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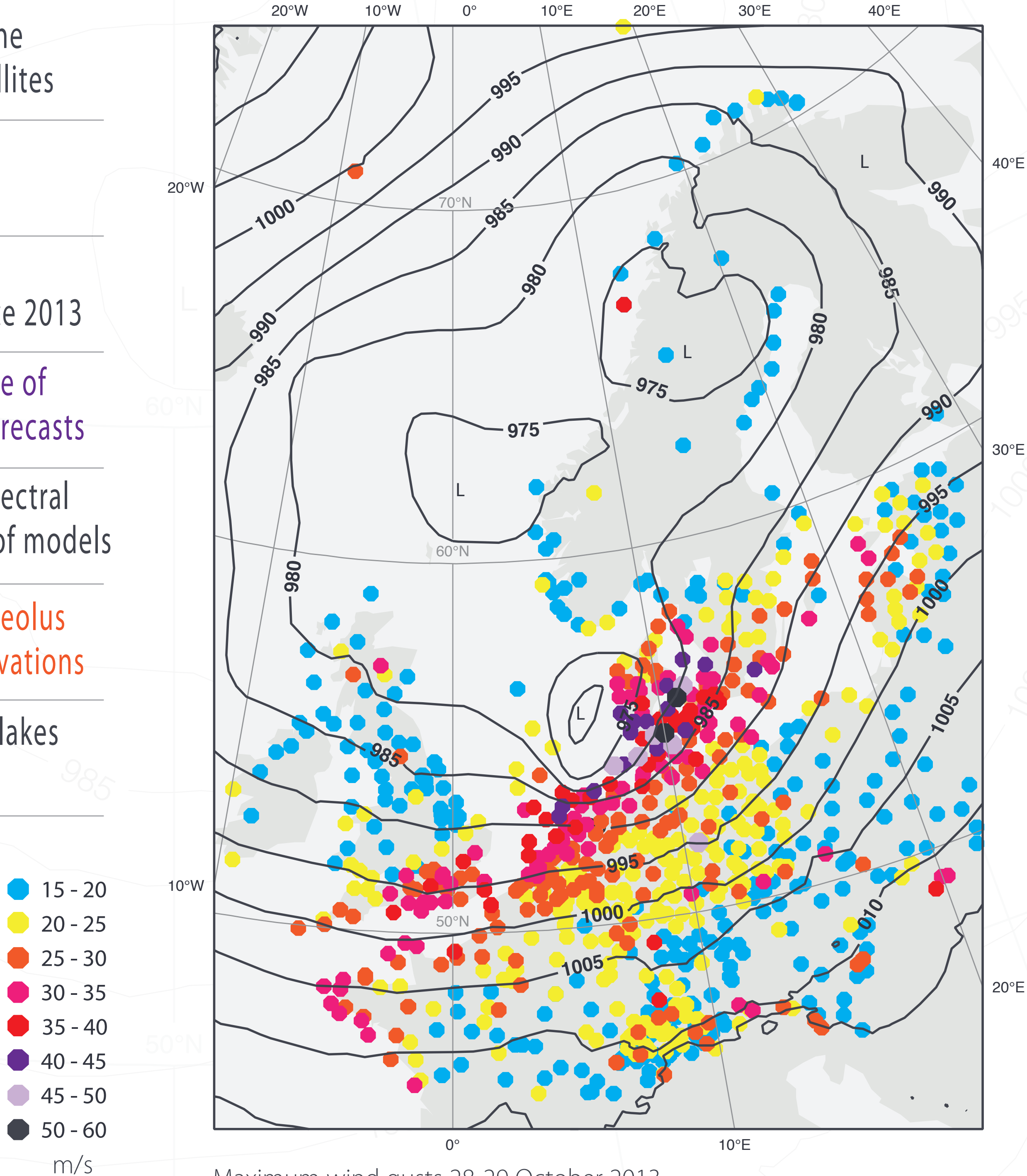
European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme



Maximum wind gusts 28-29 October 2013

Educational Programme 2014

ECMWF

Meteorological Course - Computer Course - NWP Course - Seminar

The contents of these events and the methods of application are on the ECMWF website at http://www.ecmwf.int/newsevents/training/2014/

Use and Interpretation of ECMWF Products

The aim is to assist Member States and Co-operating States in advanced training on the operational aspects of the ECMWF forecasting system.

Applications closed

Use of Computing Facilities

The objective of this course is to introduce users of ECMWF's computing and archive systems to the Centre's facilities, and to explain how to use them.

Deadline for applications: 13 December 2013

Numerical Weather Prediction

There are five modules providing scientific training on a variety of topics including data assimilation, numerical methods for Earth-System modelling, parametrization of subgrid physical processes, predictability and ocean-atmosphere ensemble forecasting.

Deadline for applications: 10 January 2014

Annual Seminar

The topic is "Use of Satellite Observations in Numerical Weather Prediction".

Deadline for applications: To be advertised on the website

The dates of these events are given on page 35 of this newsletter

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GENERAL

PUBLICATION POLICY
The *ECMWF Newsletter* is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States. The *ECMWF Newsletter* is not peer-reviewed.

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Front cover image : Maximum reported wind gusts on 28 to 29 October 2013 associated with wind storm named St Jude (UK), Christian (Germany) and Simone (Sweden), together with the surface pressure for 12 UTC on the 28th.

Number-crunching

The success of ECMWF is a testament to European investment in talented people and also in supercomputer capability. If one looks back over the 38 year history of ECMWF's supercomputing, the comparative numbers are mind-boggling but worth reflecting on.

The first version of ECMWF's global model was run on a CDC6600, which was capable of sustaining about 1 million floating point operations per second (1 MFlop). A single floating point operation is, for example, when two (real) numbers are added together. One might be amazed at a computer being able to manage a million of these a second – especially for those of us of a certain age who learnt arithmetic at school using the then best available technology of a hand-driven mechanical calculator. But even so a ten-day numerical weather prediction took around 12 days to complete its calculations!

The first supercomputer at the ECMWF Shinfield Road site was the Cray-1A which was about 50 times faster than the CDC. It delivered ECMWF's first operational global weather forecast on 1 August 1979. It could sustain 50 million Flops and the ten-day forecast took around five hours to complete. The Cray-1A had a single processor.

At the Centre, as I write this editorial, we are starting to take delivery of our next supercomputer, a Cray XC30. We anticipate that it will have a capability to sustain over 200 Teraflops (200 trillion Flops) running our forecast application. Also it will comprise something like 160,000 processors. One needs to be careful when comparing these figures with those published about computer systems. There are many measures of computer power and often the peak performance is quoted, which is the maximum theoretical speed of the computer but is not relevant for real applications. The peak figures are much larger than those for the sustained power but for ECMWF it is the sustained performance using our codes that really matters.

Of course nowadays there are many more calculations required to create a ten-day numerical weather prediction than back in the 1970s. So the massive increase in computer capacity has enabled us to include much more science and to forecast much greater detail in the weather – today our equivalent mesh on which the calculations are done involves a 16 km by 16 km area (with 137 levels in the vertical). It is expected that our new Cray will enable the Centre to introduce a 10 km grid (and new science) in 2015.

A real question is whether in future we can sustain the investment needed to enable the Centre to have the computer capacity necessary to keep up with scientific advances and with the sort of detail needed by users of weather forecasts?

Alan Thorpe

Florence Rabier – Director of Forecasts

FLORENCE RABIER INTERVIEWED BY BOB RIDDAWAY

What attracted you to making a career in meteorology

When I was young I was good at maths and physics and at one time I thought this might lead to a career in engineering. But that did not really appeal to me. Then my thoughts turned to meteorology. It was the scientific and technical aspects of the subject that attracted me rather than being passionate about the weather. I have no regrets about the choice I made at that young age. To pursue my chosen career I studied at the Ecole Nationale de la Météorologie in Toulouse and then took up a post at Météo-France.

What did you do at Météo-France?

I initially worked on the development of a wave model which eventually became operational. I then gained a Diplôme d'Etudes Approfondies which allowed me to start a programme of research aimed at gaining a PhD. I decided to work on four-dimensional data assimilation and I was fortunate in having the opportunity to work with Olivier Talgrand and Philippe Courtier who have played a leading role in the development of data assimilation, and in particular variational methods. I gained my PhD in 1992 and this was awarded the Prize André Prud'homme by the French Meteorological Society. In 1992 I was delighted to be able to join ECMWF on secondment.

Did you pursue your interest in data assimilation at ECMWF?

Yes I did – I joined the Data Assimilation Section and stayed there for six years. During this period I played a major role in the implementation of a new data assimilation method (4D-Var) in 1997, which was a first worldwide. Also I carried out research into forecast error statistics and the adjoint sensitivity of forecast error to initial conditions. Working at ECMWF was a very enjoyable and satisfying experience, and it allowed me to develop my expertise in data assimilation. But in 1998 the time had come for me to return to Météo-France.

What next at Météo-France?

I joined the NWP Division and concentrated on the use of satellite data, particularly data from the hyper-spectral sounder IASI (Infrared Atmospheric Sounding Interferometer) developed by CNES and EUMETSAT. IASI had been designed to provide operational meteorological soundings of temperature and humidity with a very high level of accuracy specifically to improve medium-range weather forecasts. I was responsible for making preparations for use of IASI data in the forecasting process, and this involved me being the leader of a contract between Météo-France, the Laboratoire de Météorologie Dynamique and EUMETSAT to support this activity.

How did your career progress?

In 2001, I was promoted to be Head of the Observations Section within the Groupe de Modélisation et d'Assimilation pour la Prévision of the Research Department. My main responsibility was developing the use of observations in the NWP models, with emphasis on making full use of new satellite data. Another interesting aspect of my job was being project manager of the OLIVE project for the set-up and management of NWP experiments through an interactive web-based interface, in collaboration with the forecasting and computer departments.

During the nine years as Head of the Observations Section I became increasingly involved in a variety of international activities. For example, I was the Principal Investigator of the Concordiasi project which involved a field experiment in Antarctica dedicated to the validation of the assimilation of IASI data and the improvement of meteorological models in polar areas. Also I was co-chair of the data assimilation and observing strategies working group of the THORPEX (The Observing System Research and Predictability Experiment) programme of WMO.

In 2010 I became Deputy Head of the Groupe de Modélisation et d'Assimilation pour la Prévision. I was then responsible for bringing research through to operational implementation in the NWP models. At the same time I continued my research activities by co-supervising PhD students and Post-Docs on the assimilation of hyperspectral data

Structure of the Forecast Department

The Forecast Department comprises a strong user-focus, with meteorological input to forecast production, forecast evaluation and diagnostics, forecast products and applications, software development, and catalogue and data services.

Production Section

Integrates, tests, implements and supports the operational forecasting system; responsible for the acquisition and pre-processing of observations, and the generation, dissemination and archiving of the Centre's forecast products; develops and maintains production systems for external projects.

Development Section

Develops software for users to process, deliver and visualise ECMWF data, including software for archiving and retrieval of data, product generation and tools for monitoring and product development.

User Support Section

Provides support and advice to users of ECMWF computing, data and software services; responsible for the ECMWF Catalogue, licensing and provision of forecast and archive products; supports Member-States' time-critical work and Special Projects; maintains relevant web-based documentation.

Evaluation Section

Assesses the performance of the ECMWF forecasting system; provides feedback to forecast users and model developers; monitors the forecasts and observing system; carries out in-depth diagnosis of the strengths and weaknesses of the forecasts; responsible for ECMWF's contribution to EFAS (European Flood Awareness System).

from IASI and the Meteosat Third Generation Infra-Red Sounder (MTG/IRS). My international activities also increased with me becoming a member of various international scientific committees, including several WMO Working Groups.

Why did you decide to apply to become Director of Forecasts at ECMWF and what are your priorities?

I have very happy memories of my time at ECMWF so I always thought it would be good to return if the opportunity arose. When the new post of Director of Forecasts was created it seemed to be a natural extension of my work at Météo-France. Not only was I interested in all aspects of the activities of the Forecast Department, but also helping create a new department would be an interesting challenge. I now want to make sure that the new department has a well-defined identity and its members work effectively as a team with a clear sense of direction.

My priority is to establish a strong user-focus and strengthen the capability for diagnostic work. In particular, I want to ensure our forecasting products meet the needs of our Member and Co-operating States, as well as supporting the activities of other service providers. To achieve this there needs to be more interaction with the users and enhanced arrangements for getting feedback about the performance of our forecasts. Also I would like to improve the transition of research developments into operational implementation. I am keen to build upon all the collaborative activities that already take place and further develop links internally within ECMWF and externally with users of ECMWF data and the research community.

What you plan to do is likely to be very demanding, so how do you relax?

I have three children so they help me forget about the stresses associated with a demanding job. Also reading, listening to opera and taking exercise help me relax. But what makes me relax most of all is having exotic holidays and visiting new places. This has led me to have a particular fascination with Asia and in particular Japanese art. Being able to relax is important, but so is feeling that the day job is worthwhile. I am sure my new job is going to be enjoyable, stimulating and rewarding. I think there are exciting times ahead.

New HPC system delivered

Cray delivered the first cluster of ECMWF's new HPC system on the 6 November. A 12 man team from Cray quickly assembled the contents of the 53 crates that had been shipped from the factory in Chippewa Falls, Wisconsin, USA, so that basic hardware testing could start late on the evening of Friday 8 November. Small test machines have been used since July to help ECMWF prepare for the new system. We hope to expedite the complex setup process so that the first users have access to the machine in late November.

Accession agreement between Serbia and ECMWF

BOB RIDDAWAY

Mr Vladan Kocic, Director of the Republic Hydrometeorological Service of Serbia (RHMSS), and Professor Alan Thorpe, Director-General of ECMWF, signed the *'Agreement between the Government of the Republic of Serbia and ECMWF on the accession of the Republic of Serbia to the ECMWF Convention'* in Belgrade on 27 September 2013. The agreement will enter in force after it has been ratified by the Serbian Parliament. Serbia will then officially join the other 20 Member States governing ECMWF and setting its strategic direction.

Commenting on the accession and its benefits to Serbia's economy and its citizens, Vladan Kocic said: *"It is an honour for me to sign the accession agreement with ECMWF, the world's leading centre in global medium-range weather prediction. I would like to express my appreciation to the Centre's Council for the unanimous decision on the accession of the Republic of Serbia to the ECMWF Convention and also to thank the Serbian Government for providing us the necessary support and for recognizing the significance of the accession for the further growth and development of RHMSS.*

The role of RHMSS in disaster risk reduction becomes all the more important taking into consideration historical data showing that the frequency and intensity of meteorological and hydrological disasters in Serbia are increasing. The share of disasters of hydrometeorological origin in the total number of catastrophes in Serbia is similar to that on a regional and global scale (around 90%).The RHMSS will use the Centre's products in particular for early warnings of extreme weather events, such as storms, heavy precipitation and heat waves. The Centre's products are vital to enable us to prepare for and respond to those events and thereby saving lives and reducing economic damages."

Signing the accession agreement between Serbia and ECMWF. The accession agreement was signed by Alan Thorpe (Director-General of ECMWF) and Vladan Kocis (Director of RHMSS) at the headquarters of RHMSS in Belgrade on 27 September 2013.

Alan Thorpe said: *"I am extremely pleased that following today's signature, the Republic of Serbia will soon become a Member State. Serbia will then be a full voting member of the ECMWF Council. A portion of the Centre's supercomputer time and archive resources will be allocated to the Republic of Serbia for its own use. Public Services in Serbia will have access to all ECMWF products and tools. I am particularly looking forward to the collaboration with our colleagues in Serbia for the mutual benefit of both the RHMSS and ECMWF."*

A reanalysis tale on the Earth's climate

MAGDALENA BALMASEDA, ERLAND KÄLLÉN

Over the second half of the 20th century, increasing greenhouse gas concentrations have led to a visible warming of sea surface temperature, most pronounced since 1975 onwards. Starting in 2004, however, that warming seemed to stall. Researchers measuring the Earth's total energy budget (i.e. the balance of radiation streaming in compared to the amount of radiation leaving from the top of the atmosphere) saw that the planet was still holding on to more heat than it was letting out. But with that energy not going into warming the surface ocean, a traditionally important energy sink, scientists were not sure where it went. It became known, in some circles, as a case of 'missing heat' or 'warming hiatus'.

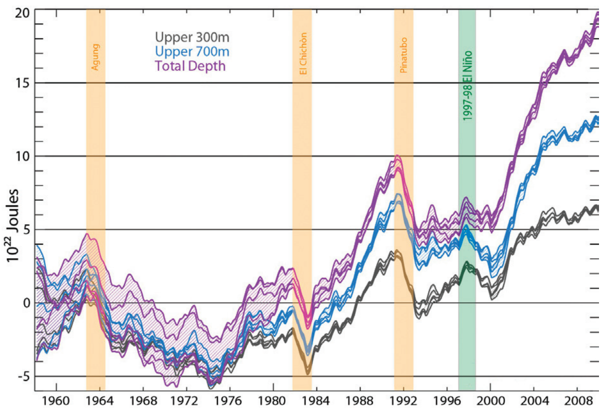
The ECMWF Ocean Reanalysis System 4 (ORAS4) has provided an interesting perspective on the origin of the 'warming hiatus'. It was produced by combining, every ten days, the output of an ocean model subject to surface forcing from atmospheric reanalysis and quality controlled ocean observations. This approach provides a continuous record of the global ocean. Five ensemble members were used to sample uncertainties in the wind forcing, observation coverage and deep ocean. For more information about ORAS4 see *ECMWF Tech. Memo No. 668* and *Q. J. R. Meteorol. Soc.*, 2013, **139**,1132–1161.

The figure shows the time evolution of the global ocean heat content (OHC) at three depth ranges (upper 300 metres, upper 700 metres and total column) as represented by the five ensemble members. Throughout the observational record the warming of the surface ocean has stalled before because of large volcanic eruptions (El Chichón in 1982 and Pinatubo 1991) and swings of the El Niño-Southern Oscillation (like the 1997/98 event). In recent years the deep ocean has continued to warm, while the OHC of the upper 300 metres appears to have stabilised. The differences in trends amongst the various ocean layers are profound. After the onset of the 1998/99 La Niña, there has been continuing warming for the ocean as a whole with considerable warming occurring below 700 metres and small warming in the upper 300 metres. In the last decade about 30% of the warming has occurred below 700 metres.

Additional experiments indicate that changes in surface wind patterns are an important factor in driving ocean heat content from the surface layers to the deep ocean. This illustrates the importance that the wind information provided by atmospheric reanalyses (*Q. J. R Meteorol. Soc*, 2011, **137**, 553–597) has for the simulation of the ocean circulation. Besides, the deep ocean warming appears robust even when the Argo observing system (i.e. the free-drifting profiling floats that measure the temperature and salinity of the upper layers of the ocean) is withdrawn from the ocean reanalysis.

The results of this study can explain why the sea surface temperature increases stalled in the 2000s. In addition, it highlights the importance of detecting, understanding and modelling the processes that lead to the vertical distribution of heat in the ocean for making decadal predictions.

More information about the results of this study can be found in the article '*Distinctive climate signals in reanalysis of global ocean heat content*' by Magdalena Balmaseda, Kevin Trenberth and Erland Källén which has been published in *Geophysical Research Letters* (2013, **40**, 1754–1759).
The publication date of the study was too late for it to be included in the most recent IPCC report from Working Group I which assessed the physical scientific aspects of the climate system and climate change. However, the article has received considerable attention from scientists and the media as well as the blogosphere. This clearly shows the emerging importance of reanalysis products from ECMWF for climate monitoring and understanding of climate change processes.



Variation of the monthly anomalies OHC from three depths from ORAS4. Shown is the OHC anomalies, with respect to the 1958–1965 base period, integrated over the upper 300 metres, upper 700 metres and total column as represented by the five member ensemble. The vertical coloured bars indicate a two-year interval following the volcanic eruptions and the 1997–1998 El Niño event. A version of this figure was published by AGU: *Geophysical Research Letters*, 2013, **40**, 1754–1759. Copyright (2013) American Geophysical Union.

New look for the NWP training course

SARAH KEELEY

We are making some changes to the numerical weather prediction course for 2014.

'*Numerical methods, adiabatic formulation of models and ocean wave forecasting*' will be replaced with '*Advanced numerical methods for Earth-System modelling*'. This new module will focus on recent advances and future challenges in high-resolution numerical modelling of the atmosphere and ocean. The module will consider various approximations to the fully-compressible Euler equations, different horizontal and vertical discretisations and different time-integration schemes, with a particular focus on accuracy and efficiency of the numerical techniques on the massively parallel computer architectures expected in the future. Coupled processes within Earth System models will also be discussed, including atmosphere-wave-ocean processes and atmospheric chemistry.

Another newly-formulated module this year will be Data Assimilation. In the past this lasted eight days and included discussion on the use of satellite data. The new five-day module will be focused on describing data assimilation methods and general aspects of assimilating observations. The very successful ECMWF/EUMETSAT NWP-SAF Satellite Data Assimilation course, which ran for the first time last year, will be extended to five days and run straight after the Data Assimilation module so that participants can attend both events if they wish.

Numerical Weather Prediction Course for 2014

The five modules that comprise the NWP course are:

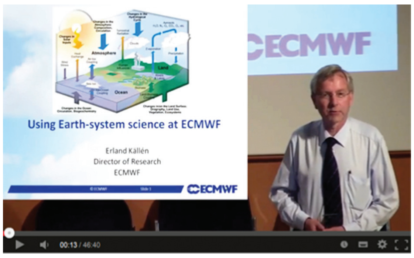
- Data assimilation (10–14 March)
- ECMWF/EUMETSAT NWP-SAF satellite data assimilation (17–21 March)
- Advanced numerical methods for Earth-system modelling (24–28 March)
- Parametrization of subgrid physical processes (31 March–10 April)
- Predictability and ocean-atmosphere ensemble forecasting (7–16 May)

Information about these modules will be available from:

http://www.ecmwf.int/newsevents/training/

Using Earth System science at ECMWF

ERLAND KÄLLÉN



Erland Källén, Director of Research, gave a lecture at ECMWF about *'Using Earth System science at ECMWF'* in July 2013. The lecture is available on the Internet via YouTube at www.youtube.com/watch?v=pCHRWuXgRHQ. The following are some of the key points made during the lecture.

Forecast models at ECMWF are incorporating Earth System components in order to increase the realism of the models and to improve forecast skill. Since the 1990s an ocean surface wave model has been coupled to the atmospheric forecast model, both to produce high quality ocean wave forecasts and to improve the modelling of low-level atmospheric flows over the world oceans. For longer-range forecasts, beyond the chaotic predictability limit of two weeks, a full ocean circulation model is necessary as the memory time of the ocean is much longer than the memory time scale of the atmosphere. In the present monthly and seasonal forecasting systems an ocean model is coupled to the atmospheric model after ten days. In the near future we will couple the ocean with the atmosphere already from day zero. In particular for tropical regions the influence of ocean surface conditions is important for atmospheric flows even on time scales of a few days.

Another area of development is the modelling of atmospheric composition. Greenhouse gases and aerosols in the atmosphere clearly have the potential to influence weather forecast skill, mainly through their effect on radiative energy fluxes. In order to include atmospheric constituents in a weather forecast model both data assimilation and a forecast model for atmospheric composition is required. Such a forecasting system has been developed at ECMWF over the past ten years and it will gradually be merged with the operational weather forecasting system. Forecasts of pollution events and greenhouse gas concentrations require a tight link between the modelling of the evolution of the weather and the atmospheric composition as well as an accurate description of sources and sinks of chemical compounds in the atmosphere.

Climate monitoring is a research and development area that has been pursued at ECMWF for several decades in the form of atmospheric reanalyses. Historic observations of temperature, pressure, winds, humidity etc. have been assimilated in a state-of-the-art analysis and forecasting system in order to produce a spatially and temporally homogeneous data record. This data set is used both as a benchmark against which new forecast model and data assimilation developments can be tested as well as a climate monitoring tool. The present main atmospheric reanalysis, ERA-Interim, goes back to 1979 and has been shown to accurately describe climate trends over the past decades. For a longer climate record, covering the whole 20th century, the oceans also need to be included. A separate ocean reanalysis has been produced for the time period 1960 to present and current research efforts are directed towards a fully-coupled atmosphere-ocean-land surface reanalysis covering the 20th century up to the present.

To fully understand global climate change related to increasing levels of greenhouse gases and aerosols in the atmosphere we need a comprehensive Earth System model including all the main processes that influence global climate. A recent example emphasising the need for such a system is the so called warming hiatus, i.e. that global surface mean temperatures have remained approximately constant over the past 15 years or so despite the ever increasing levels of carbon dioxide and other man made greenhouse gases in the atmosphere. Looking at the Earth System, instead of just focussing on surface temperatures, a better understanding can be achieved of how the warming induced by greenhouse gas increases is distributed within the Earth System. Recent results indicate that the surface warming hiatus can be explained by an increased heat uptake by the tropical oceans and increased heat content in deeper ocean layers.

An assessment of solar irradiance components produced by the IFS

ALBERTO TROCCOLI[1],
JEAN-JACQUES MORCRETTE[2]

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[2]*European Centre for Medium-Range Weather Forecasts, Reading, UK*

Since the introduction of cycle 37r2 on 18 May 2011, the Integrated Forecasting System (IFS) produces diagnostics of the direct solar radiation at the surface in addition to the surface net and downward solar radiation which were already available. This new quantity is of great interest to the solar power industry and potentially to other user groups (e.g. agriculture). It should be stressed that in other scientific communities:

- The downward solar radiation at the surface (i.e. the incident solar radiation) is called global horizontal irradiance (GHI).
- The direct solar radiation at the surface is called direct horizontal irradiance (DHI).

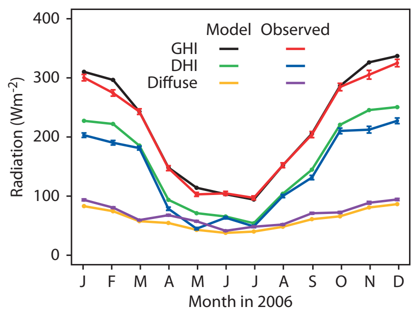
The diffuse component is obtained as the difference of the two, namely GHI–DHI. In this article the terms GHI and DHI will be used.

Before its introduction into the

operational IFS, an assessment of GHI, DHI and the diffuse components, forecast out to 5 days, was carried out with one year (2006) of observations collected by the Australian Bureau of Meteorology (*Troccoli & Morcrette*, 2012: Forecast assessment of surface solar radiation over Australia, *World Renewable Energy Conference*, Denver, USA). Measurements are made following the specifications of the Baseline Surface Radiation Network (BSRN). The 30-minute averages are used for our assessment of the three solar irradiance components, although 3-hourly means are constructed from these observations in order to match the temporal resolution of the model output.

Here we show a summary of that study concentrating on monthly means at the Adelaide station for which the dataset was the most complete, including some aerosol measurements. The IFS performance at many other Australian stations has been assessed. The assessment for four of these, including Adelaide, is discussed in *Troccoli & Morcrette* (2012). It should be noted that direct irradiance forecast for Adelaide, given its coastal location and the influence of a strong mid-latitude circulation, can be challenging (see below). The forecast model was run at a T255 L91 resolution (corresponding to a horizontal grid of about 80×80 km^2) for five days at 3-hourly intervals over the whole year 2006.

The first figure presents the monthly averages of the three components



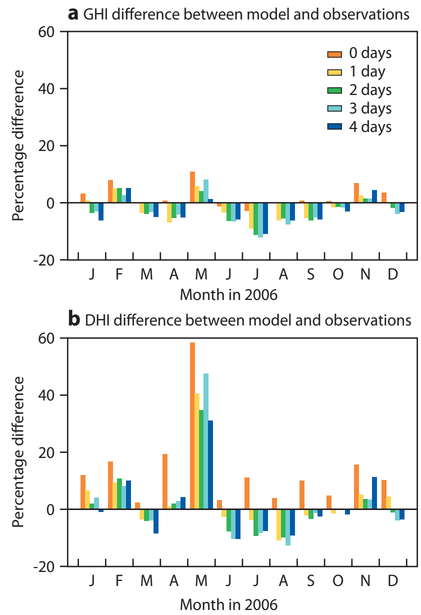
1 Comparing the model solar radiation with the observations. There is a close agreement between the model quantities and the observations as shown by the monthly averages of the three components of solar radiation (global GHI, direct DHI and diffuse) for both observations (with error bars) and the ECMWF model for Adelaide in 2006.

of solar radiation (global, direct and diffuse) for both observations (with error bars) and the ECMWF model for Adelaide in 2006. It shows that the modelled GHI is in close agreement with the observations; it is within the observed GHI error bars for all but the extended summer months (November to February) and May. The monthly relative biases are normally only a few percent, with Adelaide (shown here) displaying the larger relative errors. In this comparison, no attempt is made to account for the representativeness error due to the model data representing an average value over an area of about 6,400 km^2 whereas the ground station observation essentially samples a point within that area. The performance is notable considering this representativeness error of the model data.

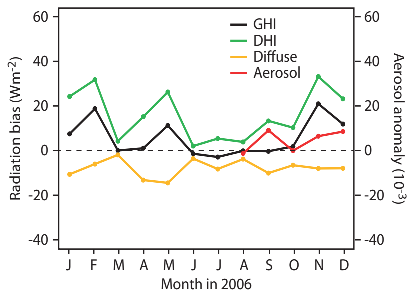
The percentage difference of monthly averages between the ECMWF model and observations for GHI for various forecast lead times is given in the upper panel of second figure. Even at day 5, the error rarely reaches 5%. The agreement is less striking in the case of DHI shown in the lower panel – generally DHI is overestimated and accompanied by an underestimated diffuse component. Given the smaller magnitude of DHI and its larger absolute error compared to GHI, the relative error of DHI is considerably larger than that of GHI and often larger than 10%. This translates in relative differences of up to 20%, with the exception of May when the error is close to 60% – see the lower panel of the second figure.

In the results presented here, the model utilises climatological values for the aerosol optical depths. In order to assess whether the deficiencies in the surface solar radiation may be attributable to the lack of a proper aerosol representation in the model, the monthly solar irradiance biases for GHI, DHI and diffuse are plotted in the third figure together with the aerosol optical depth (AOD at 500 nm) for Adelaide for the months (August to December) when this quantity was available. The AOD appears correlated with the bias in DHI.

Accounting for a positive anomaly in aerosol loading within the solar radiation scheme of the model should lead to a reduction in the DHI and in the DHI positive error. Such information is now available within the MACC (Monitoring Atmospheric Composition and Climate) system run at ECMWF. Consequently, work is being carried out to explore potential improvements in GHI and DHI linked to using AODs from MACC.



2 Assessing the relative difference between modelled and observed GHI and DHI for different lead times. (a) The percentage difference of monthly averages of GHI between the ECMWF model and observations for various forecast lead times. (b) As (a) but for DHI. Note that for GHI the relative error rarely reaches 5% whereas for DHI the relative error is considerably larger.



3 Investigating whether deficiencies in DHI may be attributable to the lack of a proper aerosol representation. Shown are the monthly biases (model minus observed) for the three components of solar radiation (global GHI, direct DHI and diffuse) for 2006 along with the aerosol optical depth (AOD) at wavelength 500 nm expressed as an anomaly for Adelaide for August to December. The AOD appears correlated with the bias in DHI.

MACC-II Summer School 2013

VINCENT-HENRI PEUCH

Interacting with users and providing training for them is integral part of MACC-II, the project in charge of developing and providing the range of pre-operational services of the European Copernicus programme on the composition of the Earth's atmosphere (see http://atmosphere.copernicus.eu and *ECMWF Newsletter No. 132*, 20-25).

MACC-II is operated by a consortium of 36 partners from 13 countries, led by ECMWF. It is expected that the Copernicus programme will enter its operational phase in 2014, following the agreement this summer by the EU Council and Parliament to include it in the scope of the European Commission's Multi-annual Financial Framework until 2020.

The MACC-II summer school took place between 9 and 15 June in Anglet, France, with Claire Granier (Université Pierre et Marie Curie, Paris, France) as the main organiser. Over 130 people had applied to attend the school, but finally we managed to host 62 participants from 23 countries. Such wide interest was not a surprise, considering the growing number of users of MACC-II as well as the fact that atmospheric composition is a major factor for many important environmental issues (e.g. air quality, greenhouse gases and other climate forcers, aerosol or the ozone hole).

The programme had three main components.

- A set of keynote lectures to provide background scientific and technical information on the range of MACC-II services. Participants had the opportunity to engage with some of the most renowned European scientists in the related domains.
- Working groups to provide opportunities for more interaction in order to address especially technical aspects (e.g. formats and data handling) and share information.
- Work in small groups to review the various sections of the current MACC-II website, provide recommendations for improving them and prepare material for Frequently Asked Questions.

A questionnaire was used to review participants' satisfaction.

- 92% gave an overall rating of four or more out of five (very good to excellent) for the extent to which the training had met their expectations.
- 84% indicated that the lectures will help them better carry out their work and most comments suggested expanding some aspects, such as health, European policies or technical data issues.
- 60% found that the duration of 7 days was appropriate, while 31% indicated that a slightly longer period would have been better.

Participants of the MACC-II summer school. The 62 participants from 23 countries were principally current users of MACC-II services, professionals expecting to use MACC-II services in the near future, as well as young engineers and scientists.

The high number of applications together and this very good feedback clearly indicate that such a format for training is appropriate and point towards organizing something similar in the future, possibly every other year, funding permitting.

The keynote lectures have been recorded and the associated videos and slides constitute the core of the e-training material that MACC-II is now making available on its website:

http://www.copernicus-atmosphere.eu/events/summerschool/

World Weather Open Science Conference

The overarching theme of WWOSC 2014 is *'Seamless Prediction of the Earth System: from minutes to months'*. ECMWF is involved with this ground-breaking conference, which will bring together the entire weather science and user communities for the first time to review the state-of-the-art and map out the scientific frontiers for the next decade and more. This promises to be a once in a generation event.

The Conference is structured around two programmes:

- The science programme will cover basic weather research that extends our knowledge of processes and systems as well as the applied research needed to put prediction systems together and assess the impacts of weather and climate events.
- The user, application & social science programme will consider the goods and services economy and the role of Government in disaster risk reduction and management and the communication of weather information.

You can get more information by visiting the conference website at:

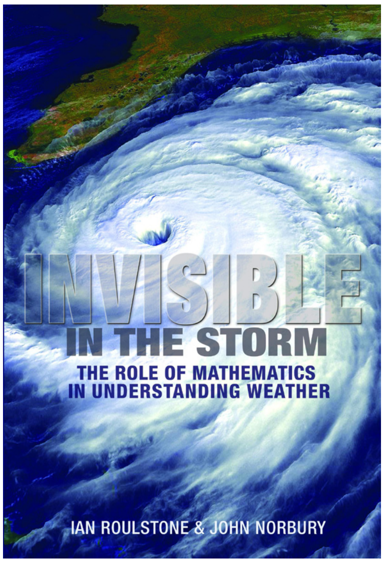
http//:www.wwosc2014.org

The role of mathematics in understanding weather

ERLAND KÄLLÉN

A book on the mathematics of numerical weather prediction has recently been published by Princeton University Press – it is called '*Invisible in the storm: The role of mathematics in understanding weather*' and is written by Ian Roulstone at the University of Surrey and John Norbury at Oxford University. The main theme of the book is to describe the historical evolution of mathematical models for weather prediction over the last century and ECMWF has a prominent place in the book. Some of the background material and many of the illustrations have been provided by ECMWF staff.

The book gives an excellent description of the revolution in meteorology that took place in the early 20th century.



Bjerknes original formulation of the equations governing the weather and Richardson's first heroic attempt at actually calculating a weather forecast is vividly described. The book goes on to discuss the pioneering work of Rossby in the 1920s and 1930s as well as the first computer based forecasts produced by Charney and co-workers in Princeton in the early 1950s. Chaos theory and the limits of atmospheric predictability is also well described, very much centred on Lorenz's landmark papers in the 1960s. The appearance of ECMWF around 1980 meant that forecast quality was moved to a new, higher level and the addition of probabilistic forecasts in the 1990s has contributed to ECMWF maintaining a world leading position in numerical weather prediction.

Even if the book is written by two mathematicians it contains very few equations and it is accessible for non-specialists. Much of the reasoning is centred on a physical understanding of the processes involved, in particular the approximations that are necessary in order to formulate a model that can be handled on a computer.

I really enjoyed reading the book and I would recommend it to specialists who want to get an overview of the history of numerical weather prediction. I think it is also well worth reading for anyone who wishes to understand the developments in the science of meteorology that has led to the present level of forecast skill.

Impact of the Metop satellites in the ECMWF system

SEAN HEALY, STEVE ENGLISH, TONY MCNALLY, ENZA DI TOMASO, GIOVANNA DE CHIARA

Recent experiments performed by the satellite section have highlighted the importance of the European Metop-A and Metop-B satellites in the ECMWF Integrated Forecasting System (IFS). Most significantly, the new results show that the combined impact of both Metop-A and Metop-B is superior to assimilating just the instruments on Metop-A. These results are important because they support the case for maintaining both Metop satellites in tandem for as long as possible.

The Metop-A and Metop-B satellites were launched on 19 October 2006 and on 17 September 2012, respectively. The satellites have the same mid-morning orbit, but are separated by 173.8 degrees in their orbital plane, leading to a 49 minute temporal separation. Metop-B is now formally the operational satellite, but Metop-A continues to provide a range of important measurements for operational NWP. The Metop payload includes the following meteorological instruments, providing temperature, moisture and lower level wind information:

- The microwave sounders AMSU-A and MHS.
- The infrared sounder, HIRS.
- The advanced infrared sounder, IASI.
- The radio occultation instrument, GRAS.
- The advanced scatterometer, ASCAT.

In operations ECMWF currently assimilates all of these instruments on Metop-A, and AMSU-A, MHS, GRAS and ASCAT from Metop-B. The operational assimilation of Metop-B IASI is being assessed.

In addition, the Metop satellites include the AVHRR high-resolution imager, which can also be used to retrieve atmospheric motion vector wind information, and GOME-2 for observing ozone. However, these instruments are not considered in this study because they are not currently assimilated operationally at ECMWF.

It should be emphasised that the AMSU-A, MHS and HIRS sounders, which form the ATOVS system, remain important for NWP, despite the introduction of new, more sophisticated instruments. AMSU-A, in particular, is still considered one of the most important systems, and the assimilation of new AMSU-A instruments generally still has a clear positive impact on forecasts.

Although the assessment of the impact of the individual instruments on a satellite is a routine activity within ECMWF, usually conducted prior to operational assimilation of the data, it is much rarer to subsequently investigate the combined impact of an entire satellite. The experiments for this Metop study cover an extended 144 day period, from 1 February 2013 to 24 June 2013. They use 12-hour 4DVAR with the current operational IFS cycle, Cy38r2, with a horizontal resolution of T511, and 137 levels in the vertical. The following configurations have been tested:

- Baseline: All observations assimilated operationally during this period except the measurements from Metop-A and Metop-B.
- Baseline plus Metop-A instruments.
- Baseline plus Metop-A and Metop-B instruments.

The baseline configuration still assimilates data from around 40 satellite instruments, including those on the United States polar satellites, and it represents a good, data rich observing system despite the removal of the Metop satellites.

In general, the data from Metop-B instruments are assimilated in the same way as for Metop-A but with the following main exceptions: Metop-B HIRS is not used currently, and AMSU-A channel 7 is assimilated from Metop-B but not from Metop-A because it is malfunctioning. The latter is significant because it has been demonstrated that the availability of channel 7 on Metop-B AMSU-A is a factor in determining the positive impact of this instrument. The Metop-B AMSU-A, MHS and ASCAT measurements have been assimilated for the entire duration of the experiments, whereas Metop-B IASI and GRAS measurements are assimilated from 20 February 2013 and 25 March 2013, respectively, because of the availability of the measurements.

As the number of satellite instruments has increased, and the resilience of the ECMWF NWP system has improved, it has become increasingly difficult to demonstrate the impact of individual satellite instruments on forecast scores quantitatively, with statistical significance. However, in contrast the suite of instruments on the Metop satellites have a clear, statistically significant impact on 500 hPa geopotential height scores for the northern and southern extratropics in the short and medium range. Figure 1 shows the fractional reduction in the root-mean-square error of 500 hPa geopotential height at days 1, 3 and 5 as a result of adding Metop-A and both Metop-A and B to the baseline system. The results are verified against the ECMWF operational analyses, but verifying against radiosonde observations also gives a statistically significant positive impact. Similar results to those shown for 500 hPa geopotential height are also obtained for other variables, such as mean-sea-level pressure and low level winds.

As with most satellite data, the impact is larger in the southern hemisphere because the in-situ observation network is much better in the north. Although the impact of adding the second satellite is smaller than the first, the additional improvement is statistically significant at the 95% level at days 1 and 3 in both hemispheres, and at day 5 in the northern hemisphere. The impact into the medium-range is a significant result.

While it might have been anticipated that the combined impact of Metop-A and B should be superior to the

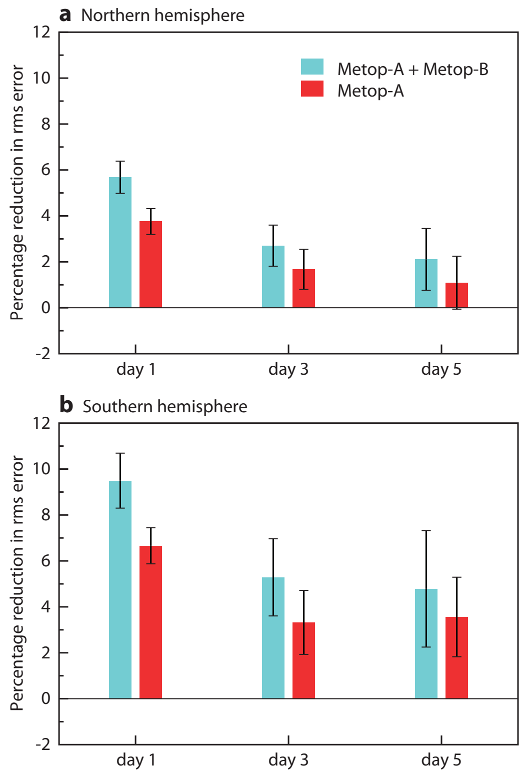


Figure 1 Impact of adding Metop satellites to the baseline system. Shown is the percentage reduction in root-mean-square (rms) error of the 500 hPa geopotential height at days 1, 3 and 5 in the (a) northern and (b) southern hemisphere extratropics as a result of assimilating just Metop-A and both Metop-A and Metop-B. The error bars are the 95% confidence interval, and represent the statistical significance of the improvements with respect to the 'no Metop' baseline experiment.

'no Metop' baseline, the fact that the two satellites produce a statistically significant impact when compared to one was not obvious prior to this experimentation, particularly given that they share the same orbit. We have not attempted to apportion this combined impact to the various instruments on Metop-B. However, we suspect it represents the accumulation of smaller positive impacts, because the impact of the individual instruments found in preoperational testing is smaller than is shown in the figure. For example, in the preoperational testing, the combined impact of Metop-B AMSU-A and MHS on the day-1 root-mean-square error for 500 hPa geopotential height was a statistically significant improvement, but it was about half the total Metop-B impact shown in the figure. However, it should also be noted that the Metop-B AMSU-A and MHS testing was for a different period.

Overall, the results are very encouraging. At the very least, we would have hoped that the availability of two Metop satellites would make the global observing system more robust through redundancy, by providing like-for-like replacements in the event of instrument failure. However, the results suggest a far more positive scenario.

In summary, having measurements available from two Metop satellites has a clear, statistically significant impact on the forecast skill of the ECMWF system.

Ocean Reanalyses Intercomparison Project (ORA-IP)

MAGDALENA A. BALMASEDA, FABRICE HERNANDEZ, TONG LEE, ANDREA STORTO, MARIA VALDIVIESO, KIRSTEN WILMER-BECKER

Several ocean reanalyses products are produced worldwide with different purposes and methodologies. The joint GODAE OceanView/CLIVAR-GSOP workshop in Santa Cruz (13-17 June 2011, *Oke et al.*, 2011) called for a community action on exploitation of the latest ocean reanalyses for real time climate monitoring and intercomparison. The first stage would be to complete an Ocean Reanalysis Intercomparison Project (ORA-IP), although the ultimate goal would be near real-time monitoring of the ocean through indices based on an ensemble of reanalyses.

A viable proposal was put forward in Santa Cruz, based on the criteria of minimum effort. The following procedure was proposed.

- **Production centres, including operational and reanalysis centres**. These would provide relevant information (i.e. gridded fields of basic primary variables) in agreed formats and grids (where applicable) to enable the agreed intercomparison procedure.
- **Processing centres**. For intercomparison purposes each processing centre would take on a particular variable in which it has a strong interest and expertise.

They would process ensemble statistics based on the input from the individual production centres, and create relevant indices or metrics or graphics which could be directly compared.

The ORA-IP workshop at ECMWF

The ORA-IP initiative proposed in Santa Cruz achieved enough momentum: (a) relevant ocean variables and responsible processing agents (de facto, individuals that volunteered to do the work) were identified, (b) the processing agents produced documents for specific data requests, grids and format, and (c) different production centres provided the data in the requested format. It was time then to assess progress and discuss the way forward, and to this end a workshop was held at ECMWF from 1 to 3 July 2013.

By the time of the workshop at ECMWF, the scope of the intercomparison exercise was the understanding of the consistency and differences between the reanalysis products, the evaluation of fit-for-purpose, and the exploitation of this variety of reanalysis using the ensemble approach. The intercomparison targeted various areas.

Ocean variable	Responsible agent	Institution
Steric height	Andrea Storto	CMCC, Italy
Sea level	Fabrice Hernandez	Mercator-Océan, France
Ocean heat content	Matthew Palmer	Met Office, UK
Depth of 20 degree isotherm	Fabrice Hernandez	Mercator-Océan, France
Mixed layer depth	Takahiro Toyoda	MRI-JMA, Japan
Salinity	Li Shi	BMRC, Australia
Surface fluxes and transports	Maria Valdivieso	University of Reading, UK
Atlantic meridional overturning at 26°N	Vladimir Stepanov & Keith Haines	University of Reading, UK
Sea ice	Gregory Smith	Environment Canada

Table 1 List of ocean variables intercompared.

- Routine monitoring of indices of societal relevance with uncertainty estimates using the ensemble.
- Production of robust data sets for understanding the ocean and for initializing and evaluating decadal prediction and IPCC models.
- Recommendations for future reanalyses production by identifying the weaknesses of existing approaches and the suitability of the ensemble approach.

The workshop format consisted of presentations by the various processing agents on the different variables, followed up by in-depth discussion of the results. Table 1 provides a list of the variables chosen for intercomparison, along with the responsible agent. The different ocean reanalyses included in the study appear in Table 2.

The following outcomes were expected.

- Specific recommendations on how to finalize the intercomparison of the chosen ocean variables (i.e. those listed in Table 1).
- Recommendations on how to make the results and data accessible to the wide climate community.
- Recommendations on how to improve the ocean observing system, assimilation methods, models and surface fluxes.

The various points were discussed in two working groups, which provided recommendations in a final plenary session.

AFFILIATIONS

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Maria Valdivieso, Department of Meteorology, University of Reading, UK

Kirsten Wilmer-Becker, GODAE OceanView, Met Office, Exeter, UK

Recommendations

The recommendations were structured in two big themes: (a) how to finalize the current intercomparison in the short term and (b) how to exploit further the ocean reanalyses (in the medium term). The importance of using reanalysis for real-time climate monitoring was acknowledged during the workshop, but not discussed explicitly. It was considered that the recommendations for two themes provided guidance and infrastructure on how to extend the intercomparison to eventual real-time monitoring.

Theme I: How to finalize the current intercomparison?

- The current intercomparison should be finalized, including the minimum base period 1993-2009. There should also be a focus study on the 2004-2009 Argo period.
- The intercomparison should include an evaluation of the ensemble mean, spread and signal-to-noise ratio for mean, seasonal cycle, interannual variability and trends.
- The ORA-IP results should be ready for presentation in the GODAE OceanView Symposium (November 2013).
- The ORA-IP initiative and results should be announced in CLIVAR Exchanges.
- The ORA-IP results should be published in a special issue of a peer-reviewed scientific journal in order to reach the wider oceanographic and climate community.

Theme II: How to exploit ensemble of ocean synthesis products further?

- Interaction with the user community should be promoted. Climate scientist, seasonal and decadal forecasts community are users of ocean reanalysis products. The reanalysis can be used for process studies, for validation of climate models, and for initialization and verification of long lead forecasts.
- The ORA-IP variables should be archived in a public data repository, including ensemble means and spreads, in the grid used for the intercomparison (1°×1° latitude/longitude regular grid) and in an user-friendly grid and format (netcdf CF-compliant format). An ORA-IP version number should be part of the metadata. The version number is important if we want to trace progress between subsequent ORA-IP, including improvements in the observing system and in the assimilation methods. Signal-to-noise ratios on different time scales are essential information to assess the adequacy of variables for process studies, forecast initialization, forecast verification and monitoring of climate indices. A public archive will benefit the interaction with the user communities.
- In addition to the ORA-IP ensemble mean and spread upon the overlapping 1993–2009 period, it would be desirable to archive the individual reanalysis products in the same grid and format, although this may not be easy in a first instance due to data policy issues.
- The information in current public web pages such as reanalysis.org and EasyInit should be as comprehensive as possible and kept up-to-date.

Product	Institution
CFSR	NCEP, USA
GODAS	NCEP, USA
Glosea5	Met Office, UK
ORAS4	ECMWF, UK
PEODAS	BMRC, Australia
GLORYS	Mercator-Océan, France
C-GLORS	CMCC, Italy
UR025.4	University of Reading, UK
GEOS5	NASA/GMAO, USA
ECDA	GFDL, USA
SODA	University of Maryland, USA
ECCO-NRT	NASA/JPL, USA
ECCO-v4	NASA/JPL, USA
GECCO2	Hamburg University, Germany
MOVE-C	MRI/JMA, Japan
MOVE-G2	MRI/JMA, Japan
MOVE-CORE	MRI/JMA, Japan
K7-ODA	JAMSTEC, Japan
K7-CDA	JAMSTEC, Japan
ARMOR3D	CLS, France (T/S & SLA)
NODC	NOAA, USA (T/S only)
EN3	Met Office, UK (T/S only)
LEGOS	LEGOS, France (SLA only)

Table 2 List of ocean reanalysis products entering the intercomparison. The product in green is an ocean-only simulation (i.e. it does not assimilate ocean observations) and those in blue are observation-only products (i.e. they do not use an ocean model) using temperature and salinity profiles (T/S) and/or sea level anomalies (SLA).

- Interaction with the Working Group for Ocean Model Development (WGCMD) in the area of model evaluation and metrics should be encouraged.
- Interaction with the observation community should be encouraged to (a) improve the observation quality control and (b) obtain guidance regarding observation uncertainty. The result of this interaction should be improved and consistent quality controlled data sets for assimilation and better formulation of the observation errors in the data assimilation.

FURTHER READING

Oke, P., M. Martin, M.A. Balmaseda, G. Brassington & K. Wilmer-Becker, 2011: *Report on the GODA Ocean View - CLIVAR GSOP Workshop on Observing System Evaluation and Intercomparison.* https://www.godae-oceanview.org/outreach/meetings-workshops/task-team-meetings/godae-oceanview-gsop-clivar-workshop/

Forecast performance 2013

THOMAS HAIDEN, DAVID RICHARDSON

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

The overall performance of the operational forecasts is summarised using a set of headline scores endorsed by the TAC, which highlight different aspects of forecast skill. Upper-air performance of the high-resolution forecast (HRES) in the extra-tropics is monitored through the anomaly correlation of 500 hPa geopotential. In 2013, HRES skill has further increased relative to ERA-Interim, which is used a reference to mitigate the effect of inter-annual atmospheric variability (see article by *Thorpe et al.* on page 15 of this edition of the *ECMWF Newsletter*). In the case of the ensemble forecast (ENS), where a similar reference does not exist, forecasts from other centres, available from the TIGGE archive, are used for comparison. Verification results for the probabilistic forecasts of 850 hPa temperature (the second upper-air headline score) show that ECMWF has maintained its lead over the other centres. The headline scores for precipitation also indicate an improvement of the HRES and ENS compared to the benchmark systems.

The two supplementary headline scores that address forecast skill for severe weather are the HRES tropical cyclone position error at forecast day 3 and the Extreme Forecast Index (EFI) skill of 10-metre wind speed at forecast day 4. The tropical cyclone position error has further decreased and reached its lowest value so far. The EFI skill of 10-metre wind speed has slightly dropped in 2013 but remains at a high level compared to the last ten years as shown in Figure 1. There is no available benchmark for the EFI so it is difficult to account for year-to-year variations in atmospheric predictability.

ECMWF continues to develop verification procedures appropriate for severe weather events. The skill of HRES in predicting extreme 10-metre wind speeds has recently been evaluated using the Symmetric Extremal Dependency Index (SEDI) which has been designed specifically for verification of rare events. Figure 2 shows that the operational forecast represents an improvement

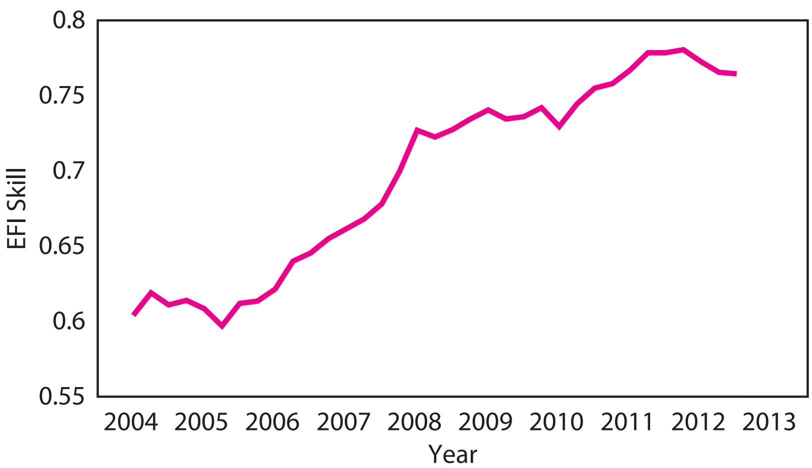

Figure 1 Skill of the Extreme Forecast Index (EFI) for 10-metre wind speed in Europe at forecast day 4. This is one of the supplementary headline scores. Shown are 12-month running average values.

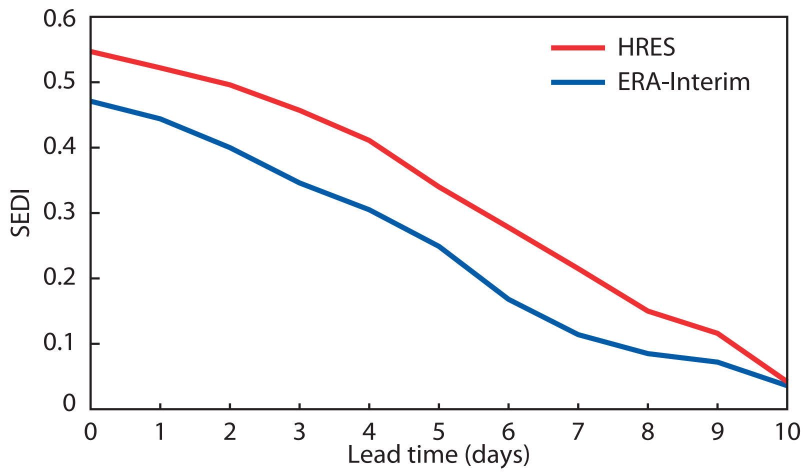

Figure 2 Symmetric Extremal Dependency Index (SEDI) for the 98th percentile of 10-metre wind speed in Europe as a function of forecast day for HRES and ERA-Interim. The verification period is July 2011 to June 2013.

Assessment of ECMWF's Technical Advisory Committee, 17–18 October 2013

A

With regard to its assessment of the performance of the operational forecasting system, the Committee:

i. congratulated ECMWF on its world leading position in global medium-range weather forecasting;

ii. noted the very high performance level of its weather forecasts and encouraged ECMWF to maintain this lead;

iii. acknowledged the benefit of the ECMWF forecasting system, particularly the EFI, in the timely and accurate forecasting of high impact weather events such as the cold spell and snow events in March and April 2013 over northern Europe, and the severe flooding in Central Europe in May and June 2013;

iv. recommended further development of severe weather indicators (such as the EFI and SOT) and combined probabilities of extreme values to support the decision-making activities in NMSs;

v. welcomed the improvements in the precipitation forecast, but noted the continued bias in 2m temperature at high latitudes in winter and spring, and the over-prediction of light precipitation; welcomed efforts at ECMWF to address these issues;

vi. welcomed the development of additional scores specifically related to surface weather; noted the importance of feedback from the Member States to identify forecast performance issues and encouraged ECMWF to develop more interactive feedback procedures with users on these issues;

vii. appreciated the use of ERA-Interim as a benchmark for identifying improvements in HRES forecast performance; recommended to consider this approach to help to set targets and monitor progress towards the principal goals of the ECMWF strategy, and emphasised the need to continue to update the re-analysis to reflect recent improvements;

viii. noted the lack of a corresponding benchmark for the ENS and the current use of the TIGGE archive to provide an alternative benchmark; recommended the development of further ENS benchmarks, based for example on the HRES or on an enhanced reforecast data set;

ix. welcomed ECMWF efforts to develop an approach to forecasting weather regimes and flow-dependent verification, and encouraged ECMWF to improve the performance of the monthly forecasting system with regard to regime transitions;

x. expressed its appreciation with regard to the introduction of IFS cycle 38r2 with an improvement of the vertical resolution to 137 levels and noted that this increase of vertical resolution will enable further scientific improvements;

xi. welcomed the upcoming improvements to the model, in particular the coupling with the ocean model from the first forecast day for the ENS and the improvements in the timing of the diurnal cycle of convection;

xii. with respect to the assimilation system, noted the large number of satellite instruments being monitored and assimilated (75 and 50 respectively), noted with interest the improvements resulting from the use of new satellite data, such as ATMS micro-wave data from Suomi NPP, improved use of micro-wave data, Meteosat 10 AMV data, and all-sky radiances;

xiii. encouraged the introduction of radar data, space-based lidar data, and supplementary satellite data (e.g. AMSU-A, NOAA MHS data over sea-ice, CrIS, and IASI on MetOp B) in the assimilation system;

xiv. welcomed the actions conducted by ECMWF to improve the scalability and flexibility of the IFS code and to process observations in a continuous mode and noted with interest that such improvements will facilitate other forecasting system improvements, particularly the dynamical core and the 4DVAR weak-constraint and long window assimilation, enabling the use of the IFS on massively parallel computers;

xv. appreciated ECMWF's user consultation processes regarding forecast products and skill through the Using ECMWF's Forecasts (UEF) meeting, regular Member State visits, and other exchanges with Member States;

xvi. welcomed the report on calibration, and encouraged ECMWF to further assess the benefits of forecast calibration.

over ERA-Interim of around two forecast days, mainly due to a reduction in the false alarm rate. This improvement indicates the significant progress made in recent years in predicting extreme events in the IFS and is consistent with the substantial increase seen in the EFI skill.

The complete set of annual results is available in *ECMWF Tech. Memo. No. 710* on 'Evaluation of ECMWF forecasts, including 2012-13 upgrades', downloadable from http://www.ecmwf.int/publications/library. This document presents recent verification statistics and evaluations of ECMWF forecasts (including weather, waves and severe weather events) along with information about changes to the data assimilation/forecasting and post-processing system. Also the performance of the monthly and seasonal forecasting systems is assessed.

FURTHER READING

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

- Medium range: http://www.ecmwf.int/products/forecasts/d/charts/medium/verification/
- Monthly range: http://www.ecmwf.int/products/forecasts/d/charts/mofc/verification/
- Seasonal range: http://www.ecmwf.int/products/forecasts/d/charts/seasonal/verification/

Note: All forecasting system cycle changes since 1985 are described and updated at:

http://www.ecmwf.int/products/data/operational_system/index.html

An evaluation of recent performance of ECMWF's forecasts

ALAN THORPE, PETER BAUER,
LINUS MAGNUSSON, DAVID RICHARDSON

Since the end of 2009 the anomaly correlation coefficient (*ACC*) measure of the skill of ECMWF's high-resolution forecasts (HRES) for the northern hemisphere extra-tropics has been essentially constant – that is, not showing an increase in *ACC* values for over 3 years. A number of new model cycles have been introduced in this period. Pre-operational testing of the new cycles demonstrated increases in skill resulting from the improvements to the data assimilation, model resolution and representation of physical processes, as regularly reported in the *ECMWF Newsletter* and on the ECMWF website. Why, then, does the operational HRES skill not reflect these improvements? If the interpretation of this period – hereafter referred to as a pause – were to be that the skill of the ECMWF HRES has reached a plateau then this is not in accord with our scientific expectations! Consequently the pause is worthy of some investigation and comment.

As well as changes to the forecasting system, there are other factors that influence forecast skill, including the potential predictability of the atmosphere and the characteristics of the particular skill measure being used. In this short contribution we consider the role of these factors in explaining the apparent pause in skill improvement.

Interpreting the ACC time series

As shown in Figure 1, the HRES pause in *ACC* over the last three years was preceded by a year (calendar year 2009) when the *ACC* increased rapidly. Note that there were three new model cycles introduced during 2009 and then in January 2010 the decrease in horizontal mesh size to 16 km was introduced. As the usual *ACC* scores are presented in the form of 12-month centred running

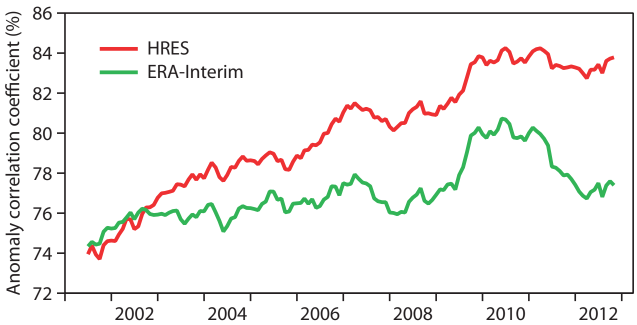

Figure 1 Time series since 2001 of the *ACC* for the 500 hPa geopotential height in the northern hemisphere extra-tropics at day 6 for HRES and ERA-Interim forecasts. A 12-month centred running-mean has been used.

averages some of the apparent increase in skill during the second half of 2009 was associated with the resolution change early in 2010.

It is important to place the period since 2009 into the context of the longer-term trends for HRES since, say, 2001. (Note that longer-term changes in the scores over the past 30 years are shown in *Janoušek et al*., 2012 and contributing factors are discussed in *Magnusson & Källén*, 2013.) The time series from 2001 to early 2013 given in Figure 1 appears to follow a trend of an *ACC* increase of about 7.5% per decade but with two significant 'anomalies' over that period: the first from mid-2006 to mid-2007 and the second more significant one from mid-2009 to mid-2011. In both these anomalies the *ACC* was well above the trend line. In fact the monthly values show that the winters 2009/10 and 2010/11 had particularly high values. It is difficult from this information alone, until more time has elapsed, to distinguish between the 'pause' picture and the 'upward trend plus anomalies' picture of the last three years.

An illuminating way to try to isolate the effect of the potential predictability of the atmosphere is by examining reforecasts using a fixed forecasting system so that the model developments do not contribute to skill changes. At ECMWF the ERA-Interim forecast system is used for this purpose. It utilises the Integrated Forecasting System (IFS) version used in operations from December 2006 to June 2007 although the horizontal resolution used is lower (80 km) than that of the then current operational model (25 km).

If one looks at *ACC* in Figure 1 for ERA-Interim there is a trend since 2001 of about 1.5% increase per decade that is most likely due to an improvement in the observational network. But superimposed on that trend are anomalies in the two periods mentioned previously for the HRES *ACC*, with the mid-2009 to mid-2011 period being highly anomalous and large. An interpretation of this is that during that period the atmosphere exhibited high potential predictability which was realised in the higher-than-trend *ACC* scores of HRES. These higher *ACC* scores in effect produced the pause by starting the three-year period of the pause with an (anomalous) high; see also *Andersson & Richardson* (2011) for discussion of high values of ACC during 2010. Between mid-2011 and mid-2012 the ERA-Interim *ACC* values dropped, alongside the apparent pause in HRES progress, which could be interpreted as a decrease of potential predictability. The difference in *ACC* between HRES and ERA-Interim shown in Figure 1 has increased in this period, indicating the improvements of the HRES relative to the fixed ERA-Interim system.

The period 2007 to 2012 has also been examined by *Langland & Maue* (2012) who draw similar conclusions about the link between skill and atmospheric variability, based on *ACC* values for ECMWF and other centres. They highlight that there is a good correlation between the *ACC* skill variations and the AO (Arctic Oscillation) index with higher than normal *ACC* values being associated with a strong negative phase of the AO (i.e. pressure is high in the Arctic and low in mid-latitudes). This situation occurred in the second anomalous period referred to here.

The relationship between *RMSE* and *ACC*

It is sometimes said that the *ACC* favours large anomalies relative to the climatology as much as (or more than) actual forecast skill improvements. However, the root-mean-square error (*RMSE*) does not depend on the size of climatological anomalies but it does depend on the accuracy of the overall level of 'activity' that a given forecasting system exhibits; in other words systems that are relatively inactive (say compared to observed analysis variations) can produce smaller *RMSE* values irrespective of their real forecast skill. Consequently it is important to consider both *ACC* and *RMSE* when evaluating the performance of an NWP system.

The definitions of *RMSE* and *ACC*, and a way to mathematically relate the two using the concept of the atmospheric activity, are shown in Box A, following the approach in the '*ECMWF User Guide*', Appendix A-2 (*Persson*, 2013). The *RMSE* does not explicitly depend on climatology (see equation (A1)) as it refers only to the contemporaneous values of the forecast and analysis; it is perhaps the simplest measure of forecast skill. Unlike *RMSE*, the *ACC* depends explicitly on climatology (see equation (A2)). In the operational verification at ECMWF, the centred version of *ACC* (in which the area-mean value is subtracted from each term) is used. For fields where the bias can be considered low, the difference between centred and un-centred *ACC* is small.

The activity of the model can be defined as the standard deviation of the difference between the forecast and climate (i.e. the forecast anomaly). For the atmosphere the activity depends upon the corresponding difference between the analysis and climate (i.e. the analysis anomaly). If the forecasting system is such that the activity of the forecast is similar to that of the atmosphere on average, the activity can be thought of as a measure that relates to the atmospheric state and not the modelling system. For a poorer forecasting system the forecast anomalies may be too low relative to the analysis anomalies, that is the model is under-active. From the definitions of *RMSE* and *ACC* (equations (A3) and (A4)), one can infer that whilst *ACC* values are largely unaffected by such under-activity the *RMSE* values will be reduced making forecasts appear to be more accurate.

Now assume that the activity in the model is the same as that in the atmosphere – this will be referred to as *ACT* (see equation (A5)). The *ACC* can now be specified in terms of *RMSE* and *ACT* (see equation (A6) which is duplicated below).

$$ACC \approx 1 - \frac{RMSE^2}{2ACT^2}$$

From this equation one can see that if the activity level was approximately constant then lower/higher values of *RMSE* go along with higher/lower values of *ACC*. However, *ACC*, *RMSE* and *ACT* vary in time so it is helpful to differentiate the above equation with respect to time so that the linkage between these time variations can be seen.

$$\frac{\mathrm{d}ACC}{\mathrm{d}t} \approx \frac{RMSE^2}{ACT^3}\frac{\mathrm{d}ACT}{\mathrm{d}t} - \frac{RMSE}{ACT^2}\frac{\mathrm{d}RMSE}{\mathrm{d}t}$$

From this tendency equation one can see that increases/decreases of *ACT* contribute in the same way as decreases/increases in *RMSE* to the overall change in the *ACC*. In principle, more complex behaviour is also possible. For example, during a period when the activity level is increasing and, say, the rate of change of *RMSE* is relatively small, an increasing *ACC* is likely to be seen. This may be why it is sometimes said colloquially that 'ACC likes big anomalies'. In general if *RMSE* were to be constant, greater/lesser levels of activity imply greater/lesser values of *ACC*.

RMSE – a different story

In Figure 2 we show the values of *RMSE* at 500 hPa for HRES at day 6. Now, if we examine the *ACC* pause from the end of 2009 we see that the *RMSE* values have largely continued to fall, except perhaps for the last 6 months. From an *RMSE* viewpoint one would not characterise the last 3 years as being a pause in the progress of forecast accuracy. In fact during the period from summer 2011 to now the monthly *RMSE* values have been noticeably lower than corresponding months in previous years. In this context it is interesting to note that *Langland & Maue* (2012) point out that an examination of the RMSE measure of HRES skill shows that during these periods of negative AO index (and high *ACC* values) the forecast skill, as measured by monthly values of the *RMSE*, was actually lower than at other times.

To interpret the variations of *RMSE* and *ACC* more quantitatively using the tendency equations we first need to consider the activity of the forecast and analysis. For the tendency equation it is assumed that the model and analysis have the same level of activity. Figure 3 shows that to a good approximation the assumption is valid (though the activity in the forecast is a little lower than in the analysis) and so either of these time series can be taken as *ACT*. The assumption is also valid for ERA-Interim which has a good level of activity.

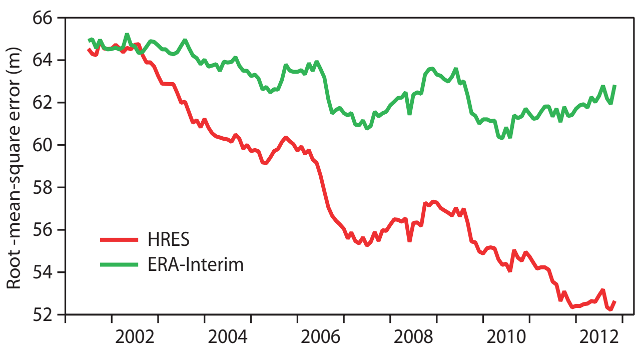

Figure 2 Time series of RMSE for the 500 hPa geopotential height in the northern hemisphere extra-tropics at day 6 for HRES and ERA-Interim. A 12-month centred running-mean has been used.

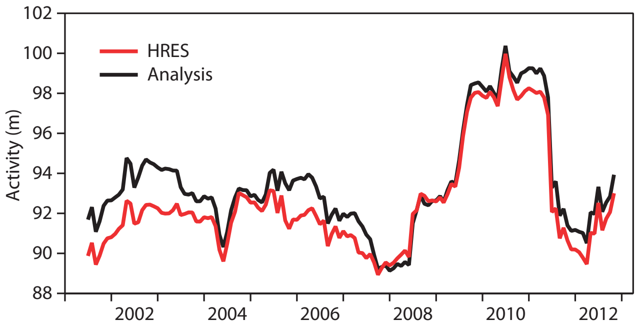

Figure 3 Activity for the analysis and forecast at day 6 in terms of the standard deviation of the 500 hPa geopotential height anomalies in the northern hemisphere extra-tropics. A 12-month centred running-mean has been used.

Typical recent values for the 500 hPa geopotential height for day-6 forecasts for HRES, taken from Figures 1 to 3, are *ACT*=94 m, *RMSE*=53 m and *ACC*=83%. Using these typical recent values of *ACT* and *RMSE* in the tendency equation allows the coefficients to be estimated as:

$$\frac{\mathrm{d}ACC}{\mathrm{d}t} \approx 0.34\frac{\mathrm{d}ACT}{\mathrm{d}t} - 0.6\frac{\mathrm{d}RMSE}{\mathrm{d}t}$$

So a 1% change in ACC can occur if (over the same timescale) there is either a change in *ACT* of about 2.9 m or in *RMSE* of about 1.7 m. For the less skilful ERA-Interim system (*ACT*=94 m, *RMSE*=62 m and *ACC*=78%) the same change in *ACT* (2.9 m) would account for a 1.3% change in ACC which is larger than that for HRES.

Figures 1 and 2 show that, as an overall trend, the *RMSE* decreases and *ACC* increases with time for HRES as the model and data assimilation improve. Indeed for much of the period (and this is true more generally) there is an extremely good (anti-) correlation between ACC and RMSE.

For the two-year period from mid-2009 to mid-2011, the atmosphere experienced a period of unusually high activity. Looking on the month-to-month anomalies in the activity (not shown), December to February 2009/10 and December 2010 stands out as much more active than normal. But the occurrence of larger amplitude anomalies does not imply a larger day-to-day variability in the atmosphere. In fact the opposite might be the case as large anomalies tend to be more persistent (e.g. we know that the AO was persistently in a negative phase during this period). Consequently, in this period that includes the first half of the pause, the relationship between *ACC* and *RMSE* is less straightforward.

During the rapid increase in *ACT* during the second half of 2009, the *RMSE* was decreasing and from the tendency equation we can see that both these tendencies contributed to the significant increase in *ACC* at that time. In mid-2011, when the *ACT* level decreased very rapidly, we see from Figure 2 that the *RMSE* also decreased rapidly. From the tendency equation we would expect that such a combination might be consistent with a rather small decrease in the *ACC*, which is in fact what happened – see Figure 1. It appears that the balance of terms in the tendency equation during the growth and decay phases of this anomaly in *ACT* was different.

In the second half of the pause, mid-2011 to end of 2012, there has been a period when the time variations of *ACC*, *RMSE* and *ACT* have returned to much smaller values and the tendency equation has been satisfied by all three terms being relatively small.

If we compare the *ACC* and *RMSE* for HRES relative to ERA-Interim reforecasts we see that there is little difference between *ACC* and *RMSE* in terms of the progress over the last three years – see Figure 4.

During the period when the *ACT* anomaly is developing (as the pause begins), the increase in *ACC* is larger for ERA-Interim (Figure 1). This is expected from the tendency equation because there are inherently larger values of *RMSE* for ERA-Interim as it is an older, lower resolution version of the forecasting system.

Conclusions regarding the pause

In conclusion, the perception of a pause in forecast skill since late 2009, derived from looking at *ACC* values, is probably erroneous. It is a reminder that the interpretation of the fluctuations in *ACC* and *RMSE* (and their correlation) can be complex and for *ACC* it relies heavily on large-scale

Relationship between *RMSE*, *ACC* and atmospheric activity

A

The definition of the root-mean-square forecast error, *RMSE*, in terms of the values of the forecast, f, and the analysis, a, is:

$$RMSE^2 = \overline{(f-a)^2} = \overline{(f-c)^2} + \overline{(a-c)^2} - 2\overline{(f-c)(a-c)} \quad \text{(A1)}$$

The definition of the un-centred *ACC* (*Wilks*, 2006) is:

$$ACC = \frac{\overline{(f-c)(a-c)}}{\sqrt{\overline{(f-c)^2}\,\overline{(a-c)^2}}} \quad \text{(A2)}$$

Here the overbar indicates a regional or global average and $\overline{(f-c)^2}$ and $\overline{(a-c)^2}$ are the squared standard deviations of the forecast anomalies and analysis anomalies from the climate, *c*, respectively; they are measures of the 'activity' in the forecast and analysis which will be denoted by ACT_f^2 and ACT_a^2. Equations (A1) and (A2) can now be written as:

$$RMSE^2 = ACT_f^2 + ACT_a^2 - 2\overline{(f-c)(a-c)} \quad \text{(A3)}$$

$$ACC \approx \frac{\overline{(f-c)(a-c)}}{ACT_f\,ACT_a} \quad \text{(A4)}$$

If we assume that the activity in the model is approximately equal to that in the atmosphere (i.e. the analysis) we can define the quantity *ACT*:

$$ACT_f^2 \approx ACT_a^2 = ACT^2 \quad \text{(A5)}$$

Combining equations (A3), (A4) and (A5), we obtain:

$$ACC \approx 1 - \frac{RMSE^2}{2ACT^2} \quad \text{(A6)}$$

Equation (A6) shows the relation between *ACC*, *RMSE* and *ACT*.

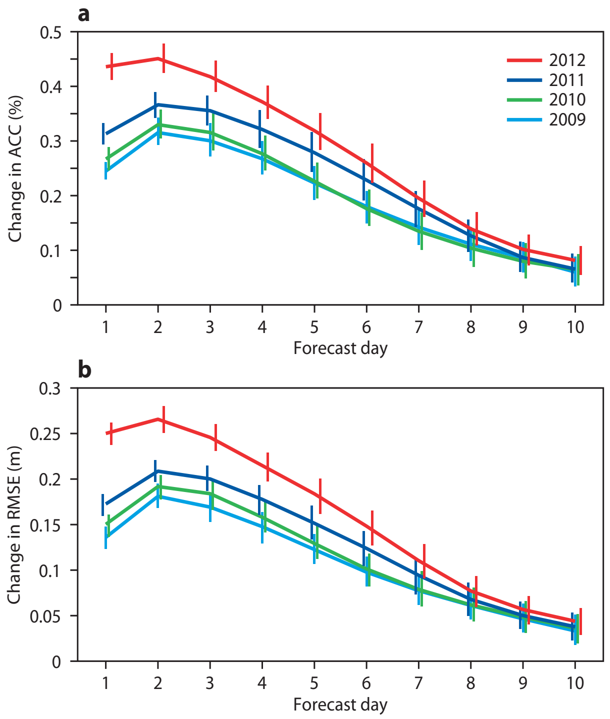

Figure 4 Relative change of (a) ACC and (b) RMSE for the 500 hPa geopotential height in the northern hemisphere extra-tropics for HRES forecasts, normalized by ERA-Interim reforecasts, as a function of forecast lead time, for the years 2009, 2010, 2011 and 2012.

climate variability such as the phase of the Arctic Oscillation (AO). We need to examine both the *ACC* and *RMSE* values of the HRES together with the *ACT* level and not just any one of these quantities in isolation.

Over the past decade there has mostly been a good anti-correlation between *ACC* and *RMSE* values. The exception is the two-year period in the first half of the pause from mid-2009 to mid-2011 when there was a very large positive anomaly in activity *ACT* level. In this period of the three-year pause there was a very large positive anomaly in the activity level that coincided with the AO being in a prolonged negative phase. During such anomalous periods for activity one can expect a variety of behaviour of *ACC* and *RMSE* such that neither one of these quantities on their own is sufficient to deduce what is happening to forecast skill. In the second half of the pause period the time variations of *ACC*, *RMSE* and *ACT* and have all been relatively small.

The use of a fixed-reference forecast system to create a reforecast dataset is a valuable way to take account of the impact of atmospheric variability on the forecast scores. Consequently, results from ERA-Interim allow the period of high potential predictability during the pause to be accounted for. Comparing with ERA-Interim shows clearly the continuing trend of improvements of the operational HRES during the pause, as a result of the changes to the data assimilation and model introduced during the period.

This article has reviewed the recent skill of the ECMWF forecasts in the context of the long-term evolution of the scores. The overall trend of skill improvement is modulated to some extent by the variability of the atmosphere itself, a sensitivity which affects different skill measures in different ways. This sensitivity is why ECMWF regularly maintains and reviews a range of verification measures alongside the headline *ACC* score together with the atmospheric variability. The use of a fixed reference system (such as ERA-Interim) has now become an important component of the evaluation strategy, providing a benchmark for the IFS and the ability to distinguish between forecasting system improvements and variations in atmospheric predictability. It is essential to maintain such a fixed system (as close as possible to the operational model), running in near-real time, with at least a decade of reforecasts.

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Effective spectral resolution of ECMWF atmospheric forecast models

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Very sharp atmospheric phenomena (e.g. frontal zones or tropical cyclones) with scales of 50–80 km or the equivalent of 3–5 model grid spacings are frequently seen in the forecasts from the ECMWF Integrated Forecasting System (IFS). Since 26 January 2010, the high-resolution forecasts (HRES) use a model with a spectral truncation of T1279 which corresponds to a horizontal grid resolution of 16 km (see Table 1 for a list of some of the common horizontal resolutions of ECMWF atmospheric forecast models). However, due to the nature of numerical solutions and parametrizations, the model effective resolution degrades to several grid spacings. It is of interest to estimate this effective resolution.

In this article we will estimate the effective model resolution at the ocean surface by comparing the spectrum of some model fields against a corresponding spectrum from the independent radar altimeter measurements. The restriction to the ocean surface is due to the fact that altimeter wind speed measurements are only possible over the water surface. It is found that the effective useful resolution of the current HRES is 3–5 grid spacings supporting the possibility of observing sharp phenomena at this scale.

Spectral analysis of surface wind speed

Spectral analysis using discrete Fourier transform is an attractive tool to resolve data series into their underlying simple sinusoidal functions covering all possible scales. This concept can be used to reveal the ability of numerical weather prediction (NWP) models in resolving various scales by comparison with available theoretical and empirical (mainly from satellite data) spectra. The first step is to establish a reference against which the model spectra will be compared.

Theoretical, experimental and observational studies show that atmospheric energy spectra follow a power law in the form of k^{-n} where k is the wavenumber (i.e. reciprocal of the horizontal scale). Theoretical studies (e.g. *Lilly*, 1989) suggest that in the upper atmosphere the exponent n has a value of 3 at large scales (small wavenumbers) changing down to 5/3 at smaller scales. There is little known about the shape of the spectrum at the surface. Oceanic surface wind observations (e.g. scatterometers) show agreement with the upper atmosphere theory as far as the exponent at small scales is concerned, i.e. n=5/3. However, it has been found by earlier studies that the value of n for larger scales varies between 2.4 and 2.6.

We have computed the spectra of the surface wind speed product from the radar altimeter (RA-2) aboard the European Space Agency (ESA) Environmental Satellite (ENVISAT). RA-2 surface wind speed measurements can be an attractive source of data to study the properties of the atmospheric spectra at the ocean surface. A typical RA-2 measurement covers a footprint of a few kilometres (typically below 10 km). This resolution is enough to resolve scales in the order of few tens of kilometres. RA-2 wind speed measurements are described further in Box A.

All continuous RA-2 data records of 7,168-km length (1,024 measurements sampled at 7 km) during a period of one year from 1 August 2010 to 31 July 2011 were extracted. There were 685 records in total. A Fast Fourier Transform (FFT) was used to compute the corresponding spectra after applying de-trending (i.e. removing linear trends) and windowing (i.e. ensuring the periodicity). The average of the 685 spectra is plotted in Figure 1. Comparing the average spectrum with the wavenumber power law, it is seen that the RA-2 spectrum follows a power law with n=2.5 for large scales and n=5/3 for smaller scales. The transition occurs at around 400-km wavelength. The spectral shape is in very good agreement with other (surface) wind spectra available

Spectral solution	Grid spacing (km)	Operational at ECMWF		Notes
		Start	End	
T511	39	21 November 2000	31 January 2006	High-resolution forecast
T799	25	1 February 2006	25 January 2010	High-resolution forecast
T1279	15.6	26 January 2010	Current	High-resolution forecast
T639	31	26 January 2010	Current	Ensemble forecast
T255	78	–	–	ERA-Interim
T2047	10	Candidate for operational use in ~2015	–	Research forecast
T3999	5	–	–	Research forecast

Table 1 Recent and possible future resolutions of ECMWF atmospheric forecast models.

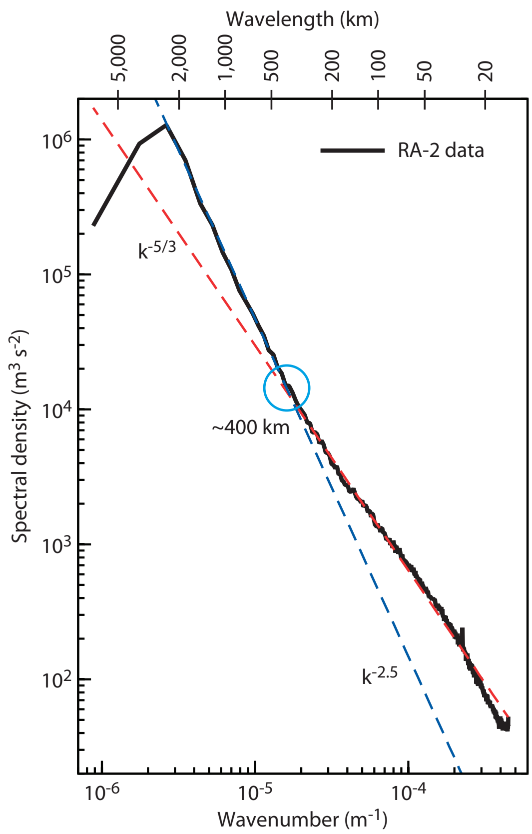

Figure 1 Globally averaged RA-2 surface wind speed spectrum during the period from 1 August 2010 to 31 July 2011. This consists of 685 spectra using data records of 7,168 km in length (1,024 measurements sampled at 7 km spacing). Best-fit power spectra are plotted for the large- and small-scale regimes.

RA-2 wind measurements

A

RA-2 aboard ENVISAT is a nadir looking instrument that transmits radar pulses towards the Earth at the speed of light. The time elapsed from the transmission of a pulse to the reception of its echo due to the reflection from the surface is proportional to the altitude of the satellite. The power and shape of the echoes contain information on the characteristics of the surface that caused the reflection.

The backscatter of RA-2 signal from the ocean surface varies depending on the roughness of the surface. The rougher (or steeper) the surface is, the lower the returned signal is. Therefore, the total strength of the returned signal is inversely proportional to the surface roughness. Furthermore, it is possible to show that the sea surface roughness (or more precisely the mean square slope of the sea surface) can be related to the wind speed.

There are several (empirical) algorithms to relate the altimeter backscatter coefficient and the surface wind speed. ENVISAT RA-2 used the algorithm proposed by *Abdalla* (2012) for this purpose. RA-2 makes measurements at a rate of 18 Hz. To reduce the noise, 1-Hz measurements are produced by averaging over a period of 1 second which corresponds to about 7 km.

RA-2 wind speeds are not assimilated in the IFS atmospheric forecast model, but are used for independent verification instead.

in the literature from other instruments (e.g. *Nastrom & Gage*, 1985 and *Xu et al.*, 2011). Therefore, the mean RA-2 spectrum is used here as a reference against which the corresponding model spectra can be compared.

Current model configuration of HRES – T1279

HRES uses the spectral transform method where some computations are done in the grid point domain and some in the spectral domain. Therefore, the global spectra are easily extractable from the model fields. Such spectra represent the atmospheric variability over the whole globe. Examples of surface kinetic energy spectra for four model grid spacings are shown in Figure 2. At large scales, the model spectra from all configurations follow the power law with n=3. At smaller scales, the model spectra follow the power law with n=5/3 with higher resolutions showing more success.

Some scientists claim that global energy spectra are significantly influenced by the variability of the orography. To eliminate this possibility and to get model spectra comparable with the altimeter data, it is necessary to consider only the model spectra over the ocean surface. However, there is no reliable method to separate the spectra over land and ocean from the global model spectra. Therefore, a FFT on the model's physical grid can be used instead. The irregular reduced Gaussian grid used by the model is not suitable for use by standard FFT algorithms which require evenly spaced data series. However, linear interpolation is ruled out as it smooths the structure of the data leading to spectra with steeper high frequency tails than the correct tails.

In order to mimic the ground tracks of polar-orbiting satellites like ENVISAT, model values at given meridians can be used. The FFT requires the meridians to be selected such that the model grid points are aligned perfectly on them. The best candidate is the prime (zero) meridian, where all grid points line up by design. However, this meridian contains a large fraction of land. This limits the ability to consider long sequences. The 180°-meridian can be used as the next best option, if about 8 km deviations in the locations of some of the model grid points are tolerated. 16,000-km record lengths (1,024 grid points) of model data along the 180°-meridian and centred around the equator are used.

ECMWF forecast fields beyond the first 24 hours (every 3 hours from 27 to 144 hours, both inclusive, then every 6 hours till 240 hours) from the analyses at 00 UTC during the period from 1 to 10 October 2011were used to compute the 10-metre wind speed. This resulted in a total of 560 records representing the surface wind speed over the ocean. The sequences were treated in a similar way to the altimeter data and the spectra were averaged to produce the model wind speed spectrum shown in Figure 3 (labelled T1279). The RA-2 average wind speed spectrum shown in Figure 1 is also plotted for comparison (labelled RA-2 data). The T1279 spectrum coincides well with that of the RA-2 and only starts to deviate at a wavelength of about 120 km, i.e. about 8 times the model grid spacing (16 km). This means that the model is able to fully resolve the same structures as does RA-2 for all scales in excess of 120 km. This scale is termed as the effective model resolution.

Future model configuration candidates for HRES – T2047 and T3999

The horizontal resolution of the HRES increases typically every 5 years. The next model horizontal resolution planned for 2015 is expected to be T2047 which corresponds to a grid spacing of about 10 km. A number of runs using this higher resolution have been already carried out by the ECMWF Research Department.

A consistent experiment covering the period from February to November 2009 was carried out starting on the 15th of each month (i.e. 10 forecasts). Forecast fields at steps 24 to 240 hours every 12 hours (i.e. 19 fields) were used to extract a total of 190 records (i.e. 19 fields from 10 forecasts) along the 180°-meridian. A FFT was used for each of these 10,240-km long records (1,024 grid points with 10 km spacing). The average of the resulting 190 spectra is shown in Figure 3 (labelled T2047). It is clear that the wind speed spectrum from the coming high-resolution forecast is able to resolve the variability for scales in excess of about 75 km. So the model fully resolves scales in excess of about 8 times the grid spacing.

Finally, the wind speed spectra from one of the candidate resolutions for the high-resolution model expected to be implemented by the end of the decade are also investigated. The spectral resolution of this candidate is T3999, corresponding to a grid spacing of about 5 km. The T3999 runs are computationally very expensive on the current ECMWF computing facilities. Therefore, only a limited number of T3999 model runs have been carried out. The results of two experiments are used here.

- The first is a 24-hour forecast run starting from 12 UTC on 17 March 1998. Five forecast fields (12 to 24 hours with 3-hour intervals) are used.
- To increase the number of cases, the fields from another experiment are used as well. This experiment is a 48-hour forecast from 12 UTC on 15 October 2010. Four forecast fields (12, 24, 36 and 48 hours) are used.

Records of lengths 10,240 km (2048 grid points) along the 180°-meridian from the 9 fields were extracted and a FFT was used to compute the spectra. The averaged spectrum of the T3999 model is shown in Figure 3 (labelled T3999). Irrespective of the noisiness of the spectrum (due to the limited number of spectra used in the averaging), it can be clearly seen that the model with a 5-km grid spacing is able to fully resolve scales as short as 30–40 km. Again, the model fully resolves scales in excess of about 8 times the grid spacing.

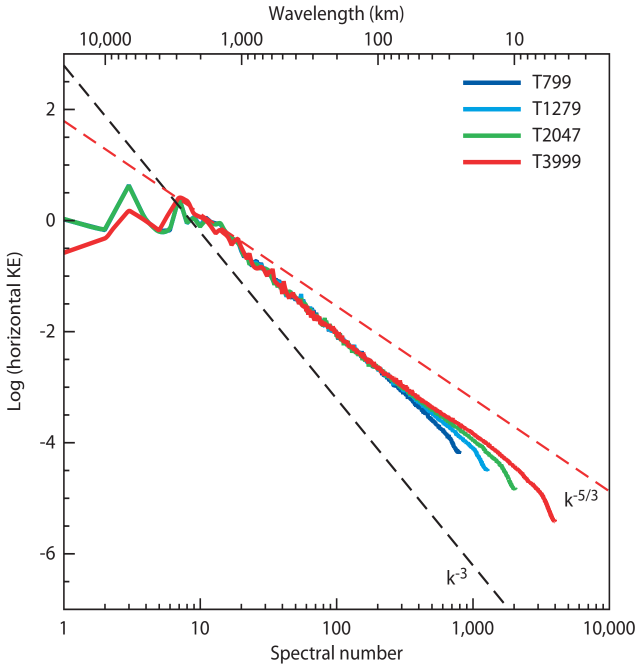

Figure 2 Typical global surface (10-metre height) kinetic energy (KE) spectra for 5-day forecasts for configurations at T799, T1279, T2047 and T3999 of the IFS atmospheric model.

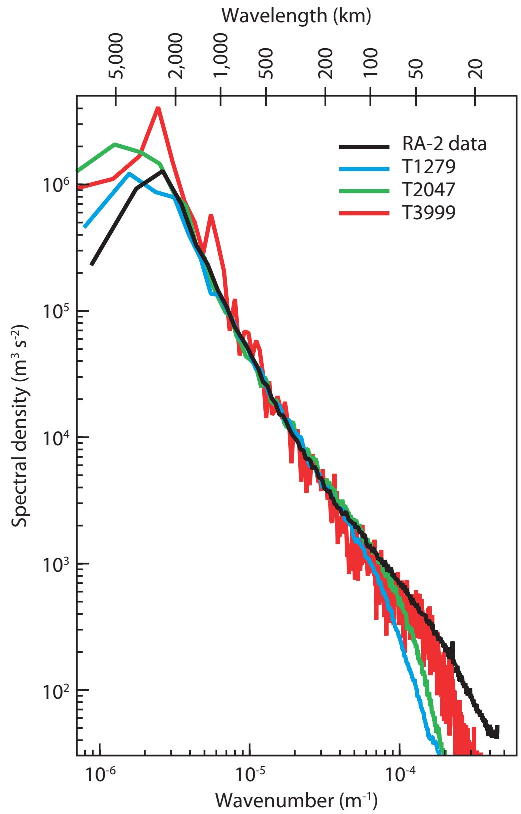

Figure 3 The surface wind speed spectrum of the current and candidates for future ECMWF model configurations compared to those of RA-2. The model configurations are T1279 (560 spectra using 512x15.6 km records), T2047 (190 spectra using 1,024x9.8 km records) and T3999 (9 spectra using 2,048x5 km records).

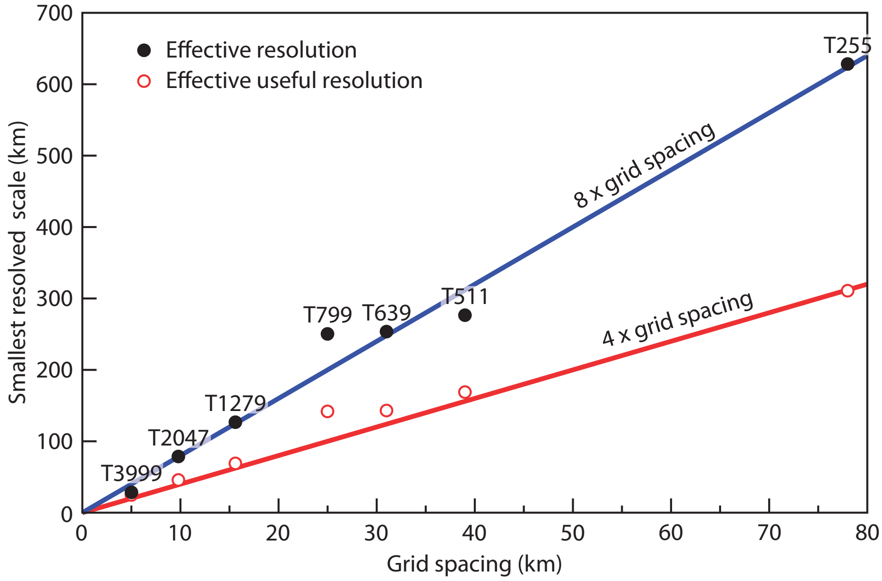

Figure 4 Effective resolution (i.e. model smallest fully-resolved scale) and effective useful resolution (i.e. model shortest scale with 50% resolution) as functions of the model grid spacing for several model configurations. The fixed ratios between the shortest resolvable scale and the used grid spacing of 4 and 8 are indicated by red and blue lines.

Effective model resolution

The effective model resolution represents the smallest scale the model is able to resolve fully. This can be found by comparing the model spectrum against a corresponding spectrum from independent measurements (or theory). Using RA-2 wind speed spectrum as a reference, it is possible to estimate the effective model resolution for the model configurations listed in Table 1. The effective model resolution as a function of the model grid spacing is shown in Figure 4.

It is clear that almost all model configurations considered in Figure 4 show effective full resolution as 8 times the model grid spacing. The model configuration T511, which was operational between 21 November 2000 and 31 January 2006, is the best cost-effective configuration as far as the effective resolution to grid spacing ratio is concerned, though of course the forecasts are less accurate than those with a higher resolution.

Beyond the full spectrally resolved energy, it is sensible to accept scales with partial spectral energy content to be quite useful information. If we relax the strict definition of the effective resolution to what can be termed as effective useful resolution by requiring the presence of at least 50% of the variability of that scale (open circles in Figure 4), the effective useful resolution of the current HRES configuration becomes 3–5 grid spacings. This needs to be taken into account when users of ECMWF products interpret the detailed information in the forecast fields.

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The expected NWP impact of Aeolus wind observations

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Aeolus is an ESA Earth Explorer satellite mission with a Doppler wind lidar payload, expected to be launched in 2015. It will provide wind information with a global distribution, a part of the global observing system that is presently lacking. Additional wind observations will improve our understanding of the general circulation, especially in the tropics. They are also expected to be very valuable for numerical weather prediction (NWP). But it is important to assess the expected impact of a future observing system that is primarily intended to provide data for use in NWP. In particular, an agency responsible for a new observing system wants to know whether the planned benefits for NWP are likely to be realised. Therefore, impact studies for the Aeolus mission have been performed at ECMWF to assess the potential impact of the data on NWP.

The Aeolus mission will provide vertical profiles of single horizontal line-of-sight (HLOS) winds, perpendicular to the satellite track. See Boxes A and B for more information about ESA's Aeolus mission and the role of ECMWF.

Assessments of the expected impact of Aeolus data have been performed in the past (e.g. *Tan et al.*, 2007; *Stoffelen et al.*, 2006). However, the mission specifications have changed significantly since these studies, as has the ECMWF Integrated Forecasting System (IFS). Consequently it is necessary to carry out a new assessment.

It is not straightforward to quantify the impact of a future spaceborne observing system. A suitable way of doing this for Aeolus is to investigate the impact of real pre-existing (good quality) wind data in ways that could provide an insight into the expected impact of Aeolus winds. With that aim in mind, we conducted Observing System Experiments (OSEs) with dual component winds (i.e. the zonal and meridional wind components) converted into Aeolus-like single component (HLOS) winds.

We have evaluated the results by using traditional verification measures (e.g. root-mean-square error and anomaly correlation of forecasts verified against operational analyses). In addition, use has been made of the more recently developed analysis and forecast sensitivity tools for measuring the information content of the wind observations for the analyses and short-range forecasts. This article describes the most interesting results from the NWP impact studies.

Wind data information content

The information content of observations used in the ECMWF assimilation system can be quantified by several diagnostic measures (*Cardinali et al.*, 2004; *Cardinali*, 2009).

- Observation Influence (OI) which provides information about the influence of the observations on the analysis (analysis impact). OI is defined as the Degrees of Freedom for Signal (DFS) per observation.
- Forecast Error Contribution (FEC) which quantifies the impact of observations on the reduction of the 24-hour forecast error (forecast impact).

ESA's Aeolus mission

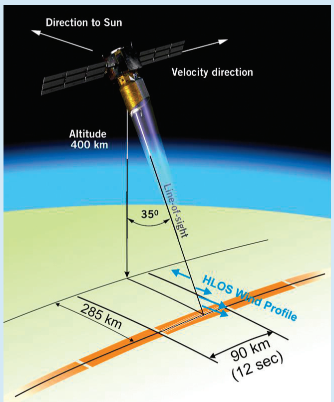
A

Aeolus is a European Space Agency (ESA) Earth Explorer mission, scheduled to be launched in July 2015 as part of the Living Planet Programme. The mission is intended to have a lifetime of three years. The Earth Explorers are designed to address critical and specific issues that are raised by the science community, while at the same time demonstrating breakthrough technology in observing techniques.

Aeolus will demonstrate the capability of a spaceborne Doppler wind lidar to make accurate, globally-distributed measurements (polar orbit) of vertical wind profiles in the troposphere and lower stratosphere (near surface to 30 km). It will measure single horizontal line-of-sight (HLOS) winds, perpendicular to the satellite track, by aiming a ultraviolet (UV) laser into the atmosphere and then detecting the Doppler-shift of the backscattered light from both molecules (clear air) and particles (clouds/aerosols). ADM-Aeolus is seen as a pre-operational mission, demonstrating new laser technology and paving the way for future meteorological satellites to measure atmospheric winds.

The Aeolus mission has suffered severe delays due to problems encountered with the state-of-the-art UV laser technology. There are still some significant instrument tests to be passed before we can be confident of the July 2015 launch date.

Further details on the mission can be found from the ADM-Aeolus Science Report (2008) and from *Stoffelen et al.* (2005).



ADM Aeolus satellite. *Schematic view of the ADM-Aeolus measurement geometry (credits: ESA/ ADM-Aeolus project).*

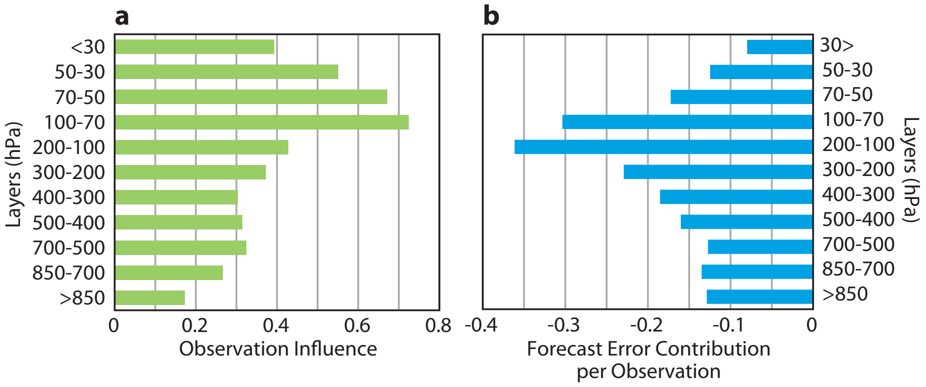


Figure 1 Information content of wind observations as a function of pressure (hPa) in terms of the global average of (a) Observation Influence (OI) and (b) Forecast Error Contribution (FEC) per observation. Period: September, 2011.

We have applied these measures in our impact studies and the results were compared. The impact of all active wind observations on the ECMWF analyses is assessed in terms of OI (Figure 1a). The corresponding impact on short-range forecasts is given by FEC per observation (Figure 1b). All active wind observations includes ships, drifting buoys, radiosondes, dropsondes, wind profilers, aircraft, scatterometers and satellite atmospheric motion vectors.

The diagnostics were taken from an experiment (using the IFS cycle Cy37r2) where we assimilated all the operationally-used observations. Both measures (OI and FEC per observation) show that most benefit from the current wind observations is obtained in the upper troposphere and lower stratosphere (50–100 hPa for analysis impact and 100–200 hPa for the short-range forecasts). Based on these diagnostics the largest impact of Aeolus observations can be expected to occur at these levels, since this is where the current observing system is providing most impact per observation. Other studies (not shown) revealed that, for the version of the IFS used in the experiments, the importance of wind observations is larger in the tropics than at mid-latitudes. This is also confirmed by the OSE results described later in this article.

Denial experiments

We have performed data denial experiments (OSEs where some observations are withdrawn from the data assimilation) to help to understand the role of observation sampling for spatially-dense observing systems used in the ECMWF data assimilation. This is of relevance to Aeolus, since observations will be densely sampled along the orbital track.

In particular we considered globally-distributed aircraft observations (temperature and wind vector) and Japanese wind profiler data (wind vector only) for the densely-sampled data. The aircraft data has a wide coverage at reasonably high spatial sampling (along flight paths) and the Japanese wind profiler network is one of the densest in the world (but only covering a relatively small part of the globe). The other in-situ wind observations (e.g. radiosondes) have lower spatial density; therefore they are unsuitable for evaluating the redundancy aspects of Aeolus observations. Here we do not discuss the results with the Japanese wind profilers since they were inconclusive (perhaps due to the small geographical area), but we summarise the main results of the aircraft denial study.

We carried out the aircraft OSEs by thinning aircraft observations to a horizontal spacing of 150 km and a vertical spacing of 50 hPa (instead of the operational values of 60 km and 15 hPa). The denser operational sampling provides on average a 47% increase in the number of observations; the difference is largest near the surface due to the ascent and descent of aircraft near airports.

Role of ECMWF

B

ECMWF is contracted by ESA to produce Aeolus wind products suitable for NWP. In particular, ECMWF is responsible for the development of the wind retrieval software through collaboration with KNMI (Royal Netherlands Meteorological Institute), Météo-France and DLR (German Aerospace Centre) – see *Tan et al.* (2008). ECMWF has been chosen as the Meteorological Processing Facility so it will provide wind products (referred to as Level-2B wind products) and auxiliary meteorological data products for ESA in an operational manner during the mission's lifetime.

ECMWF will also be responsible for the monitoring of Aeolus wind retrievals, and will assess the impact of Aeolus winds on the global NWP system. The intention is to assimilate HLOS winds operationally if they are shown to provide positive impact. ECMWF will also participate in readiness tests, calibration/validation activities and the mission's commissioning phase.

The Aeolus processing software along with detailed documentation is made available for NWP centres from the website: ***http://data-portal.ecmwf.int/data/d/software/aeolus***.

It is expected that an increase in wind profile information will be a valuable addition to the global observing system, as was again recently identified by a WMO expert team (Andersson & Sato, 2012). If Aeolus observations are of sufficient quality, they are expected to provide a significant positive impact on global NWP. Therefore, ECMWF has been separately contracted to investigate the expected impact of Aeolus data given some significant changes to the mission design over recent years.

Figure 2 shows the information content of the two experiments in terms of FEC diagnostics. This illustrates that the additional observations (with close proximity to others) do not provide a corresponding increase in information content. In other words, the extra aircraft observations are partially redundant due to the capability of the data assimilation to propagate information typically 200–400 km away from the location of an observation.

The results given in Figure 2 have important implications for the expected impact of the Aeolus mission, since (as discussed in Box C) the measuring technique has been changed from the original Burst Mode (BM) to the more densely-sampled Continuous Mode (CM). To some extent, the aircraft thinning study can guide our expectations about the impact of Aeolus CM as compared to BM. We can conclude that the CM will not provide significantly more impact than the BM because of the described redundancy.

Line-of-sight data assimilation experiments

The ability of the IFS to assimilate HLOS winds has been in place since around 2006, but until now no data assimilation studies have been carried out using HLOS data derived from real wind observations. Some experiments using HLOS winds will now be described.

Numerical tools were developed to convert vector wind observations (i.e. with zonal and meridional wind components available) to Aeolus-like HLOS wind observations. As with the previous studies, this allows us to use real wind observations from the current observing system for the investigations. HLOS wind information was extracted from radiosondes, aircraft and wind profiler observations. The HLOS winds were chosen to point in the zonal direction for most experiments, since the real Aeolus data will be close to the zonal direction for the tropical and mid-latitude portions of the orbits (typically 10° of zonal wind direction).

We designed and executed several OSEs, but here we highlight just two main results from these studies.

- We compared the impact of HLOS and vector winds to that of mass (temperature and humidity) observations. This examines the importance of wind observations for global NWP. However, we have to be careful with the interpretation of the results because wind is measured by radiosondes, aircraft and wind profilers, but temperature is only measured by radiosondes and aircraft (and humidity uniquely by radiosondes).
- We studied the ability of the data assimilation system to utilise single component HLOS winds compared to vector winds (both components). In this study one should keep in mind that for the control run the radiosonde, aircraft and wind profiler observations were removed, thereby significantly degrading the observing system.

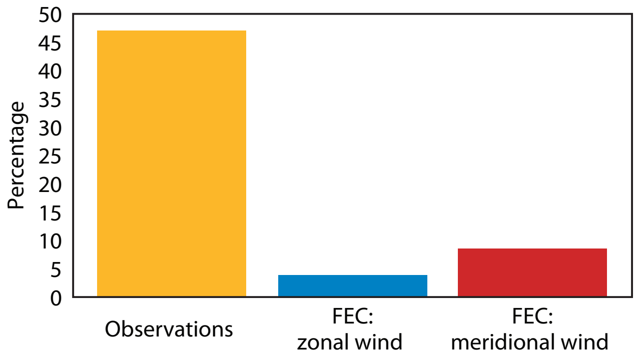


Figure 2 The impact of the increase in spatial density of aircraft observations (control versus denial experiment) as measured by the globally-averaged FEC diagnostics (also averaged vertically). The yellow histogram shows the increase in observation amount. The blue and red histograms show the increase in the zonal and meridional wind FEC values. All figures are the percentage increase of values as compared to the denial experiment. Period: September, 2011.

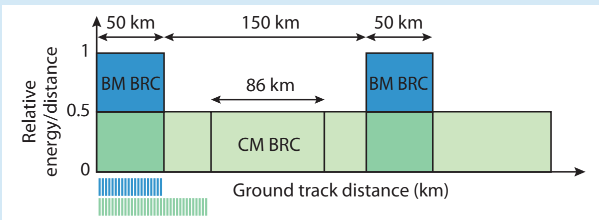
Comparing the impact of HLOS and vector winds and mass observations

Figure 3 shows the impact of HLOS (zonal) wind, vector wind and mass observations on zonal wind predictions. The corresponding results for the impact on temperature are shown in Figure 4. The impacts are quantified in terms of the percentage reduction in the root-mean-square errors relative to a control without any of the examined observation information. For each figure, the impact is split into the northern hemisphere extra-tropics and the tropics.

Aeolus processing and operations concept changes

C

Our studies paid particular attention to the fact that the operational concept of Aeolus has recently been changed from the so-called Burst Mode (BM, with a high temporal frequency of laser shots, but with gaps when the laser is not fired) to Continuous Mode (CM, half the temporal frequency of laser shots, but without any gaps) for engineering reasons – see the figure below. Also, the lidar laser energy will be reduced (at least for the start of the mission) by one third, in order to reduce the risk of laser-induced damage and ensure the three-year lifetime of the mission. These technological changes influence the spatial distribution and accuracy of the Aeolus wind data and consequently they had to be taken into account in the study of expected NWP impact.



Operational concept of Aeolus. *Comparison of the concepts for the Aeolus Basic Repeat Cycle (BRC) for the Burst Mode (BM) and Continuous Mode (CM).*

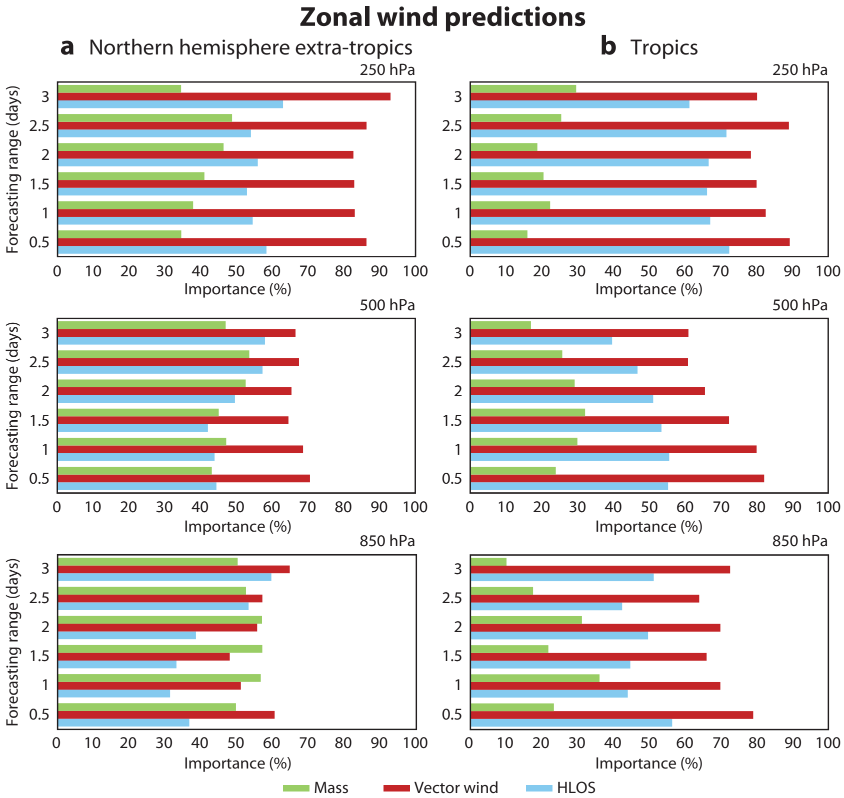


Figure 3 The importance (in percentage) of HLOS (zonal) wind, vector wind and mass observations for the zonal wind predictions for (a) northern hemisphere extra-tropics and (b) tropics for 250 hPa (upper panels), 500 hPa (middle panels) and 850 hPa (lower panels). Blue colours show the impact of HLOS winds, red colours show the impact of the vector winds and green colours show the impact of mass information. The vertical axis is the forecast range from 0.5 day to 3 days.

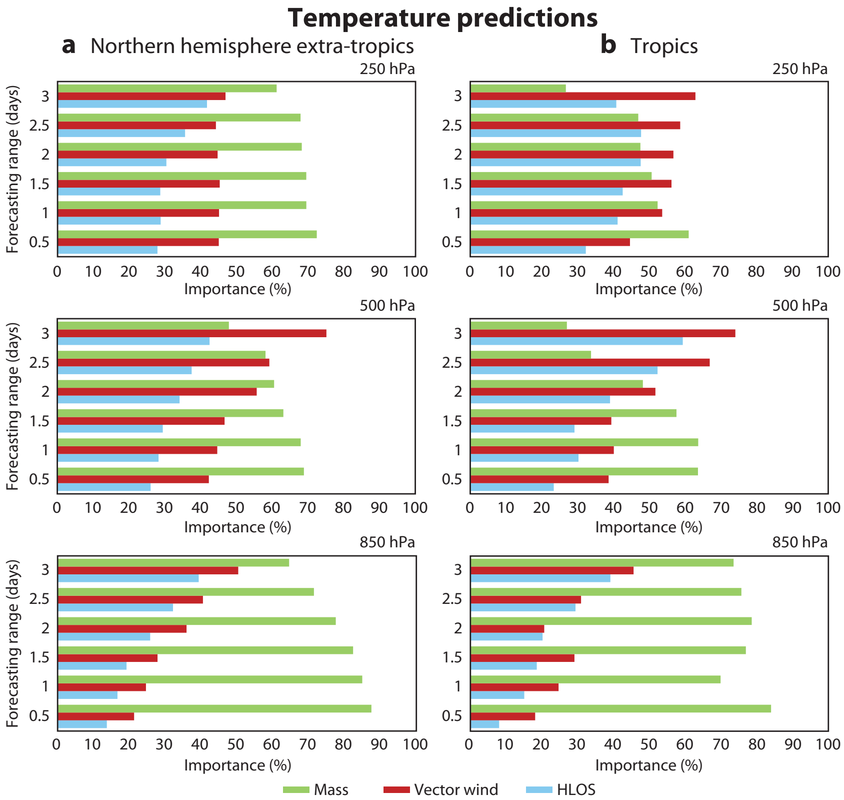


Figure 4 As figure 3, but for the importance (in percentage) of HLOS (zonal) wind, vector wind and mass observations for the temperature predictions.

Figure 3 shows that, out of the total impact obtained from all observation information, HLOS and vector winds have a significant impact on the zonal wind forecast for 12 hours to 3 days, especially for the tropics. This is also true for longer forecast ranges (not shown).

As shown in Figure 4, the HLOS and vector winds are less useful for forecasts of temperature than for zonal wind – adding temperature and humidity observations at lower levels provides significantly more impact. However, winds can provide larger impacts at higher altitudes (see also the diagnostics illustrated in Figure 1), more so in the tropics than in the extra-tropics. The impact of wind observations for improving the wind and temperature forecasts highlights the important role of wind observations and the potential benefit of using Aeolus data.

We now compare the information content of HLOS and vector winds. Figures 3 and 4 show that almost everywhere the HLOS winds are able to provide more than 50% (typically 70% to 75%) of the vector wind impact; this is due to the multivariate nature of the assimilation scheme spreading the information from the observation to other variables. The degree of impact varies slightly with the forecast variable, region and altitude, but generally the HLOS winds are more useful in the tropics. Consequently there is a promising indication that Aeolus data will have a beneficial impact in the tropics. Note, however, this result does not show that the zonal wind component is more important than the meridional component – this can only be assessed by carrying out a similar study which compares the impact of the meridional wind component and vector wind (both components).

Spatial distribution of the impact of HLOS winds

We investigated the spatial distribution of the impact of HLOS winds. Figure 5c shows the impact of HLOS data compared to the experiment where no observation information from radiosondes, aircraft and wind profilers was assimilated. It is clear that the largest impact is obtained in the tropical region (despite observations being sparsely distributed there, as can be seen in Figures 5a and 5b showing the locations of the observations), with the highest impact being around the aircraft cruise level. This impact is mostly seen outside convectively active areas such as the Atlantic south of the equator, the Pacific at the equator and Australia (there is little convective activity because the Intertropical Convergence Zone (ITCZ) is further north). One possible explanation is that the degraded observing system is unable to simulate the tropical circulation properly, which is corrected by the additional wind information.

The lack of impact for the southern hemisphere is due to the sparsity of observations (see again the coverage of all the data and the profilers in Figures 5a and 5b). Aeolus will have a much more uniform global coverage than the conventional data used in this study; therefore we can expect Aeolus to provide a significant positive impact in areas where there are few direct wind observations.

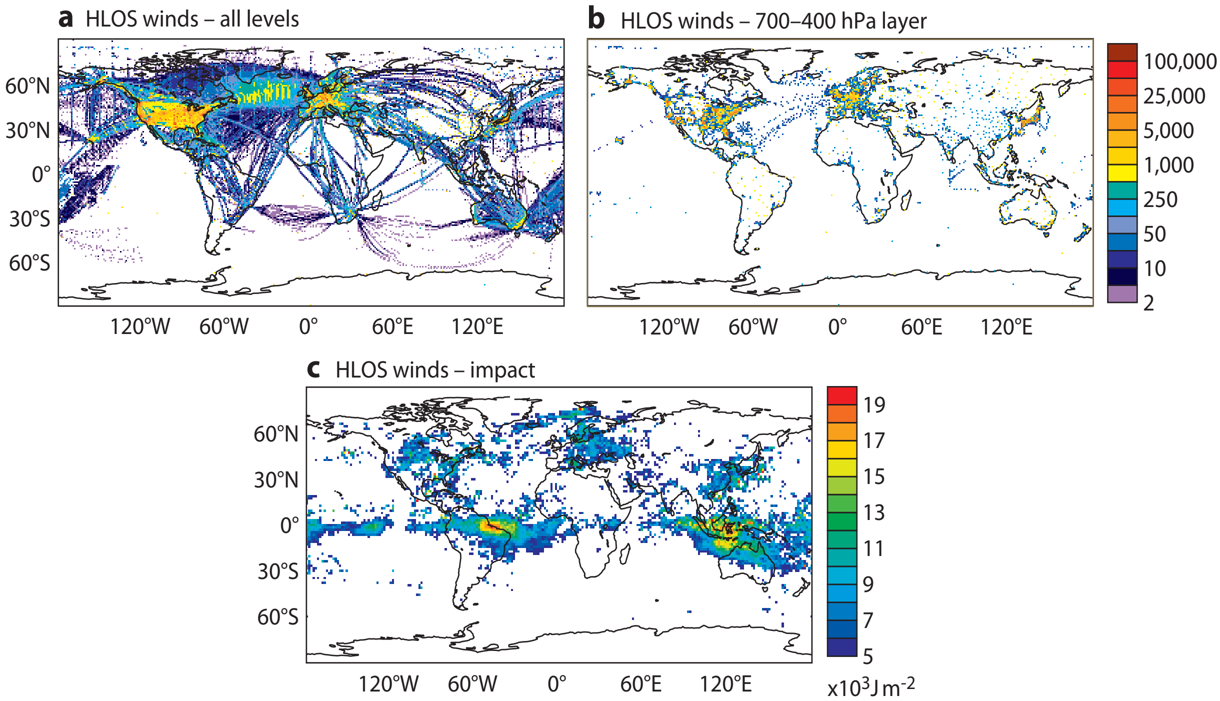


Figure 5 The distribution of HLOS data used in the experiments for (a) all vertical levels and (b) the 700–400 hPa layer (this highlights the radiosonde locations). (c) The impact of HLOS winds as measured by the decrease of the mean integrated total energy (in Jm^{-2}) of the 24-hour forecast error compared to the experiment without wind, temperature and humidity data.

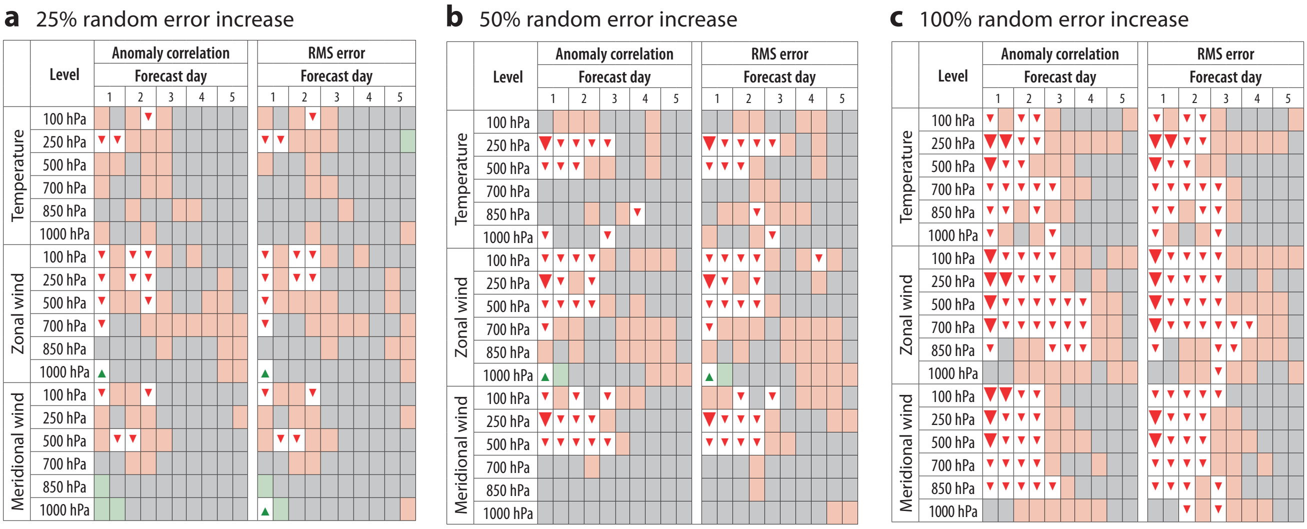


Figure 6 Scorecards for the northern hemisphere extra-tropics for (a) 25%, (b) 50% and (c) 100% observation error increase with corresponding observation Gaussian noise being added. Red (green) triangles indicate significant degradations (improvements) for the HLOS experiment with random errors compared to the experiment without any random error. Green and red shadings indicate differences which are not statistically significant, and grey shading indicates little difference.

Impact of increased random and systematic errors

As discussed in Box C, Aeolus wind quality might be reduced due to technical reasons. In order to assess how this could change the NWP impact we carried out some experiments to assess the effect of degrading the quality of HLOS observations. To achieve this we ran experiments that independently increased the random and systematic errors of the HLOS observations.

The impact of random errors was tested by increasing observation errors by 25%, 50% and 100% (this involved modifying the assigned data assimilation observation error and adding Gaussian noise to the observation values in line with the increases). The results are summarised for the northern hemisphere extra-tropics by Figure 6 in the form of the ECMWF scorecard for verification against operational analyses.

The scorecards show the significance of changes in the root-mean square error and anomaly correlation between the HLOS experiment and its reference for various variables and levels. It shows that the 25% HLOS observation degradation (this is the most realistic level expected for Aeolus) results in a very small decrease in NWP impact (with respect to the no degradation case). The deterioration increases with the further enlargement of the observation error, but the deterioration is still small even for the 100% case (when the observation error is, for example, increased from 2 m/s to 4 m/s). This implies that the planned increase of random errors for Aeolus is not a major concern from the point of view of global NWP impacts of the mission. CM helps to some extent by also providing observation information redundancy due to the high sampling along the orbit.

The testing of the effect of systematic observation error comprised experiments where we added a 0.5 m/s, 1 m/s and 2 m/s constant positive bias to the observations (without any changes in assigned observation errors). The impact of systematic errors is shown via scorecards in Figure 7, but now the experiments are compared to the control without wind, temperature and humidity observations.

From the scorecards it is clear that the degradation is much larger than was the case for the random errors with our chosen levels of systematic error. In particular, unbiased HLOS winds give a very significant positive impact, which becomes a very significant negative impact when the winds are biased by 2 m/s. This means that biases (at magnitudes possible for Aeolus) can be very detrimental for the Aeolus observations and they should be avoided by every possible means (or at least these biases should be understood with a view to correcting them). The actual level of systematic errors for Aeolus is unclear; this will be investigated in the near future.

Summary and outlook

This article presented some investigations of the impact of assimilating Aeolus-like single component wind data, with emphasise on the most important results of the impact studies conducted in the framework of an ESA-ECMWF study. The results confirm that additional wind information (of Aeolus quality) is likely to be highly beneficial for global NWP. This statement remains true even with an increase of random observation errors (with the expected 25% decrease in accuracy of the Aeolus satellite due to limitations of the laser output energy), but systematic errors greater than 0.5 m/s are very damaging.

The Aeolus team at ECMWF is confident that the mission will provide positive global forecast impacts if the random errors remain around 2–3 m/s and the systematic errors can be kept below 0.5 m/s.

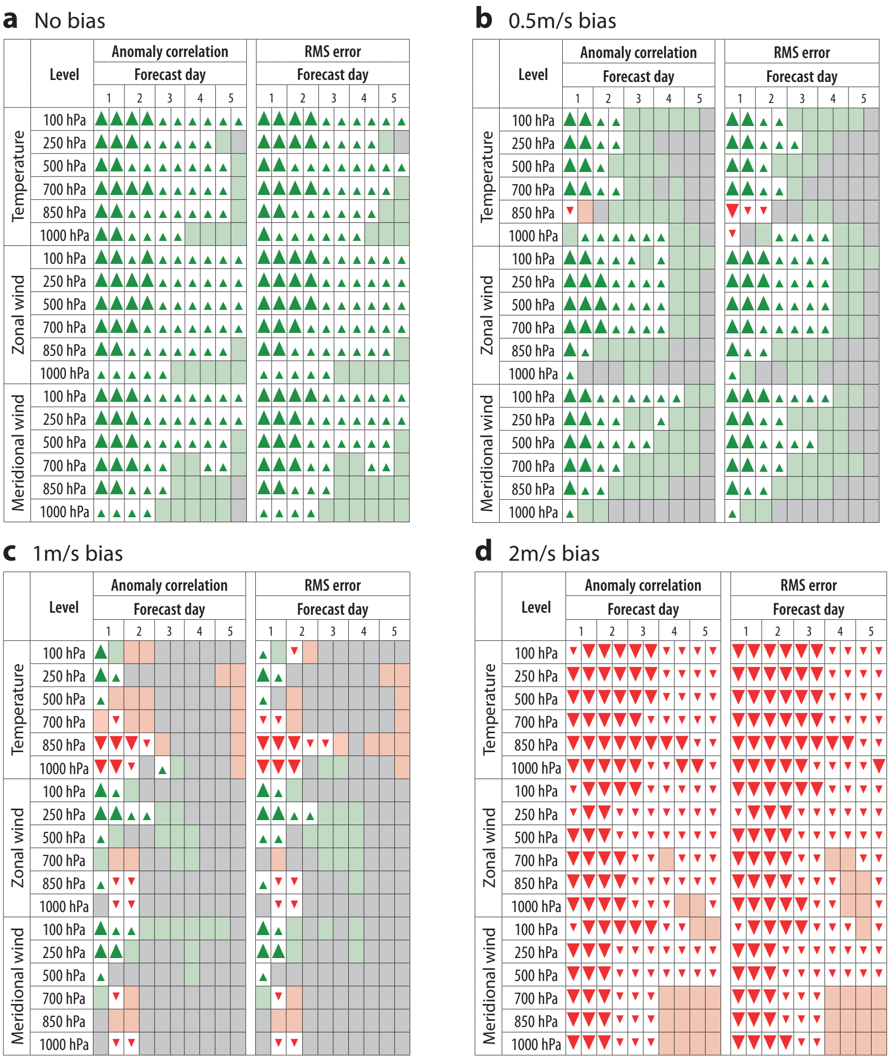


Figure 7 Scorecards for the northern hemisphere extra-tropics for (a) no bias and (b) 0.5 m/s, (c) 1 m/s and (d) 2 m/s positive bias added to the observations. Green (red) triangles indicate significant improvements (degradations) for the HLOS experiment with systematic errors compared to the experiment without HLOS (and temperature and humidity) data. The green, red and grey shadings have the same meaning as in Figure 6.

FURTHER READING

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More up-to-date information on Aeolus can also be found on ESA's website: http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/ADM-Aeolus/ESA_s_wind_mission

Interactive lakes in the Integrated Forecasting System

GIANPAOLO BALSAMO

Lakes are an important component of the land surface – they can influence the weather on local to regional scales. Their characteristics differ substantially from the surrounding land primarily due to the differences in albedo, roughness and heat storage. However, until recently they have been neglected in most numerical weather prediction (NWP) models.

Research aimed at introducing lakes into the operational NWP models at ECMWF has started by first considering medium-complexity schemes that can satisfy the constraint of having a low computational cost. FLake (*Mironov et al.*, 2010), a freshwater lake scheme, is a particularly appropriate choice of scheme as it predicts the vertical temperature structure and mixing conditions in lakes of various depths on time scales from a few hours to a few years, while maintaining a relatively low number of prognostic fields (7 in total). The model is intended for use as a lake parametrization scheme in NWP, climate modelling and other prediction systems for environmental applications. FLake has been implemented in the operational regional weather forecast model of Deutscher Wetterdienst (the German weather service) and used for research at several meteorological services across Europe including Météo-France, UK Met Office and Swedish Meteorological and Hydrological Institute.

FLake has been assessed for implementation in the atmospheric model of ECMWF's Integrated Forecasting System (IFS) using a set of preparatory studies: first in an offline experimental framework by *Dutra et al.* (2010) and *Balsamo et al*. (2010), and then extended to a fully-coupled lake-atmosphere simulations by Balsamo et al. (2012). More recently the possibility of treating sub-grid lakes using the land surface tiling methodology has been considered. With this approach each grid box is divided into fractions of different types of land use represented by the tiles. *Manrique Suñén et al*. (2013) have assessed the merits and limitations of the tiling methodology when there are contrasting surfaces by using field observations from a Finnish pine forest (Hyytiälä) and a small nearby lake (Valkea-Kotinen). The surface energy budgets are shown in Figure 1 as observed at the sites and simulated by the IFS land surface scheme extended with a lake tile (from FLake). These results show that the land surface model is able to characterize the main difference between the two sites.

The capacity of treating sub-grid water bodies within each model grid-box is thus important for providing more accurate boundary conditions to the atmosphere. Consequently, the lake model has been configured to allow the coupling of both resolved and sub-grid lakes (those that occupy less than 50% of a grid-box) to the IFS atmospheric model.

The set of preparatory actions to introduce the lakes in the Integrated Forecasting System at ECMWF covers the areas: (a) preparation of the ancillary datasets (lake cover and lake depth), (b) preparation of the lake initial conditions over the past 35 years and (c) evaluation of the impact of including lakes in several operational configurations and a variety of spatial resolutions.

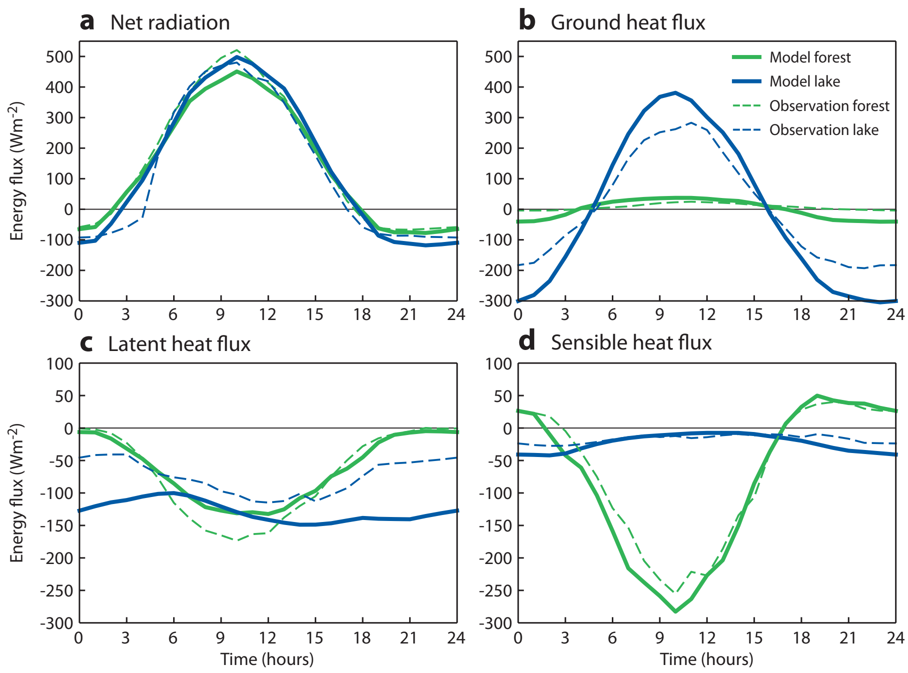

Figure 1 Mean diurnal cycle of energy fluxes for July over a Finnish lake and a near-by forest measured by eddy-covariance and simulated by the lake and forest tiles of the IFS land surface scheme.

The response of short-range weather forecast for near-surface temperature to the representation of lakes is examined in a set of forecast experiments covering one full year with FLake activated and in two analysis experiments covering two-months in winter and summer.

It has been found that the impact of sub-grid lakes is beneficial in reducing forecast error over the northern territories of Canada and over Scandinavia, particularly in spring and summer seasons. This is mainly attributed to the heat storage effect of the lakes, which delays the seasonal temperature cycle.

FLake implementation at ECMWF

FLake is suitable for NWP and climate modelling due to its accuracy and low computational cost. It is based on a two-layer representation of the time-evolving temperature profile and on the budgets of heat and kinetic energy. For more information see Box A.

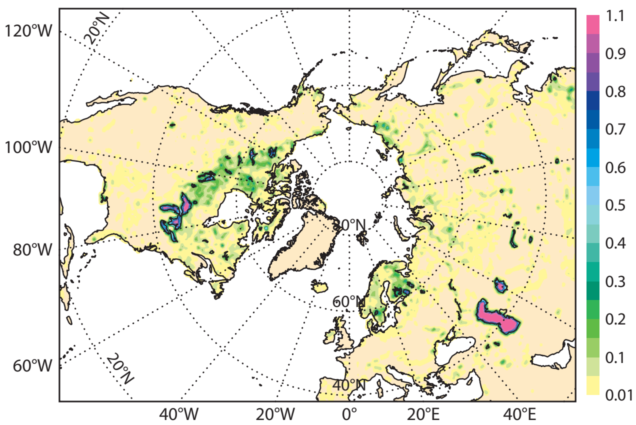

Figure 2 Lake Cover as a fraction of a gridbox as provided by the GLCC land-cover map. Lakes are only included if they occupy more than 1% of a grid box.

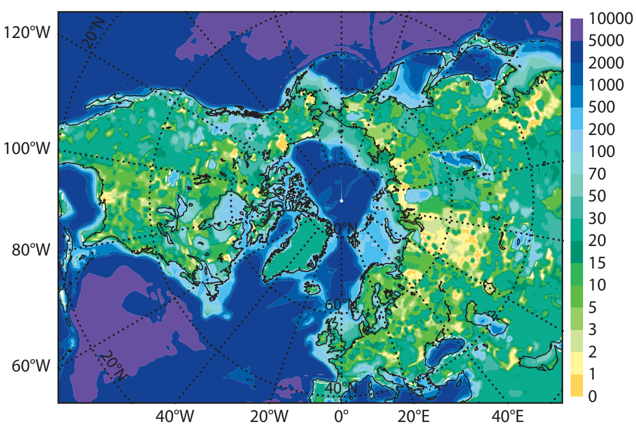

Figure 3 The merged product consisting of lake and ocean depths. For lakes a default value of 25 m was assumed for inland grid points where there was no information. Also minimum and maximum values of 1 m and 60 m were set. The ocean depths were taken from ETOPO1 a global relief model of Earth's surface that integrates land topography and ocean bathymetry produced by NOAA's National Geophysical Data Centre.

Global fields for lake cover and lake depth, as well as initial conditions for the lake physical state, have been derived in order to start the forecast experiments.

In the version of FLake used with the IFS atmospheric model the constant spatial fields of lake cover and lake depth are derived as follows.

- ***Lake cover***. The lake cover is provided by data from the US Department of Agriculture - Global Land Cover Characteristics (GLCC) – see Figure 2.
- ***Lake depth***. This variable is only available for a few lakes and it represents a real challenge for remote sensing. Use was made of the compilation of lake depths provided by Kourzeneva et al. (2010) supplemented by data about the Caspian Sea. The lake depth data was then merged with ocean depth data so that the performance of FLake could be assessed for coastal regions – see Figure 3.

Lakes constitute a new modelling component, with a set of new prognostic variables (i.e. mixed layer temperature and depth, bottom and average temperature, shape factor, and lake ice temperature and depth). So a way has to be found of setting up of initial conditions needed to initialize the IFS high-resolution forecast – see Box B.

Verification of FLake output

FLake simulations have been carried out based on the 'lake-planet' configuration – it is assumed each surface grid-box is entirely covered by a lake with the specified lake depth. The main advantage of this configuration is the ease of interpolation to all model grids and resolutions from the GLCC lake cover dataset (which is expected to be updated in the near future).

FLake in the IFS atmospheric model

A

The structure of the stratified layer between the upper mixed-layer and the lake bottom, the thermocline, is described using the concept of self-similarity (assumed shape) of the temperature-depth curve. The same concept is used to describe the temperature structure of the lake ice. A new lake tile (unit land cover characteristic) based on FLake has been introduced in the IFS land surface scheme, HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land), for research purposes and has been validated in global offline simulations. In the IFS implementation of FLake the surface fluxes of heat, moisture and momentum are computed by the HTESSEL routines. For the time being snow over lakes is not allowed and there is no representation of the bottom sediment interaction with the water columns.

The prognostic variables included in FLake are: mixed-layer temperature, mixed-layer depth, bottom temperature, mean temperature of the water column, shape factor (with respect to the temperature profile in the thermocline), temperature at the ice upper surface, and ice thickness. There is no water balance equation; the lake depth and the lake surface area (or fractional cover) are the two main ancillary fields input to the model and are kept constant in time.

The realism and accuracy of the FLake results were assessed in terms of lake temperature and ice formation and compared with satellite-based observations (MODIS) at 4 km resolution.

The period between 2001 and 2008 is used for validation. The comparison between model and observations is shown in Figure 4 in terms of annual mean lake temperature. The results are largely unbiased. The largest differences between lake-planet and MODIS surface temperatures are found over the Caspian Sea and the southern regions of the North-American Great Lakes (positive bias) and over Norwegian lakes (negative bias). These results are consistent with the intrinsic limitations of FLake over deep waters (not shown).

The Interactive Multisensor Snow and Ice Mapping System (IMS) (*Helfrich et al.*, 2007) was used to validate the ice formation and break-up dates in the lake-planet simulations. An overall 10-day bias in ice duration is comparable to errors for snow duration over land (not shown). Therefore, these results are considered satisfactory. They highlight, however, the importance of incorporating ice information into operational NWP. An extract of the long-term evolution of lake temperature and lake ice depth for Ladoga Lake is illustrated in Figure 5. This shows the variability in summer maximum temperature (with up to 4°C differences) and the span in ice cover duration.

Forecast experiments

Sets of 10-day forecasts covering one full year have been performed with the operational high-resolution model (version Cy36r3) at T399 spectral resolution (~50 km horizontal resolution). Two experiments were performed with Flake (LAKE) and without FLake (NOLAKE). Forecasts are run 10 days apart to cover the period from 1 January to 31 December 2008 (37 forecasts per experiment). In the NOLAKE experiment, sub-grid lakes are treated as land only and resolved lakes are treated as ocean points with initial surface temperature provided by a monthly climatology lagged by one month (to represent a typical time-scale for lakes to respond to the energy that they are receiving).

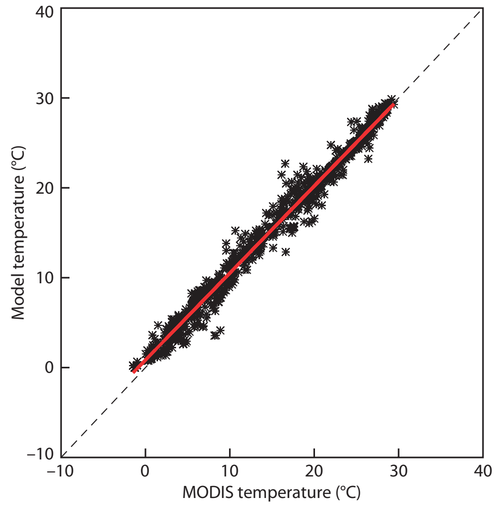

Figure 4 Comparison between the lake-planet mixed-layer temperature simulations and the MODIS LST for 2001–2008 over grid points where the model lake fraction is greater than 10%.

For two lakes near real-time data was used for specifying the initial temperature conditions: the Caspian Sea and the US Great Lakes.

The effect of FLake on near-surface air temperature is evaluated for the 48-hour forecasts.. In the following discussion 2-metre temperature sensitivity and impact are defined as follows.

- 2-metre temperature sensitivity is the mean difference of LAKE compared to NOLAKE for the 48-hour forecast. This assesses the impact of the LAKE versus NOLAKE representation in terms of whether a warming or a cooling is produced.
- 2-metre temperature impact is the mean absolute error reduction obtained with LAKE compared to NOLAKE, and evaluated with respect to the operational analysis. This is a measure of the added skill of forecasts when lakes are taken into account.

FLake initial conditions

B

A straightforward procedure would be to initialize the model with physically reasonable fields and allow for a long spin up so that fields can reach an equilibrium state (depending on the lake depth, months to years might be necessary to reach this state). However, this is not an option due to the high computational cost of long-term integrations. In this study we used initial conditions derived from a model-based retrospective simulation of lake prognostic fields. This was achieved by carrying out a long-term offline simulation of the land surface scheme forced by the ECMWF ERA-Interim reanalysis.

Lake simulations driven by ERA-Interim meteorological forcing have been realized with a configuration named 'lake-planet'. This assumes each surface grid-box is entirely covered by a lake with the specified lake depth from the merged bathymetry product. The advantage of this configuration is that it provides continuous fields at the water-land interface and thereby allows a simpler interpolation of the simulation output and independence from the lake cover dataset (which can be subject to updates).

The lake-planet experiment consists of a 35 years off-line run (1979–present) of the FLake model driven by 3-hourly atmospheric forcing from ERA-Interim. The ECMWF N128 Gaussian grid was adopted, which has a resolution of about 80 km. The continuity of lake-planet fields permits spatial interpolation of the model climatology onto different target grids (e.g. a higher resolution grid) via standard bi-linear procedures. This procedure permits the initialization of the prognostic variables required for the lake initial conditions for past dates and is essential for the re-forecasts of past weather (that support all anomaly-based products at ECMWF).

In Figure 6 (right column) the 2-metre temperature sensitivity shows a pronounced cooling effect in spring and summer. This is due to the incoming radiation being stored in the lake (with a relatively small impact on surface temperature) rather than being used to warm the atmosphere. The heat stored during spring and summer (which resulted in an atmospheric cooling) is then released during autumn (leading to a warming of the near-surface air). An additional cooling mechanism is that lakes evaporate more than dry land, resulting in lower near-surface temperatures. This can give an overall cooling when averaged through the year.

The impact of FLake on the forecasts of 2-metre temperature is shown in Figure 6 (left column) by comparison with an analysis of in-situ observations (SYNOP and METAR). A marked positive impact is obtained in spring and summer, particularly in the vicinity of North American lakes and the European large lakes.

Two data assimilation experiments for winter (January and February 2013) and summer (June and July 2012) are performed to assess the temperature forecasts for LAKE compared to NOLAKE. In both cases the forecasts are verified against their own analysis.

Figure 7 shows the results of the assimilation experiments in terms of the reduction in root-mean-square error of the forecast. Use of FLake has had a positive effect in the areas depicted by cyan/blue shading. The winter experiment shows neutral impact across the atmosphere with the exception of an area around the Great Lakes (not shown), while the summer impact is largely positive over the northern hemisphere and it is shown to propagate through the troposphere. These results reflect the better performance of FLake in predicting the surface temperatures in summer compared to the winter season when lake ice predictions are controlling the impact on the atmosphere. Overall the impact of FLake is positive and shows encouraging results for future operational implementation.

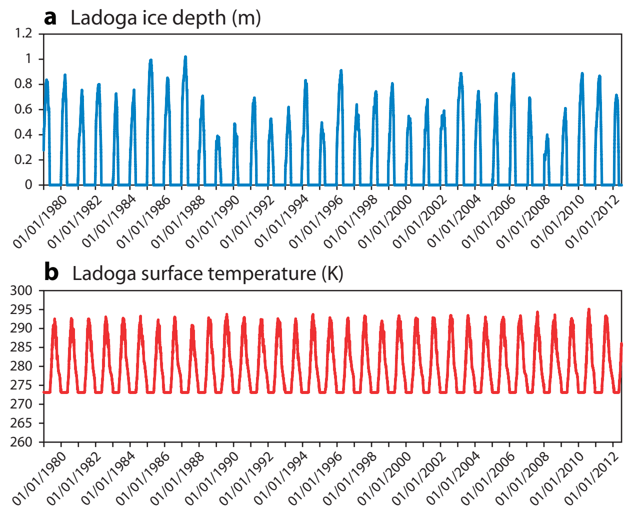

Figure 5 Extract of the lake reanalysis forced by ERA-Interim for Ladoga Lake showing (a) the ice depth and (b) surface mixed-layer temperature during 1979–2012.

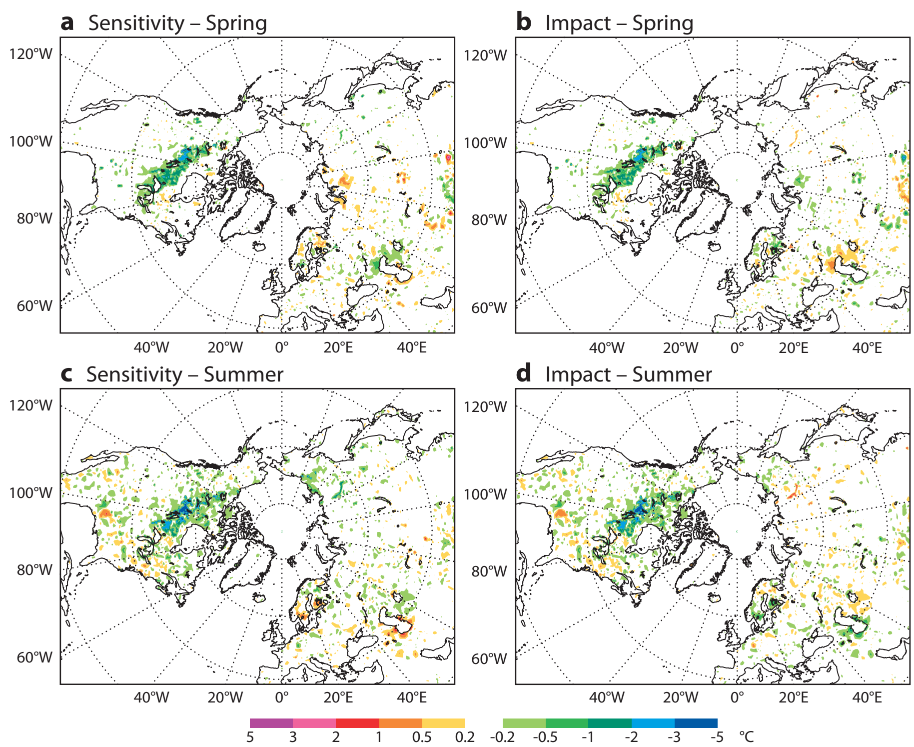

Figure 6 (a) Sensitivity (i.e. mean difference) and (b) impact (i.e. difference of mean absolute errors) of 48-hour 2-metre temperature forecasts (valid at 00 UTC) for LAKE compared to NOLAKE simulations for spring (March, April, May). (c), (d) As (a) and (b) but for summer (June, July, August). Negative values indicate cooling, which usually translates into a forecast improvement (i.e. reduction of errors compared to the 2-metre temperature analysis).

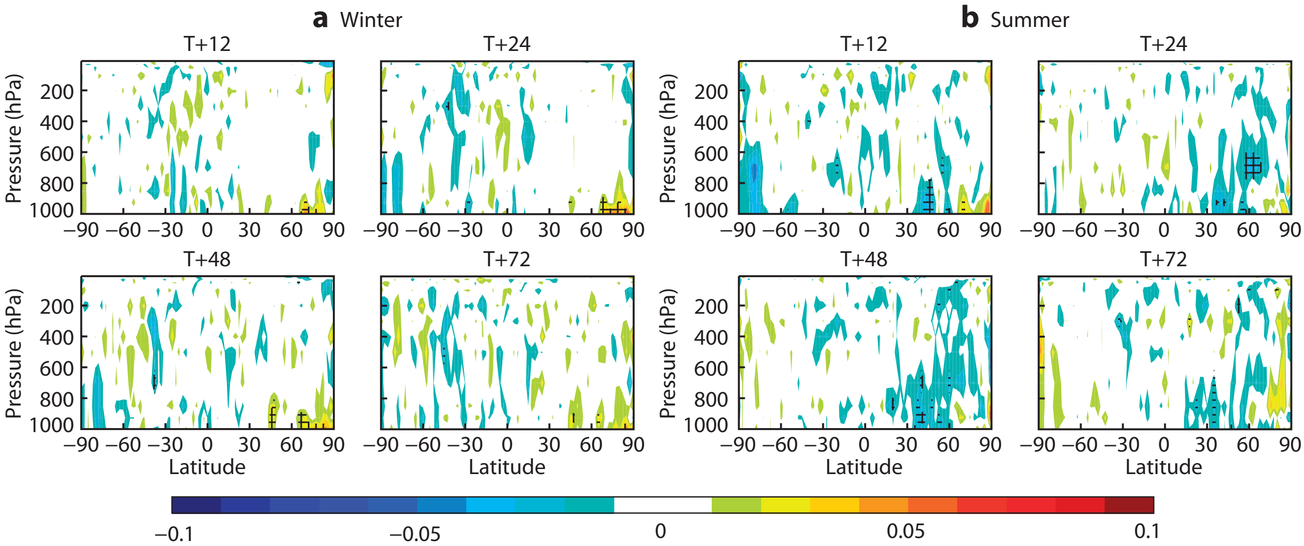

Figure 7 Impact on the temperature forecasts for LAKE compared to NOLAKE data assimilation experiments verified against the own analysis in terms of normalised difference in root-mean-square error for (a) winter (January and February 2013), (b) summer (June and July 2012). Negative (cyan/blue) areas indicate a reduction in root-mean-square error and therefore an improvement in the forecast (dashed areas indicate 95% significance).

Summary and outlook

The introduction of lakes via FLake in the IFS atmospheric model produces a realistic delay in seasonal evolution of temperature with a cooling in spring and summer and a warming in autumn. The forecasts that included lake-atmosphere interaction using FLake show a non-negligible impact on near-surface air temperature as a consequence of heat storage in the lakes. Less spring and summer warming is shown to be largely beneficial by significantly reducing forecast errors up to 72 hours; this improvement is particularly evident in the near-surface temperatures.

A careful initialization of the lake ice is required in winter cases and this will be subject to further testing. The potential of activating FLake for land points with sub-grid shallow sea-water will be also explored to mitigate forecast biases along coastal areas and estuaries.

The interaction with the lake modelling community has been very beneficial to this work and is acknowledged together with the Nordic Networks (NetFAM, MUSCATEN) that supported the organization of three dedicated lake workshops.

FURTHER READING

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Jan 27–31	Training Course – Use and interpretation of ECMWF products
Feb 3–7	Training Course – Use and interpretation of ECMWF products
Feb 11–3	Co-ordinating Committee on Remuneration (CCR)
Feb 10–14	Computing Training: HPCF (Use of new Cray system)
Feb 17–21	Computing Training: HPCF (Use of new Cray system)
Feb 25–28	Computing Training: GRIB API: library and tools
Mar 3–7	Computing Training: Introduction for new users/MARS
Mar 4–6	Global Flood Working Group (*4th Meeting*)
Mar 10–14	NWP Training: Data assimilation
Mar 17–21	NWP Training: ECMWF/EUMETSAT NWP-SAF satellite data assimilation
Mar 24–28	NWP Training: Advanced numerical methods for Earth-system modelling
Mar 31–Apr 10	NWP Training: Parametrization of subgrid physical processes
Mar 30–Apr 1	Advisory Committee for Data Policy (*15th Session*)
Apr 23–25	Computing Training: Introduction to ecFlow
Apr 28– May 2	Computing Training: Magics/Metview
Apr 28 (tbc)	Policy Advisory Committee (*37th Session*)
Apr 29–30 (tbc)	Finance Committee (*94th Session*)
May 7–16	NWP Training: Predictability and ocean-atmosphere ensemble forecasting
May 19–20 (tbc)	Security Representatives' Meeting
May 21–22 (tbc)	Computer Representatives' Meeting
Jun 4–6	Using ECMWF's Forecasts (UEF2014)
Jun 8–12	WISE Meeting
Jun 16–18	ROM SAF Workshop on 'Applications of GPS radio occultation measurements'
Jul 9–10	Council (*81st Session*)
Sep 1–4	Annual Seminar on 'Use of satellite data'
Oct 6–8	Scientific Advisory Committee (*43rd Session*)
Oct 9–10 (tbc)	Technical Advisory Committee (*46th Session*)
Oct 13–17 (tbc)	EUMETNET STAS and PFAC
Oct 21 (tbc)	Policy Advisory Committee (*38th Session*)
Oct 22–23 (tbc)	Finance Committee (*94th Session*)
Oct 24 (tbc)	Advisory Committee of Co-operating States (*20th Session*)
Oct 27–31	Workshop on 'High performance computing in meteorology'
Nov 3–7	Combined H-SAF and HEPeX workshops on 'Coupled hydrology'
Dec 3–4	Council (*82nd Session*)

tbc: to be confirmed

ECMWF publications

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Technical Memoranda

709 **Kaiser**, **J.W.**, **A. Heil**, **M.G. Schultz**, **S. Remy**, **O. Stein**, **G.R. van der Werf**, **M.J. Wooster** & **W. Xu**: Final report on implementation and quality of the D-FIRE assimilation system. *July 2013*

708 **Bormann**, **N.** & **M. Bonavita**: Spread of the ensemble of data assimilations in radiance space. *October 2013*

707 **Tang**, Y.M., **M.A. Balmaseda**, **K.S. Mogensen**, **S.P.E. Keeley** & **P.A.E.M. Janssen**: Sensitivity of sea ice thickness to observational constraints on sea ice concentration. *September 2013*

706 **Geer**, **A.**; All-sky assimilation: better snow-scattering radiative transfer and addition of SSMIS humidity sounding channels. *October 2013*

705 **Bechtold**, **P.**, **N. Semane**, **P. Lopez**, **J.-P. Chaboureau**, **A. Beljaars** & **N. Bormann**: Representing equilibrium and non-equilibrium convection in large-scale models. *September 2013*

Proceedings

Workshop on Parametrization of Clouds and Precipitation, 5–8 November 2012

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