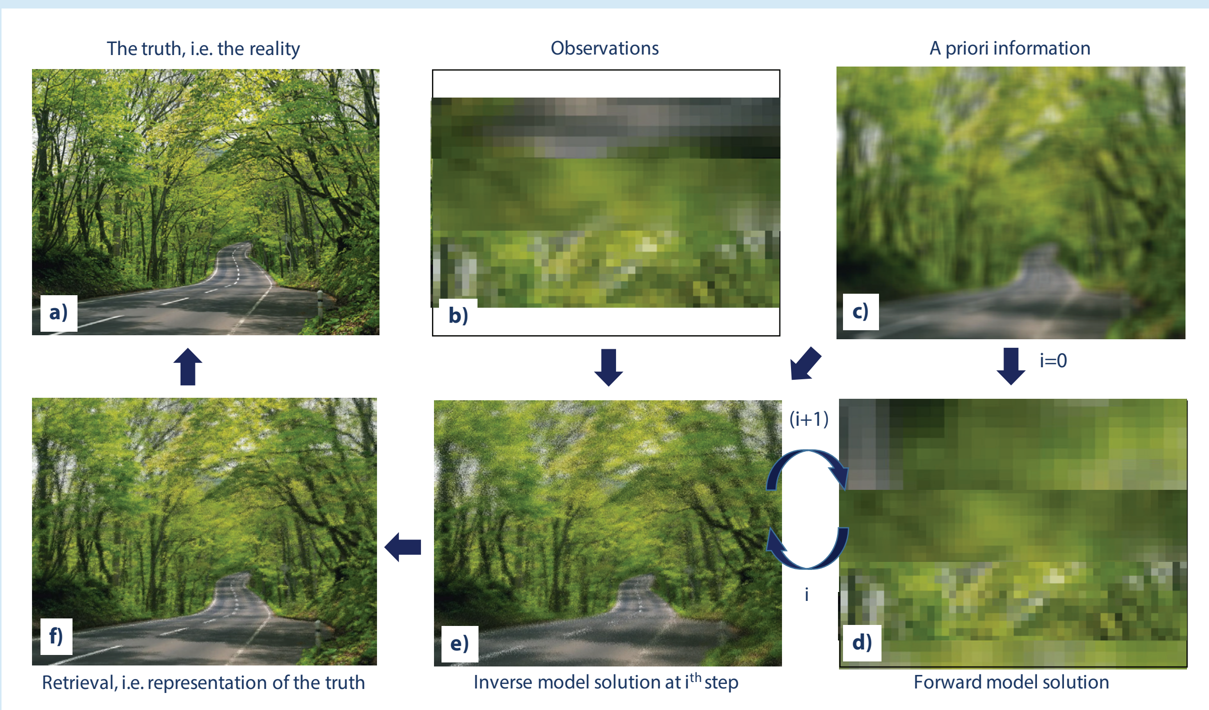
The **satellite measurements** (panel b) do not directly render an image of the truth, but something (the radiances) that can be transformed to represent it. Panel b) also symbolically shows that the sensitivity of a satellite instrument is not necessarily the same everywhere. Additionally, each remote instrument is designed to have a specific number of **degrees of freedom**. This is the maximum number of independent pieces of information the instrument is able to provide. In the picture, this could be the number of independent colours.

If we have a finite number of measurements, an infinite number of different solutions could produce the same measured radiances. This problem can be overcome by including prior knowledge of what the state of the system is. This **a priori information** (panel c) provides an indication of what the truth is, but the picture is smoothed and the details are difficult to see. The closeness of the prior to the truth depends on its source. In many cases, a short-range forecast can be used as prior, and this can have a good degree of accuracy; in other cases, the retrieval algorithm can utilise a multi-year observation-based climatology, which can infer information on the main elements of the truth, i.e. a road and some trees, but not the specific details characterising the scene at the moment the 'true' picture was taken.

The observations, the prior, their error characterisation, and the forward model, which gives the model equivalent of the observations (panel d), are the elements used to derive a **model representation** of the truth (panel e). This model representation renders a picture that can largely be related to the truth, although many details are not well captured. This is not the final representation but it is used iteratively in the retrieval process together with the observations until convergence is reached.

The final **retrieval product** (panel f), also referred to as a Level 2 product to distinguish it from the radiances, which are normally called Level 1 data, is the best fit to the a priori information and the observations in a way that is consistent with their errors. The difference between the retrieval and truth is the so-called **retrieval error**. This error is a consequence of many factors; it depends on limitations and errors that affect the satellite measurements, and on limitations and errors in the RTM and the a priori information.

As for the observations, the retrieval quality is not the same everywhere but varies according to the instrument sensitivity, the quality of the prior, and the level of sophistication included in the forward model. The sensitivity of the retrieval product to the truth is referred to as the **Averaging Kernel Matrix**.



information and rigorously handle non-linear effects. However, it can be difficult to implement because it requires a forward model that can simulate all the observations (made in different geometries and spectral regions). It is also computationally costly because the retrieval algorithm has to deal with a large amount of data. The implementation of DF is simpler but can lead to a loss of information, especially if the standard retrievals to be fused are available on different vertical grids. This possible loss of information is limited within the AURORA project by applying the Complete Data Fusion method (*Ceccherini et al.*, 2015). A brief introduction to the DF method used here is given in Box C.

In AURORA, DF is used on retrievals obtained from simulated measurements in different spectral regions from both the S4 and S5 platforms. The spectral ranges considered encompass UV, visible and thermal infrared (TIR) spectral bands. Total column ozone from measurements in the three spectral ranges and ozone profiles from the UV and TIR measurements are produced for both S4 and S5 observations. The complete DF is then applied to merge the standard ozone retrievals. The DF result is a synergistic ozone product fully characterised in terms of uncertainty, which is described by the variance-covariance matrix (VCM), and vertical sensitivity of the retrieval to the true profile, which is described by the averaging kernel matrix (AKM). This fused ozone product is then exploited within a DAS to generate ozone analyses and forecasts up to about day 5.

Two DASs are available within the AURORA consortium: ECMWF's Integrated Forecasting System (IFS), and the Dutch national weather service's global chemical transport model (TM5). The assimilation of fused products has never been tested before and thus the impact on analysis and forecast performance compared with assimilating standard retrievals has never been assessed. Two experiments are envisaged with the two DASs, as schematically shown in Figure 1: one assimilating the fused product (labelled Exp 1) and the other assimilating standard ozone retrievals (labelled Exp 2). An additional baseline experiment that uses neither the fused product nor the standard retrievals is also envisaged. A thorough assessment of the resulting ozone analyses and forecasts will show whether and how well the DASs can exploit the additional information generated by DF.

The ozone analyses and forecasts generated by the two DASs are then used to calculate tropospheric ozone information and a UV index at the surface. These represent the AURORA products, which are planned to be used in two

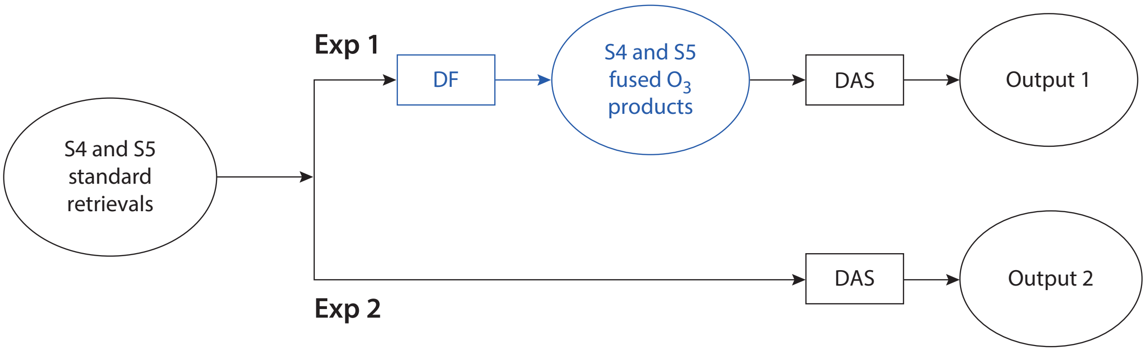


Figure 1 A schematic representation of the two experiments to be run with both DASs.

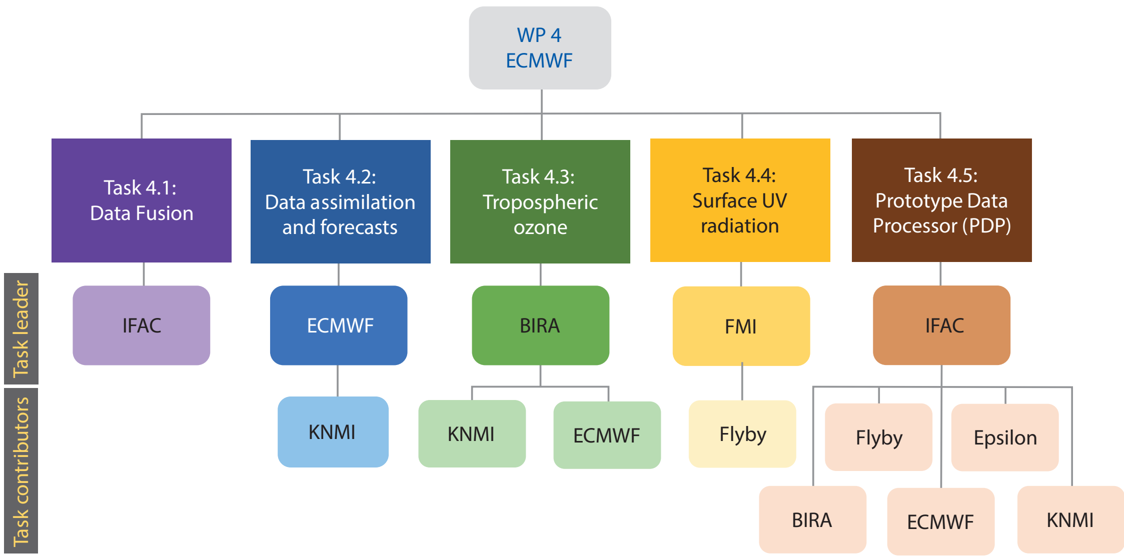


Figure 2 Roles of the AURORA partners involved in Work Package 4.

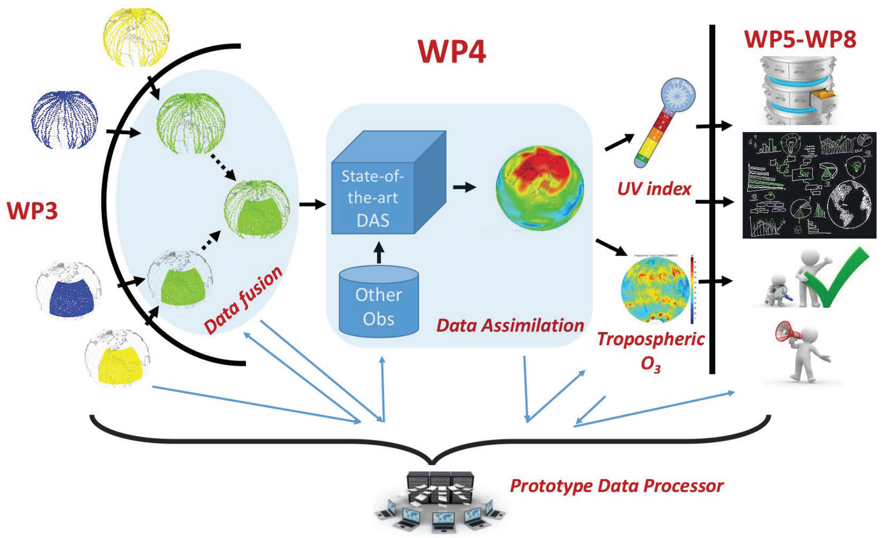


Figure 3 Envisaged data flow within the AURORA project (black arrows). In practice, all data pass through the Prototype Data Processor (blue arrows). ECMWF leads WP4, which includes five main tasks: data fusion; data assimilation; the calculation of tropospheric ozone; the calculation of a UV index; and the development of the Prototype Data Processor. Work package 3 focuses on the Sentinel data simulation and retrieval; work packages 5 to 8 cover the following aspects: data acquisition and storage (WP5), web services and data visualisation (WP6), data validation and quality assurance (WP7), and outreach and dissemination (WP8).

Complete Data Fusion

C

The DF method used within the AURORA project is the Complete Data Fusion method presented by *Ceccherini et al.* (2015). It makes it possible to blend atmospheric vertical profiles retrieved from remote sensing measurements provided by different sources whilst limiting any loss of information. This is achieved by taking into account the retrieval errors of the retrieved profiles (i.e. the variance–covariance matrix), and the sensitivity of the retrieved profiles to the true profile (i.e. the averaging kernel matrix).

The DF method has been developed on the assumption that the forward models, which are used within the retrieval procedure to simulate the satellite measurements, are linear. On that assumption, it can be shown analytically that the solution obtained with complete data fusion coincides with the solution obtained with simultaneous retrieval. The DF algorithm further assumes that each retrieved product is available on a fixed vertical grid. Although not a strict requirement, ideally the standard retrievals obtained from different sources should be available on the same vertical grid.

The a priori information used in the individual retrieval procedures is removed before combining the information extracted from the measurements. The use of new a priori information is not strictly necessary, although it can be included in the DF to limit unexpected behaviours in the fused profile.

Because it is based on an analytical method, the DF does not require the use of any additional models, which can introduce external information. An important aspect of this technique is that the fused product represents the same physical variable as the original retrievals, making its use completely transparent to users.

The method can be used successfully to extend the vertical coverage of the final product, for instance, by exploiting complementary datasets with individual sensitivity limited in the vertical domain. However, it is unsuitable for spatial or temporal interpolation, or for extrapolation purposes. The application of DF can also result in a fused product of superior quality in altitude regions where both original measurements have information content different from zero.

demonstration applications concerning air quality in major cities and personal UV dosimetry, respectively.

First big challenge

The AURORA project aims to demonstrate how user-driven applications can exploit the wealth of information provided by Copernicus Sentinel-4 (S4), -5 (S5) and -5P (S5P) measurements without the complication of handling huge data volumes. However, the S4 and S5 satellites are scheduled to be launched after the completion of the AURORA project in January 2019.

This poses a big challenge to the project, which needs to create a credible data flow and data infrastructure before the Sentinel datasets become available. For the purposes of the project, simulated observations which replicate operational Sentinel data as closely as possible need to be used. In practice, the simulated observations will be derived using the same instrumental characteristics as those of the Sentinel sensors.

A subset of NASA's second Modern-Era Retrospective analysis for Research and Applications (MERRA2) reanalysis is used to generate the atmospheric scenarios required to simulate the Sentinel measurements. The project does not have sufficient resources to perform a conventional Observing System Simulation Experiment (OSSE), which would require the simulation of all observations to be assimilated. However, the experiment's setup still meets the basic requirement for any OSSE study, which is to use two different models to simulate the measurements and to perform the assimilation. Based on this consideration, the list of required parameters, and the reanalysis characteristics (e.g. horizontal resolution), it was decided that the NASA MERRA2 reanalysis (*Bosilovich et al.*, 2015) was best suited to the needs of the AURORA project.

Figure 4 Representatives of the AURORA consortium and members of the External Expert Advisory Board at the first AURORA progress meeting in Reading, UK, on 20 and 21 July 2016.

ECMWF's contribution

ECMWF has a crucial role within the AURORA project, with contributions covering three main work packages (WPs): WP3 (atmospheric scenarios and data simulation), WP4 (data fusion; data assimilation and forecasts; calculation of tropospheric ozone, calculation of the UV index at the surface; and development of the Prototype Data Processor), and WP8 (dissemination and exploitation).

In WP3, ECMWF is responsible for the preparation of the atmospheric scenarios that are used to simulate the Sentinel-4 and -5 observations. These consist of a selected set of model outputs retrieved from the MERRA2 reanalysis. This set of model outputs includes both meteorological fields and variables describing cloud and aerosol properties. This task has already been completed.

In WP4, ECMWF is both the WP leader and task contributor. In particular, it is responsible for running the IFS DAS to generate the global ozone analyses and forecasts that are then used to calculate the tropospheric ozone products and surface UV index. This contribution is mirrored at KNMI, where the TM5 DAS is also used to produce global analyses and forecasts of ozone. All partners involved in WP4 then contribute to the development and testing of the whole data processing chain. An overview of the role of all partners involved in WP4 is given in Figure 2.

Figure 3 shows the data flow within WP4 and in relation to the work performed in other WPs. Conceptually, the data flow is represented by the black arrows. In practice, the Prototype Data Processor is being developed to make data accessible from a shared geospatial database through user-customisable dashboards. This is represented by the blue arrows.

In WP8, ECMWF contributes to the outreach activities of the consortium, in particular by promoting the AURORA work and outcomes to the Copernicus Climate Change and Atmosphere Monitoring Services.

Expected impact

The AURORA project is expected to have a significant impact on both the scientific and the technological front. It will also develop applications that could be useful to a range of users, including the general public.

On the scientific front, the application of data fusion methods is completely new, especially in combination with data assimilation. This has generated considerable interest, especially since the fused products are of greater quality than individual retrievals while still representing the same physical variable as the original, unfused data.

The wealth of data that the Copernicus S4 and S5 will deliver (an estimated 27.7 million measurements per day at solar zenith angles smaller than 80°) is overwhelming and perhaps even prohibitive for many key players in the scientific community, industry, and the public sector. If the AURORA project succeeds in simplifying access to data and its information content, and even in providing added-value products, then new possibilities can open up, especially in terms of applications and services. Potential users outside the AURORA consortium will be welcome to test the AURORA datasets in demonstration applications once the AURORA products become available towards the end of the project. However, it is worth remembering that simulated observations will be used instead of real S4 and S5 measurements. Thus, caution will need to be exercised when drawing conclusions from using AURORA data.

Two technological elements will be developed: the AURORA interface and a web-based Geographic Information System platform providing automatic access to harmonised data and to a user-friendly customised interface. The latter will provide advanced techniques for data visualisation. All these elements are expected to significantly facilitate the use of Copernicus Sentinel data by a wide community of scientists and application developers. They will also suggest a possible model for operational data dissemination to users.

FURTHER READING

Bosilovich, **M. G.**, **S. Akella**, **L. Coy**, **R. Cullather**, **C. Draper**, **R. Gelaro**, **R. Kovach**, **Q. Liu**, **A. Molod**, **P. Norris**, **K. Wargan**, **W. Chao**, **R. Reichle**, **L. Takacs**, **Y. Vikhliaev**, **S. Bloom**, **A. Collow**, **S. Firth**, **G. Labow**, **G. Partyka**, **S. Pawson**, **O. Reale**, **S. D. Schubert**, & **M. Suarez**, 2015: MERRA-2: Initial Evaluation of the Climate, *NASA TM-2015-04606*, **43**, available from http://gmao.gsfc.nasa.gov/pubs/tm/.

Ceccherini, **S.**, **U. Cortesi**, **S. Del Bianco**, **P. Raspollini**, & **B. Carli**, 2010: IASI-METOP and MIPAS-ENVISAT data fusion, *Atmos. Chem. Phys.*, **10**, 4689–4698.

Ceccherini, **S.**, **B. Carli** & **P. Raspollini**, 2015: Equivalence of data fusion and simultaneous retrieval, *Optics Express*, **23**, 8476–8488.

Dragani, **R.**, 2016: A comparative analysis of UV nadir-backscatter and infrared limb-emission ozone data assimilation, *Atmos. Chem. Phys.*, **16**, 8539–8557, doi:10.5194/acp-16-8539-2016.

doi:10.21957/cblxtg

Global radiosonde network under pressure

BRUCE INGLEBY, MARK RODWELL, LARS ISAKSEN

In early January 2015, ECMWF's automated monitoring system started warning of reductions in the number of Russian radiosonde reports. As a result of budget constraints, Russia had cut its radiosonde programme from two ascents per day to one. There were representations from ECMWF and WMO to the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet) that this was a serious reduction in the global observing system. In its representations to Roshydromet, ECMWF was able to present results from experiments which showed that reductions in Russian radiosonde reports as seen in 2015 have a significant impact on forecast performance. At short range the increased errors are mainly over Russia, moving downstream over the Pacific at longer range and then affecting forecast scores for the whole of the northern hemisphere. In April 2015, Roshydromet reversed its decision and resumed making two ascents per day.

More recently there were similar reductions to one ascent per day in Mexico and Brazil, where the number of stations affected is smaller but regionally significant. Over the last few years a number of remote island stations have also stopped making radiosonde reports or are planning to do so.

The effects of smaller-scale reductions in the number of reports in other parts of the world are more difficult to assess. In some cases radiosonde reports are particularly important because they come from data-sparse areas.

Beyond numerical weather prediction (NWP), radiosonde reports are also useful for general forecasting, climate studies and the calibration of satellite data.

Russian radiosondes

There are about 800 active radiosonde stations worldwide and many report twice per day at 00 and 12 UTC (nominal times – the ascent can take about two hours). A few stations report four times per day but some report just once. Russia provides data from 111 radiosonde stations. This is more than any other country, so the Russian cutback in early 2015 constituted a major change. ECMWF's automated warning system (*Dahoui et al.*, 2014) alerted us to the Russian change in January 2015. Very quickly ECMWF performed impact studies to compare the quality of control forecasts (CONTROL) using full Russian radiosonde data with that of test forecasts using reduced data in line with the cutbacks made in early 2015 (TEST). The experiments covered the period December 2013–February 2014 (forecast resolution T511, equivalent to a grid spacing of about 40 km) and April–June 2014 (forecast resolution T639, equivalent to about 31 km). Both tests used the operational IFS configuration of 137 vertical levels and 12-hour 4DVar, with successive analysis inner-loop resolutions of TL95/TL159/TL255 and an outer-loop resolution of TL639. During the cutback, some of the Russian stations ceased their 00 UTC ascent (for the most part those east of 110°E, see Figures 1 and 2a) and others ceased their 12 UTC ascent. The ECMWF experiments mirrored this as closely as possible.

Over Russia, radiosondes provide the main information source for the lower/mid-troposphere. There are few

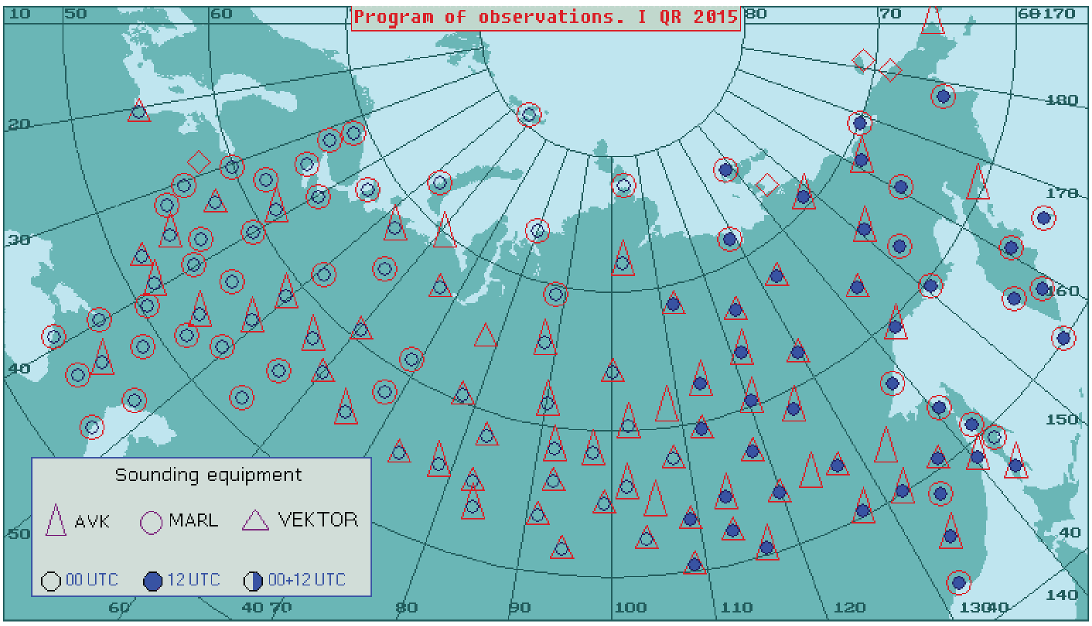


Figure 1 Russian radiosonde network in early 2015, showing which stations reported at 00 UTC and which at 12 UTC (courtesy of A. Kats, Roshydromet). AVK, MARL and VEKTOR are different radiosonde manufacturers, as is Meteorite, represented by diamond symbols.

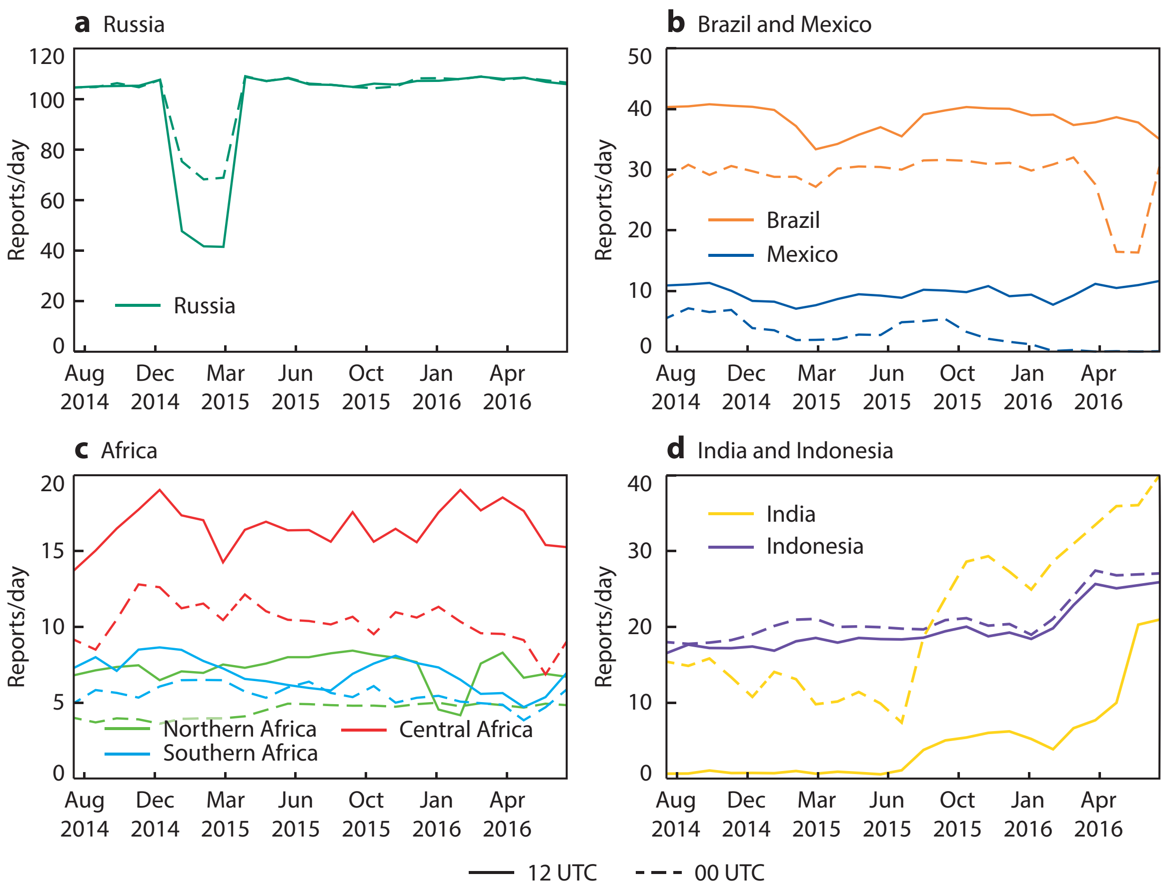


Figure 2 Monthly average number of radiosonde reports per day at 00 UTC (dashed lines) and 12 UTC (solid lines) for August 2014 to July 2016 inclusive, for (a) Russia, (b) Brazil and Mexico, (c) Africa and (d) India and Indonesia. Only reports that include temperature are included. India and Indonesia both make significant numbers of wind-only (PILOT) reports, generally to lower altitude, which are not included in the count. For technical reasons, one Mexican station from which data was received in BUFR format only in May and June 2016 is not included.

reports from aircraft ascents/descents and no wind profilers, and the uncertainty of land surface emissivity and skin temperature makes it difficult to use lower/mid-tropospheric satellite sounding channels. For infrared satellite instruments, the skin temperature issue makes cloud screening very difficult and limits the use of tropospheric channels both in snow and snow-free conditions. Microwave instruments are easier to use when the land is snow free. When snow or ice is present, high uncertainty in emission, scattering and skin temperature, frequently in combination with significant heterogeneity, limits the use of tropospheric microwave channels over large parts of the boreal winter hemisphere, as well as Antarctica. Figure 3 shows representative mid-tropospheric temperature data usage in wintertime for infrared and microwave satellite data as well as aircraft and radiosonde in situ data.

Consistent with the reduced use of satellite data over land in boreal winter, the impact on forecasts of reducing the radiosonde data was greatest during the cooler months tested (December–February). Results for these months show that 48-hour forecasts of 500 hPa geopotential height fields over Russia were degraded by 4–10%, as measured by root-mean-squared (RMS) differences from analyses (Figure 4). Similar results were also obtained for forecasts of temperature, wind and relative humidity. At longer lead times, these degradations propagate eastwards and eventually affect the entire northern hemisphere. While the largest effects are centred on Russia and the Pacific stormtrack, the detrimental impact on northern hemispheric scores as a whole (Figure 5) amount to about half a year of progress in NWP development (based on progress over the last ten years).

Figure 6 shows that Russian radiosonde temperature and humidity observations are somewhat lower quality than those from other radiosondes north of 50°N, but the winds have similar RMS statistics. One factor specific to Russian radiosondes is that pressure is derived from radar heights and, at low radar elevation angles, it has large uncertainty. However, from our results it is clear that Russian radiosondes provide a very valuable contribution to the global observing system and the accuracy of NWP forecasts.

Other regions

Between October 2015 and February 2016, Mexico, which has 13 stations, cut back from mainly two reports per day to one. In March/April 2016, about half of the 40 Brazilian radiosonde stations went from two to one report per day, although this was largely reversed in July 2016 (Figure 2b). It should be noted that various other Latin American stations only report once per day, generally at 12 UTC (Table 1). Numbers of reports from Africa are relatively low and quite variable (Figure 2c). The variability may partly arise from telecommunications issues rather than from ascents not being made at all. Some countries in the world do not make reports at all.

Remote island stations may be more expensive to maintain, and equipment failures may take longer to rectify. In the Atlantic, Ascension Island stopped reporting in September 2010 and Gough Island is being considered for closure. The numbers from Gough have been somewhat erratic recently. The most recent report from Cape Verde was in June 2016. In the Tropical Western Pacific, Nauru stopped reporting at the end of August 2013 after 15 years of operation, and Manus Island stopped in July 2014 after 18 years. Vanuatu last reported in April 2016 and, much further East, Galapagos last reported in January 2016. In the Indian Ocean, Gan in the Maldives is still reporting but has some gaps in the record due to technical problems, including the breakdown of the hydrogen generator (Box A). On a more positive note, the numbers of reports from India and Indonesia have increased recently (Figure 2d). The Indian reports are of somewhat mixed quality (temperatures from some stations are excluded from the ECMWF assimilation due to poor monitoring statistics) although they have improved in recent years.

A challenge all regions face is the migration from alphanumeric TEMP/PILOT code to binary BUFR code for radiosonde reports. The BUFR code allows reporting of high vertical resolution data, including the position of

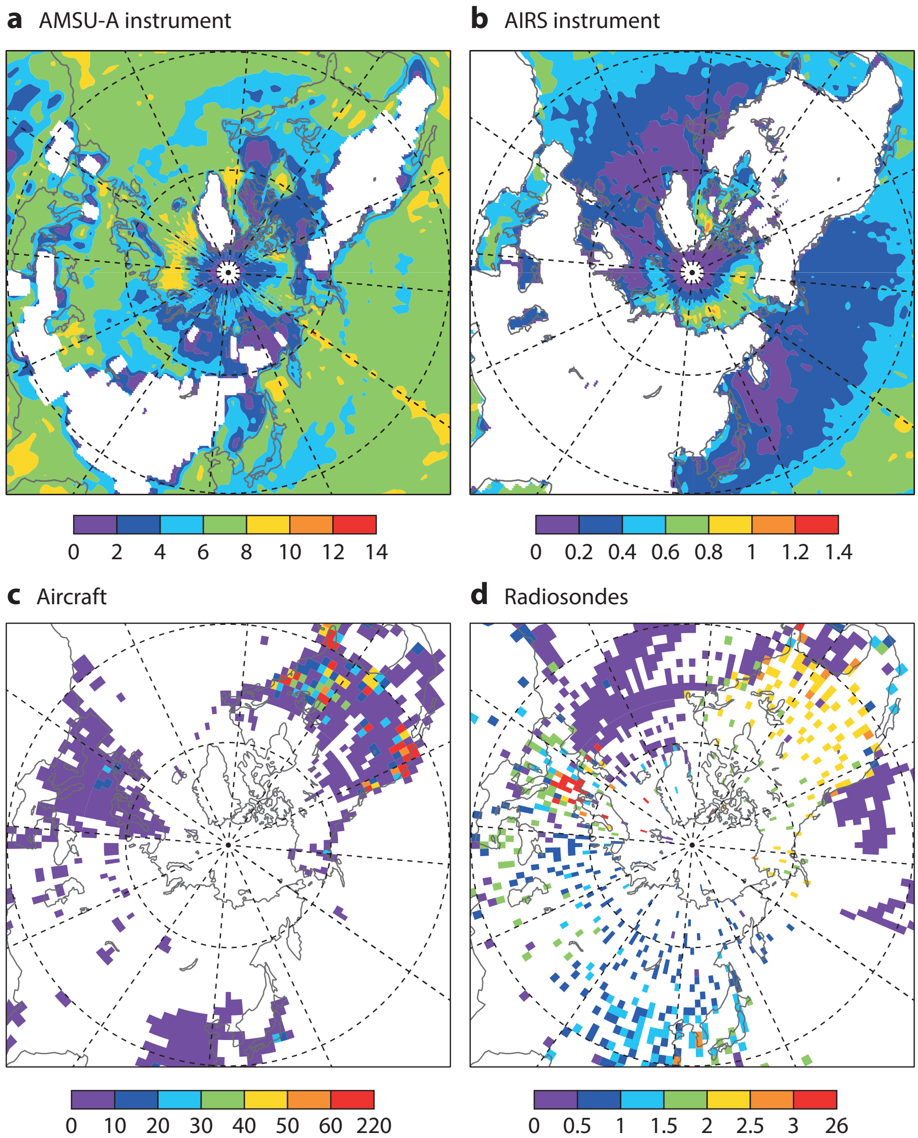


Figure 3 Average observation counts for temperature at about 500 hPa per 12-hour cycle per 2° grid box for (a) AMSU-A microwave radiometer, channel 5, (b) AIRS infrared sounder, channel 215, (c) aircraft reports, and (d) radiosonde reports, based on actively assimilated data from December 2014 to February 2015. Note the satellite observation gaps over Russia (bottom-left quadrant) and the lack of aircraft data, except near a few airports.

each level, and also enables higher-precision reporting (*Ingleby et al.*, 2016). So far the adoption of high-resolution reporting is mostly confined to Europe and Australia, and unfortunately many of the other BUFR reports do not meet the regulations and are unusable. Updated information on the migration to BUFR is available at *https://software.ecmwf.int/wiki/display/TCBUF/*.

Importance for NWP

Within Europe there are regular discussions about the observing system and its importance in NWP through EUMETNET, a grouping of 31 national meteorological services. There is also some pooling of resources to support radiosonde launches from 18 ships in the North Atlantic, of which on average seven are active on any particular

Inflating radiosonde balloons

A

All radiosonde stations need either hydrogen or helium to inflate the balloons. Hydrogen generators are expensive to purchase and require ongoing maintenance and technical understanding. They also need a good power supply and clean water. Despite this, and the unfortunate frequency of generator failures, most remote locations have to rely on hydrogen generators. Using helium is not a viable alternative for these stations because of its high price and the logistics of supply. Except for accidents (premature burst), the height which a particular radiosonde reaches is determined primarily by the size of the balloon and the amount of gas used.

Region	Number of stations	0000 UTC		1200 UTC	
		Total number	At least 25 T30 reports	Total number	At least 25 T30 reports
Africa	43	25	1	37	10
Asia	301	294	192	265	159
S America	55	37	7	54	19
N America & Caribbean	156	138	119	156	128
SW Pacific	97	95	52	70	14
Europe	151	143	97	134	98
Antarctica	15	9	2	11	3

Table 1 Number of radiosonde stations from which reports are received at ECMWF (in TEMP format) for July 2016 by WMO region. For 0000 UTC (2100–0859 UTC window) and 1200 UTC (0900–2059 UTC window) the 'total number' column gives the number of stations which reported at that time and the second column the number of stations which reported 30 hPa temperature at least 25 times.

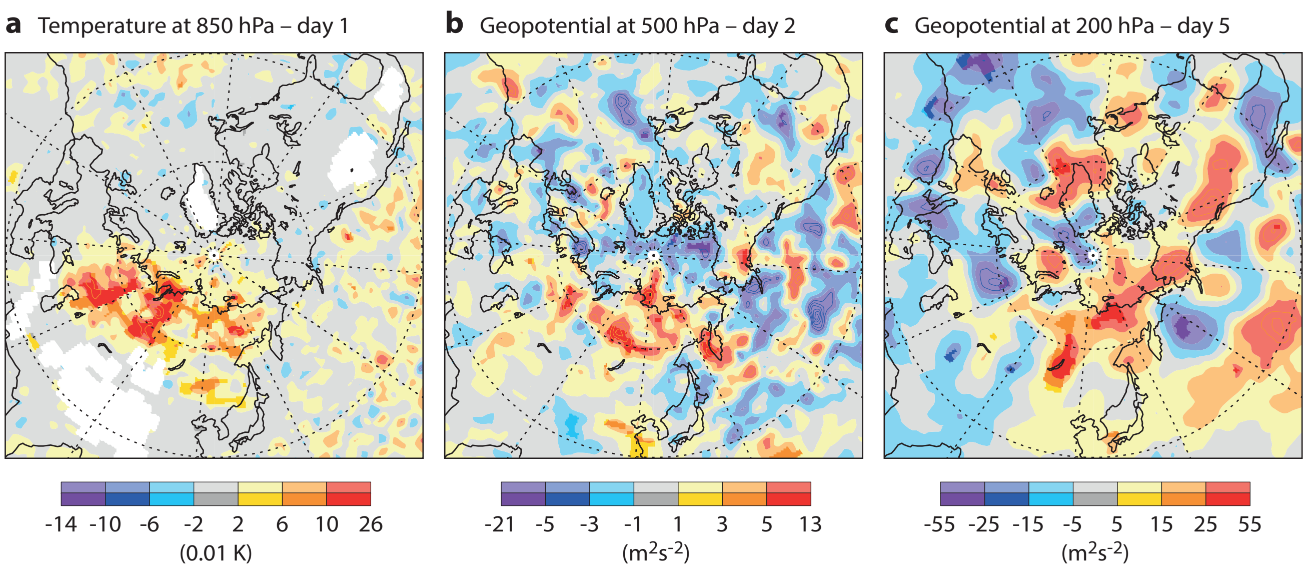


Figure 4 Difference in RMS error between CONTROL and TEST forecasts shown for (a) temperature at 850 hPa at day 1, (b) geopotential at 500 hPa at day 2, and (c) geopotential at 200 hPa at day 5. Positive (yellow/red) values imply larger errors in the TEST forecasts. Increased temperature errors in day 1 forecasts are concentrated over Russia. Larger errors in day 2 forecasts of geopotential at 500 hPa are clustered over the North Pacific as well as Russia. Increased errors in day 5 forecasts of geopotential at 200 hPa show the impact on the jet stream, which will communicate the differences across the hemisphere. The experiment covers the period December 2013–February 2014. Saturated colours denote statistical significance at the 5% level.

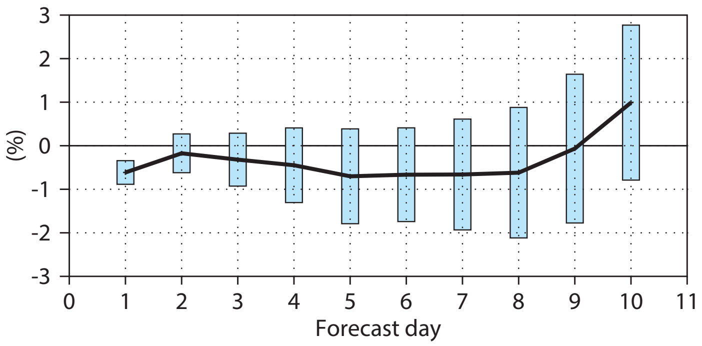


Figure 5 Relative difference in RMS error between CONTROL and TEST forecasts of geopotential height at 500 hPa in the northern hemisphere extratropics (20–90°N). The bars indicate 95% confidence intervals. Negative values indicate that the forecasts with fewer radiosonde reports were worse than those with full radiosonde reports. The experiment covers the period December 2013–February 2014.

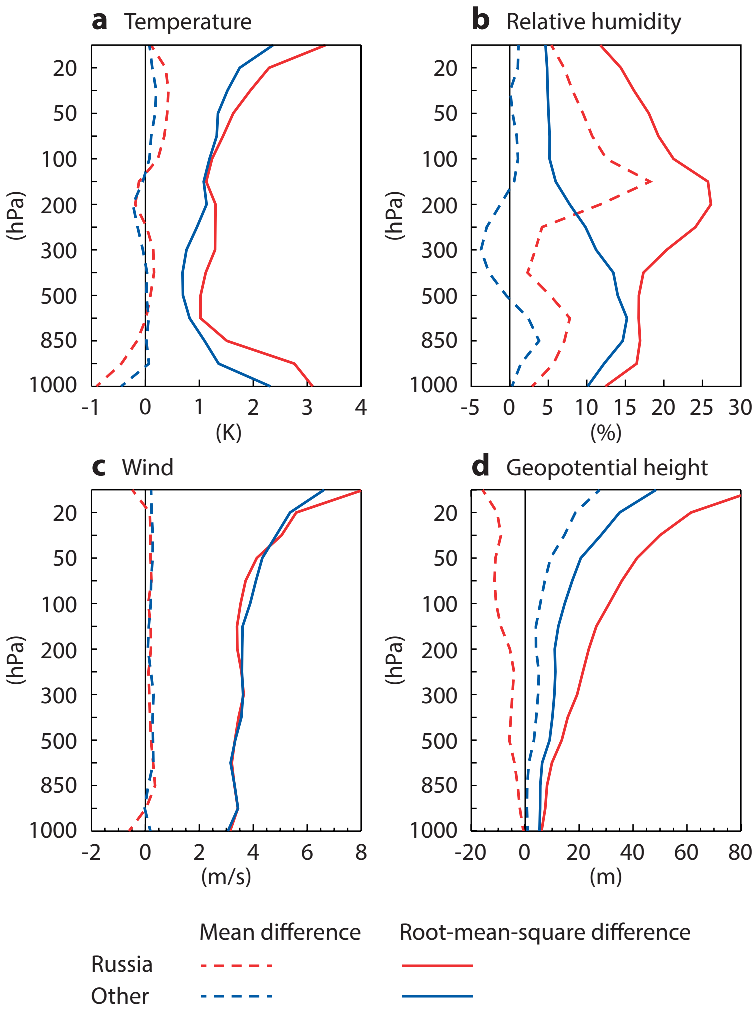


Figure 6 Observation minus background (12-hour forecast) statistics for Russian radiosondes and other radiosondes north of 50°N. Results are shown for standard-level data that passed the operational first guess check, October 2014–March 2015. For wind, the mean speed difference and the RMS vector difference are shown. Note that upper-tropospheric humidity from Russian radiosondes is not assimilated in the ECMWF system. The very large near-surface temperature differences partly stem from the fact that the forecast model has difficulty representing the very sharp low-level inversions that occur in winter over Russia and to a lesser extent over other land areas.

day, and from a number of land stations. EUMETNET also funds aircraft (AMDAR) reports from European aircraft, and ECMWF helps to provide monitoring to ensure that the various observing systems are providing good-quality data.

Besides the direct impact of radiosondes on weather forecasts, they also have an indirect effect as a result of being used as reference data – helping to bias-correct satellite sounding and aircraft temperature data, especially in the troposphere. In the stratosphere, a EUMETNET-funded ECMWF study by *Radnoti et al*. (2012) found that satellite radio occultation measurements were a valuable source of reference data. From an NWP perspective, radiosondes, aircraft (on ascent and descent) and wind profilers complement each other in terms of the variables provided: radiosondes are less frequent but ascend higher and also measure humidity, while only a small proportion of aircraft have humidity sensors. Radiosondes are also used extensively for forecast verification.

The large number of Russian radiosonde stations involved in the cutback makes it relatively easy to get a clear view of their importance. It is much more difficult to assess the impact of a few radiosonde stations when smaller changes to the observing system are contemplated. However, for global analysis and forecasting, radiosonde reports from remote island stations are especially valuable because they come from data-sparse areas. Being surrounded by ocean, they are also particularly useful for the bias correction and validation of satellite data. An OSSE (Observing System Simulation Experiment) performed by *Privé et al*. (2014) suggested that doubling the number of radiosonde reports per day would be beneficial for weather forecasts.

Drive for availability and quality

There are two initiatives by GCOS (Global Climate Observing System) to try to ensure the availability and quality of radiosonde data suitable for climate studies. About 170 stations worldwide are designated as GUAN (GCOS Upper Air Network) sites with a commitment to long-term operation, a guideline that at least 25 reports per month should reach 30 hPa, and compliance with best practice for GUAN stations. The role of radiosondes as reference instruments is promoted by the GRUAN (GCOS Reference Upper Air Network) project, envisaged to be a network of 30 to 40 sites across the globe. Currently GRUAN reports are available from about ten stations using the Vaisala RS92 radiosonde. Most of these stations also send real-time observations using the manufacturer's algorithms. GRUAN provides estimates of the measurement uncertainty. One notable feature is that upper level temperature uncertainty is much lower at night than in sunlight (*Dirksen et al*., 2014).

At present, for operational NWP the designation of a station as GRUAN or GUAN makes no difference to its processing. GRUAN is useful for minimising and quantifying errors in radiosonde data, and as a standard against which to compare the worldwide radiosonde network and satellites. The best operational radiosondes outside GRUAN (launched from about 450 stations using RS92 and other good-quality radiosonde types) also provide accurate data, and with better coverage. As noted by *Eyre* (2016), NWP satellite bias correction methods need good proportions of reference observations in order to work well. The Met Office and ECMWF are looking at the role of radiosondes in calibrating satellite sounding data as part of the EU-funded GAIA-CLIM project.

FURTHER READING

Dahoui, **M.**, **N. Bormann** & **L. Isaksen**, 2014: Automatic checking of observations at ECMWF. *ECMWF Newsletter* **No. 140**, 21–24.

Dirksen, **R.J.**, **M. Sommer**, **F.J. Immler**, **D.F. Hurst**, **R. Kivi** & **H. Vömel**, 2014: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde. *Atmos. Meas. Tech.*, **7**, 4463–4490, doi:10.5194/amt-7-4463-2014.

Eyre, **J.R.**, 2016: Observation bias correction schemes in data assimilation systems: a theoretical study of some of their properties. *Quarterly Journal of the Royal Meteorological Society*, doi: 10.1002/qj.2819.

Ingleby, **B.**, **P. Pauley**, **A. Kats**, **J. Ator**, **D. Keyser**, **A. Doerenbecher**, **E. Fucile**, **J. Hasegawa**, **E. Toyoda**, **T. Kleinert**, **W. Qu**, **J. St James, W. Tennant** & **R. Weedon**, 2016: Progress towards high-resolution, real-time radiosonde reports. *Bull. Amer. Meteor. Soc.*, Early online release doi: 10.1175/BAMS-D-15-00169.1.

Privé, **N.C.**, **R.M. Errico** & **K.-S. Tai**, 2014: The Impact of Increased Frequency of Rawinsonde Observations on Forecast Skill Investigated with an Observing System Simulation Experiment. *Mon. Wea. Rev.*, **142**, 1823–1834, doi: 10.1175/MWR-D-13-00237.1.

Radnoti, **G.**, **P. Bauer**, **A. McNally** & **A. Horanyi**, 2012: ECMWF study to quantify the interaction between terrestrial and space-based observing systems on Numerical Weather Prediction skill. *ECMWF Technical Memorandum* **No. 679**.

doi:10.21957/pu5hkz

Use of forecast departures in verification against observations

MOHAMED DAHOUI, GABOR RADNOTI,
SEAN HEALY, LARS ISAKSEN, THOMAS HAIDEN

Forecast users need to know how well ECMWF forecasts predict the actual observed conditions. Recent work makes it possible to assess the performance of our forecasts through detailed and accurate comparisons against all available observations. The forecast verification has thus been extended to incorporate all the observations used and quality-controlled by the data assimilation system (4DVAR).

Forecast verification is routinely performed against a subset of observations: radiosondes, SYNOP stations and buoy data for upper air, near-surface and wave forecasts, respectively. These observations provide independent verification, but they lack temporal and spatial coverage, leading to sampling issues. Extending the verification to other observation types, GPS radio occultation (GPS-RO) data for example, is very useful where the coverage of radiosondes is insufficient.

Computing forecast departures

The first step in data assimilation produces a precise comparison between observations and their counterparts from a short-range forecast (see Box A). This procedure has now been applied to forecast steps up to day 10, leading to the computation of forecast departures (observation minus forecast) against all quality-controlled observations. The computation of forecast departures is performed with respect to observed quantities (e.g. satellite radiances, GPS-RO bending angles). For ranges beyond 12 hours, the forecast is independent of the set of observations against which it is verified. This is also true of the quality control tests applied to observations, which are based on recent short-range forecasts. The availability of such forecast departures has a number of benefits for the verification of forecasts:

- The verifying observations are to a large extent independent from the forecasts being verified.
- Verification can be carried out against a wide range of observation types with good availability in time and space. The variety and redundancy of the observing system helps users to disentangle forecast and observation errors.
- For longer ranges (typically beyond 48 hours), forecast errors are significantly larger than typical observation errors. This significantly reduces the undesirable effect of observation errors masking forecast improvements.
- It is possible to estimate the forecast error growth rate and model activity.
- There is increased synergy between observation monitoring activities and forecast verification activities.

Figure 1 shows an example of statistics of forecast departures for successive forecast ranges up to three days for AMSU-A radiances. It highlights the increase in the random and systematic components of the forecast error as the range increases. Figure 2 shows the difference in day-3 forecast departures for radiances from Metop-A/AMSU-A Channel 14 between two model cycles (IFS cycles 41r1 and 41r2). The plot shows a statistically significant reduction in the upper stratospheric temperature bias caused by a slight cooling in model cycle 41r2. Figure 3 shows the distribution of the same comparison for all used Metop-A/AMSU-A channels, highlighting the temperature bias change.

The general availability of observation-minus-forecast differences has the potential to allow the estimation of the relative impact of assimilated observations on forecast quality (*Todling*, 2012). This method is being explored.

Main operations to compare forecasts with observations in the IFS

A

The differences between observations and the short-range forecast are the most important input for the data assimilation process. Their computation is based on sophisticated infrastructure involving the following operations:

- Interpolation from forecast time to observation time (in 4DVAR this means running the forecast model over the assimilation window)
- Horizontal and vertical interpolations
- Vertical integration
- Horizontal integration for limb geometry observations
- Converting model variables to the observed geophysical quantity (not needed when the observed quantity is directly represented by the model)
- Computing the differences between observed and simulated quantities (background departures)
- Quality control checks (first-guess checks plus variational quality control)
- Data thinning (avoiding over-sampling and problems due to correlated errors)
- Data blacklisting (for systematic poor performance or ongoing assessment)

Stratospheric forecast verification

The verification of forecasts in the stratosphere is best performed against GPS-RO-derived observations. GPS-RO have a good vertical resolution as well as a global and homogeneous distribution (around 3,000 profiles daily) and, most importantly, their biases are small enough for the data to be assimilated without bias correction. Initially the forecast departures were produced against bending angles only (which is the quantity being assimilated). However, bending angle statistics are not easy to interpret when dealing with biases, mainly due to the combined impact of temperature and moisture on bending angles. To address this limitation, the computation of departures procedure has been extended to enable the comparison

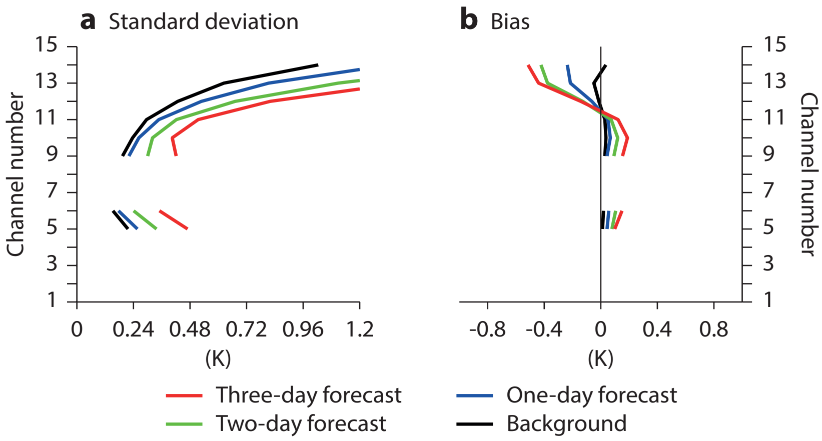


Figure 1 Statistics of forecast departures for radiances from all used channels from Metop-A/AMSU-A for successive forecast ranges over the southern hemisphere extratropics, showing (a) the standard deviation (random error) and (b) the bias (mean error). The forecasts were produced between 1 September and 30 September 2015 using a lower resolution of IFS Cycle 41r1.

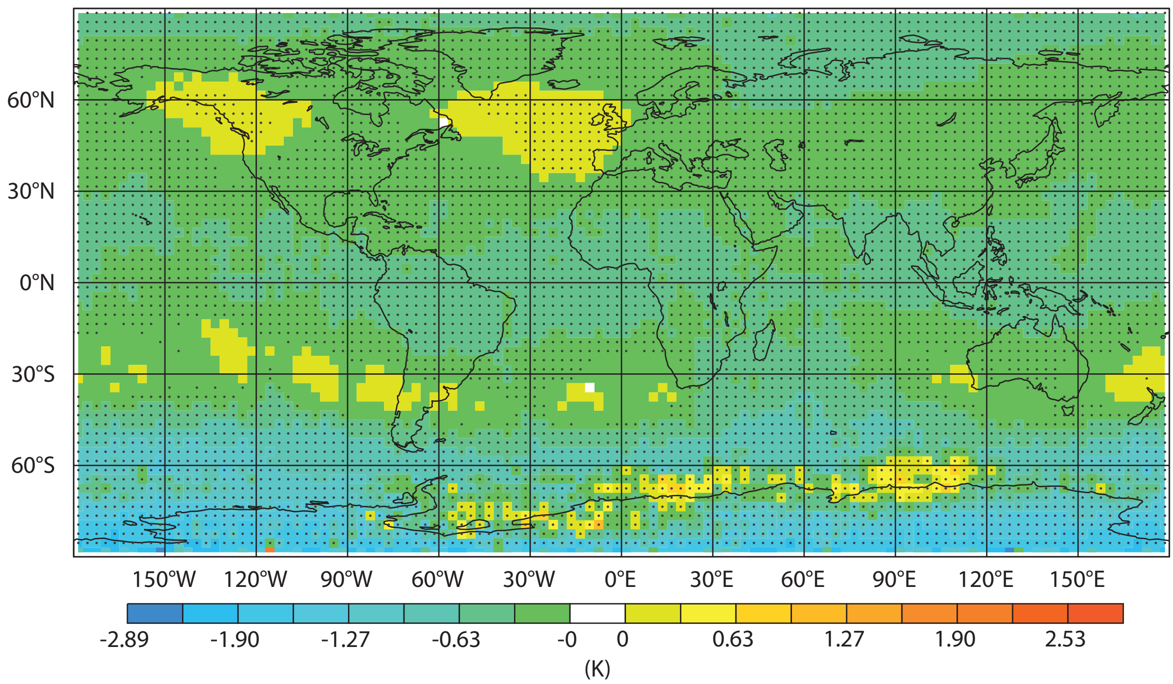


Figure 2 Statistics of differences between day-3 absolute mean forecast departures for radiances from Metop-A/AMSU-A channel 14 between an experiment based on IFS Cycle 41r2 and a control experiment based on IFS Cycle 41r1. Negative values indicate that the mean forecast departures using IFS Cycle 41r2 are smaller. Dots indicate areas where the differences are statistically significant at the 95% confidence level. The forecasts cover the period from 31 August to 1 October 2015.

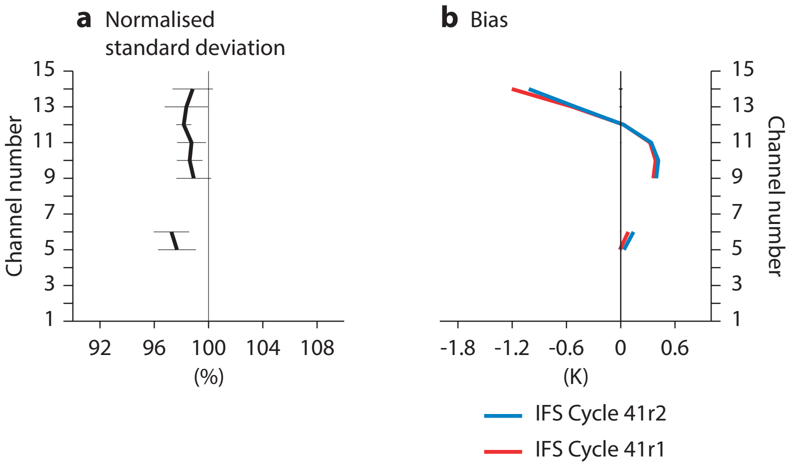


Figure 3 Statistics of the differences in day-3 forecast departures, for radiances from all used channels from Metop-A/AMSU-A, between an experiment based on IFS Cycle 41r2 and a control experiment based on IFS Cycle 41r1 over the northern hemisphere extratropics, showing (a) the standard deviation of the forecast departures from the experiment normalised by the standard deviation (random error) of forecast departures from the control experiment and (b) the bias (mean error) for IFS Cycle 41r2 and IFS Cycle 41r1. The forecasts cover the period from 1 September to 30 September 2015.

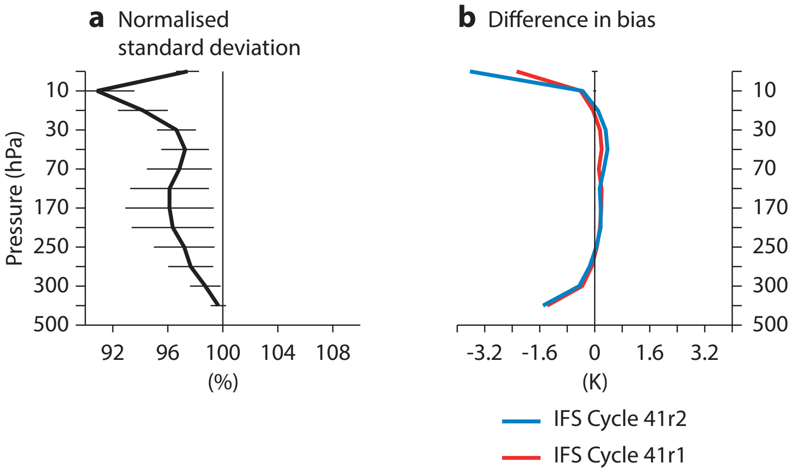


Figure 4 Vertical profile of statistics of the differences in day-3 forecast departures, for temperature retrieved from GPS-RO instruments, between an experiment based on IFS Cycle 41r2 and a control experiment based on IFS Cycle 41r1 over the northern hemisphere extratropics, showing (a) the standard deviation from the experiment normalised by the standard deviation from the control experiment and (b) the bias (mean error) for IFS Cycle 41r2 and IFS Cycle 41r1. The forecasts cover the period 1 November 2014 to 30 January 2015.

of any forecast range (up to day 10) against temperature retrievals from GPS-RO (see Box B). This extension offers a good method to assess the impact of model changes on systematic errors. Since GPS-RO temperature retrievals require a priori information on the upper atmosphere, it is important to restrict the use of temperature retrievals to the atmospheric region less constrained by the prior (below the 5 hPa level). Furthermore, standard GPS-RO temperature retrievals are performed in dry conditions, which makes them less valid in the troposphere. Despite the good accuracy of temperature retrievals in the mid- to lower stratosphere, they remain to some extent dependent on the quality of the prior information used. For this reason, in order to obtain robust results when comparing model cycles, it is important to use the same prior (preferably the operational short-range forecasts) for GPS-RO temperature retrievals based on different model versions.

Figure 4 shows a comparison of day-3 forecast departures for GPS-RO temperature retrievals in November 2014 to January 2015 between the then operational cycle 40r1 and the then pre-operational cycle 41r1 over the northern hemisphere extratropics. It shows a reduction in the standard deviation in the pre-operational cycle, which is an indication of improvement.

Outlook

There are plans to routinely compute and archive the differences between forecasts and observations (the departures). These departures will be used for forecast verification and for assessments of observation impact on forecast quality. The details of the implementation (resolution of the model and the set of forecast ranges to consider) will be defined in due course.

Procedure to compute forecast departures against GPS-RO bending angles and retrieved temperatures

B

- Extraction of surface pressure, surface elevation, pressure, temperature and humidity on model levels from the desired forecast range and a short-range (6-hour) forecast.
- Retrieval of the GPS-RO data from the BUFR file.
- Usage of a 1D operator to compute the bending angles using the desired forecast range and 6-hour forecast. There is no time or horizontal interpolation (usage of the forecast time and the nearest grid point). The 2D aspects are ignored (no horizontal integration is performed).
- Usage of a 1D operator to retrieve temperatures in the stratosphere using the desired forecast range and 6-hour forecast. The procedure starts by deriving the refractive index profile, which involves the use of a priori information. The pressure (at each impact height) is derived using the relation between refractivity, pressure and temperature and assuming dry conditions. The temperature is then computed using the ideal gas law.
- Quality control of observations based on observation fit to 6-hour forecast.
- Computing of bending angle departures for the desired forecast range.

FURTHER READING

Todling, R., 2012: Comparing two approaches for assessing observations impact. *Monthly Weather Review*, **141**, 1484–1505.

ECMWF publications

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

Technical Memoranda

784 **Ollinaho, P., S.J. Lock, M. Leutbecher, P. Bechtold, A. Beljaars, A. Bozzo, R.M. Forbes, T. Haiden, R.J. Hogan, I. Sandu**: Towards process-level representation of model uncertainties: Stochastically perturbed parameterisations in the ECMWF ensemble. *September 2016*

783 **Han, W., N. Bormann**: Constrained adaptive bias correction for satellite radiance assimilation in the ECMWF 4D-Var system. *September 2016*

782 **N. Bormann**: Slant path radiative transfer for the assimilation of sounder radiances. *July 2016*

781 **Schlemmer, L., P. Bechtold, I. Sandu, M. Ahlgrimm**: Momentum transport in shallow convection. *August 2016*

776 **De Chiara, G., S. English, P. Janssen, J.R. Bidlot**: ASCAT ocean surface wind assessment. *July 2016*

ERA Report Series

26 **Hirahara, S., M. Alonso Balmaseda, H. Hersbach**: Estimates of variations and trends of global surface temperature. *2016*

ECMWF Calendar 2016/17

Nov 15–17	EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) Workshop
Nov 21–24	UERRA General Assembly
Nov 29–30	ECOMET General Assembly and EUMETNET Assembly
Dec 1–2	Council
Jan 16–19	Computer User Training Course: ecFlow
Jan 23–27	Computer User Training Course: HPC Facility Cray XC40
Jan 30–3 Feb	Training Course for Trainers, Training Champions: Use and Interpretation of ECMWF Products
Feb 6–10	Training Course: Use and Interpretation of ECMWF Products
Feb 20–24	Computer User Training Course: Introduction for New Users/ MARS
Feb 28	Council, Extraordinary Session
Feb 28–1 Mar	Workshop on Data Policy
Feb 28–3 Mar	Computer User Training Course: ecCodes, GRIB
Mar 1–3	Workshop on Meteorological Operational Systems
Mar 4–5	Hackathon on Open Data
Mar 6–9	Computer User Training Course: ecCodes, BUFR
Mar 13–17	NWP Training Course: Advanced Numerical Methods for Earth System Modelling
Mar 20–24	NWP Training Course: Parametrization of Subgrid Physical Processes
Mar 27–31	NWP Training Course: Data Assimilation
Apr 3–7	EUMETSAT/ECMWF NWP SAF Training Course: Assimilation of Satellite Data
Apr 24	Policy Advisory Committee
Apr 25–26	Finance Committee
May 8–12	NWP Training Course: Predictability and Ocean–Atmosphere Ensemble Forecasting
May 16–17	Security Representatives' Meeting
May 17–19	Computing Representatives' Meeting
Jun 12–16	Using ECMWF's Forecasts (UEF)
Jun 21–22	Council
Sep 11–15	Annual Seminar
Oct 2–5	Training Course: Use and Interpretation of ECMWF Products
Oct 9–11	Scientific Advisory Committee
Oct 12–13	Technical Advisory Committee
Oct 16	Policy Advisory Committee
Oct 17–18	Finance Committee
Dec 7–8	Council

Contact information

ECMWF, Shinfield Park, Reading, Berkshire RG2 9AX, UK

Telephone National	0118 949 9000
Telephone International	+44 118 949 9000
Fax	+44 118 986 9450

ECMWF's public website http://www.ecmwf.int/

E-mail: The e-mail address of an individual at the Centre is firstinitial.lastname@ecmwf.int. For double-barrelled names use a hyphen (e.g. j-n.name-name@ecmwf.int).

Problems, queries and advice	Contact
General problems, fault reporting, web access and service queries	calldesk@ecmwf.int
Advice on the usage of computing and archiving services	advisory@ecmwf.int
Queries regarding access to data	data.services@ecmwf.int
Queries regarding the installation of ECMWF software packages	software.support@ecmwf.int
Queries or feedback regarding the forecast products	forecast_user@ecmwf.int

Index of Newsletter articles

This is a selection of articles published in the *ECMWF Newsletter* series during recent years.
Articles are arranged in date order within each subject category.
Articles can be accessed on ECMWF's public website – http://www.ecmwf.int/en/research/publications

COMPUTING

METEOROLOGY

Observations & Assimilation

Forecast Model

Probabilistic Forecasting & Marine Aspects

Meteorological Applications & Studies

ECMWF
Newsletter | Number 149 – Autumn 2016
European Centre for Medium-Range Weather Forecasts
www.ecmwf.int