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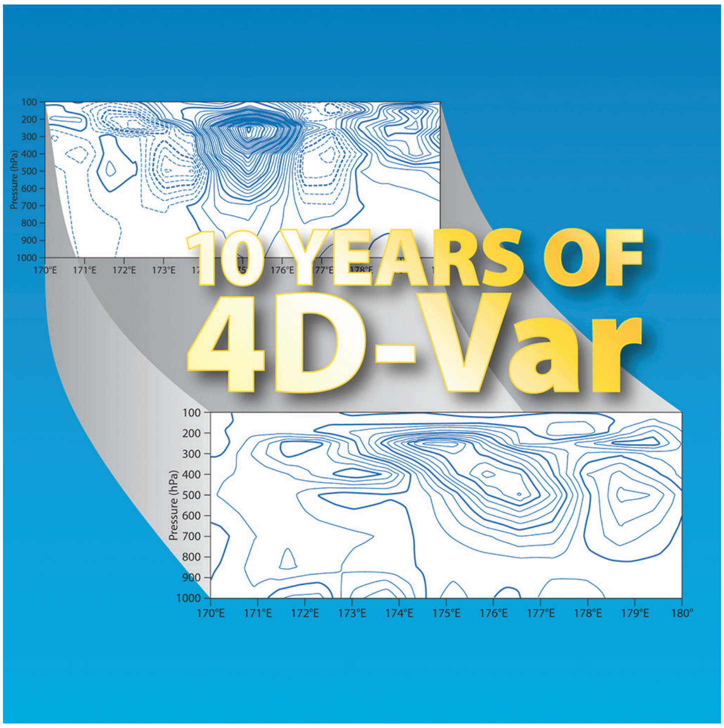

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Towards a climate data assimilation system: status update of ERA-Interim

Sakari Uppala, Dick Dee, Shinya Kobayashi, Paul Berrisford, Adrian Simmons

The process of reanalysis involves using observations from past decades in a state-of-the-art forecasting system that is more sophisticated than that available when the observations were made. This process provides a set of high quality global analyses which have been used for a wide variety of applications in sectors such as agriculture, water management, air quality and health.

The Reanalysis Section of ECMWF has in the past produced three major reanalyses: FGGE, ERA-15 (*ECMWF Newsletter No 73*) and ERA-40 (*ECMWF Newsletter No 101*). The last of these consisted of a set of global analyses describing the state of the atmosphere and land and ocean-wave conditions from mid-1957 to mid-2002. Now progress is being made in producing 'ERA-Interim'. This is a reanalysis of the atmospheric state covering the period from 1989 until real time, using a 12-hour 4D-Var data assimilation system as described in *ECMWF Newsletter No 110*. The plans are to continuously update ERA-Interim in near-real-time when it reaches present.

Here some comparisons will be made between ERA-40 and ERA-Interim, and occasionally reference will be made to two other sets of reanalyses:

- JRA-25 produced by the Japanese Meteorological Agency (JMA) and the Central Research Institute of Electric Power Industry (CRIEPI).
- NCEP-DOE reanalysis 2 produced by the National Centers for Environmental Prediction and the National Center for Atmospheric Research in the USA.

As the second half of 2003 is now being analysed, ERA-Interim has progressed beyond the end of ERA-40. After completion of the first four years it was decided to revise the configuration of the system, as discussed in *ECMWF Newsletter No. 111,* and to rerun the initial segment. Other shorter reruns for later periods have been completed as needed for technical reasons.

The first ten years, 1989–1998, of the validated ERA-Interim analysis daily products, comprising the merged production run and the reruns, can now be accessed by MARS users (`expver=1`, `class=ei`). Also available are the twice daily ten-day forecasts and monthly means. The ERA-Interim archive is more extensive than that for ERA-40, e.g the number of pressure levels is increased from ERA-40's 23 to 37 levels and additional cloud parameters are included. It is expected that the next five years of ERA-Interim, 1999–2003 will be released after validation around June 2008 and that the production will catch up with real time during the second half of this year. ERA-Interim products are also publicly available on the ECMWF Data Server, at a 1.5° resolution, including several products that were not available for ERA-40.

The ERA-Interim website will provide information on the current status and latest developments. Near the end of the year ERA-Interim will be running as a Climate Data Assimilation System, which will open new opportunities for climate monitoring. A subset of the current reanalysis monitoring information, together with some additional climate monitoring indices recommended by WMO, will be included on the ERA-Interim web site. Details will be decided later as what can be provided will depend on available resources.

ERA-Interim quality aspects

Based on internal evaluations and comparisons with other reanalyses, the quality of ERA-Interim products is generally good and its long-term homogeneity has improved considerably over that of ERA-40. Internal validation of the ocean wave height analysis produced with ERA-Interim also indicates a higher degree of homogeneity. Verification against independent buoy measurements shows rms errors that are stable and much smaller than in ERA-40. Also there is reduced 10-metre wind speed bias over extratropical ocean areas in the northern hemisphere.

While it is not possible to state exactly how each new component of the ERA-Interim data assimilation system contributes to these improvements, we can, in broad terms, state the following.

- 4D-Var with a 12-hour window makes better use of asynoptic observations than the 6-hour 3D-Var FGAT used in ERA-40, especially for the "relatively sparse" HIRS, MSU and the stratospheric SSU radiances in the early 1990s.

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- The upgraded moisture analysis together with improved model physics have resulted in smaller humidity increments, lower precipitation and reduced spindown during the model integration relative to ERA-40.
- Compared to the static bias corrections used in ERA-40, the new variational bias correction scheme (VarBC) is better able to maintain consistency among different components of the observing system. This facilitates the extraction of the true signal present in the data, and helps to maintain time continuity by reducing analysis increments (e.g. in the stratosphere).

New satellite data types improving the analysis quality

ERA-Interim will make use of data from the increasing number of new instruments on satellites from 2003 onwards as discussed by Graeme Kelly and Jean-Noël Thépaut in *ECMWF Newsletter No. 113*. In particular 4D-Var and VarBC will improve the extraction of information from data provided by high-resolution instruments. Nevertheless, specially designed observing system experiments may be needed to help interpret climate signals in the ERA-Interim time series.

The transition from a stratospheric analysis dominated by SSU radiance data to one primarily controlled by AMSU-A occurred in August 1998. Prior to the transition, SSU channel 3 radiances (with peak sensitivity at 1 hPa) were used without bias correction in order to prevent a drift of the assimilation towards the model climate in the upper stratosphere. With the introduction of AMSU-A in August 1998 it was decided to switch to using AMSU-A channel-14 radiance data (also peaking at 1 hPa) without bias correction, and to allow VarBC to correct SSU channel 3 in order to maintain consistency between the two sensors. Since the constraints provided by the two sensors are qualitatively different, this transition produced a noticeable but unavoidable shift in the upper-stratospheric temperature analysis. This has resulted in a jump in temperature at levels higher than 10 hPa in mid-1998, as also occurred in ERA-40. Fundamentally, in the absence of additional high-quality observations, there is no way to further improve the fidelity of the upper-stratospheric climate signal without improving the assimilating model.

ERA-Interim has started to benefit from GPS radio occultation (GPS-RO) data reprocessed by UCAR from June 2001 onwards; for details of the operational use of these data see Sean Healy's article in *ECMWF Newsletter No. 111.* It has been demonstrated (by Shinya Kobayashi, not shown here) that the use of GPS data results in a further reduction of the residual oscillations in the mean vertical temperature observation-background structures that are not well-resolved by AMSU-A observations.

Hydrological cycle

Several of the problems found in ERA-40 have been eliminated or significantly reduced in ERA-Interim, most notably the excessive precipitation over the tropical oceans from the early 1990s onwards. The mean total precipitation over the tropical oceans for the period 1989–1998 (Figure 1) shows an overall reduction. Over tropical land areas and in the extratropics the ERA-Interim precipitation is slightly higher than in ERA-40. Figure 2 shows that over tropical oceans total precipitation in ERA-Interim is substantially lower than in ERA-40 as well as being somewhat lower than the JRA-25 precipitation. However, ERA-Interim precipitation still exceeds estimates from the Global Precipitation Climatology Project (GPCP). Until 1997 both JRA-25 and ERA-Interim are in relatively close agreement, but from then on JRA-25 indicates a small upward trend in precipitation. A small decrease in precipitation in ERA-Interim occurs in 1992, probably due to an increase in SSM/I rain-affected radiances used in the analysis.

A major part of the explanation for the improved precipitation in ERA-Interim results from both the improved moisture analysis and the model physics. The global total column water vapour in ERA-Interim is now significantly lower than in ERA-40. ERA-Interim and JRA-25 total column water vapour show very good agreement (Figure 3). Over the tropical oceans the total column water vapour from ERA-Interim is also closer to the SSM/I values produced by Remote Sensing Systems than ERA-40 (not shown).

The excessive precipitation in ERA-40 resulted in a large positive bias in the hydrological precipitation minus evaporation (P-E) balance (Figure 4). In ERA-Interim precipitation remains slightly higher than evaporation until 1991, but from then on the balance is close to zero. The JRA-25 balance is slightly negative until 1995 and is very good from then on. The NCEP-DOE reanalysis 2 has a very good P-E balance throughout.

There are strong indications that the Brewer-Dobson circulation, which is too strong in ERA-40, is more reasonable in ERA-Interim. For example, the annual cycle of specific humidity in the tropical lower stratosphere is much smaller than in ERA-40, due to reduced vertical transport across the tropopause. Preliminary diagnostic studies of 'age of air' have shown that ERA-Interim provides a much improved dataset for driving models of stratospheric chemical transport and stratosphere-troposphere exchange.

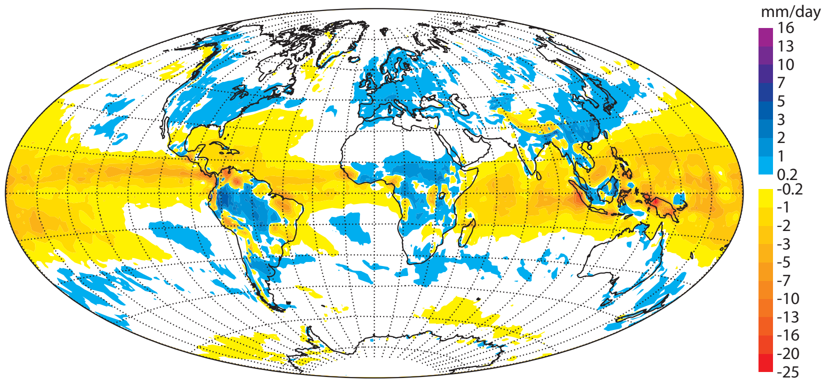

Figure 1 The difference of total precipitation between ERA-Interim and ERA-40 for 1989–1998. Units: mm day^{-1}.

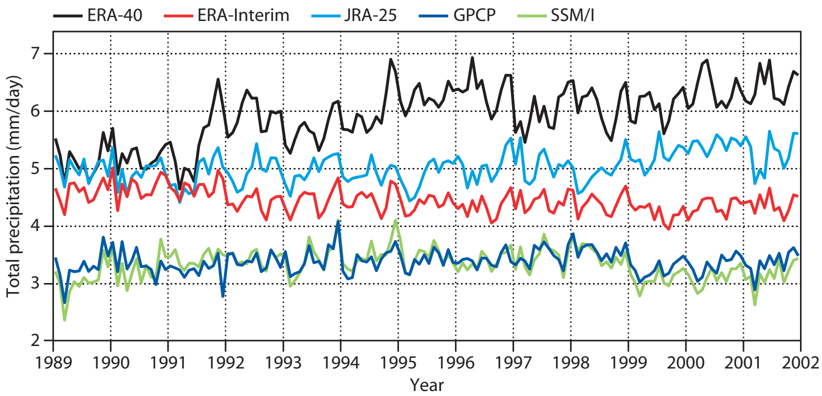

Figure 2 Time series of monthly mean total precipitation rate averaged over tropical oceans from the ERA-40, ERA-Interim and JRA-25 reanalyses, from SSM/I retrievals and from GPCP. Units: mm day^{-1}.

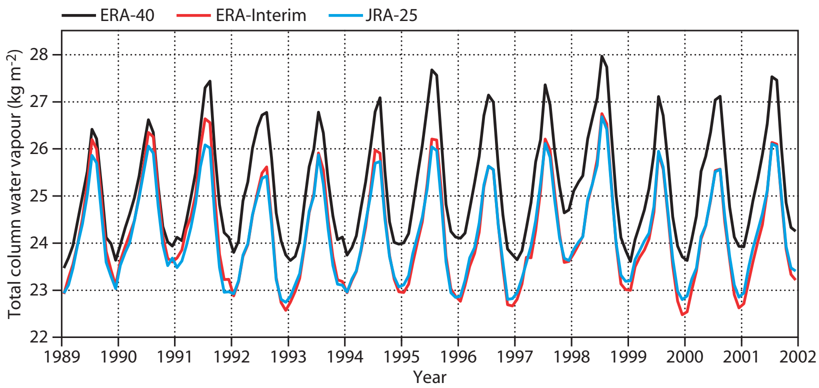

Figure 3 Global total column water vapour in ERA-40, ERA-Interim and JRA-25. Units: kg m^{-2}.

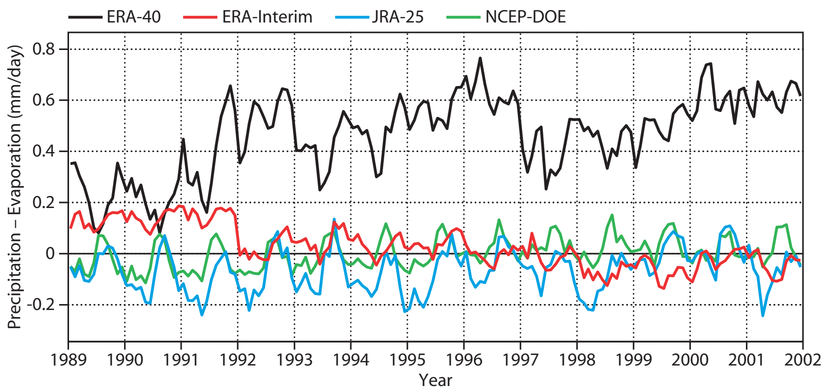

Figure 4 Global precipitation minus evaporation in ERA-40, ERA-Interim, JRA-25 and NCEP-DOE reanalysis 2. Units: mm day^{-1}.

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Variational radiance bias correction during the first ten years

A major problem with the use of observations for climate analysis is the presence of biases. Of particular importance is the effect on the estimation of climate signals of changes in these biases, their sampling frequencies, and details of the analysis techniques. This problem also exists in atmospheric reanalyses; they combine many different types of observations together with information from sophisticated models in order to produce accurate and dynamically consistent estimates of global atmospheric parameters.

In spite of best efforts to remove all systematic errors at the source, some residual biases inevitably remain. Their presence can be readily detected in a reanalysis system by monitoring the data against a common reference. The data assimilation then provides a final opportunity to correct the biases in the data, and possibly in the model as well, based on the consensus of all information presented to the analysis system. This idea, along with the practical challenge of dealing with a heterogeneous and evolving observing system, has led to the development of automated bias correction schemes embedded in the analysis component of the data assimilation system.

Questions about the long-term stability of the VarBC were raised at the *Workshop on Bias Estimation and Correction* held at ECMWF in November 2005. Do we have enough unbiased observations to anchor the system and will the variational bias corrections remain bounded? In this regard static bias corrections were considered safer even if suboptimal, but it was recognised that they are also dependent on special characteristics of the period during which the bias corrections were estimated. For example, the Pinatubo eruption in 1991 affected subsequent bias corrections of radiances in ERA-40. This in turn was partly responsible for the excessive and gradually increasing tropical precipitation.

Variational bias correction provides an automatic inter-calibration of the observing system in the context of the forecast model combined with all available observations. This results in bias corrections that improve the consistency of the information entering the analysis. Figure 5 shows bias corrections produced during the first ten years of ERA-Interim, in this case for radiance data from MSU channel 2 on NOAA-10, NOAA-11, NOAA-12 and NOAA-14 satellites. The corrections account for systematic errors in the data (e.g. due to calibration issues) but also for errors in the fast radiative transfer model used to simulate the data (e.g. due to inaccurate spectroscopy). However, there is the possibility that these corrections may also falsely correct the data for errors in the background which are due to forecast model bias, especially where observations are sparse (such as in the stratosphere).

The range of corrections produced by VarBC is rather small, and the slow trend detected in the NOAA-11 bias most likely corresponds to a drift of the instrument calibration. The variations in the correction patterns for the overlapping satellites (e.g. in 1996 for NOAA-14 and NOAA-12) may be due to actual differences between individual instruments or, alternatively, could reflect different exposures of the instruments to short wave radiation. There are strong indications that variational bias correction of radiance data is generally beneficial to the quality of the ERA-Interim reanalysis. For example, the vertical consistency of the temperature analysis, as well as the fit to radiosonde data in the polar regions, is much improved compared to ERA-40. A wealth of information will be available on the details of bias corrections that needs to be evaluated in collaboration with satellite data producers and radiance transfer modellers.

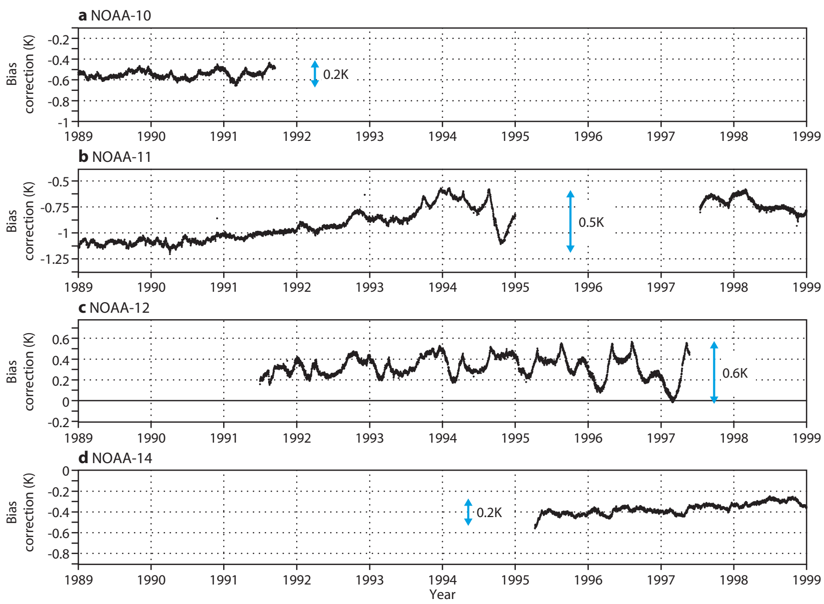

Figure 5 Global mean bias corrections for MSU channel 2 radiances from (a) NOAA-10, (b) NOAA-11, (c) NOAA-12 and (d) NOAA-14 in ERA-Interim.

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Improving the consistency between SSU and AMSU in ERA-Interim

Stratospheric temperature analyses are dominated by satellite data and therefore strongly affected by biases present in these data and/or in the radiative transfer models used to model them. In ERA-40, two problematic periods were identified in the stratospheric temperature analysis after 1979. One is the early 1980s when the observations from the Stratospheric Sounding Unit (SSU) had significant biases due to leakage of gas from the pressure modulation cell. The other is from the late 1990s to early 2000s when observations from SSU and the Advanced Microwave Sounding Unit A (AMSU-A) overlapped. In ERA-40, the static bias correction system was unable to resolve the significant discrepancy between the observed SSU and AMSU-A radiances and those computed by the Radiative Transfer model for TOVS (RTTOV) – see Figure 6. This led to blacklisting of the SSU top channel after AMSU-A observations became available, causing a second jump in temperatures above 10 hPa in mid-1999.

For better use of SSU and AMSU-A observations in reanalysis, the biases in these observations have been investigated using co-located observations produced by the Simultaneous Nadir Overpass (SNO) technique. This technique utilizes simultaneous observations at the orbital intersections over polar regions and provides reliable estimates for the inter-satellite biases with little ambiguity. The biases estimated by this method were used for verification of the radiative transfer modelling, and it was found that the biases in the SSU observations can be simulated by taking into account the gas leak from the pressure modulation cell. It was also found that the principal cause of the discrepancy between SSU and AMSU-A was the inaccurate modelling of the Zeeman effect in the computation of the AMSU-A radiances – Figure 7.

Accordingly, new regression coefficients have been computed for RTTOV using a revised line-by-line model, and experiments were carried out to test the impact of the new RTTOV. The control assimilation using the old RTTOV tends to create spurious peaks around model levels 6 and 10 (2 and 5 hPa respectively) when the strong polar vortex develops in winter. This is because the weighting function for AMSU-A channel 14 in the old RTTOV is located too high; this results in too warm radiance simulations when the mesosphere is warmer than the stratosphere. Such a situation occurs in polar regions in winter. Using the new RTTOV these spurious peaks have been reduced and the vertical temperature structure varies more smoothly with seasons. The monthly averaged zonal mean temperatures also demonstrate the significant reduction of the spurious peaks in the polar regions.

The ERA-Interim stratospheric analysis from 1998 onwards already benefits from the more accurate modelling of AMSU-A. The better modelling of SSU and AMSU-A radiances is expected to increase significantly the time consistency of all future stratospheric temperature analyses.

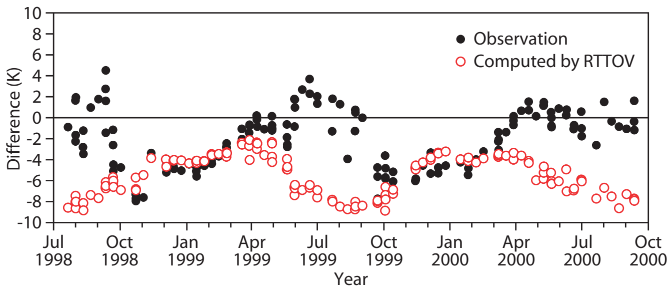

Figure 6 Differences in the observed radiances between SSU3 on NOAA-11 and AMSU-A14 on NOAA-15 over Antarctica compared to differences computed by the standard RTTOV. The difference computed by RTTOV is inconsistent with the observations in the polar winter.

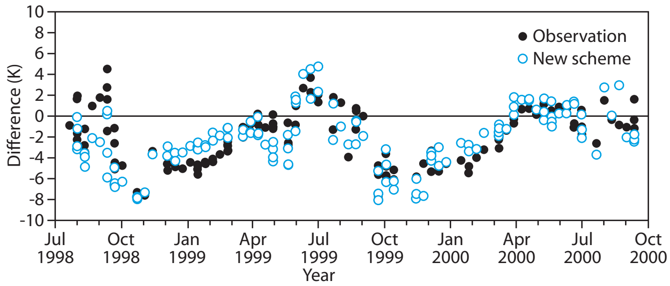

Figure 7 Differences in the observed radiances between SSU3 on NOAA-11 and AMSU-A14 on NOAA-15 over Antarctica compared to differences computed with a new scheme consisting of the standard RTTOV for SSU and a line-by-line model without the Zeeman effect for AMSU-A. The new scheme is in better agreement with the observations than if the standard RTTOV is used for AMSU-A.

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Forecast performance

Ten-day forecasts have been run twice daily from both the ERA-40 and ERA-Interim analyses. We can see a substantial improvement in forecast skill of ERA-40 over ECMWF operations for 1989–1990. ERA-Interim in turn improves substantially on ERA-40, especially in the southern hemisphere. The ability of 4D-Var to use the satellite data more effectively is a key factor in the larger improvement in the southern hemisphere. Even during 1999–2001, when operations already used 4D-Var and a higher resolution T511 assimilating model, the ERA-Interim forecasts perform better than operations and more so again in the southern hemisphere. Other improvements to the model and the analysis together with the variational radiance bias correction contribute to this. By comparing the performance between 1989–1990 and 1999–2001 in both hemispheres (see Figure 8) we conclude that ERA-Interim forecasts have a more uniform quality in time and space than forecasts from ERA-40, implying a more homogeneous analysis and product quality in ERA-Interim.

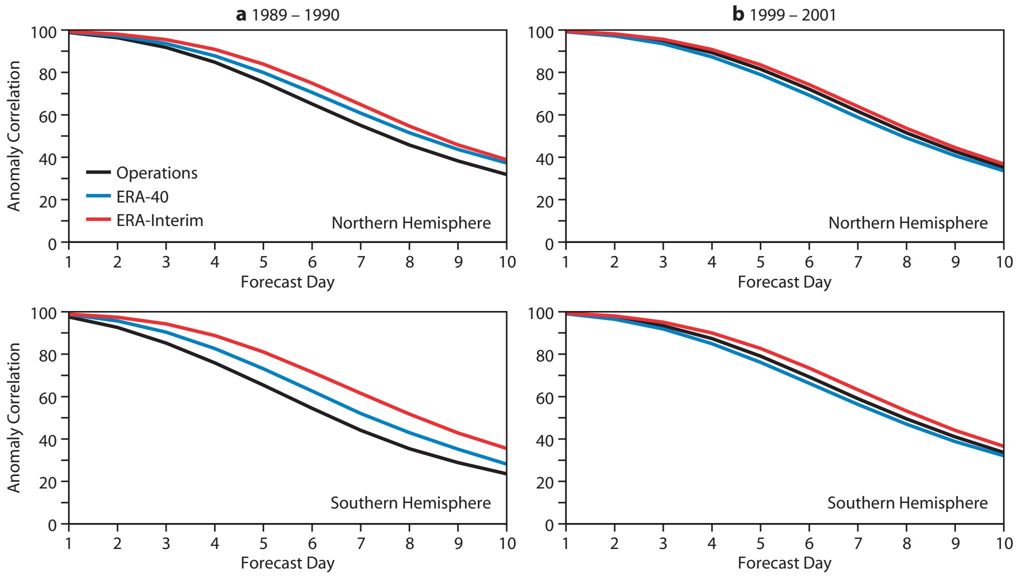

Figure 8 Mean anomaly correlation of 500 hPa geopotential for ERA-Interim, ERA-40 and original operations for (a) 1989–1990 and (b) 1999–2001. Top panels: extratropical northern hemisphere. Bottom panels: extratropical southern hemisphere.

Future outlook

The ERA-Interim reanalysis at ECMWF is the latest iteration of a process which combines developments in modelling, data-analysis techniques and computing power together with new data rescue efforts and experience gained from previous reanalyses to produce a succession of reanalyses of increasing quality. ERA-Interim benefits from many analysis and model improvements made since ERA-40 was produced, particularly in the ability to make good use of satellite radiances. After three decades of NWP development and continuous feedback from the scientific community, reanalyses are now approaching the qualities required for climate-change studies. Also, the hydrological cycle, surface fluxes and surface parameters together with the boundary layer quantities have improved over the sensitive and data sparse polar areas. Comparisons with stratospheric datasets show that we can now have good confidence in reanalyses up to 10 hPa through the years when satellite observations are available.

As seen from the news item about the *Third International Conference on Reanalysis* on page 3 of this edition of the *ECMWF Newsletter,* new reanalysis activities have now been funded in the US and Japan and are firmly established. It is urgent that similar support be re-established in Europe. To achieve this, ECMWF has engaged in extensive consultations with a number of European organizations and will aggressively seek funding under the European Commission Research and Development Framework Programmes and other sources.

Several important improvements are on the horizon. Together with the use of higher resolution models and improved analysis methods, the data assimilation can be better configured for reanalysis purposes. There are exciting developments in the use of cloud- and rain-affected radiance data for reanalysis.

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Active coupling of the atmospheric, ocean, land and ice components will become possible in the coming years. Collaborative work on improved observational input and boundary forcing data, the ongoing homogenization work on radiances and conventional data, and the increased availability of reprocessed satellite data will further advance the role of reanalyses in climate-change assessments and other applications. For the data-sparse historical periods, modern analysis schemes such as 4D-Var have demonstrated their ability, when properly tuned, to transfer information from data-dense to data-sparse areas. Therefore the concept of a century-long reanalysis is realistic and needs to be considered as a key goal for future reanalysis activities.

Further Reading

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