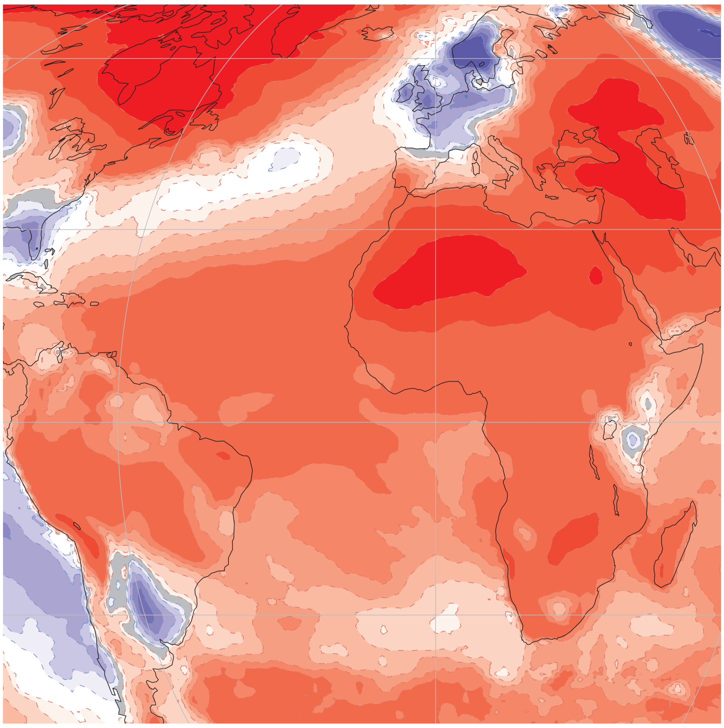
ECMWF Feature article

from Newsletter Number 139 – Spring 2014

METEOROLOGY

Climate reanalysis



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doi:10.21957/qnreh9t5

This article appeared in the Meteorology section of ECMWF Newsletter No. 139 – Spring 2014, pp. 15–21.

Climate reanalysis

Dick Dee interviewed by Bob Riddaway

Dick Dee *is the Head of the Reanalysis Section at ECMWF. He is responsible for leading a group of scientists producing state-of-the art global climate datasets. This has involved coordinating two international research projects: ERA-CLIM and ERA-CLIM2.*

The ERA-CLIM2 project has recently started – what is its purpose?

This exciting new project extends and expands the work begun in the ERA-CLIM project that ended in December 2013. The aim is to produce physically consistent reanalyses of the global atmosphere, ocean, land-surface, cryosphere and the carbon cycle – see Box A for more information about what is involved in reanalysis. The project is at the heart of a concerted effort in Europe to build the information infrastructure needed to support climate monitoring, climate research and climate services, based on the best available science and observations.

The ERA-CLIM2 project will rely on ECMWF's expertise in modelling and data assimilation to develop a first coupled ocean-atmosphere reanalysis spanning the 20th century. It includes activities aimed at improving the available observational record (e.g. through data rescue and reprocessing), the assimilating model (primarily by coupling the atmosphere with the ocean) and the data assimilation techniques (e.g. related to data assimilation in coupled models). The project will also develop improved data services in order to prepare for the need to support new classes of users, including providers of climate services and European policy makers.

Who is involved in ERA-CLIM2 and how is it funded?

The project will be conducted by ECMWF together with sixteen other institutions in Europe and Russia: two international organisations, four national meteorological services, five academic institutions and five national research centres. At ECMWF, four scientists in the Reanalysis Section and one in the Forecast Department will be working on ERA-CLIM2. The project as a whole will require 88 person-years of effort and significant computing and data handling. The overall cost is €15 million, approximately half of it funded by the EU within the 7th Framework Programme (FP7) for Research and Technological Development.

The main strategic objectives of FP7 are to strengthen the scientific and technological base of European industry, encourage its international competitiveness, and promote research that supports EU policy development. Specifically, ERA-CLIM2 is one of several current FP7 projects aimed at improving the EU's capacities in the area of climate change adaptation and mitigation.

Earlier you mentioned the ERA-CLIM project – would you tell me more about its purpose and who was involved?

ERA-CLIM was a very successful project conducted by ECMWF together with eight other institutes in Europe, Russia and Chile. The goal was to improve the available observational record for the 20th century, and to develop the observational input and technical infrastructure needed to produce a climate reanalysis going back 100 years or more. A large portion of the project was dedicated to data rescue, with a focus on early upper-air observations in sparsely observed regions critical for climate (e.g. in the tropics and at high latitudes). This has already resulted in a huge increase in the digitised instrumental record for the early 20th century, more than doubling the total number of pre-1957 weather observations from kites and early radiosondes ready for reanalysis (see Figure 1). ERA-CLIM also kick-started an important international activity in satellite data rescue by investigating the availability of data records from pre-operational satellites and their potential use in future climate reanalyses. The project produced the first comprehensive inventory of early satellite data for reanalysis, including priorities for data rescue and information about next steps (see Table 1 for an excerpt of the inventory).

ERA-CLIM provided substantial support to the UK Met Office Hadley Centre for developing improved global estimates of sea-surface temperature and sea-ice concentration during the 20th century. The Met Office also developed important new data collections with high-quality sub-surface and surface ocean observations for reanalysis.

 doi:10.21957/qnreh9t5

What is reanalysis?

A

Reanalysis is a method for producing a comprehensive and physically consistent numerical description of the climate as it has evolved in the recent past. The aim is to extract maximum information from the relevant instrumental record by using the best available models to assimilate different types of observations, e.g. from weather stations, ships, balloons, aircraft and a large variety of satellites. The use of models in a reanalysis ensures that all observations are interpreted in a consistent manner and that spatial and temporal gaps in the data are filled based on physical and dynamical constraints. The use of observations from multiple sources makes it possible to reduce uncertainties, to detect bad observations and, in some cases, even to correct them. The reanalysis generates time series of gridded estimates for many different variables, including some that are not directly observed such as stratospheric winds, radiative fluxes, root-zone soil moisture, etc. To maintain the best possible temporal consistency in these time series it is imperative that the models and data assimilation methods used in a reanalysis production remain unchanged throughout.

A global reanalysis typically spans multiple decades at sub-daily frequency and moderate spatial resolution determined by available computational resources. Reanalysis products are very widely used in research and education, as indicated by numerous citations in the scientific literature. The encyclopaedic nature of a reanalysis enables many applications that are difficult or impossible to achieve with observations alone. For example, one can calculate climatologies and probability distributions for many variables, study the statistics of extreme weather events in different locations, and compute diagnostics of the global energy budget and the hydrological cycle. Modern reanalysis productions are often continued in near-real time using observations as received by operational forecasting centres. This makes it possible to use reanalysis for monitoring climate change, and to support a variety of applications and climate services that require timely information about the current state of the climate.

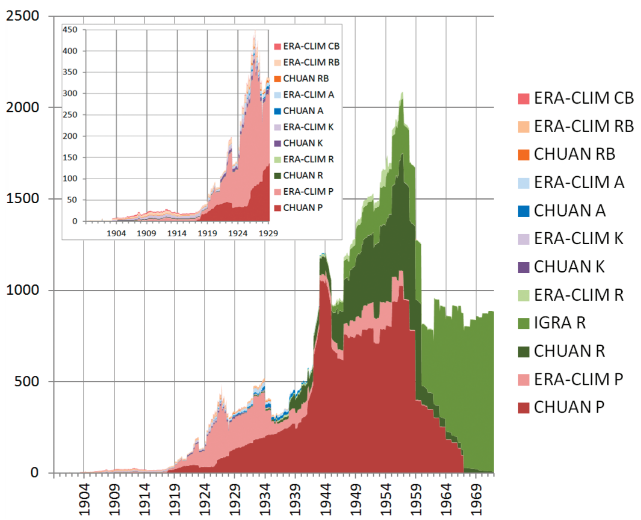

Figure 1 Number of upper-air records recovered in ERA-CLIM for various observing platforms, compared with those available in the existing data collections CHUAN (Comprehensive Historical Upper-Air Network) and IGRA (Integrated Global Radiosonde Archive). CB: captive balloon, RB: registering balloon, A: aircraft, K: kite, R: radiosonde, P: pilot balloon. Reproduced from *Stickler et al.* (2014, *Bull. Am. Meteorol. Soc.,* in press).

Did ECMWF's technical infrastructure need to be developed for ERA-CLIM and what were the main outputs from the project?

A great deal of work had to be done to prepare the Integrated Forecasting System (IFS) for a century-long reanalysis. The IFS forecast model was supplied with boundary conditions and radiative forcing data appropriate for a climate simulation (*ECMWF Newsletter No. 133*, page 3), and vast numbers of input observations were organised, checked for quality, archived, and prepared for reanalysis. Various modifications had to be made to the data assimilation scheme in order to optimize performance, both in terms of computational efficiency and scientific quality. We described some of the technical challenges associated with running such a major reanalysis production on the ECMWF computing and data handling systems in an earlier newsletter article (*ECMWF Newsletter No. 134*, page 6).

In the end we were able to complete ERA-20C, ECMWF's first global atmospheric reanalysis of the 20th century within a reasonable amount of time. ERA-20C is based on surface observations only (surface pressure and marine winds) and provides 3-hourly atmospheric data for the period 1900-2010 at 125 km horizontal resolution and on 91 vertical levels. We also produced the corresponding set of model simulations for the same period (ERA-20CM); this will be useful for assessing the impact of the observations on quality and temporal consistency of the reanalysis. Finally we generated a higher-resolution (25 km) land-surface model integration (ERA-20CL) using the meteorology from ERA-20C. Taken together, the ERA-20C/M/L reanalysis products constitute a major new dataset for climate research (see Figures 2 and 3). The combined set, with hundreds of terabytes of data, is currently being prepared for public release via the internet (see Table 2).

Another important contribution to the technical infrastructure at ECMWF that came from ERA-CLIM is the Observation Feedback Archive, designed to provide better access to the input observations used in reanalysis – see Box B for more information.

Instrument	Characteristics	Immediate concern	Recom-mendation
NEMS	Microwave spectrometer, with two water vapour channels near 22 GHz (5 mm) and three channels near 59 GHz (10 mm), spatial resolution 180 km at nadir	Nadir-viewing only, data on microfiche	**Reject for now**
SCAMS	Microwave spectrometer, with one water vapour channel near 22 GHz (5 mm), three channels near 59 GHz (10 mm), one window channel, spatial resolution 150 km at nadir	Data recovery in process by NSSDC	**Consider for assimilation**
SSM/T	Microwave temperature sounders precursors to AMSU-A and AMSU-B but with bigger fields-of-view. Met Office preparing homogenized data for ERA-CLIM.	RT forward model needed for SSM/T	**Assimilate**
SMMR	Microwave radiometer, ten channels: dual-polarization measurements at 6.63, 10.69, 18.0, 21.0, and 37.0 GHz, spatial resolution 150 km at nadir	Raw radiance data not found	**Keep looking for data**
SSH	Discrete filter radiometer, six channels in the 15 micron CO_2 band, one window channel, eight water vapour channels in the 22–30 micron band, one channel in the 10 micron ozone band	Data lost forever?	**Keep looking for data**
HIRS on Nimbus-6	Discrete filter radiometer, seven channels in the 15 micron CO_2 band, two window channels, two water vapour channels, five channels in the 4.3 micron band, spatial resolution 25 km at nadir	Data recovery in process by NSSDC. Digital version of the SRF not found	**Assimilate**
SCR	Radiometer observing through a pressurized optical cell, six channels in the 15 micron CO_2 band, spatial resolution 112–160 km at nadir (Nimbus-5: eight channels in the 15 micron CO_2 band, three window channels, one water vapour channel at 18.6 microns, spatial resolution 30 km at nadir)	RT coefficients challenging	**Validate**
PMR	Radiometer observing through a pressurized optical cell	RT coefficients challenging	**Assimilate**
HRIR	Visible and infrared imager, 8 km spatial resolution at nadir, 3.5–4 micron channel (and also 0.7–1.3 for Nimbus-3)	Digital version of SRF not found	**Validate**
MRIR	Infrared imager, five channels including a water vapour channel in the 6.7 micron band	Digital version of SRF not found	**Validate**
THIR	Infrared imager, one window channel and one water vapour channel in the 6.7 micron band	Only JPEG images available, raw radiance data lost forever?	**Keep looking for data**
IRIS	Michelson interferometer, covering 5–20 microns with 5 cm^{-1} normalized apodized spectral resolution (Nimbus-4: 6.25–25 microns, 2.8 cm^{-1} resolution), nadir spatial resolution 144 km	Short time period, calibration biases	**Validate**
SIRS	Grating spectrometer, covering 11–15 microns (Nimbus-4: 11–36 microns), nadir spatial resolution 220 km	Narrow swath (up to 12 degrees only from nadir)	**Consider for assimilation**
AVHRR	Imager on polar orbiters, atmospheric motion vector (wind) retrievals at the poles. EUMETSAT and CIMSS working on reprocessing.	Reprocessing not complete yet	**Assimilate**
SeaSat	First scatterometer ever. Suspicious end-of-life.	Very short dataset (97 days)	**Validate**
NSCAT	Scatterometer from U.S.	Short dataset (9 months)	**Assimilate**

Table 1 Selection of early satellite instruments with potential impact on reanalysis, with recommendations for future use.

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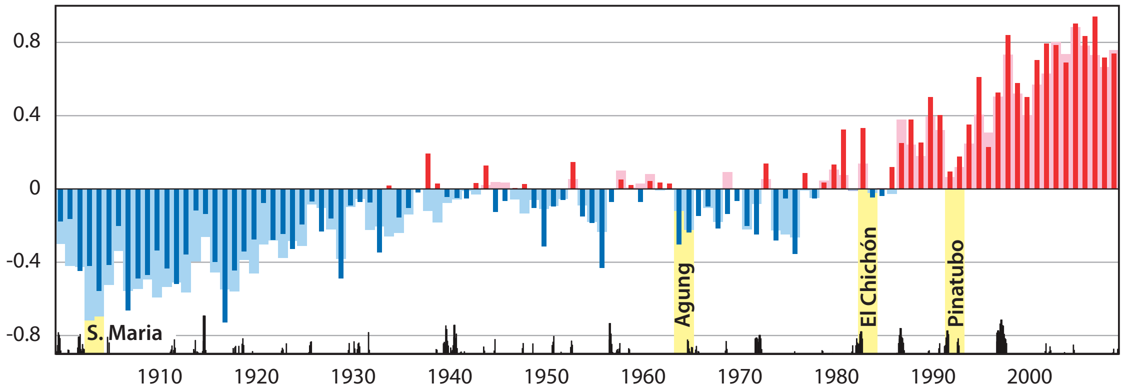
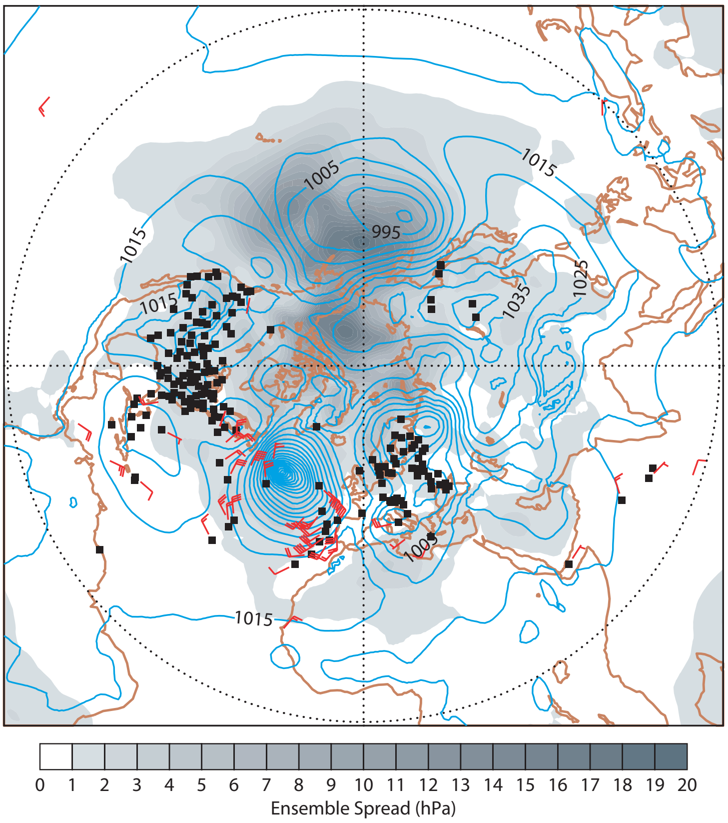


Figure 2 Verification of ERA-20CM annual-mean 2-metre temperature anomalies (K) (light shading) against independent estimates from station observations based on CRUTEM4 version 2.0.0 (dark shading). Yellow bars mark major volcanic events; timing and strength of El Niño events is indicated along the horizontal axis. The CRUTEM4 dataset is produced at the Met Office Hadley Centre (available at www.metoffice.gov.uk/hadobs). Anomalies are computed relative to 1961–1990 averages, and the comparison is for area-weighted averages taken over all grid boxes for which CRUTEM4 has values. Reproduced from *Hersbach et al.* (2013, *ERA Report Series No. 16,* ECMWF, UK).




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

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

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

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

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

Figure 3 The map shows the ERA-20C reanalysis of surface pressure (hPa) at 12 UTC on 3 February 1899 in the northern hemisphere (blue contours), with locations of all surface observations used (black dots: surface pressure; red vanes: 10-metre winds). Also shown are error estimates for the reanalysis (grey shading). Note the very deep low-pressure system in the North Atlantic and the large uncertainties in the active but poorly observed North Pacific. An extract from The New York Times published on 16 February 1899 describing the severity of the weather in the North Atlantic is also shown.

Improving access to observations

B

A major outcome of ERA-CLIM is the Observation Feedback Archive (OFA). Its function is to provide direct access to all input observations used in a reanalysis, together with 'quality feedback'. This is information generated by reanalysis pertaining to the quality of the observations, such as quality control indicators, bias estimates, estimates of observation uncertainty, and reanalysis fit to observations. The OFA also provides identifiers and other information that enables users to trace each individual observation to its source, and ultimately to retrieve additional metadata relevant to the quality of the observation. Examples of such metadata include images of logbooks or journals used to record early weather observations, documentation of the instruments used, or of changes in the environmental conditions for the instrument location.

The thinking behind the OFA is that users of reanalysis products need better tools for answering questions about the assimilated observations. The information content of a reanalysed field or parameter strongly depends on the types of observations used, where they are located and how well they are represented in the final product. This is especially relevant for climate reanalyses that extend far back in time. For the ERA-CLIM and ERA-CLIM2 projects we therefore adopted a strict data policy requiring all observations used in reanalysis to be made available to users, without exception.

The OFA will provide a dynamic, user-friendly interface for selecting, visualising, and retrieving observations from the ECMWF archive. The facility is still in an early stage of development and will be greatly expanded and improved in coming years. Please visit apps.ecmwf.int/datasets/ to try out the current version.

Reanalysis provides a wide range of data, but how will this data support the provision of climate services?

Climate services encompass a wide range of activities that deal with generating, processing and delivering information about past, present and future climate and its effect on society and the environment. Applications include monitoring and seasonal prediction of droughts, policy development in agriculture, water use, health and urban planning, climate-related risk assessments for the reinsurance industry, optimal design of sustainable energy projects, and much more. Reanalysis already supports many of these activities by providing consistent estimates of a large set of climate variables, with the possibility of updating these estimates close to real time. Global reanalyses of the atmosphere, ocean and land surface are used to calibrate the coupled models needed for seasonal prediction, and, more generally, to validate and improve climate models. Production of high-resolution reanalyses for limited domains (e.g. Europe, or the Arctic) requires boundary conditions and other background information from global reanalyses.

Indeed, a central place for reanalysis in the information chain for climate services is foreseen in current plans of the European Commission for the establishment of an operational Copernicus Climate Change Service. To prepare for this, we have already started to transfer some of the reanalysis activities at ECMWF from research to operations, ultimately to combine monitoring, evaluation and dissemination of near-real-time reanalysis and forecast products. We are also working hard to replace the current ERA-Interim reanalysis, which is based on a 2006 version of the IFS, with a new atmospheric reanalysis of the satellite-dominated modern observing period.

ERA-20C	Global atmospheric reanalysis from 1900–2010, 3-hourly data at 125 km spatial resolution and 91 vertical levels.
ERA-20CM	Global atmospheric model simulations from 1900–2010, monthly data at 125 km spatial resolution and 91 vertical levels.
ERA-20CL	Global land-surface reanalysis from 1900–2010, 3-hourly data at 25 km spatial resolution.

Table 2 Summary of ERA-20C/M/L family of reanalysis products.

doi:10.21957/qnreh9t5

As well as supporting climate services, should reanalysis data be used to estimate trends and low-frequency variability?

The short answer is yes, but with great care. Early generations of reanalyses, and some recent ones as well, have produced spurious shifts and other artefacts in the data that can be attributed to a number of causes. Some of these are technical in nature; for example, improper use of satellite observations, transitions between multiple production streams, or various mistakes that can occur in a complex reanalysis production. A much more difficult issue to deal with is the presence of biases in the assimilating model. This inevitably leads to residual biases in the reanalysis, which change over time depending on the quality and quantity of the assimilated observations. Since major changes in the observing system tend to occur on timescales relevant for climate, the impact of model biases can deteriorate the representation of climate signals and trends in a reanalysis. In short, the 'climate quality' of a reanalysis depends on the accuracy of the assimilating model as well as on the observational coverage. Of course, any other method for estimating trends from observations suffers from the same fundamental difficulty – which is, in fact, that neither models nor observations are perfect.

Nevertheless, between producing ERA-40 and ERA-Interim a great deal of progress was made at ECMWF in addressing many of the technical issues just mentioned. The ERA-Interim reanalysis uses a more sophisticated data assimilation method, based on a 4DVAR analysis that generates automatic bias adjustments for satellite observations. Technical facilities for observation handling, monitoring and diagnostics, have greatly improved as well. All of these factors have led to a much better representation of trends and low-frequency variability in ERA-Interim, as has been demonstrated for near-surface temperature and humidity by comparisons with independent estimates obtained from in-situ observations (see Figure 4).

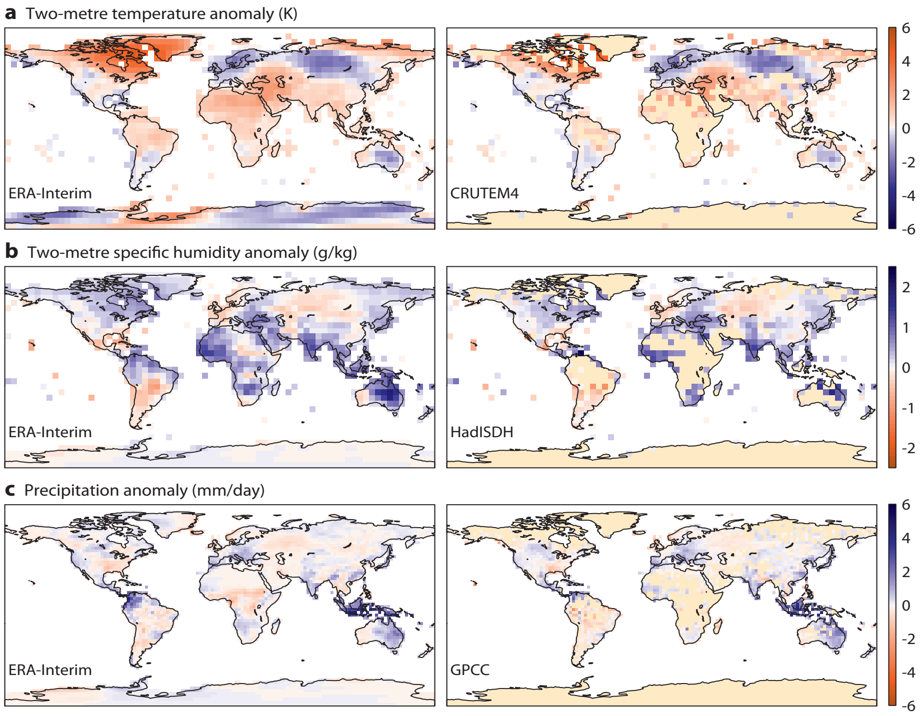

Figure 4 Anomalies for 2010 relative to 1981–2010 in (a) surface air temperature (K), (b) surface specific humidity (g/kg), and (c) precipitation rate (mm/day) from ERA-Interim (left) and from three climate datasets: CRUTEM4 (a, right), HadISDH (b, right) and GPCC Full Data Reanalysis Version 6 (c, right). ERA-Interim values for a particular variable are averaged over the 5° or 2.5° grid boxes of the dataset with which comparison is made, and are plotted for grid boxes that are at least 10% land or where there are otherwise data values for comparison. Values from CRUTEM4, HadISDH and GPCC are plotted only for grid boxes with a complete monthly data record for 2010. For GPCC it is also required that there be at least one station per grid box. 2010 was a relatively warm and moist El Niño year. This figure is taken from *Dee et al.* (2014, *Bull. Am. Meteorol. Soc.,* in press).

The range of reanalysis activities you have described is very impressive. How do you know whether reanalysis products are being used by climate scientists and the EU is getting value for money from its investment in reanalysis?

The impact of reanalysis on climate science and applications is indicated by the large body of scientific work that makes use of reanalysis products. Journal articles describing global atmospheric reanalyses are consistently among the highest-cited in geosciences, with (according to Google Scholar at the time of this writing) 1,856 citations of *Dee et al.*, 2011 (on the ERA-Interim reanalysis) and 4,627 of *Uppala et al.*, 2005 (on the earlier ERA-40 reanalysis). As reported in the literature, reanalysis products are used for studies in a broad range of subjects in atmospheric science, oceanography, climate science, and in many application areas such as energy, health and the environment.

International awareness of the ERA-CLIM and ERA-CLIM2 projects has grown as well, with numerous users in the scientific community inquiring about availability and characterization of future data products. The full impact of these projects on climate science will not be realized until the first major reanalysis datasets for the 20^{th} century are published, later in 2014. The EU will get excellent value for money from these projects, because the existing reanalysis capability at ECMWF is state-of-the-art and has been largely paid for by its Member States.

What scientific and technical expertise does ECMWF bring to its long involvement in reanalysis activities?

Producing a reanalysis is a complex technical feat involving multiple disciplines, with lots of opportunity for error. ECMWF's core business is, of course, numerical weather prediction for the medium range (days to weeks ahead). Tools and systems developed for this purpose include state-of-the-art forecast models, data processing systems that handle millions of weather observations daily, and the world's largest archive of meteorological data. Together these provide the basic technical infrastructure needed for production and dissemination of high-quality reanalysis products. The most important ingredient that the Centre provides, however, is its highly collaborative work environment, created over many years by motivated scientists and developers who enjoy working together. The benefit to reanalysis of this collaborative spirit cannot be underestimated.

Clearly the meteorological community as a whole benefits from reanalysis activities, but how does ECMWF benefit?

Reanalysis has always been closely connected with the development of the operational forecasting system at ECMWF. A reanalysis of observations collected for the First Global Experiment of the Global Atmospheric Research Programme (FGGE) started only months after the first operational forecast was issued in August 1979, with the aim to improve the use of observations for initializing the forecasts. This was the beginning of a strong and lasting feedback loop between improvements in the global observing system, advances in data assimilation, and development of better forecast models through reanalysis. Successive reanalyses produced at ECMWF have improved along with the forecasts (e.g. due to model improvements, introduction of 4DVAR). Conversely, many new developments especially in data assimilation benefit from reanalysis activities (e.g. the use of humidity observations, treatment of biases in observations).

Today, many of the Centre's probabilistic forecast products, such as those based on the Extreme Forecast Index (EFI), would not be possible without reanalysis. Similarly, the skill of seasonal forecasts depends on the quality of the reanalyses that are used to correct systematic errors in the coupled models used to produce the forecasts. And, of course, the familiar measure of forecast skill based on anomaly correlations requires climatologies derived from reanalyses.

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Can you give me a specific example of how ECMWF has used reanalysis data?

The ability to update a reanalysis (and associated forecasts) in near-real time provides a powerful way to assess changes in performance of ECMWF's IFS. Since reanalyses are produced with a fixed configuration of the IFS, it can be very useful to compare the evolution over time of medium-range forecast skill with that of reforecasts produced with the reanalysis system. This is illustrated in Figure 5 for anomaly correlations of 500 hPa geopotential height forecasts averaged over the hemispheres, obtained from operations and from reanalyses (ERA-40 prior to 2002, and ERA-Interim from 1979 to 2013).

The figure shows, for example, the effects of atmospheric predictability (common to all curves), the role of an improving observing system (visible in the reanalyses), including better satellite data (convergence of hemispheric scores for ERA-Interim), and of improvements in satellite data assimilation (convergence of hemispheric scores for operations). Comparing the slopes in the top and bottom panels suggests that, on average, at most 15% of medium-range forecast skill improvement achieved during the last three decades can be directly attributed to the evolution of the observing system – the lion's share is due to advances in modelling and data assimilation. The figure does not show, of course, that the research and development conducted at ECMWF that led to those advances benefited greatly from the improved observations – a perfect example of the feedback loop mentioned earlier.

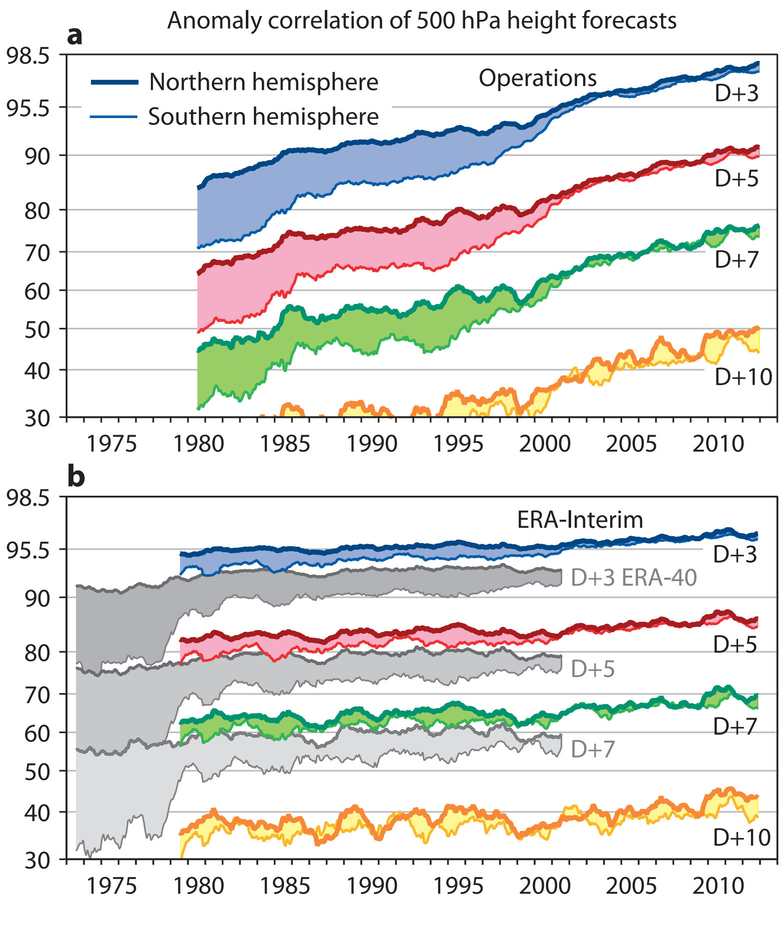

Figure 5 Twelve-month running mean anomaly correlations (%) of 3-day, 5-day, 7-day and 10-day 12 UTC forecasts of 500 hPa height for the extratropical northern and southern hemispheres from (a) ECMWF operations from January 1980 to May 2013 and (b) ERA-Interim from 6 January 1979 to April 2013 and ERA-40 from January 1973 to December 2001. The shading shows the difference in scores between the two hemispheres at the forecast ranges indicated. This figure is taken from *Dee et al.* (2014, *Bull. Am. Meteorol. Soc.,* in press).

So far the discussion has focused on atmospheric reanalyses.
Are there different types of reanalysis produced by ECMWF and other organisations?

Apart from the global atmospheric reanalyses that many are familiar with, ECMWF also produces separate reanalyses of the ocean and (more recently) of the land surface. Both depend on estimates of meteorological forcing obtained from atmospheric reanalyses. A relatively short (from 2003) reanalysis of global atmospheric composition was produced within the framework of the MACC (Monitoring Atmospheric Composition and Climate) project, using a version of the IFS that includes chemically reactive gases, aerosols and greenhouse gases. The ERA-CLIM2 project mentioned earlier will take the first steps toward consolidating these separate reanalyses into a single, consistent reanalysis of the coupled Earth system.

Other types of reanalyses are being developed, both at ECMWF and elsewhere, to support a variety of applications in climate science and environmental modelling. These include extended climate reanalyses such as ERA-20C that span a century or more, which tend to assimilate only a select subset of observations in order to maintain some degree of uniformity in the observational input over the period in question. On the other side of the spectrum, regional reanalyses produced at increased spatial resolution can potentially provide additional benefit from high-resolution observations. In all cases, the goal is to make the best possible use of the available instrumental record.

Now a final question. What do you find particularly rewarding about being involved in reanalysis activities?

I really enjoy the collaborations we have both here at ECMWF and elsewhere. The European projects we are involved in have connected us with many interesting people, not least those who are dedicated to the painstaking but heroic task of preserving historic climate observations. These people, while not very visible, are highly motivated to do their part in advancing climate science. The other rewarding aspect of working on reanalysis is the enormous amount of goodwill and support from users who are well aware of its value for their work. Finally, I am excited about our role in climate services development – it is an opportunity to have a real and positive impact on the well-being of society.

Further reading

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Uppala, S.M. & **coauthors,** 2005: The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.,* **131,** 2961–3012.

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