A new Head of Operations

At its 60th session in June 2004, the Council appointed Walter Zwieflhofer to become the next Head of Operations at ECMWF.

Walter graduated in Computer Science at the Technical University of Vienna. He then joined Control Data Corporation, a computer manufacturer. There he worked in pre-sales and technical support for customers in Austria and Eastern Europe.

He started at ECMWF in 1981 in the System Software Section as an analyst supporting the Centre's Cyber machines. In his technical career at the Centre he worked in a variety of roles: software development, operating system support, computer security and both local and wide area networking. Major projects he was deeply involved in include the Centre's very first Data Handling System and the establishment of the Regional Meteorological Data Communications Network (RMDCN).

In 1992 he became Head of Section with responsibility for Computer Security, Internal Networks and Workstation Systems, and from 1997 he held the post of Head of Computer Division. In this latter role he was responsible for the financial management of the Centre's computer budget and was involved in a number of procurements, ranging from supercomputers over high-availability systems to enhancements of the technical infrastructure at ECMWF. Walter is recognized internationally as an expert in high-performance computing systems for meteorological applications and has been invited to participate in several national review boards for supercomputing procurements.

Throughout his career at ECMWF he was involved in the provision of 24-hour operational services for the meteorological community and, in the later years, in the management of such services.

Walter's greatest exposure to the weather elements came in 1985/86 during a round-trip of the Atlantic in a sailing boat he and his wife Martina had restored and fitted out. Walter is now 48 and his main interests outside work are outdoor activities such as golf, and playing bridge when it rains.

In this issue

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Front Cover

A major ECMWF project – ERA-40, a 45-year reanalysis of the global atmosphere and surface conditions, is discussed in the article on page 2 of this issue.

Editorial

On page 2 Sakari Uppala and colleagues give a detailed account of a major ECMWF project, the 45-year reanalysis of the global atmosphere and surface conditions. This project, a successor to the earlier ERA-15 project, has had access to more extensive data sources than before and provides a rich source of information over the period 1957–2002 about the earth-atmosphere system, including the ozone distribution, the radiation budget, the hydrological cycle, the soil temperature and moisture and the ocean waves. Jan Haseler describes on page 21 the Early-Delivery Suite that has recently become operational. This enables the 0000 UTC products to be made available to every Member and Co-operating State before the end of their working day, and Jan shows that the use of an early cut-off time for the data does not lead to any substantial degradation in the quality of the forecasts. A short article on page 30 by François Lalaurette, Claud Gibert and Jan-Erik Paulson explains a new false-colour scheme for the depiction of clouds in graphical output of forecasts. Finally, we note that this summer marks the end of an era with the retirement of David Burridge as Director of ECMWF (see page 33), and the dawn of a new era with the appointment of Dominique Marbouty as the new Director (see ECMWF Newsletter 99).

Peter White

Changes to the operational weather prediction system

- On 25 May NOAA-16 HIRS radiances were blacklisted
- On 15 June a major upgrade of web services, with a substantial increase in forecast products (00 and 12 UTC forecasts – whichever is the most recent – are given the same status; a ten-day archive of graphical products is accessible online; tropical cyclone forecasts and verifying observations are offered – *Member States only*)
- On 29 June the early-delivery suite (cycle 28r2) was implemented: by shifting the 12-hour 4D-Var data-assimilation window by six hours, and running an early additional uncycled six-hour 4D-Var. The operational products are now disseminated around four hours earlier without any noticeable impact on the forecast quality.

Planned changes

A new version of the IFS (cycle 28r3) is currently in pre-operational testing. It involves important changes in both the physics (including more frequent updates of radiation computations), data assimilation (revision of ATOVS and AIRS assimilation, activation of MSG clear-sky radiances and KNMI SCIAMACHY ozone products) and the EPS (changes in the convection numerics reducing the time-step dependency, changes in the targeting and sampling of tropical cyclones, Gaussian sampling for all singular vectors instead of selection and rotation).

François Lalaurette

ERA-40: ECMWF 45-year reanalysis of the global atmosphere and surface conditions 1957–2002

The comprehensive global multi-decadal datasets generated by reanalysis of past observations using the same data assimilation techniques as applied in numerical weather prediction have become a mainstay of many types of atmospheric research. The first extended ECMWF reanalysis, ERA-15, and the NCEP/NCAR RA-I reanalysis were both carried out in the mid 1990s, and their products quickly found widespread application, including areas where, traditionally, analyses of a single variable or observations alone had been used. The ERA-40 reanalysis completed in 2003 can be considered as the first of a second generation of global reanalyses, the design of which has greatly benefited from the experience of carrying out ERA-15, from development work on the ECMWF forecasting system and from feedback provided by the user community (see http://www.ecmwf.int/research/era/).

The principle of a reanalysis has long roots in observational science and reanalyses are regularly performed within the climate research community. The availability of better methods of analysing past data, a better understanding of observation errors and biases, new observational sources, has led to a new improved version of climate analysis.

The very first 'reanalysis' at ECMWF and the simultaneous 'reanalysis' at the Geophysical Fluid Dynamics Laboratory (GFDL) in the USA were carried out in 1980, based on observations taken during 1979, the year of the First GARP[1] Global Experiment (FGGE). At that time, global data assimilation was improving rapidly, and with it forecast quality. The initial aim then was to learn how to use the new global observing systems and special observations deployed. A longer-term objective was to learn more about the global atmospheric general circulation and how its analysis was affected by the different observing systems, especially in the tropics and Southern Hemisphere. The period of one year was not long enough for serious climate studies, but the year remains as a landmark in the development of the global observing system and is seen as a dividing line in the quality of modern reanalyses that extend backwards in time to the 1940s or 1950s. This first ECMWF reanalysis was later repeated with an improved analysis system and better observation collection and quality.

Paradoxically, the subsequent archived operational ECMWF analyses have proved to be difficult to use in many applications because of inconsistencies in quality brought about by frequent improvements to the data assimilation system. There was a clear need for a longer reanalysis well before ERA-15 was begun. However this had to be preceded by technological developments in terms of computational power and the capability of storing, retrieving and handling increasing amounts of information. Evolution towards ERA-40 shows this clearly. Whereas, within roughly a two-year period starting in 1980 only a one-year global analysis (FGGE Level IIIb) was produced, a 15-year period (ERA-15) was analysed starting in 1994 and a 45-year period (ERA-40) was analysed starting in 2000. At the same time the volume of stored information increased dramatically: 10 GB (FGGE)→2000 GB (ERA-15)→70,000 GB (ERA-40). This represents not only the effects of longer reanalysis periods and finer resolution, but also the requirements of users for a greater range of information from the data assimilation and forecasts.

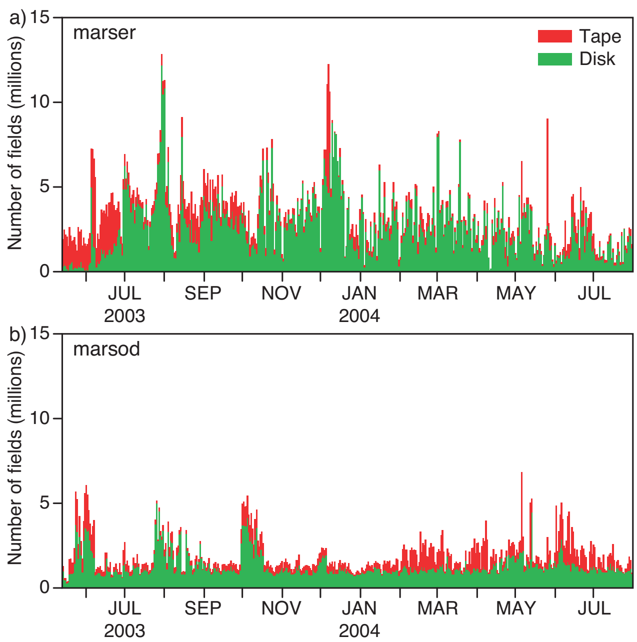


Fig. 1 Number of fields retrieved each month by users from archives; (a) ERA-40 and (b) operational .

The flexibility of access to these datasets has also had to evolve. Whereas the FGGE analyses were available only by explicitly mounting up to 50 tape reels, all of the ERA-15 and ERA-40 products are available effectively on-line for users from the ECMWF Member States and Co-operating States. The activity of these users in accessing ERA-40 products during the last year can be seen in Figure 1, which also shows the access to operational products. Users retrieve an average of about 100,000 ERA-40 fields each day, reflecting an increasing number and complexity of applications. About 400 GB of ERA-40 products are also accessible on-line worldwide on the ECMWF public data server (for details see http://data.ecmwf.int/data/d/era40_daily/ and page 19 of ECMWF Newsletter No. 99). More than 2000 users have downloaded data from this server.

The idea of using a data assimilation system, targeted to produce high quality initial states for daily medium-range forecasts, to create a long series of time-consistent analyses has been highly successful. The uses of ERA-40 reanalyses already extend from studies on bird migration to the detection of climatic temperature trends and to studies of seasonal variations of climate and their better prediction.

[1] Global Atmospheric Research Programme.

Reanalyses provide the comprehensive information source that uniquely can support such a variety of applications. Several factors contribute to this. The data assimilation system during reanalysis is as far as possible kept unchanged. The analysis is multivariate, and a six-hour forecast, the background, provides the most accurate *a priori* estimate for the analysis. Each analysis represents a state of the model after iteratively adjusting the background towards observations in a way that is optimal, given estimates of the accuracy of the background and observations. The differences between background, analysis and observations are archived for each value offered to the analysis. In addition the physical processes are 'recorded' during the model integration from one analysis to the next, the time interval during which they should be closest to the truth. All the synoptic and asynoptic observations, describing the instantaneous weather, control the data assimilation and the quality of its products over the period.

In addition to traditional diagnostic studies many new applications have arisen. Integrations of ocean, hydrological, chemistry transport, limited-area and climate models are using the reanalyses as external forcing. The quality of these reforecasts and 'secondary' reanalyses are closely linked to the quality and characteristics of the input reanalysis.

The new and improved applications using ERA-40 data, some of which are discussed later in this article, demonstrate by their quality that changes in the ECMWF data assimilation system, analysis and model since ERA-15 have been large enough to justify producing the new ERA-40 reanalysis so soon after ERA-15.

From ERA-15 to ERA-40

The ERA-15 reanalysis of 1979-1993 was completed in 1996. Soon afterwards, the idea of a new, second-generation, ECMWF reanalysis (ERA-40) from 1957 onwards was born. The idea was supported by feedback at ECMWF and from the wider user community. Deficiencies in the ERA-15 analyses had been identified, many of which were solved by subsequent developments of the ECMWF data assimilation system. There was also a need for a longer reanalysis period and to extend this up to more recent years; the seasonal forecasting system needed a long calibration and training period.

A new variational data-assimilation scheme had been developed and implemented for operational forecasting at ECMWF in 1996. The long serving optimum interpolation (OI) scheme, used in ERA-15, became a part of history. An important characteristic in the reanalysis context, the time continuity of the analyses, was improved with the variational scheme. Through the complex observation operators and improved background error modelling the variational data assimilation brought the model, analysis and observations to a closer interaction. More information than earlier could be exploited, especially from satellite radiances. A separate retrieval step was not needed and more of the original signal in the radiances was retained in the analysis. As a consequence, model levels were needed higher in the stratosphere in order to calculate the radiance equivalents from model profiles more accurately. The number of levels was increased from 31 to 50 with top level at 0.1 hPa. The improved representation of boundary-layer processes necessitated a further increase in the number of levels to 60.

The production of a three-dimensional ozone field consistent both with available ozone observations and the dynamical state of the atmosphere was needed for investigations of the composition of the atmosphere and, in the longer term, for feedback into the radiation parametrization and wind analysis. A parametrization of ozone was included. It relaxes ozone towards climatology in the absence of observations, but it is weak enough not to interfere with observations when they are available (for details see ERA-40 Report Series No. 4). Concentrations of aerosols and CO_2 were prescribed; the aerosols varied geographically and vertically (but not over time) and Intergovernmental Panel on Climate Change (IPCC) trends were specified for CO_2 and several other radiatively active gases.

A prognostic soil temperature and soil moisture scheme was introduced. The analysis of soil variables is driven by increments from a univariate OI analysis of screen-level temperature and humidity. Model-generated snow is modified by the analysis from snow-depth data where available, but is otherwise relaxed towards climate.

A coupled ocean-wave model was also introduced, and wave height analysed using satellite data when available. The ocean surface temperatures and the ocean ice cover have been provided externally in a consistent way, based on the monthly HadISST analysis until November 1981 and on the weekly National Centers for Environmental Prediction (NCEP) 2D-Var analyses thereafter. Both datasets have been interpolated to daily values (for details see ERA-40 Report Series No. 12).

In terms of the ECMWF Integrated Forecasting System (IFS), the ERA-40 system was based on cycle 23r4 of the IFS, which was operational from June 2001 to January 2002, (for details see http://www.ecmwf.int/research/ifsdocs_old). It includes, however, several modifications, some of which were introduced in subsequent operational cycles. The largest differences from operations in the second half of 2001 were imposed for reasons of cost: the use of three-dimensional variational (3D-Var) rather than four-dimensional variational (4D-Var) data assimilation and the use of T159 (~125 km) horizontal resolution rather than T511 (~39 km).

Observation systems 1957-2002

The availability of observations is the necessary precondition for a reanalysis and the quality of a reanalysis depends on the quality of both the observing systems and the data assimilation system (model and analysis). Whereas a reanalysis has a limited 'useful' lifetime, the value of observations increases in time. More information than before can be exploited from a given set of observations in a new reanalysis using an improved data assimilation system.

The International Geophysical Year (IGY), July 1957 to December 1958, had as its goal: "... to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in a space and time, so that results could be collated in a meaningful manner." Not only are the reanalysis efforts a part of this objective but also, as a consequence of the IGY, the

observing system started to develop towards an integrated global system, including the polar areas. As an indication of a new 'era', the first artificial earth satellite, Sputnik 1, was launched on October 4, 1957. The year of 1957 was an appropriate starting point for ERA-40.

The observing system has from then on evolved together with the development of operational forecasting requirements. Daily forecasts were produced by the National Meteorological Center (NMC), Washington, for the Northern Hemisphere from 1955 to 1973, and from then on for the whole globe. Consequently more observations and with higher frequency were needed over the model domain to produce the analysis. In support of this, several large measurement campaigns and experiments, including satellite and conventional observations, were carried out, one of them GATE (the GARP Atlantic Tropical Experiment) in 1974. It was the first major experiment of the Global Atmospheric Research Programme, whose goal was to understand the predictability of the atmosphere and extend the time range of daily weather forecasts to over two weeks. After a careful assessment of the results, under the leadership of WMO, requirements for the global observing system were specified and the First GARP Global Experiment was planned and implemented from December 1978 to November 1979, with two Special Observation Periods. Due to its success, the global observing system today still bears the FGGE 'hallmark', despite many changes.

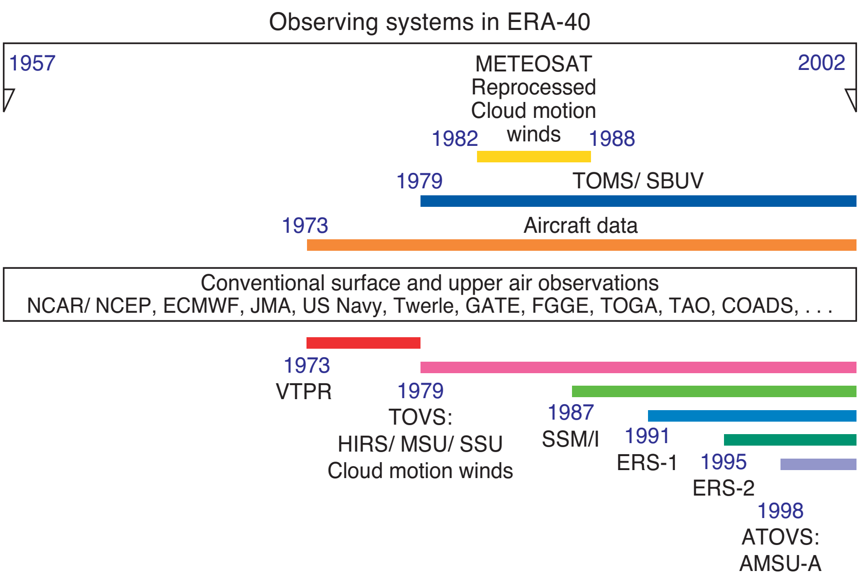
Name	Data source	Data supplier
bom_temp	Australian Antarctic data	Australian Bureau of Meteorology National Climate Centre
chin	China	NCEP/NCAR
coun	Countries	NCEP/NCAR
fgge2b	First GARP Global Experiment Final Level 2b	ECMWF
fran	France	NCEP/NCAR
gate	GARP Atlantic Tropical Experiment	NCEP/NCAR
jmaera15	Japan Meteorological Agency archives	Japan Meteorological Agency
mars2	ECMWF operational GTS data	ECMWF
misc	Miscellaneous	NCEP/NCAR
navyraob	US Navy raobs	NCEP/NCAR
ncepupa	NCEP operational GTS data	NCEP
on29	ON29 NCEP rawinsondes	NCEP/NCAR
on20raob	ON20 NCEP rawinsondes	NCEP/NCAR
raob	Raobs	NCEP/NCAR
rusu	Russia	NCEP/NCAR
td52	TD52 Global Pilots	NCEP/NCAR
td54	TD54 US radiosondes and Pilots	NCEP/NCAR
toga_rs	Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment	Center for Ocean Atmospheric Prediction Studies
twer	TWERLE Drifting balloons data	NCEP/NCAR
usaf	US Airforce	NCEP/NCAR
usct	US control radiosondes	NCEP/NCAR

Table 1 Sources of radiosonde data for ERA-40 (see also Fig. 3)

The main satellite observing-system epochs are [2]: (red indicates data not used in ERA-15)

1957-72 No satellites
1973-78 VTPR
1979 TOVS (HIRS, MSU, SSU), AMV
1987 TOVS (HIRS, MSU, SSU), AMV, SSM/I
1991 TOVS (HIRS, MSU, SSU), AMV, SSM/I, ERS
1998 TOVS (HIRS, MSU, SSU), AMV, SSM/I, ERS, ATOVS (AMSU)

Schematically the systems are shown in Figure 2.



VTPR	Vertical Temperature Profile Radiometer
TOVS	TIROS (Television InfraRed Observational Satellite) Operational Vertical Sounder
HIRS	High-resolution InfraRed Sounder
SSU	Stratospheric Sounding Unit
AMV	Atmospheric Motion Vectors
SSM/I	Special Sensor Microwave/Imager
ERS	ESA Remote-sensing Satellite
ATOVS	Advanced TOVS
AMSU	Advanced Microwave Sounding Unit

[2] Satellite instrument acronyms

Fig. 2 Schematic illustration of the use of observing systems in ERA-40.

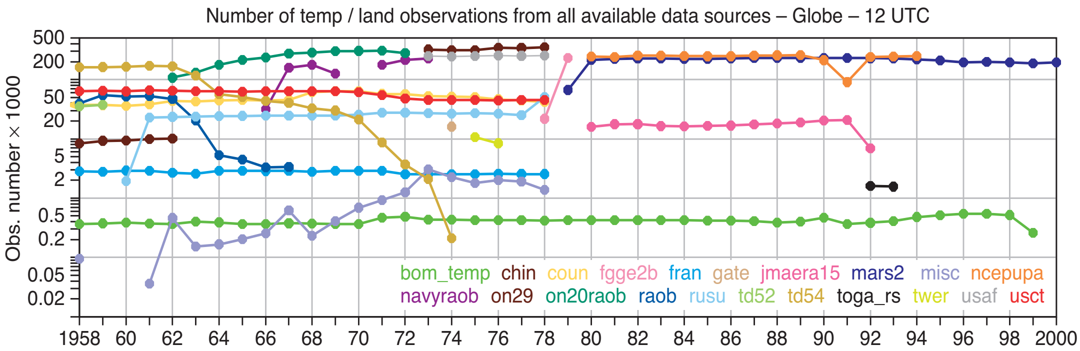


Fig. 3 Sources of radiosonde data for ERA-40 (see Table 1 for an explanation of the data sources indicated in the colour key – note the logarithmic scale)

Conventional upper-air, surface and aircraft data

The conventional observations for ERA-40 originate from many sources, reflecting the evolution of the global observing system and the archiving by various past users, (for details see ERA-40 Report Series No. 17). Most of the data from the numerous pre-1979 sources were collected as a dedicated effort at the National Center for Atmospheric Research (NCAR), and delivered to ECMWF through NCEP. The main datasets after 1979 originate from global forecasting centres: ECMWF, NCEP and JMA (Japanese Meteorological Agency).

The coverage of the Northern Hemisphere by radiosondes is relatively good and, to a large extent, uniform throughout the period, and radiosonde quality gradually improves, partly due to the quality control and feedback from operational centres. Even though the number of radiosondes decreased in the 1990s, the overall quality of the observing system has improved, due to increases of other data types such as satellite radiances, atmospheric motion vectors, aircraft data and profilers. The contribution of the fixed weather ships to the observing system over the North Atlantic was important before 1979. In the Southern Hemisphere and in the tropics the amount of radiosonde data increases gradually. Here, however, over the large ocean areas, over the Antarctic, Africa and South America, the conventional observing system alone is not sufficient to produce high quality analyses. Therefore, 1979 brings a more dramatic improvement in the quality of analyses in the Southern Hemisphere than in the Northern Hemisphere.

One of the sources of surface data, the Comprehensive Ocean Atmosphere Data Set (COADS), is the most extensive collection of global surface marine data over the period. It was produced by a collaborative effort of NOAA (National Oceanic and Atmospheric Administration) and NCAR. A new and significant system of drifting buoys was introduced in 1979 in the Southern Hemisphere and tropics and, later in the period, in the Northern Hemisphere.

Aircraft data appear first in 1973 in the Northern Hemisphere and became global in 1979, although with most of the flights (and therefore most of the data) still in the Northern Hemisphere. They have, since then, improved significantly both in coverage and quality, also providing profiles on take-off and landing since the 1990s.

The various sources of data contain a considerable number of duplicates, observations with the same identification, location and time. The necessary merging of observations and the selection of the better of the duplicates for analysis input was done using a 'PREODB' database. A predefined priority, based on the assumed quality of each source, was used to select from duplicates. For multi-level radiosondes and PILOT data the observation with more levels was selected.

Figure 3 and Table 1 indicate the different sources of radiosonde data. The pre-1979 sources typically contain data for a limited area and period. After 1979 sources are fewer, global and they provide data for a long period. They also originate from operational centres, which gives them a more consistent standard in terms of coding, coverage and quality.

The benefit of merging, even in later years, is demonstrated in Figure 4 for the 12 UTC radiosonde reports in 1994. The top panel shows those radiosonde/dropsonde reports that are in the NCEP archive but not in the ECMWF archive, in total 15,956 reports. The bottom panel shows, vice versa, the radiosonde reports in the operational ECMWF archive but not in the NCEP archive, in total 727 reports. The Global Telecommunications System (GTS) has clearly worked more effectively on the routes to NCEP and therefore highlights, even for recent years, the importance of data collection from different sources for reanalysis and climate studies. Figure 5 illustrates the monthly radiosonde and surface data coverage in 1958 and 1998 respectively.

The PREODB is a useful tool not only to perform merging, but also to carry out studies on observing systems additional to the reanalysis itself. The analysis input is the product of a unique effort, where more observations than ever before available are included in the same dataset, allowing investigations and general experimentation throughout the period. However PREODB suffers from the incompleteness of the data provided to it.

Use of satellite data in ERA-40

Satellite and conventional data are extensively used in the analysis of temperature, wind and humidity. The influence of conventional data is limited to the troposphere and lower stratosphere, but over the large ocean areas and polar regions, as well as in the upper stratosphere above 10hPa, the analysis is

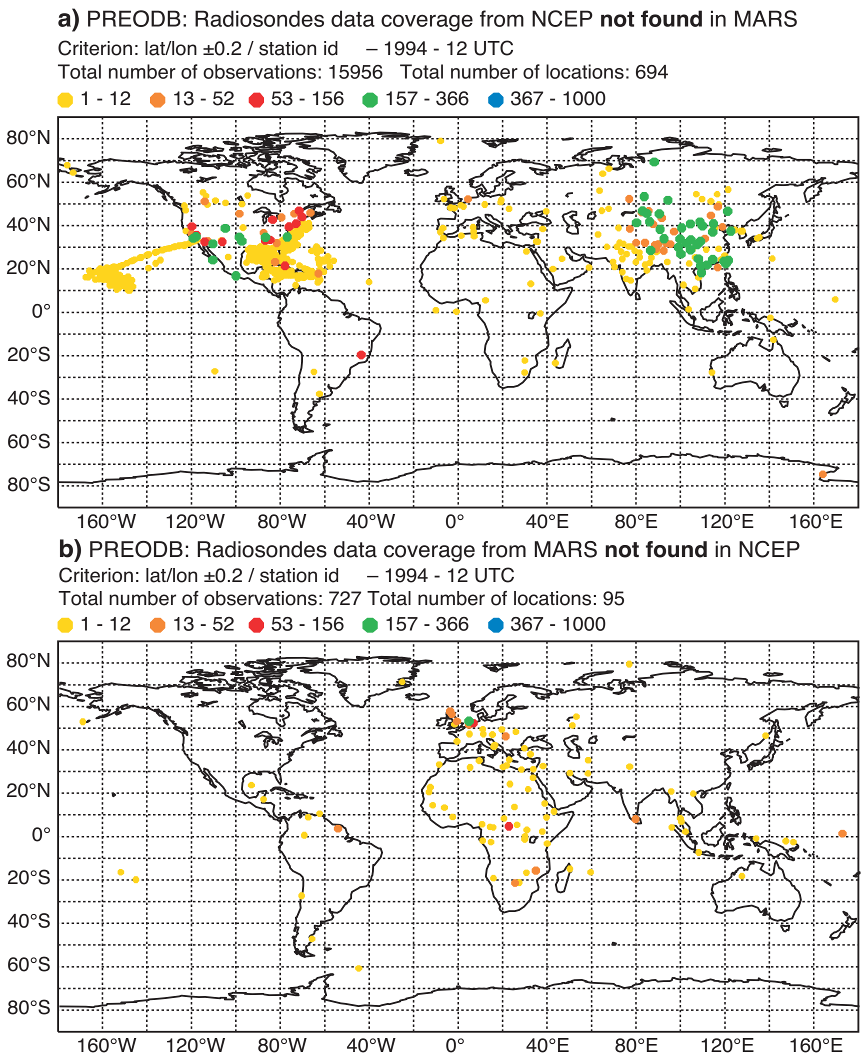


Fig. 4 Illustration of the benefit of merging observation sources. Locations of the 12 UTC radiosondes for 1994 (a) found in the NCEP but not in the ECMWF archive and (b) found in the ECMWF but not in the NCEP archive.

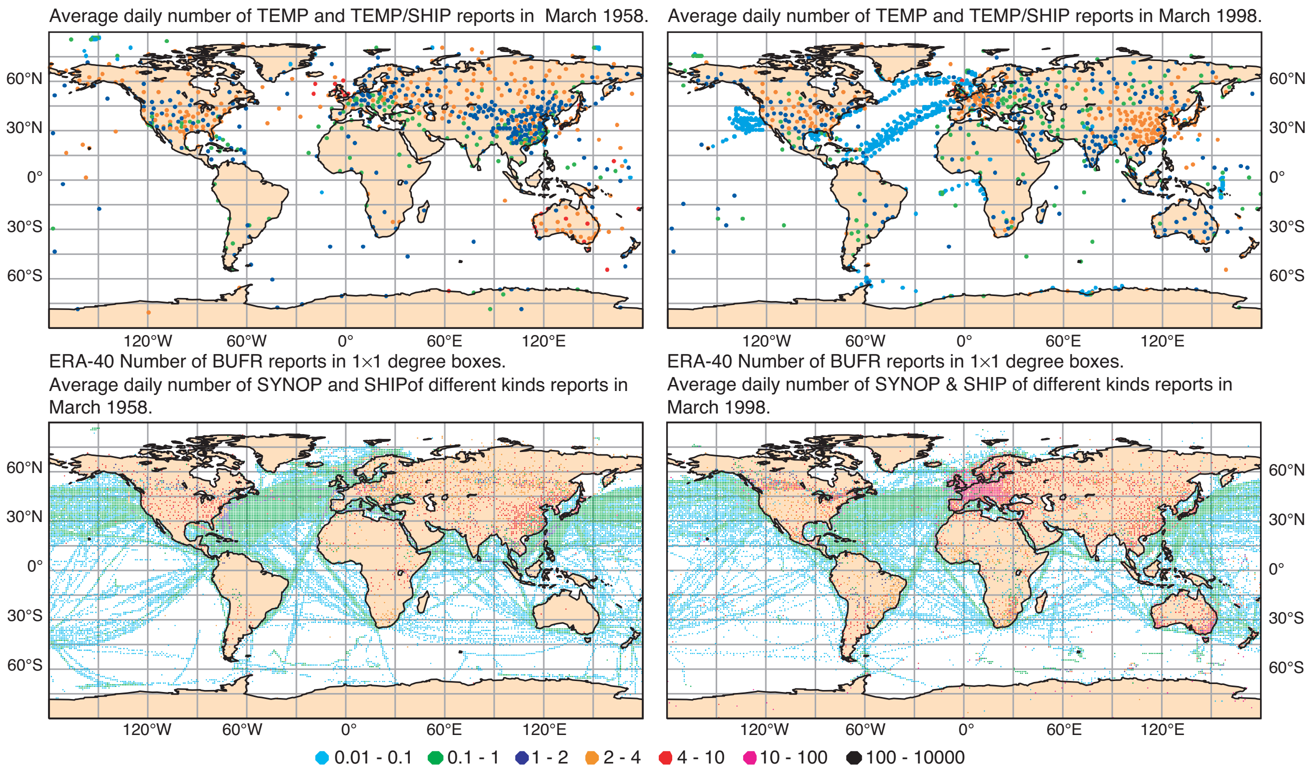


Fig. 5 The monthly coverage of radiosonde (upper) and surface (lower) observations in 1958 (left-hand panels) and 1998 (right-hand panels).

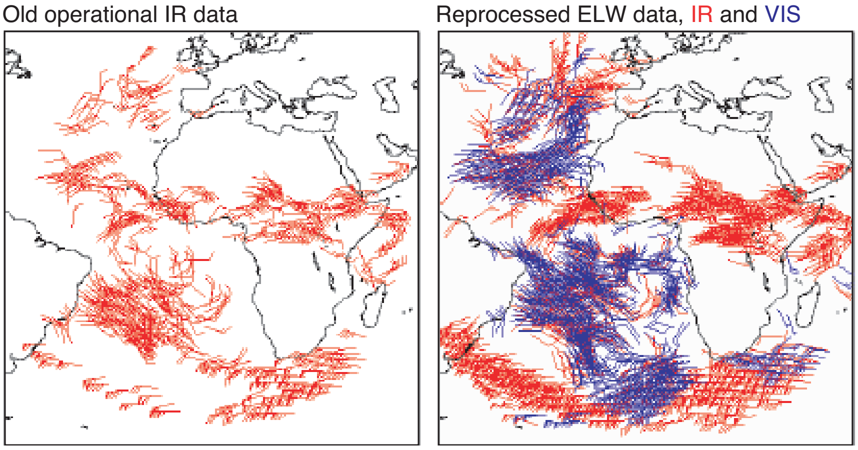


Fig. 6 The reprocessed AMVs (right) provide considerably improved coverage compared with the old operational infrared wind dataset (left), including additional winds from the visible and the water-vapour channel.

mainly driven by the satellite data. If there are no data at all, the analysis is equal to the background.

Satellite data are the only sources used for the analysis of ozone. Externally-produced retrievals of total column ozone from TOMS (Total Ozone Mapping Spectrometer) and ozone layer profiles from SBUV (Solar Backscatter Ultra-Violet radiometer) are used. Before 1979 the ozone analysis results from the ozone parametrization and model dynamics (though conditioned by the analyses of temperature and wind). Ozone profiles are also available from a network of radiosonde stations. They are too sparse and too infrequent to be used in the analysis, but they have an important role in validation, as do the more numerous ground-based measurements.

Ocean surface parameters from satellites

The ocean wave height analysis, a separate OI analysis, is based only on the use of satellite data from the Altimeter onboard ERS. Data starts in 1991; before then the wave products are based on the coupled wave model driven by the surface winds from the reanalysis. ERS also carries a scatterometer, which measures microwaves backscattered from the ocean surface. Each measurement yields two ambiguous winds 180° apart. Based on dynamical criteria, one of the winds is selected within 3D-Var. These winds are used in ERA-40 from 1993 onwards. Surface wind speed is also derived from the SSM/I microwave data using a 1D-variational technique from July 1987 onwards.

Atmospheric Motion Vectors

Atmospherics Motion Vectors (AMVs), or satellite cloud-drift winds, from geostationary satellites have been produced routinely by the satellite data centres since 1979. The plan was to have five satellites to cover all of the tropics and for the different satellite agencies to produce low- and high-level AMVs, around 850 and 200hPa. The target area in the beginning was 20°S-20°N and the system has since been extended to middle latitudes. Full coverage was not achieved for most of period; there is, in general, a lack of AMVs over the Indian Ocean.

The first AMVs were, in fact, produced from the ATS (Application Technology Satellite) satellite. These AMVs were retained in the NCAR archives, but coded as pilot data. As a consequence, interestingly and unintentionally, ERA-40 used these AMVs in January-April 1973.

AMVs are products, with different method used by each producer, and therefore they have gone through many improvements over the years. This was very clearly seen in ERA-15, where the fit of the background winds to these derived observations improved significantly over time for the AMVs of all producers. Reprocessing of AMVs is, therefore, desirable and improves reanalysis quality and time consistency.

In support of ERA-40, EUMETSAT reprocessed Meteosat-2 and -3 data for the period 1982-1988 in order to produce AMVs and Clear-Sky Radiances (CSRs) using today's state-of-the-art processing algorithms. The reprocessed AMVs provide considerably improved coverage compared to the old operational infrared wind dataset, including additional winds from the visible and the water-vapour channel, Figure 6. CSRs are a new product that has become available since Meteosat-2 was operational. Although the Meteosat CSRs were not assimilated in ERA-40, they have been passively monitored to assess their potential for use in the future reanalyses. Similar reprocessing has recently been done in Japan for GMS data from 1987 onwards. A similar effort for USA satellite data would be welcomed.

Satellite sounding data: VTPR → TOVS → ATOVS

The Vertical Temperature Profile Radiometer (VTPR) data, available from November 1972 to February 1979, represents the first sounding instrument. It is an eight-channel instrument mounted on the NOAA-2 to NOAA-5 satellites, with two VTPR instruments on each spacecraft. Temperature and humidity profiles retrieved from the radiance data were produced and distributed operationally with the intention to complement and partly replace radiosondes. The quality expectations for the retrievals were not, however, fulfilled. Retrievals with a horizontal resolution of about 600km were used in the NCEP/ NCAR reanalysis from 1975 onwards.

At NCAR, Roy Jenne had the foresight to maintain the original raw level-1c radiance archive, even though direct assimilation of these radiances was not envisaged at the time. As a special effort at ECMWF, this dataset was pre-processed, 'cleaned' and structured into a modern dataset of level-1c radiances. Six of the eight channels are very similar to HIRS channels. From the analysis point of view VTPR radiances were used as if they were 'low-resolution HIRS' data. Their use was found to be improved by the introduction of PAOBS

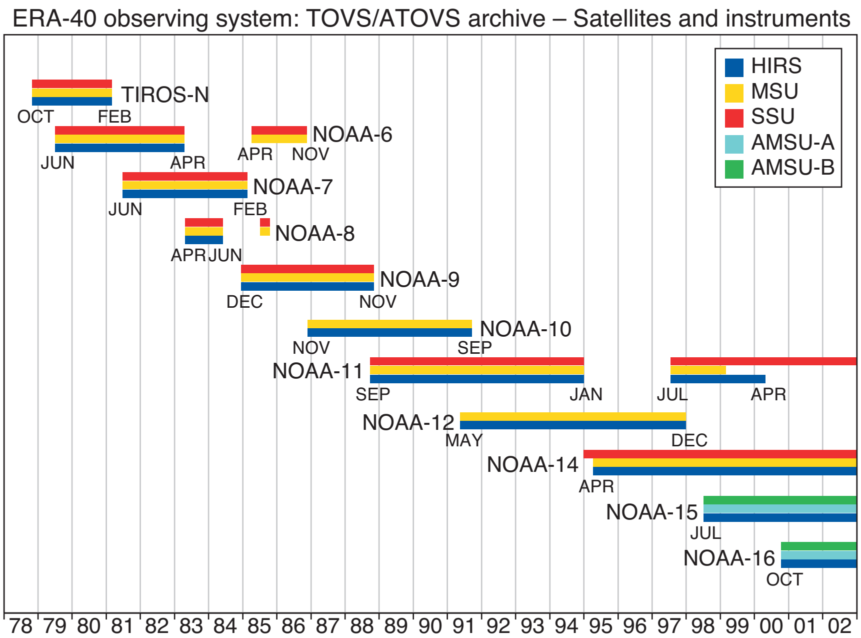


Fig. 7 Satellites with TOVS/ ATOVS instruments from 1978 onwards.

(pseudo surface-pressure observations over the data-sparse southern oceans). For the VTPR period PAOBs were constructed from gridded operational Australian surface-pressure analyses. Extensive subjective use of imagery from the NOAA satellites had been used to fix the location and intensity of surface features in these analyses.

As the successor of VTPR, TOVS data offers continuous and global coverage from October 1978 until today, Figure 7, (for details see ERA-40 Report Series No. 16). TOVS consists of three instruments, the HIRS, MSU and SSU. Historically, SSU represents the first European sounder instrument. Specifications were written by the Met Office, which also calibrated and validated the instruments and used the data to produce stratospheric analyses and temperature trends. ERA-40 benefited from the advice of two of those most closely involved in this work, David Pick and John Nash.

ATOVS, from July 1998 onwards, is an evolutionary improvement of TOVS. ATOVS comprises three instruments, HIRS and two Advanced Microwave Sounding Units (AMSU-A and AMSU-B). AMSU-A sounds temperature throughout the troposphere and stratosphere, and replaces both MSU and SSU.

In ERA-15, TOVS data were used below 100 hPa in the form of 1D-variational temperature and humidity retrievals derived from the NESDIS (National Environmental Satellite Data and Information Service) Cloud-Cleared Radiances (CCR), and above 100 hPa in the form of the original NESDIS retrievals, the quality of which varied over the years. Conversely, ERA-40 uses the level-1c radiances directly. A radiative-transfer model is used to calculate equivalent radiances from model fields, and the model fields are adjusted by the 3D-Var analysis to improve the fit of model equivalents to the measured radiances at the same time as improving the fits to other observations. This provides better quality control of the multi-spectral radiance data and allows the assimilation to retain more of the signal in the data.

Radiances in the humidity analysis

Radiosonde profiles and surface reports provide the conventional input data for the humidity analysis. Moisture and rainfall are, however, particularly abundant over the tropical oceans. Satellites and the parametrization of moist processes thus play a particularly important role in the humidity analysis.

In ERA-40 the humidity-sensitive infra-red VTPR and HIRS radiances from cloud-free regions are directly assimilated, and SSM/I microwave radiances are used indirectly through 1D-Var retrievals of Total Column Water Vapour (TCWV) in rain-free regions. ERA-40 was a pioneering effort to make extensive direct use of the infrared radiances in the humidity analysis. Unforeseen effects of volcanic aerosols from the eruption of Mt. Pinatubo in 1991 (discussed further below) led to development of a revised thinning, channel selection and quality control of HIRS radiances, which was applied after 1997 and for the years leading up to 1989.

Scope for improving analysis input

Before 1967 there are significant gaps in the coverage of synoptic surface data from many countries, which affect the quality of the analysed near-surface parameters for the early years of ERA-40. Amongst these are Australia, Brazil and France 1957-1966, Mexico 1960-1966, Canada 1964-1966, Sweden and Norway 1961-1966, Finland 1964-1966, Spain 1963-1966, Portugal, United Kingdom and Ireland 1962-1966 and Italy 1962-1964.

ERA-40 had good snow data only for Canada from 1957 onwards and the former USSR from 1966 onwards. No snow data for Northern Europe, America or Japan was used prior to 1976.

A merging of the contents of the upper-air reports from different sources would be beneficial for both future reanalyses and for direct study of the data. This requires further work, as before 1979 common station identifiers were not always used, and the duplicate-removal software used in ERA-40 did not detect these cases.

The data used by the ERA-40 analysis are mainly data that were once exchanged through the Global Telecommunications System (GTS). It would clearly be desirable in view of the deficiencies in coverage experienced by ERA-40 to include the full quality-controlled surface and upper-air datasets from national archives in future reanalyses. The data in these archives are often of higher resolution, both in time and space, and also contain climate-station data. This would especially improve surface analyses and, thus, the quality of national applications using them. Furthermore, future reanalyses will be at higher resolution and use improved data assimilation systems that would benefit more than ERA-40 from use of these data. All such observations would be included in the feedback information from these reanalyses, and thus be available for further exploitation at national level, creating a link between climate research groups and reanalysis centres.

Biases in observations

Observation error is assumed to be unbiased in the analysis. Identification and, if possible, correction of systematic errors from observations is therefore important for analysis quality. In ERA-40, radiosonde temperatures later in the period are corrected and satellite data (radiances, backscatter from scatterometer, altimeter wave height) are bias-tuned using the background forecast as a reference. Satellite data bias-tuning is necessary in order (1) to achieve a smooth transition from satellite to satellite, and (2) to correct errors that vary with scan angle and air mass. It needs to be done carefully; failure to tune correctly the observation-minus-background biases in the NOAA-4 VTPR radiances caused an upper-stratospheric temperature analysis anomaly of up to 10K in 1975 in ERA-40. The radiosonde temperature corrections are particularly important as they have an indirect effect on the quality of the radiance tuning, since the bias-tuning of satellite radiances is done using background values close to radiosonde locations.

Radiosonde temperature bias correction

Radiosonde temperatures are generally prone to errors due to solar heating and long-wave cooling of the sensor, and may be affected by some less well-known and more instrument-specific errors. Errors tend to be small for the latest instruments, and corrections are provided by the manufacturers and usually applied before transmission of the data to NWP centres. In older data, not only are errors generally larger, but there is also uncertainty as to the instrument type and whether a correction was applied at the station. To address this, radiosonde stations are separated into groups depending on station identifier and/or position to get a manageable number of corrections and stable statistics. The groups are defined to represent different countries or areas that are assumed to use similar types of sonde. On average 97.5% of the reports could be assigned to such groups.

Radiation effects introduce a bias that is a function of solar elevation. The bias relative to the background temperature is thus divided into four different classes of solar elevation: < -7.5°, < 7.5°, < 22.5° and > 22.5° over the horizon. The mean error is subtracted to give a correction that is independent of systematic model error as long as the diurnal component of this model error is small. Corrections are calculated from the statistics of background departures over the preceding 12 months, for the four different solar elevation classes. The final decision as to whether to apply or modify a correction is made manually for each group. The effect of correction is illustrated in Figure 8.

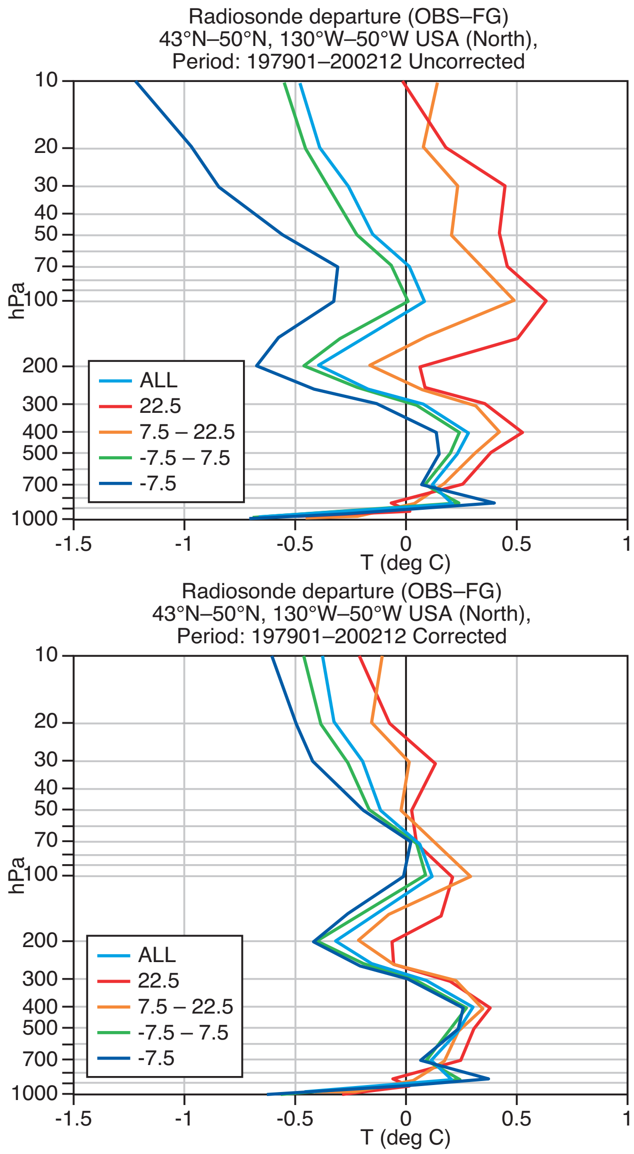


Fig. 8 The mean temperature departures, radiosonde-minus-background, in the four solar elevation angles; before correction (top) and after correction (bottom). Statistics for 1979-2001.

Bias correction of radiosonde temperatures was applied only after 1979 in ERA-40 (for details see ERA-40 Report Series No. 15). For this period there was good experience from ERA-15 and subsequent ECMWF operations of correcting biases in geopotential. Corrections before 1979 would have been larger, more variable in time and space, and would have carried a greater risk of error. Since ERA-40

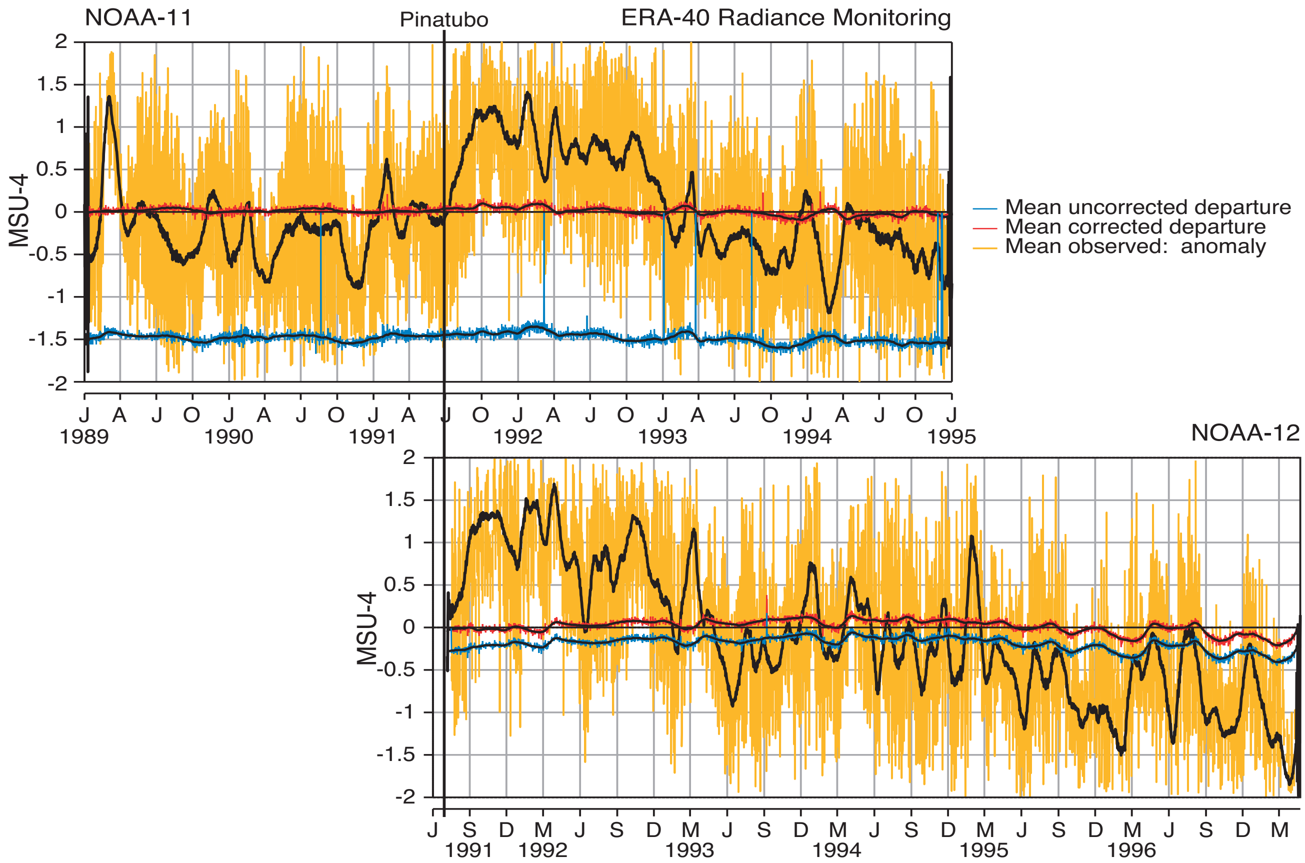


Fig. 9 Departure of background simulated brightness temperatures from measured brightness temperatures (K), with (red) and without (blue) bias correction, from the NOAA-11 (upper) and NOAA-12 (lower) satellites, and the measured brightness-temperature anomaly, plotted six-hourly (brown) and as seven-day averages (black).

was the first analysis of these data at ECMWF it was decided that the best approach was to accumulate departure statistics without corrections, and to utilize them to derive the corrections for a future reanalysis.

Satellite radiance bias-tuning

In ERA-15 it was necessary to calculate new satellite bias adjustments at the end of each month, and then to use them the next month. In ERA-40, the bias-tuning for each channel is much more stable. In most cases a single bias adjustment is applied for the lifetime of a satellite, a change being made only if there is a substantial drift in the radiances from a particular channel. Establishment of the corrections for a new satellite is more straightforward when there is overlap between satellites, as this allows data from the new instrument to be monitored passively in the assimilation alongside the old, and the adjustments determined prior to active assimilation of the data.

Several factors contribute to the stability of the bias-tuning in ERA-40. The method of bias correction has been improved, scan-angle correction is dependent on latitude and background values are used as predictors instead of measurements in the regression. The use of level-1c radiances avoids the need to change bias corrections in response to changes introduced by NESDIS in producing cloud-cleared radiances and stratospheric retrievals.

Figure 9 shows as an example how MSU channel-4 radiances, representing a weighted average of upper tropospheric and lower stratospheric temperature, are corrected with overlapping satellites, NOAA-10 and NOAA-12.

Assimilation-system testing, production and monitoring

The production of ERA-40 analyses was preceded by an extensive experimentation program, where the analysis and model improvements since ERA-15 were tested during different periods, in total about 25 years of data assimilation. At the same time, the effects and performance of those conventional and satellite systems that had not been used at ECMWF before, were tested including pre-1979 conventional data, VTPR, SSM/I, TOVS and ERS data. Also preparatory work was carried out to test all the externally received observations and sea surface temperature/ice (SST/ICE) datasets, the method of merging the different observation sources, the tuning and correction of observation biases and the design of the production suite including the monitoring tasks.

Production of the ERA-40 analyses began more than three months later than planned, and proceeded slowly during the first year as problems were investigated and solutions tested. Production was accordingly reorganised into three streams, rather than the two initially planned. The first covered 1989-2002, the second ran from 1957 to 1972 rather than 1988, and the third covered 1972 to 1988. Completion of the planned production was ensured by a six-month extension to the duration of the project, and by initiating a small number of parallel-running sub-streams to bridge the gaps between the main streams. Examining overlaps between the streams shows few signs of problems associated with this multi-stream production strategy. Slight jumps in mean temperatures in the troposphere arise due to differences in satellite bias correction. Such impacts are more marked in the upper stratosphere, where discontinuities can also be seen in the water-vapour fields, due to their slow evolution.

Ensuring as near to continuous production as possible was demanding on manpower, involving resolution of a variety of minor technical problems (during evening, weekend and holiday periods as well as the standard working day). The effort devoted to this, plus the underlying reliability of the computer systems and application software, meant that production suffered no technical delay significantly longer than 12 hours throughout the period. There was also minimal loss of products from main production due to archiving problems, and it was possible to replace all losses by short reruns.

Another task that required immediate attention from time to time was management of the changes from one satellite in a series to the next. This involved, at a minimum, a temporary blacklisting of data from the new instrument until sufficient monitoring statistics could be determined to derive bias corrections. In cases where there was no overlap between satellites, it was necessary then to go back and repeat the analysis for the blacklist-period with the new data active.

Monitoring of ERA-40 production was carried out both by ECMWF and by the validation partners. Defects detected by the validation partners included:

- Unrealistic hydrological behaviour over several land areas in early stream-2 analyses, detected by the Max-Planck Institute (MPI) and eventually traced by ECMWF to unrealistic screen temperatures in one of the observational datasets.
- Unrealistic rainfall in the 1990s over tropical oceans detected by several validation partners' monitoring as well as that of ECMWF.
- Assimilation of erroneous early ERS-1 altimeter ocean-wave-height data revealed by monitoring by the Royal Netherlands Meteorological Institute (KNMI).
- Problems with the post-processing of fields onto pressure surfaces and low-resolution grids, found by NCAR and corrected by ECMWF.

ECMWF's monitoring was concentrated, in the first instance, on regular examination of time-series of the fits of background fields to satellite radiance data, of observational counts for conventional data and of area-means of background, analysed and increment fields for a wide range of variables, including comparisons with ERA-15. This enabled many potential problems to be nipped in the bud, but unfortunately not all.

Validation of ERA-40

In the following paragraphs include a selection of the validation work carried out by ECMWF and the validation partners.

Validation against observations

The synoptic quality of analyses was carefully monitored in tests prior to production. Special attention was paid to a selection of past storm cases, such as the October 1987 storm over United Kingdom. Diagnosis was performed on the rate of detection of tropical cyclones.

Long-term statistics have been derived from the analysis feedback information, a product of ERA-40 that includes the departures between observed values and corresponding analysis and background values. Figure 10 shows time-series of six-hourly background and analysis fits to SYNOP and SHIP surface-pressure measurements for the extratropical Northern and Southern Hemispheres. A general improvement in the fit to the surface-pressure measurements occurs over the period of ERA-40. Changes in data coverage might affect this, as increased coverage in the subtropics (where variance is lower) would tend to lower values in plots such as these in which no area-weighting is applied. However, the improvement in the background fit at the beginning of 1979 almost certainly is a consequence of the major improvement of the whole observing system that took place at the time.

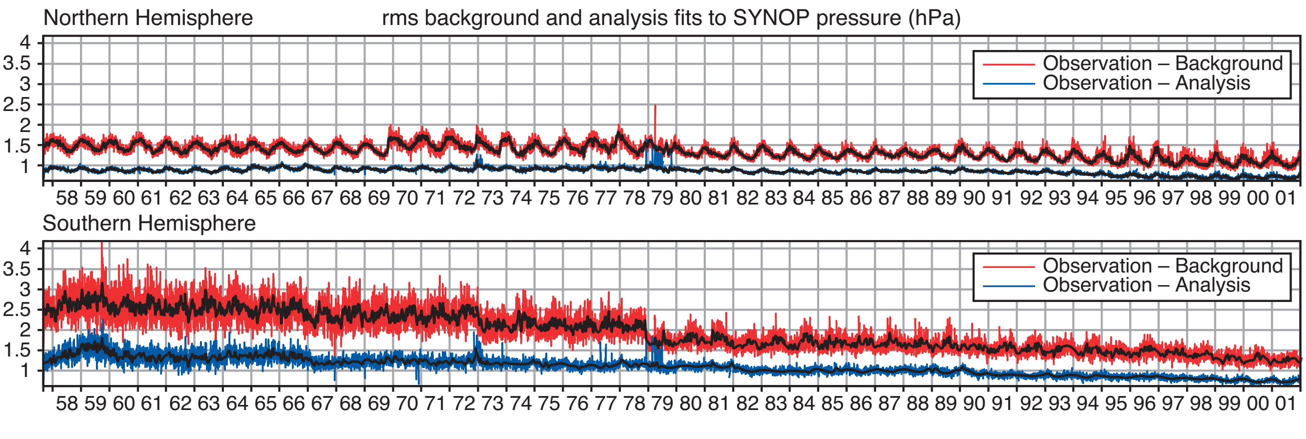


Fig. 10 Root-mean-square ERA-40 background (daily (red) and 15-day moving average (black)) and analysis (daily (blue) and 15-day moving average (black)) fits to 00 UTC SYNOP and SHIP surface pressure observations over the extratropical Northern (upper) and Southern (lower) Hemispheres.

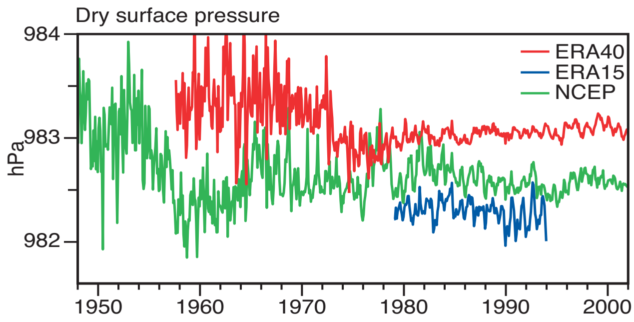


Fig. 11 Time-series of global-mean surface pressures (hPa) for the dry air pd for three different reanalyses from ERA-40 (red), ERA-15 (blue) and NCEP/NCAR (green).

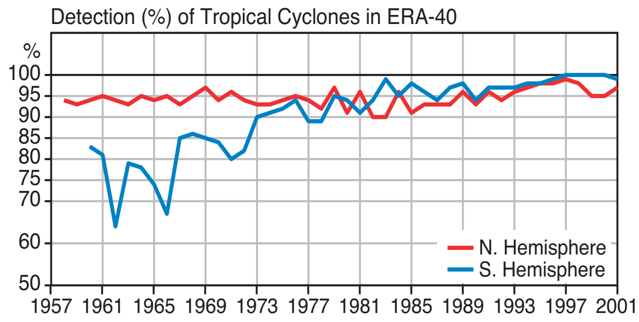


Fig. 12 The detection (%) of tropical cyclones in the ERA-40 analyses as compared with the best-track dataset in the Northern Hemisphere (red) and Southern Hemisphere (blue).

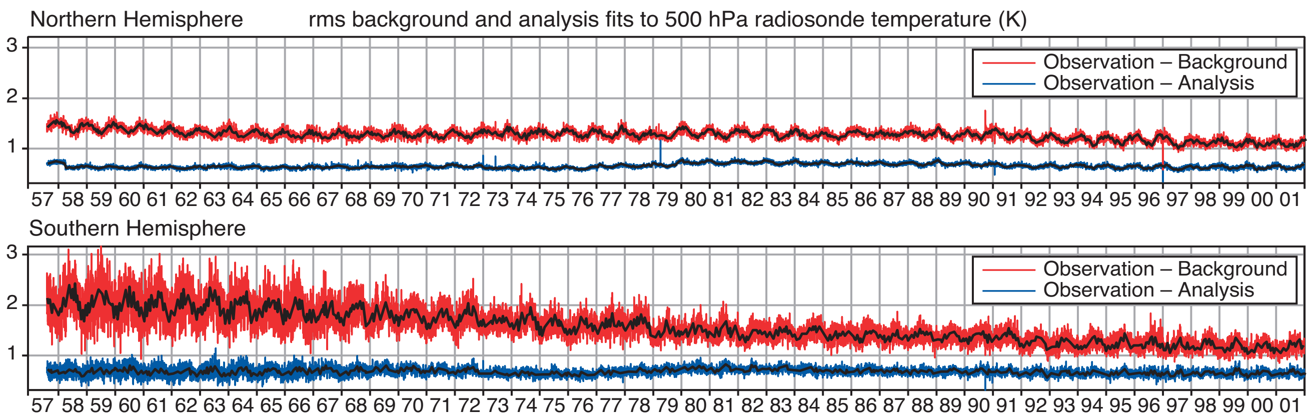


Fig. 13 As Figure 10, but for the 500 hPa geopotential observations.

Figure 11 shows time-series of the mean analysed surface pressure of dry air (pd), a quantity that should be (almost exactly) conserved, for the NCEP, ERA-15 and ERA-40 reanalyses. It is apparent that the two biggest discontinuities occur in 1973 and in 1979, when there were major changes to the observing system. Judged by the constancy of pd, the NCEP reanalyses get progressively noisier going backwards in time prior to the mid-1990s, much more so before 1979, and fluctuations become quite wild before the mid-1960s. Clearly the use of the coarse-resolution VTPR radiances and Australian PAOBS has kept the ERA-40 reanalyses more stable back to 1972. Large spurious fluctuations from month to month and year to year occur for ERA-40 before 1972. They originate mainly from the lack of data in the Southern Hemisphere as measured by the analysis uncertainty in surface pressure, the blue curve in Figure 10.

The impact of the use of VTPR and the PAOBS can also be seen in the percentage of tropical cyclones detected in the ERA-40 analyses compared with the independent best-track dataset, Figure 12. In the Northern Hemisphere the rate is greater or equal to 90% over the whole period, whereas in the Southern Hemisphere 90% is exceeded only from 1973 onwards. ERA-40 is a big improvement over ERA-15 in this respect: in ERA-15 the detection rate was around 80% in the Northern Hemisphere.

Figure 13 shows fits to 500hPa radiosonde temperatures. Again, a general improvement occurs over the period of ERA-40 (more so than for surface pressure) and this may include a component directly due to decreasing error in the measurements that are fitted. The root-mean-square background fit drops from about 1.4K to 1K over the period for the Northern Hemisphere, and from about 2K to 1K for the Southern Hemisphere. The fit of the analysis to the radiosonde data is poorer in the 1980s than earlier, as the analysis has to match TOVS radiance data as well as radiosonde data for these years. However, the fit of the background field is unchanged in the Northern Hemisphere and improves in the Southern Hemisphere, a sign of an analysis that has been improved overall by the availability of the new data. A similar effect for the VTPR data introduced in 1973 may have been masked by the assimilation of a relatively large number of duplicate radiosonde observations from 1973 to 1976. The decline in fit of the analysis to the radiosonde data does indeed begin 1977.

Quality of medium-range forecasts

A measure of the accuracy of analyses is provided by the skill of the medium-range forecasts run from them. Accordingly, forecasts to ten days ahead have been run twice daily from the ERA-40 analyses.

Figure 14 shows three examples of results, indicating the forecast range (in days) at which the anomaly correlation of 500 hPa height, on average, drops below 60% for each year from 1958 to 2001. The regions of the extratropical Northern

Hemisphere, Europe and Australia/New Zealand are chosen for presentation as they are relatively well observed throughout ERA-40, giving reasonable confidence in the accuracy of the verifying analyses.

For each region the ERA-40 forecasts improve over time, indicating improvement over time of the observing system (assuming no trend in the predictability of the atmosphere). However, for the Northern Hemisphere as a whole, and for Europe in particular, the average length of the forecasts (red curve) is more than six days throughout, indicating good synoptic accuracy of the analyses for the whole of the period. In contrast, the ERA-40 forecasts for Australia/New Zealand are very much poorer prior to the major improvement to the observing system that was introduced for FGGE in 1979, and poorer still prior to 1973, when VTPR data were first assimilated. The ERA-40 analyses for the Southern Hemisphere before 1979 must be used with much more caution than either their counterparts for the Northern Hemisphere or the later analyses in both hemispheres.

Observing-system improvements beyond 1979 can be seen to have had larger impacts on Southern- than Northern-Hemisphere forecast accuracy, bringing forecast-skill levels of the two hemispheres closer.

The same is true of operational forecasting-system improvements, which generally have had a larger impact on forecast skill than the observing-system improvements since 1979. This is seen by comparing the extent to which the ERA-40 and operational medium-range forecasts improve between

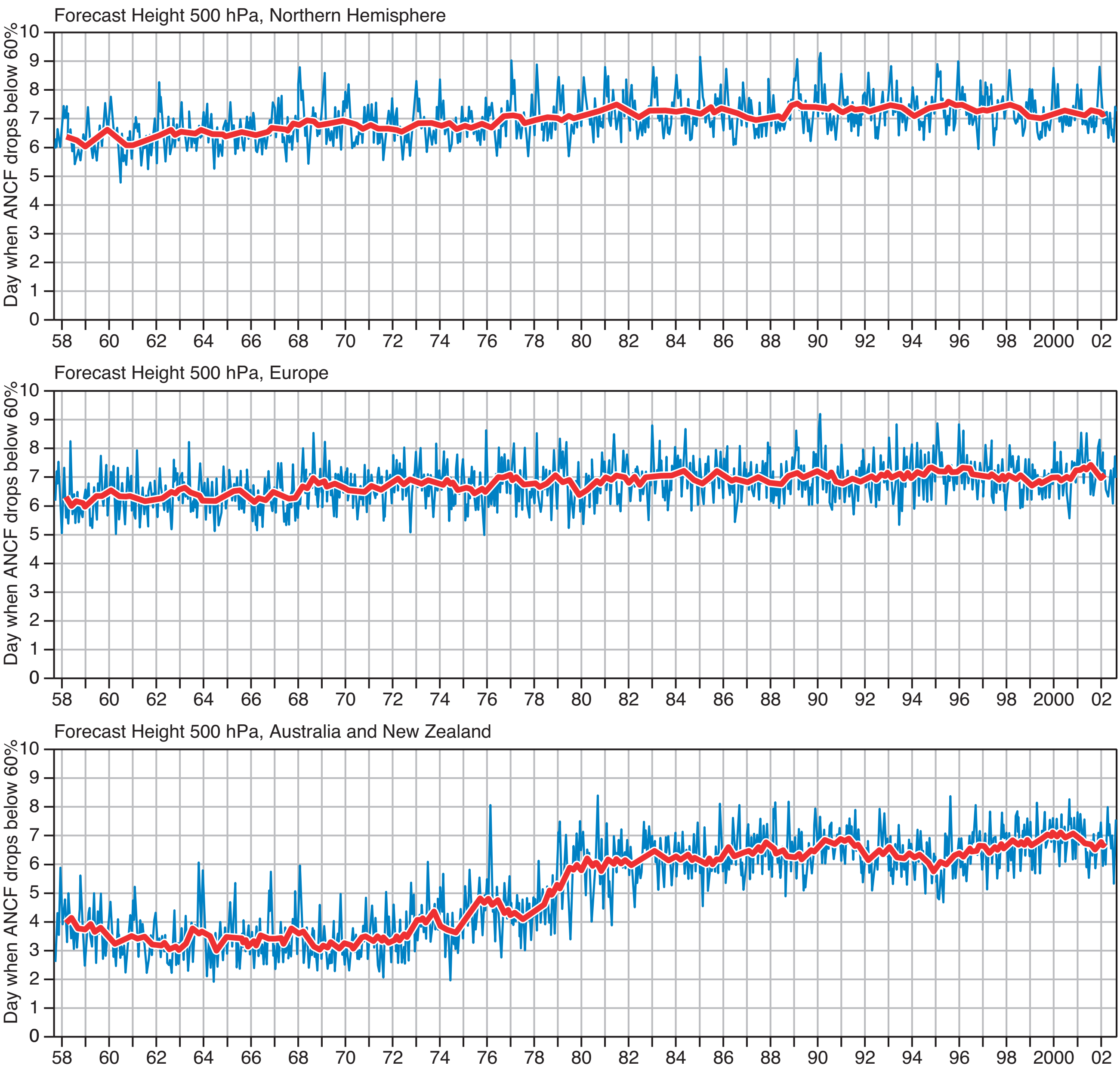


Fig. 14 The forecast range (in days) at which the anomaly correlation of 500 hPa height on average drops below 60% for each year from 1958 to 2001 for the Northern Hemisphere (top), Europe (middle) and Australia and New Zealand (bottom). The blue and red curves represent moving monthly and annual averages respectively.

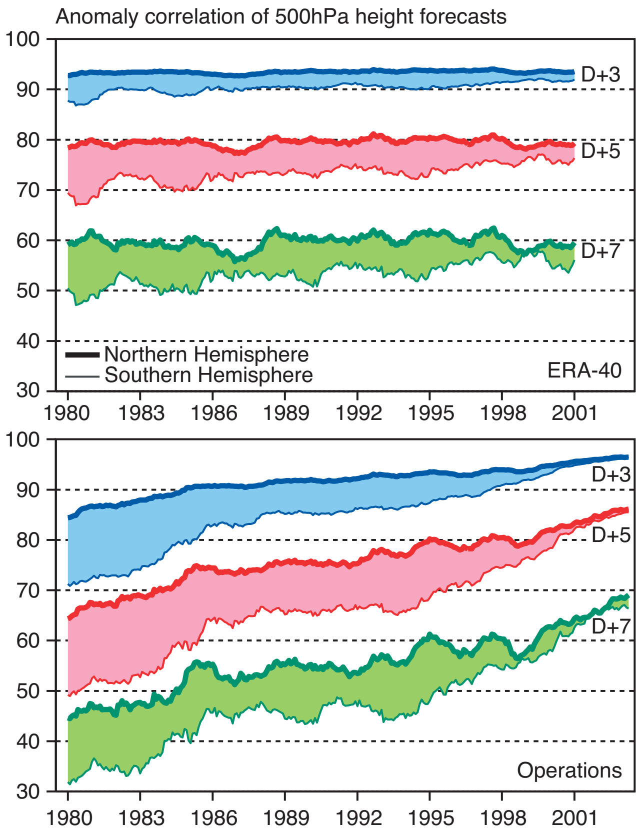


Fig. 15 The time evolutions, 1980-2001, of anomaly correlations of 500 hPa height forecasts at days D+3, D+5 and D+7 for ERA-40 (upper) and for ECMWF operations (lower) in both hemispheres. The area between the hemispheric anomaly correlations is shaded.

1980 and 2001, Figure 15. ERA-40 performance does not fully match that of ECMWF operations in 2001 because of its use of lower horizontal resolution and 3D- rather than 4D-Var. For the Northern Hemisphere, skill levels for the early years of ERA-40 are comparable with that of ECMWF operations in the mid 1980s.

The ERA-40 system has been used to make a special analysis to mark the fiftieth anniversary of the North-Sea storm of the night of 31 January to 1 February 1953. The storm was the worst in living memory in Europe. More than eighteen hundred people drowned as The Netherlands was struck by a devastating surge of water driven by the storm, and there were in excess of three hundred more deaths around the British Isles.

The period from 1 January to 10 February 1953 was analysed. In Figure 16 the analysis of 500hPa height for 00 UTC 1 February is compared with the corresponding hand analysis represented by the wall hanging in the ECMWF Council Chamber, a gift from The Netherlands. The similarity between the two is evident, indicating that today's analysis techniques can be extended successfully to the pre ERA-40 period in the Northern Hemisphere. The corresponding three-day forecast, in the same figure, shows remarkably good skill. The skill extends well beyond six days, although the predicted storm has lower intensity and an error in phase. The case has since been reanalysed with the high-resolution ensemble system (ERA-40 Report Series No. 10).

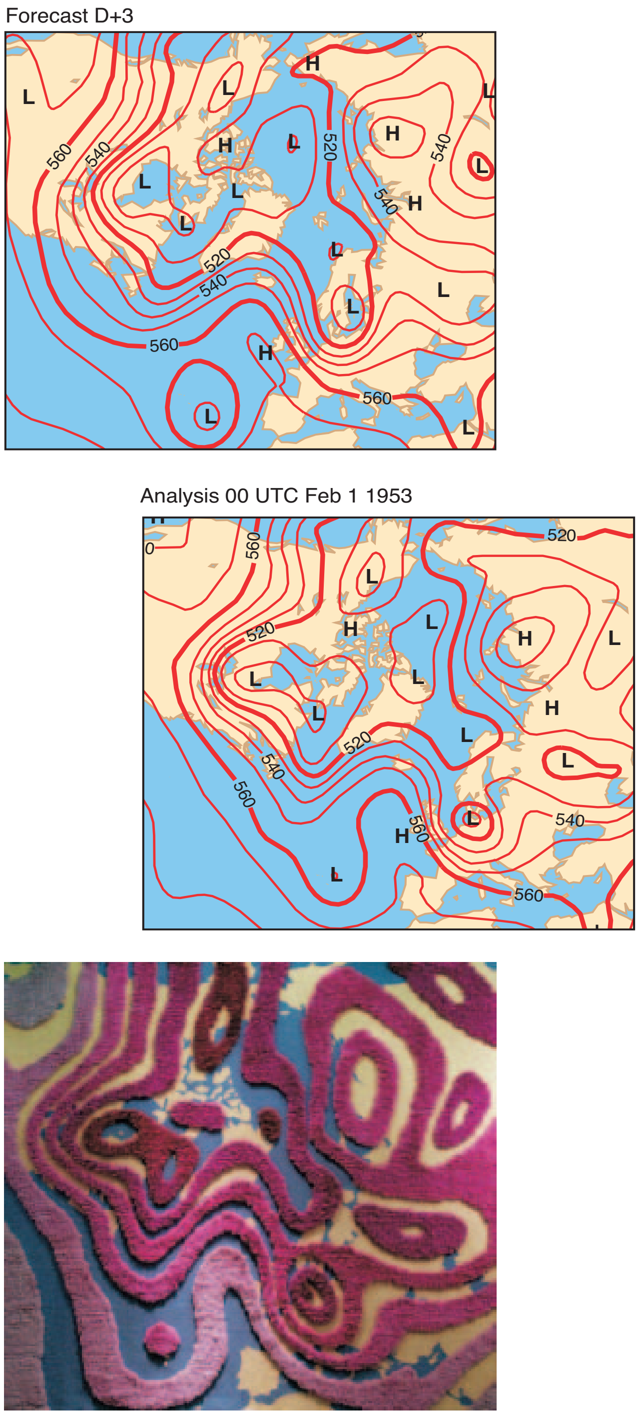


Fig. 16 The analysis and the three-day forecast of 500 hPa height at 00 UTC 1 February 1953 compared with the corresponding hand analysis represented by the wall hanging in the ECMWF Council Chamber.

Temperature trends and low-frequency variability

An open question prior to the start of ERA-40 was whether the analyses would be good enough to exhibit realistic trends over the last four or more decades, or whether changes in the observing system and model biases would mask true variations. In this respect ERA-40 has shown considerable, though qualified, success.

Basic global-mean temperature trends and low-frequency variability appear to have been captured well over much of the troposphere and lower stratosphere from at least the late 1970s onwards, when comparison is made with the careful analyses of raw instrumental records that are a key element of global-change studies. ERA-40 represents a significant advance over ERA-15 and the NCEP/NCAR analysis in this respect. Figure 17 compares a time-series of monthly-mean screen-level temperature anomalies based on ERA-40 analyses with the corresponding time-series derived from an independent analysis of monthly climate-station data by the Climatic Research Unit (CRU) of the University of East Anglia (blue). Values are averaged over all Northern Hemisphere land points for which there are sufficient station

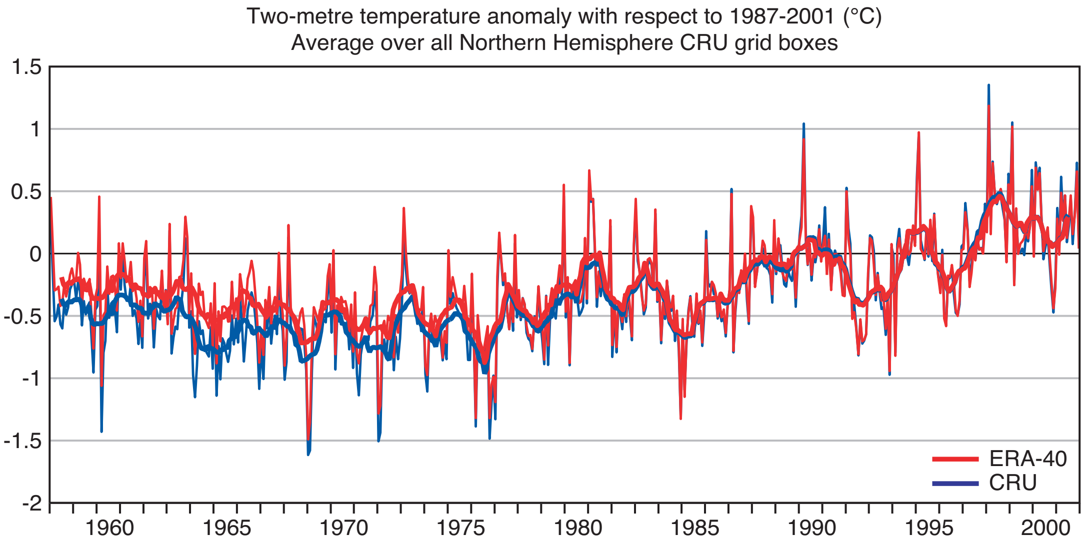


Fig. 17 Time-series of monthly and 12-monthly two-metre temperature anomalies from ERA-40 (red) and from the CRU (blue) analyses of Jones and Moberg, averaged for Northern Hemisphere data points and adjusted to give zero mean difference for the period 1987-2001. Anomalies are defined with respect to monthly climate means for the period 1961–1990.

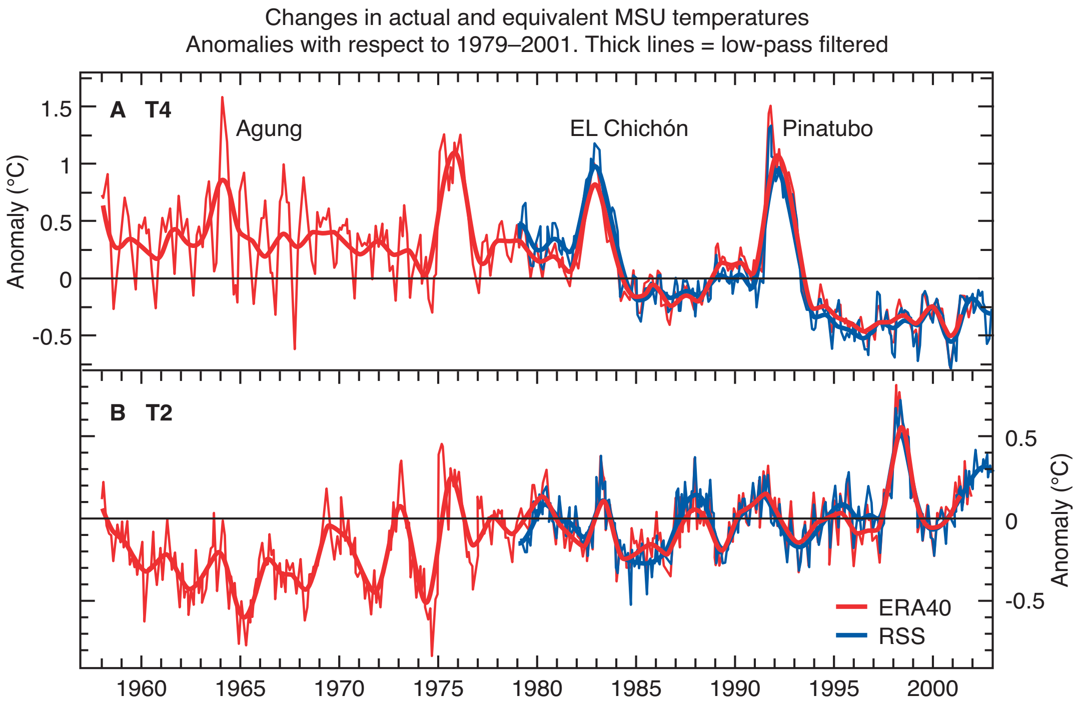


Fig. 18 Equivalent MSU temperature anomalies derived from ERA-40 analyses (red) compared with a time-series of actual MSU data (blue) adjusted to take into account such factors as inter-satellite bias differences and orbital decay. Figure provided by Ben Santer, using the MSU data values produced by *Mears et al*.

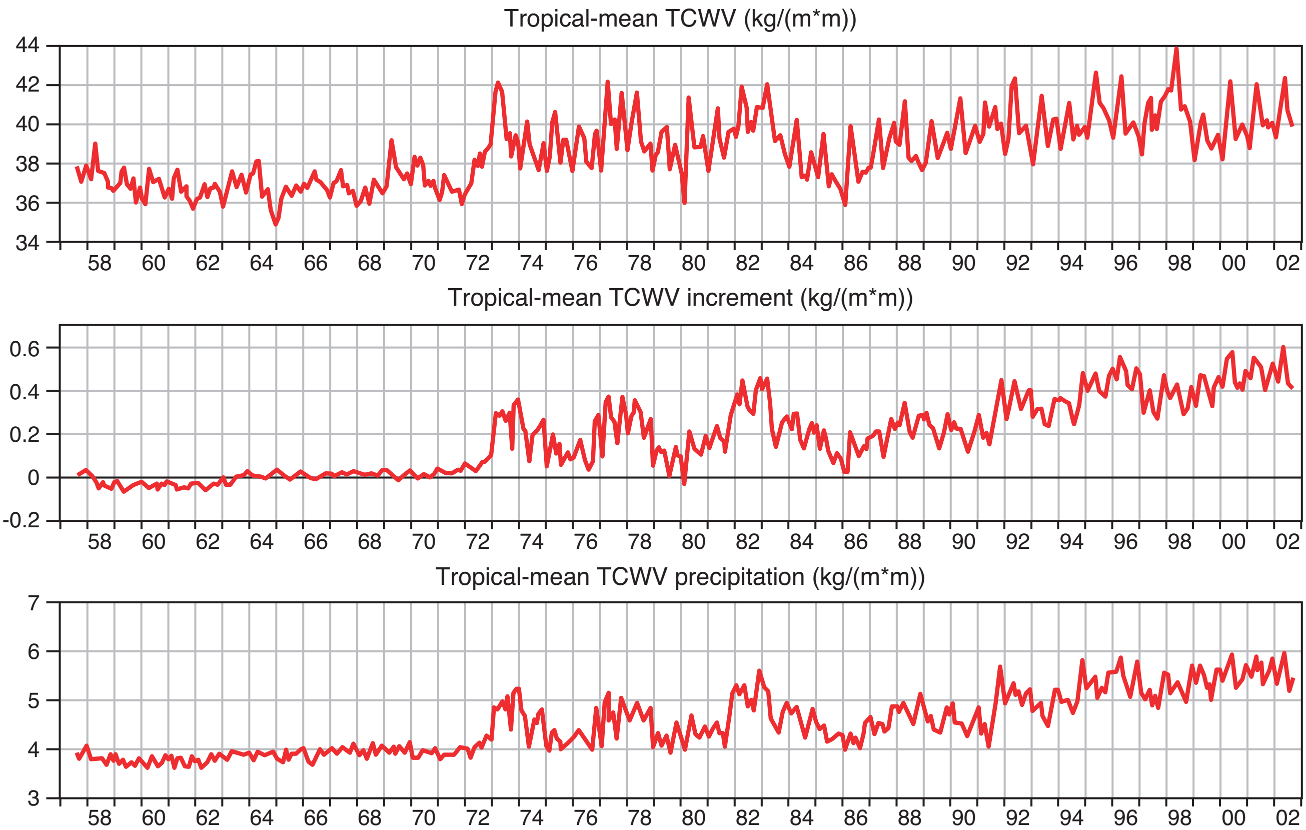


Fig. 19 Time series showing monthly-mean ERA-40 total column water-vapour analyses averaged over the tropics (top), the corresponding analysis increments (middle) and the tropical mean precipitation from background six-hour forecasts (bottom).

data to define the CRU analysis, (for details see ERA-40 Report Series No. 18). Figure 18 compares global-mean indicators of mid- to upper-tropospheric temperature (labelled T2) and lower-stratospheric temperature (labelled T4) from ERA-40 analyses and MSU satellite data (Santer, personal communication). These figures show that ERA-40 has produced a set of three-dimensional atmospheric analyses that reproduces both the well-documented warming that has occurred at the surface since the mid 1970s, and the cooling that has occurred in the lower stratosphere. Various studies of the data records from radiosondes and MSU are not in close agreement as regards trends in mid-tropospheric temperature; further studies of the fits of ERA-40 background forecasts and analyses to raw MSU, radiosonde and other observational data may help reconcile current differences.

Hydrological cycle and surface fluxes

Particularly close attention was paid to monitoring aspects of the hydrological cycle during production following an apparently spurious increase in tropical rainfall diagnosed following the volcanic eruption of Mt. Pinatubo and problems associated with erroneously coded synoptic humidity measurements that required the analysis of the earliest years to be stopped and repeated.

Figure 19 presents time-series relating to TCWV averaged over the tropics. A pronounced change occurs at the beginning of 1973, when humidity-sensitive radiances from the VTPR instrument were first assimilated. After this time, TCWV is generally higher and presumably more realistic given the agreement with independent SMMR (Scanning Multi-channel Microwave Radiometer) and SSM/I retrievals discussed in the following section. In parallel, however, increments in TCWV become large and generally positive, with most of the added moisture rained out in the tropics in the six-hour forecasts, as shown by the correlation between the increment and precipitation graphs in Figure 19. There is considerable interannual variability in these time-series, but a general upward trend in the time-series of increments and precipitation is clear. Values from late 1991 to the end of 1996 lie above the general trend line, reflecting problems stemming from the un-modelled effects of Pinatubo aerosol on HIRS radiances. The root cause of the trend lies elsewhere, however, in the way the satellite data are assimilated. The general increase in increments and precipitation most likely reflects the increasing amount of satellite data assimilated, HIRS radiances from 1979 onwards, additional SSM/I data from one satellite in 1987 and data from two SSM/I satellites from 1999 onwards.

Comparing monthly precipitation totals from ERA-40 and the Global Precipitatation Climatology Project (GPCP) for selected regions shows that ERA-40 precipitation is substantially too large only in the tropics, especially over the oceans. Here patterns of precipitation appear realistic, but rainfall amounts in precipitating areas are much higher than GPCP values. The discrepancy is larger than can be ascribed to uncertainties in the GPCP estimates. ERA-40 precipitation is in much better agreement with GPCP in the extratropics, not only with respect to the climatological means but also with respect to the interannual variability of monthly totals. Patterns of interannual variability in the tropics are also in reasonable agreement with GPCP.

A new formulation of the humidity analysis has been developed and introduced in operations. It inhibits the moistening of regions that are already close to saturation, and reduces excessive short-range tropical precipitation. It will be part of the system used for future ECMWF reanalyses. Meanwhile, motivated by the need to use ERA-40 precipitation fields to force ocean-model integrations within the ENACT (Enhanced Ocean Data Assimilation and Climate Prediction) project, a post-processing procedure has been developed for application to the oceanic precipitation fields to compensate for the excessive tropical precipitation, particularly after 1991 (ERA-40 Report Series No. 13).

Evaporation in ERA-40 over the oceans tends to be higher in mid-latitudes and lower in some regions of the tropics than climatology.

An ISLSCP-II dataset has been prepared in collaboration with NASA. It contains near-surface fields (e.g wind, humidity, temperature, pressure), fluxes (sensible- and latent-heat fluxes, stresses) and surface and subsurface fields for the period 1986-1995 at 1o resolution. A comparison between ERA-40 and other selected ISLSCP-II (International Satellite Land-Surface Climatology Project–II) products can be found in ERA-40 Report Series No. 8.

The ERA-40 snow analysis used only conventional snow-depth measurements. No satellite snow-cover data entered the analysis. As discussed earlier, the pre-1979 period suffers from the lack of in-situ observations, especially over Europe, US and Japan. In this case, the snow analysis is relaxed towards the climate.

The snow water equivalent produced by ERA-40 for later years has been compared with that analysed by the Safran/Crocus model of Météo-France (ERA-40 Report Seies No. 14). Observations from synoptic stations, automatic weather stations in mountains and outputs from Safran/Crocus were used to calculate the snow cover at various elevations in the French Alps. The comparison is difficult due to the different elevations of the observations and assimilating model. However, ERA-40 captures a significant part of the interannual variability. The years with poor snow cover from 1989/90 to 1992/93 are reasonably well simulated. Underestimation of snowfall (for the winters of 1994/95 and 1998/99 especially) is also seen. The snow-cover evolution during winter is realistic, and the daily evolution is in most cases in agreement between ERA-40 and Safran/Crocus. These results are better than found for ERA-15.

The radiation budget

The interaction between atmospheric humidity, the radiation budget and the large-scale atmospheric circulation is fundamental in determining climate variability and change. The representation and improvement of these processes in numerical models is limited by the paucity of high-quality observations. Reanalyses potentially address this limitation by enhancing the existing network of observations through a self-consistent data assimilation system. Further, the ability to provide detailed coverage of the present-day climate in the context of the synoptic situation provides a powerful means of understanding the subtle processes important for determining the climate state and its variation.

The clear-sky radiation budget simulated by ERA-40 compares well with independent satellite data, Earth radiation budget satellite data from the ERBE (Earth Radiation Budget Experiment), ScaRaB (Scanner for Radiation Budget) and CERES (Clouds and the Earth's Radiant Energy System) for clear-sky out-going long-wave radiation (OLR) and clear-sky albedo, suggesting significant utility of these products. The clear-sky OLR is particularly well simulated when effects of satellite sampling are taken into account and provides independent validation of temperature and humidity in ERA-40. The excellent agreement in TCWV between ERA-40 and microwave satellite data, Figure 20, also indicates that surface downwelling long-wave fluxes are likely to be of high quality. Interannual variation of TCWV in ERA-40 is improved over ERA-15. Spurious changes in low-latitude mean TCWV following the eruptions of El Chichon and Pinatubo and for the 1995/6 period nevertheless reduce the utility of using ERA-40 to study global trends in water vapour.

While observed cloud fields away from stratocumulus regions are reasonably well captured, the radiative properties of cloud, which relate more to model parametrizations than to the observational input, are not so well simulated. This leads to a poor all-sky radiation budget in ERA-40. Nevertheless, careful use of dynamical fields from ERA-40 to sub-sample observed all-sky radiation fields from satellite data offer a powerful tool for evaluating cloud properties in climate models. The use of the clear-sky radiation budget from ERA-40 in such studies would be of additional value, partly due to the quality of these products and also because the clear-sky sampling inconsistency between models and data is circumvented. The application of these techniques and exploitation of the high-quality ERA-40 products provide an opportunity for improving the understanding of the climate system and, therefore, can improve our ability to simulate more accurately the Earth's climate and future changes.

Ozone analysis and aspects of the quality of the stratospheric analyses

TOMS total column ozone and SBUV ozone profiles were assimilated from January 1979 onwards, with the exception of the two-year period 1989-1990. The gap results from the fact that ozone analysis was under development when ERA-40 started production for 1989. The TOMS and SBUV instruments cannot provide measurements in the polar night, and TOMS data are unavailable globally for several periods, notably in 1995 and 1996.

The analyses draw closely to the TOMS data when available, capturing the observed interannual variability. They also provide plausible values for the periods when TOMS data are missing. The assimilation of SBUV data is evidently sufficient to provide a reasonable control on the assimilating model, since in the absence of data the model tends to produce too little ozone in the tropics and too much ozone in springtime at high latitudes.

Comparison with independent measurements has been made. Time-series of monthly-mean total-ozone analyses are compared in Figure 21 with the available ground-based measurements from four stations. Ground-based measurements were not included in the assimilation. Agreement between the analyses and the independent validation data is generally good for the years 1979-1988 and 1991-2002 when data has been used. The analyses capture trends and low-frequency variations. The largest discrepancy during this time is underestimation of the ozone-hole depth at the South Pole in October. The ERA-40 analyses nevertheless depict the pronounced increase in depth of the hole during the 1980s.

Results are more mixed when ozone data are not assimilated. Values at the South Pole are mostly underestimated prior to 1979, partly because too-cold temperatures trigger unrealistically the destruction of ozone by parametrized heterogeneous chemistry. Elsewhere, the ERA-40 system produces quite reasonable ozone values for the period prior to 1973 when no satellite data of any type was assimilated. However, at the mid- and high-latitude Northern Hemisphere stations the ERA-40 values are clearly too high in the years when satellite temperature data but not ozone data are assimilated. Use of the three-dimensional velocity fields from ERA-40 to drive long-term chemical transport models has been found by users to produce an 'age of air' in the stratosphere that is much too young, indicating that the Brewer-Dobson circulation in the ERA-40 data assimilation is considerably too strong. Evidence from the ERA-40 ozone (and stratospheric humidity) fields suggests that the assimilation of radiance measurements disrupts the model's balance and enhances the Brewer-Dobson circulation.

The quasi-biennial oscillation of statospheric winds is well analysed throughout the reanalysis period, Figure 22. Validation of the analysed winds against a selection of stations in the tropics shows very good agreement. This indicates that even a few observations can trigger the data assimilation to capture the oscillation. Features such as the strong temperature fluctuations during sudden stratospheric warmings or the value of the temperature minima reached in winter in the polar vortex are much better represented in ERA-40 than ERA-15. The near-tropopause water-vapour field is also more realistic, and comparison with MOZAIC (Measurements of Ozone and water vapour by Airbus In-service airCraft) measurements has shown that, as for ozone, the short-term variability of this field is of good quality.

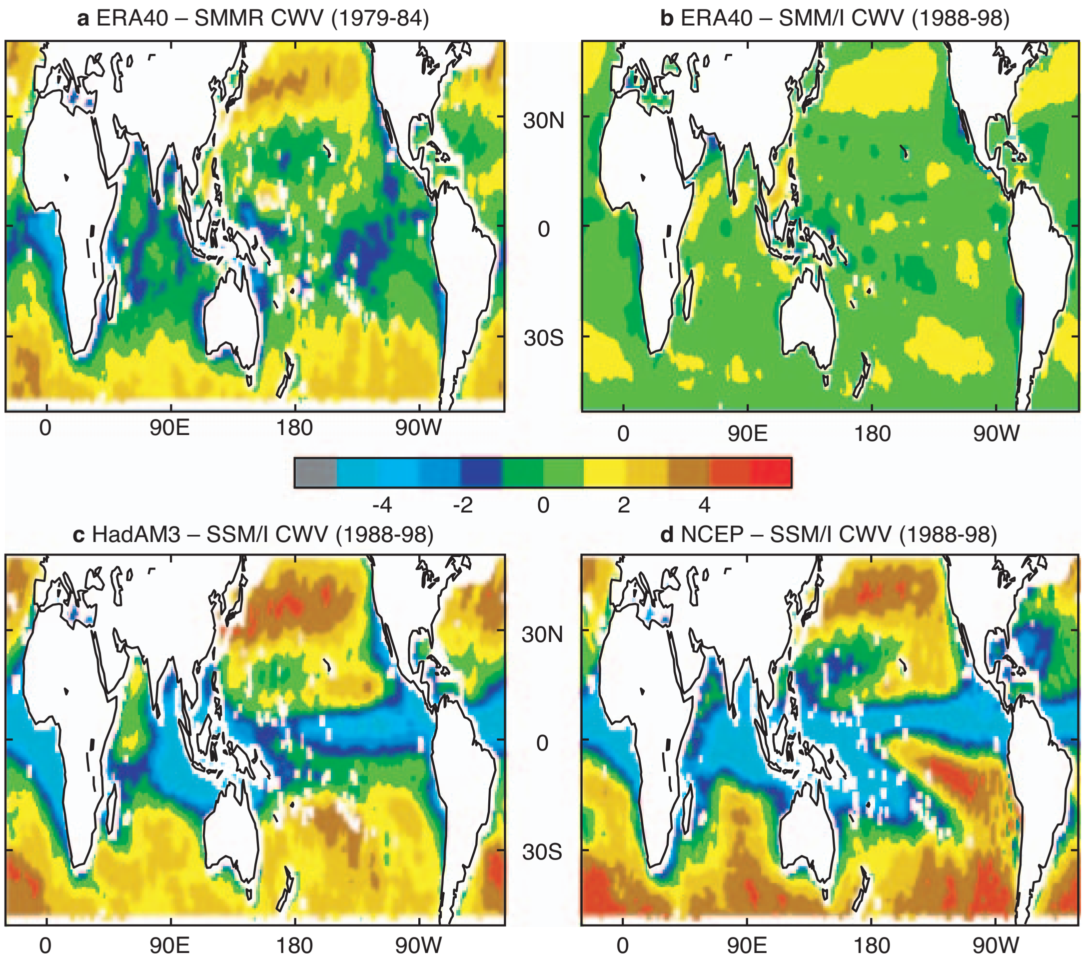


Fig. 20 Difference maps for TCWV (kgm^{-2}) for (a) ERA-40 minus SMMR, (b) ERA-40 minus SSM/I, (c) HadAM3 minus SSM/I and (d) NCEP minus SSM/I. ERA-40 used SSM/I data, but not SMMR data.

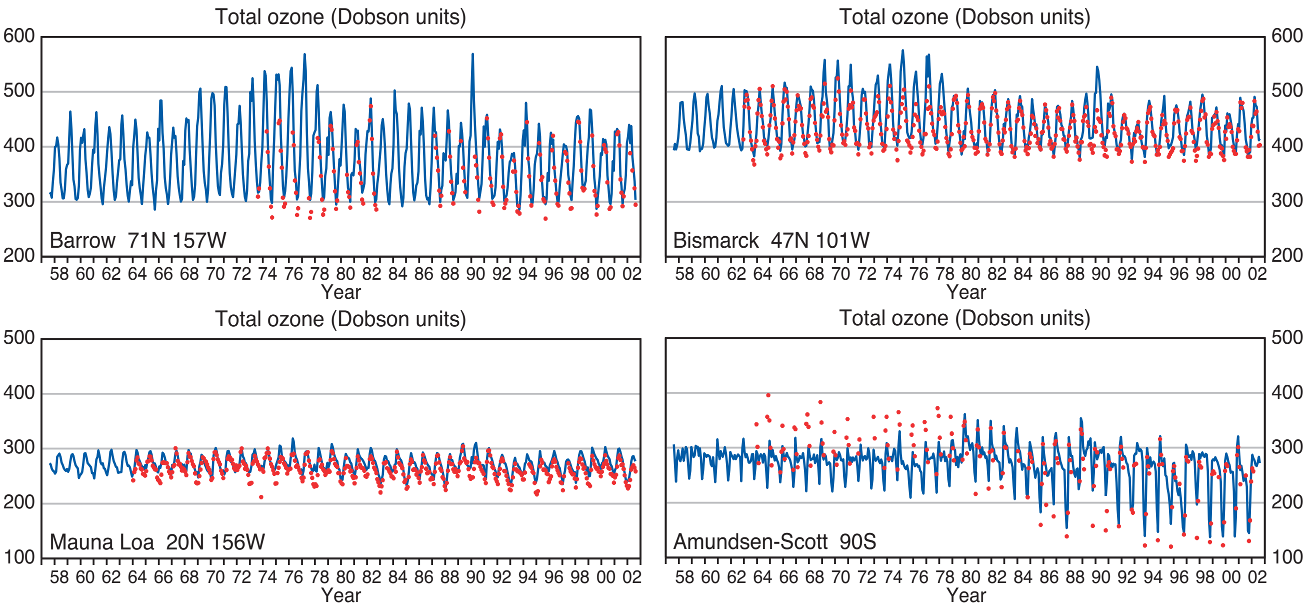


Fig. 21 Time-series comparing monthly-mean ERA-40 analyses of total ozone (blue) with monthly means of ground-based measurements from NOAA/CMDL (red dots) for four stations. Monthly-mean measurements are shown only for months in which at least ten measurements were reported.

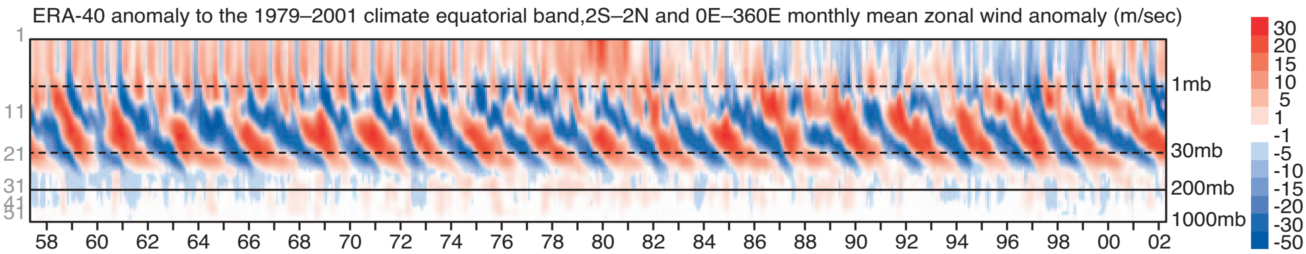


Fig. 22 Quasi-biennal oscillation in the equatorial band 2°S–2°N illustrated by the monthly-mean zonal-wind anomaly (ms^{-1}) from the 1979–2001 climate.

Ocean waves

One of the constituents of the ERA-40 dataset is ocean wave data. This is the first reanalysis dataset in which an ocean wind-wave model was coupled to the atmospheric model. Moreover, it provides the longest and most complete existing wave dataset. After adequate validation, the ERA-40 ocean wave product is the natural choice for studies of climatology and variability of ocean waves and for predicting extreme values of wave parameters over the whole globe. Statistical analysis of the ERA-40 ocean winds and waves with observations has indicated some underestimation of high wind speeds. The results also show a remarkable agreement between ERS-1 and TOPEX (The Ocean Topography EXperiment) altimeter measurements.

The wind speed and significant wave height data from several reanalyses have been collected, assessed and compared by KNMI. In these 'wave reanalyses', the wave models were forced one way or the other by ERA-40 winds, NCEP-NCAR reanalysis winds or by winds from a kinematic reanalysis of the NCEP-NCAR surface wind fields. At a synoptic timescale the differences between the various reanalysis winds and waves are large. In terms of monthly means the differences in the wave fields are significant, while the differences in the wind-speed fields are significant only in certain areas. The longer-term behaviour of both winds and waves in the various datasets analysed is, however, quite similar, an indication that the large-timescale features are equally present in all datasets.

The main limitations of the ERA-40 wave products are the existence of inhomogeneities in time due to the assimilation of different altimeter significant-wave height datasets, and the underestimation of high significant-wave height values, which discourages the use of the data in design studies where a good description of the data in all ranges is important. A method based on non-parametric estimation has been designed at KNMI to improve on ERA-40 significant-wave height fields, thus creating a new 45-year global six-hourly dataset - the C-ERA-40 dataset. This was achieved by taking into account the changes in the error characteristics of the ERA-40 data, using the differences between certain ERA-40 values and the corresponding TOPEX measurements.

Global estimates of 100-year return values of wind speed and significant-wave height have been calculated based on the ERA-40 dataset taking into account the underestimation of the high significant-wave height peaks, Figure 23. The global estimates based on three different 10-year periods show differences in the Northern Hemisphere storm tracks. These differences can be attributed to decadal variability in the Northern Hemisphere, and can be linked to changes in global circulation patterns. In the tropics and the Southern Hemisphere the estimates based on the different decadal datasets are comparable.

Based on both ERA-40 and C-ERA-40 datasets, a web-based wave atlas has been produced describing the wave climate and variability for use in ocean engineering applications, detailed strategic planning of shipping routes and scientific areas such as climate research. The atlas contains a lot of information not accessible in the presently available literature. Significant-wave height and mean-wave period scatter tables for different directional sectors are included, for example. The atlas is available at http://www.knmi.nl/waveatlas.

Future reanalyses

Production of the ERA-40 products and archive has been completed, but work continues on diagnostic studies, on preparation of reports (18 of which are already available from the Centre's website http://www.ecmwf.int/publications/library/do/references/list/192) and on provision of advice to users of ERA-40 data. Liaison will continue with the team in Japan that has recently begun a 25-year reanalysis (JRA-25) covering the period 1979-2005. In addition, preparations are being made for a new, 'interim', reanalysis to be started in 2005. The interim reanalysis will repeat a later part of ERA-40, from 1991 onwards at least, and be extended in close to real time until superseded by a comprehensive new reanalysis. It will benefit from significant recent developments of the ECMWF forecasting system, some partly as a response to the diagnostic work carried out on ERA-40, and will form the baseline for testing new versions of the Centre's data assimilation system for various configurations of the observing system past and present, and for new activities in environmental monitoring. In parallel, work will be undertaken on improving the underlying observational database.

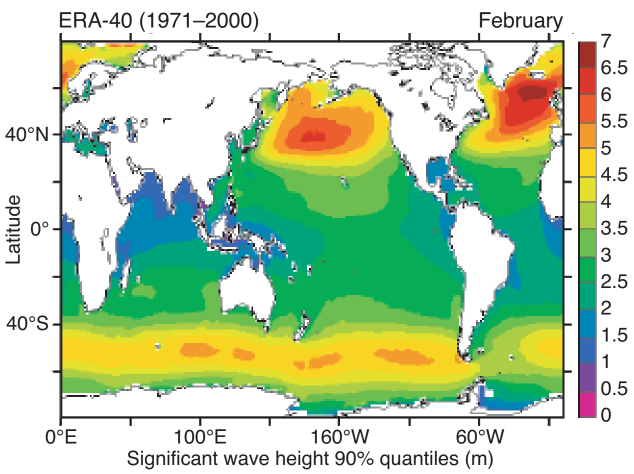


Fig. 23 90% quantiles of significant-wave height for February, showing that the most extreme waves occur in the North Atlantic.

The work will be carried out with a view to initiating a comprehensive new ECMWF reanalysis in 2008 or beyond.

Project organization

ERA-40 has been a very large project in many senses. ERA-40 has required high-performance computing power for six years for testing the data assimilation system and then producing the analyses. Large server and mass-storage resources (~100TB) have also been required. Planning of ERA-40 has required wide expertise and knowledge of global observing systems, conventional and satellite, and their characteristics from the past to the present, how to compose the optimum sea-ice dataset, how to assimilate the historical data in an optimal way within the time and resource constraints, how to define and monitor the quality of analyses for the full period, and how to built a technical framework for the production. Once launched, the assimilation process had to continue without interruptions with no possibilities for any major rerun during the production. Therefore, careful planning of the project with its logistics and thorough testing of the system components, technical and scientific, were the key elements to the successful completion of ERA-40.

The planning of ERA-40 was based on the ERA-15 experience and the developments within ECMWF research and operations. Motivation and specifications of the ERA-40 plan was done by Adrian Simmons with the help from ERA-15 Project Manager Rex Gibson, Per Kållberg and Sakari Uppala. After a successful application for EU funding, the ERA-40 project was partially funded under contract EVK2-CT-1999-00027/ EC Fifth Framework Programme and by Member States and Co-operating States of ECMWF. The project was supported by Fujitsu Ltd through provision of additional computing capacity to ECMWF. ERA-40 was also supported by WCRP and GCOS.

An External Advisory Group was formed to give guidance and to reflect the requirements for products and the quality expectations by the coming ERA-40 user community. As an action, a working group was set up to provide ERA-40 with the best available SST and ICE dataset; Nick Rayner (Met Office), Richard Reynolds (NCEP) and John Walsh (University of Illinois). Also the recalculated coefficients for the ozone chemisry parametrization were provided by Météo-France. Products to drive chemistry transport models were later added as required by a consortium of European research groups.

The ERA-40 Project Group was formed comprising Sakari Uppala as the Project Manager, Per Kållberg, Sami Saarinen and Angeles Hernandez. Secondees for limited periods were provided: Xu Li (Institute of Atmospheric Physics China), Kazutoshi Onogi (Japan Meteorological Agency) and Mike Fiorino (Program for Climate Model Diagnosis and Intercomparison, USA). After the departure of the secondees, Niko Sokka (Finnish Meteorological Institute) joined the ERA-40 project, followed by Ulf Andrae (Swedish Meteorological and Hydrological Institute) and then Vanda Da Costa Bechtold (Portuguese Meteorological Institute). Adrian Simmons was as the overall project coordinator between the partners and European Union and he was also responsible for the higher level management of the project. ECMWF personnel very closely involved with ERA-40 were; Jan Haseler concerning the PrepIFS and SMS environment and Graeme Kelly concerning the use of satellite sounder data.

The successful completion of ERA-40 was supported by many other people at ECMWF among them: Erik Andersson, Peter Bauer, Anton Beljaars, Jean Bidlot, Niels Bormann, François Bouttier, John Chambers, Frederick Chevallier, Antje Dethof, Milan Dragosavac, Keith Edwards, Mike Fisher, Manuel Fuentes, Élisabeth Gérard, Claude Gibert, Mats Hamrud, Elias Holm, Graham Holt and operators, Lars Isaksen, Peter Janssen, Christina Koepken, Petra Kogel, Tony McNally, Jean-Jacques Morcrette, Baudouin Raoult, Deborah Salmond, Roger Saunders, Tony Stanford, Agathe Untch, Drasko Vasiljevic, Pedro Viterbo and Nils Wedi.

ECMWF had six partners in the ERA-40 Project with different validation responsibilities:

- **Koninklijk Nederlands Meteorologisch Instituut** – Ocean waves. *Andreas Sterl, Sofia Caires, Gebrand Komen*
- **Max-Planck-Institut für Meteorologie** – Hydrological cycle. *Stefan Hagemann, Klaus Arpe, Lennart Bengtsson*
- **Météo-France** – Ozone, Stratospheric analyses, Ocean surface fluxes & Alpine snow. *Pascal Simon, Sylvana Buarque, Eric Martin*
- **Met Office** – Clear sky radiation simulation. *Richard Allan, Antony Slingo, Vicky Pope*
- **National Center for Atmospheric Research** – Observations and mass, heat, energy & moisture diagnostics. *Kevin Trenberth, Roy Jenne, Dennis Joseph*
- **University of Reading** – General circulation, Climate variability. *Brian Hoskins, Paul Berrisford, Kevin Hodges, Julia Slingo*

In addition Jack Woollen from NCEP collaborated throughout the project, recoding most of the conventional observation from their original format to the BUFR, and making them available for ERA-40.

Further reading

ECMWF ERA-40 Report Series.
http://www.ecmwf.int/publications

Access to the products

A full set of six-hourly and monthly-mean pressure-level and surface fields at 2.5° resolution can be downloaded from http://data.ecmwf.int/data

For full-resolution data and further enquiries, e-mail data.services@ecmwf.int

Sakari Uppala, Per Kållberg, Angeles Hernandez, Sami Saarinen, Mike Fiorino, Xu Li, Kazutoshi Onogi, Niko Sokka, Ulf Andrae and Vanda Da Costa Bechtold

Early-delivery suite

The early-delivery suite is a reorganisation of the data assimilation system in order to make the operational products available earlier. In particular, it makes the 0000 UTC products available before the end of the working day, even in the easternmost Member States where local summer time is three hours ahead of Universal Time. It became the operational data assimilation system on 29 June 2004.

Figure 1 shows the original 12-hour 4D-Var data assimilation configuration. The 0000 UTC analysis uses observations from the time window 1501 - 0300 UTC. On reception at ECMWF, the observations are stored in the Reports Data Base. At 0745 UTC, the first family of extraction tasks takes observations for the period 1501 - 2100 UTC from the Reports Data Base, and prepares input files for the analysis. At 0800 UTC, the second family of extraction tasks prepares the input analysis observation files for the period 2101 - 0300 UTC. Any observations that arrive after the relevant extraction task has run are not used by the analysis. The three-hour forecast from the previous day's 1200 UTC analysis provides the first guess for the 0000 UTC analysis at 1500, the start of its 12-hour observation window.

The 1200 UTC analysis uses observations from the time window 0301 - 1500 UTC. The extraction tasks for observations for the periods 0301 - 0900 UTC and 0901 - 1500 UTC are run at 1900 and 1915 UTC, respectively. The three-hour forecast from the 0000 UTC analysis provides a first guess for the 1200 UTC analysis at 0300 UTC, the

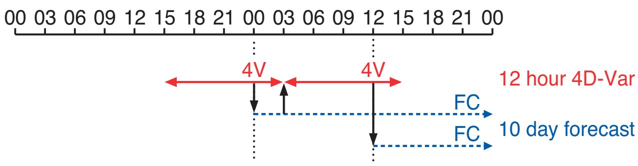


Fig. 1 Organisation of the original 12-hour 4D-Var data assimilation suite.

start of its 12-hour observation window. Ten-day forecasts are run from the analyses at 0000 UTC and 1200 UTC.

Figure 2 shows the early-delivery configuration. The 12-hour 4D-Var analysis is run with an observation window that is shifted forwards by six hours. The 0000 UTC analysis uses observations in the time window 2101 - 0900 UTC, while the 1200 UTC analysis uses observations in the window 0901 - 2100 UTC. These analyses are run with a delayed-cut-off time, in order to use the maximum possible number of observations. The extraction tasks for observations in the periods 2101 - 0300 UTC and 0301 - 0900 UTC are run at 1345 and 1400 UTC, respectively, while the extraction tasks for 0901 - 1500 UTC and 1501 - 2100 UTC are run at 0145 and 0200 UTC. The first guess for the 0000 UTC analysis is the nine-hour forecast from the previous day's 1200 UTC delayed-cut-off analysis. The first guess for the 1200 UTC analysis is the nine-hour forecast from the 0000 UTC delayed-cut-off analysis. It is these 12-hour delayed-cut-off assimilations that propagate information forwards from day to day. There

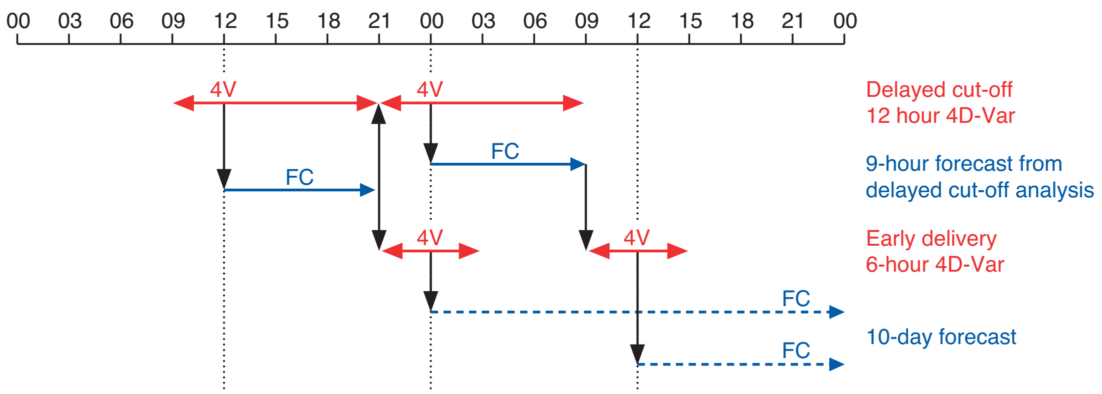


Fig. 2 The early-delivery configuration.

is no loss of observational information compared with the original 12-hour 4D-Var data-assimilation configuration.

The early-delivery analyses do not propagate information from cycle to cycle. Each analysis is reinitialized with the best available model fields from the delayed-cut-off assimilation. The 0000 UTC early-delivery analysis is a six-hour 4D-Var analysis, which uses observations in the time window 2101 – 0300 UTC. The cut-off time is 0400 UTC, and any observations that arrive after this time will not be used by the early-delivery analysis. However, if they arrive by 1400 UTC, they can still be used by the delayed-cut-off 12-hour 4D-Var 0000 UTC analysis. The first guess for the 0000 UTC early-delivery analysis is the nine-hour forecast from the previous day's 1200 UTC delayed-cut-off 12-hour 4D-Var analysis.

The early-delivery 1200 UTC analyses is a six-hour 4D-Var analysis that uses observations in the time window 0901 – 1500 UTC, with a cut-off time of 1600 UTC. Its first guess is the nine-hour forecast from the delayed-cut-off 12-hour 4D-Var 0000 UTC analysis. Ten-day forecasts are run from the early-delivery analyses at 0000 and 1200 UTC.

As well as the observations that are actively used by the analysis, there are also some that are passed passively through the system. Statistics of departures from the first guess and analysis are gathered for the passive observations, but they are not used by the analysis. This is useful, for example, for monitoring the quality of new observation types prior to their operational use. All observation monitoring is done in the delayed-cut-off 12-hour 4D-Var analyses, and no passive data needs to be input to the early-delivery analyses.

Operational schedule

Figure 3 shows the operational schedule for the 0000 UTC suite with the original data assimilation scheme. The suite begins at 0800 UTC with the extraction of the observations, followed by the 12-hour 4D-Var analysis. When the analysis completes, at about 0930 UTC, the ten-day forecast and the Ensemble Prediction Scheme (EPS) are triggered to start. Dissemination of the forecast is scheduled between 1115 (day 1) and 1245 UTC (day 10). The EPS dissemination is scheduled between 1335 (day 0) and 1415 UTC (day 10).

Figure 4 shows the operational schedule for the 0000 UTC early-delivery suite. Observations are extracted at 0400 UTC, and there is a further saving of about 30 minutes compared with the original data assimilation scheme because the analysis is now six-hour 4D-Var rather than 12-hour 4D-Var. The forecast dissemination is scheduled between 0715 (day 1) and 0845 UTC (day 10), while the EPS dissemination is scheduled between 0935 (day 0) and 1015 UTC (day 10).

Table 1 sets out the dissemination times for the original and early-delivery suites at 0000 and 1200 UTC. Products from the 0000 UTC early-delivery suite are made available four hours earlier than before, while the 1200 UTC products are available 3¼ hours earlier.

Experimentation

The early-delivery system has been extensively tested during 2003 and 2004, and its impact on the quality of the forecasts is essentially neutral. Combined scores are presented below for the following periods

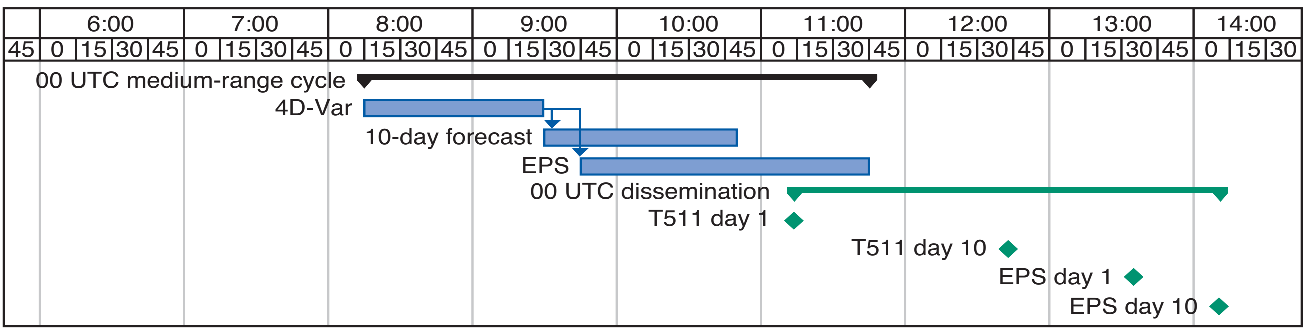


Fig. 3 Operational schedule for 0000 UTC suite with original data assimilation scheme

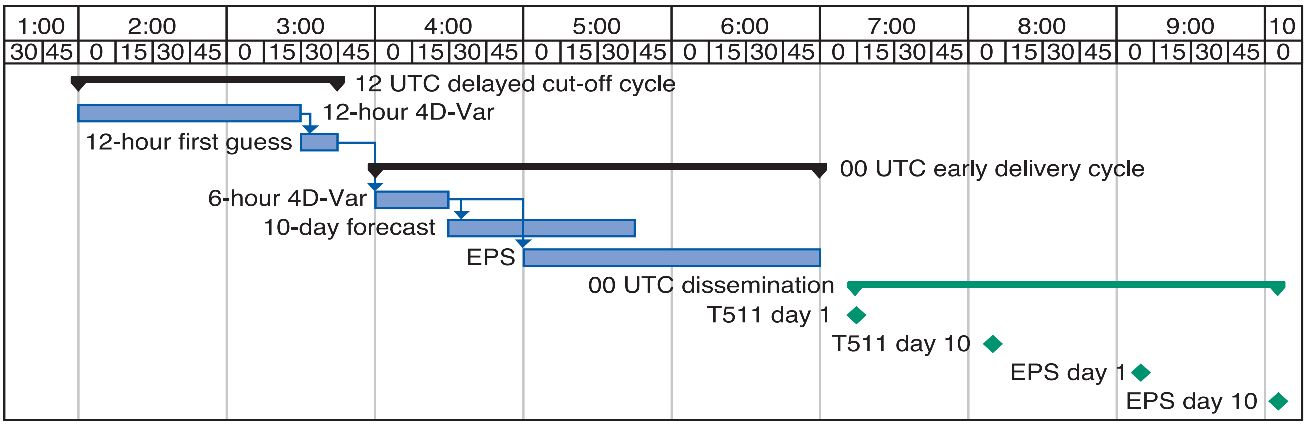


Fig. 4 Operational schedule for the 0000 UTC early-delivery suite.

	Original suite (UTC)	Early-delivery suite (UTC)
0000 UTC, Deterministic forecast, day 1	1115	0715
0000 UTC, Deterministic forecast, day 10	1245	0845
0000 UTC, EPS, day 0	1335	0935
0000 UTC, EPS, day 10	1415	1015
1200 UTC, Deterministic forecast, day 1	2230	1915
1200 UTC, Deterministic forecast, day 10	0000	2045
1200 UTC, EPS, day 0	0050	2135
1200 UTC, EPS, day 10	0130	2215

Table 1 Dissemination times (UTC) for the original and early-delivery suites.

1 February – 18 June 2004 (139 days)
12 October – 30 November 2003 (50 days)
1 September – 30 September 2003 (30 days)
1 June – 7 August 2003 (68 days)
17 January – 27 February 2003 (42 days)

The scores for February–June 2004 have been taken from the pre-operational testing of the early-delivery system, while the scores for the earlier periods have been taken from Research Department experiments. Forecasts from the early-delivery analyses are compared with forecasts from control analyses with the original 12-hour 4D-Var configuration. The control forecasts are taken from either the operational suite or the pre-operational testing of the same software release as the corresponding early-delivery experiment.

Figure 5 shows the anomaly correlation for the 500 hPa geopotential-height forecast error for the Northern Hemisphere extratropics, averaged over 329 days, for the forecasts from the early-delivery analyses (red) and the control analyses (blue). The impact of the early-delivery scheme is neutral. There is a similar neutral comparison for the Southern Hemisphere at 500 hPa.

Figure 6 shows the anomaly correlation for the 1000 hPa geopotential-height forecast error for Europe, averaged over 329 days, for the forecasts from the early-delivery analyses (red) and the control analyses (blue). The impact of the early-delivery scheme is again shown to be neutral.

Observation cut-off time

A set of early-delivery experiments was run for September 2003, to investigate the effect of the observation cut-off time on the quality of the subsequent forecasts. Starting from the same delayed-cut-off shifted-window 12-hour 4D-Var assimilation, three different early-delivery experiments were run. For the six-hour 4D-Var analyses for 0000 UTC, with observations in the time window 2101 – 0300 UTC, the first experiment used only those observations that had been received by 0400 UTC, the second used observations that had been received by 0600 UTC and the third used observations that had been received by 0800 UTC.

Figure 7 shows the anomaly correlation for the 500 hPa geopotential height forecast error for the Northern Hemisphere extratropics, averaged over 30 days from 1 September 2003, for the ten-day forecasts from the 0000 UTC early-delivery analyses with different observation cut-off times. In these experiments, use of the observations that arrived after 0400 UTC gave no significant gain in forecast quality. Accordingly, all subsequent early-delivery experimentation was run with an observation cut-off time of 0400 UTC for the 0000 UTC analysis and 1600 UTC for the 1200 UTC analysis.

Delayed-cut-off observations

In the early experimentation, the shifted-window 12-hour 4D-Var data assimilation used the observations that had been presented to the operational suite. Observations for the intervals 0301 – 0900 UTC and 0901 – 1500 UTC had been extracted from the Reports Data Base at 1900 and 1915 UTC, respectively, and observations for 1501 – 2100 UTC and 2101 – 0300 UTC had been extracted at 0745 and 0800 UTC, respectively. Since the start of December 2003, a separate delayed-cut-off (STREAM=DCDA) set of observations has also been saved, with observations from 0901 – 1500 UTC and 1501 – 2100 UTC extracted at 0145 and 0200 UTC, respectively, and observations from 2101 – 0300 UTC and

0301 – 0900 UTC extracted at 1345 and 1400 UTC, respectively. These are the same extraction times as are now used for the delayed-cut-off observation stream in the operational early-delivery suite. The delayed-cut-off observation stream has more late-arriving data than the old operational suite for the periods 2101 – 0300 UTC and 0901 – 1500 UTC, and fewer late-arriving data for the periods 0301 – 0900 UTC and 1501 – 2100 UTC.

Two early-delivery experiments were run for February and March 2004. One used the operational observations in its shifted-window 12-hour 4D-Var assimilation and the other used the new delayed-cut-off observation stream. The

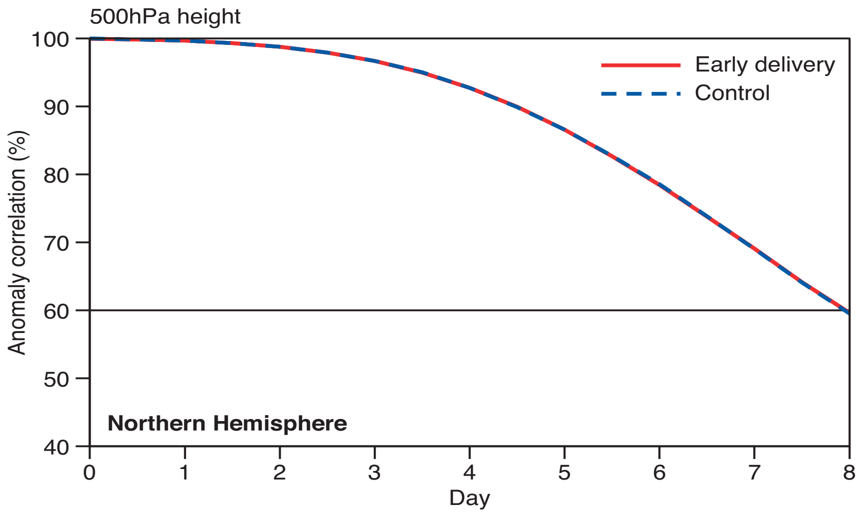


Fig. 5 Anomaly correlation of the 500 hPa geopotential height forecast error for the Northern Hemisphere extratropics, averaged over 329 days, for the forecasts from the early-delivery analyses (red) and the control analyses (blue). The curves overlap almost entirely, demonstrating equivalent performance.

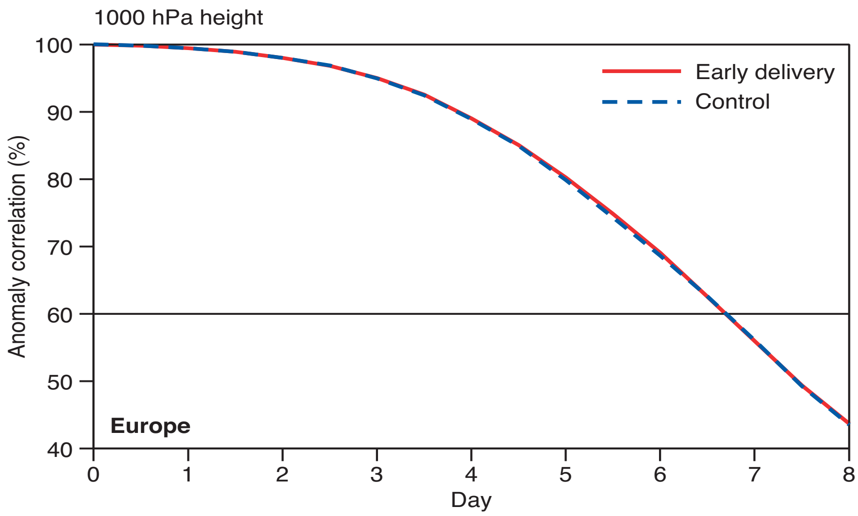


Fig. 6 Anomaly correlation of the 1000 hPa geopotential-height forecast error for Europe, averaged over 329 days, for the forecasts from the early-delivery analyses (red) and the control analyses (blue).

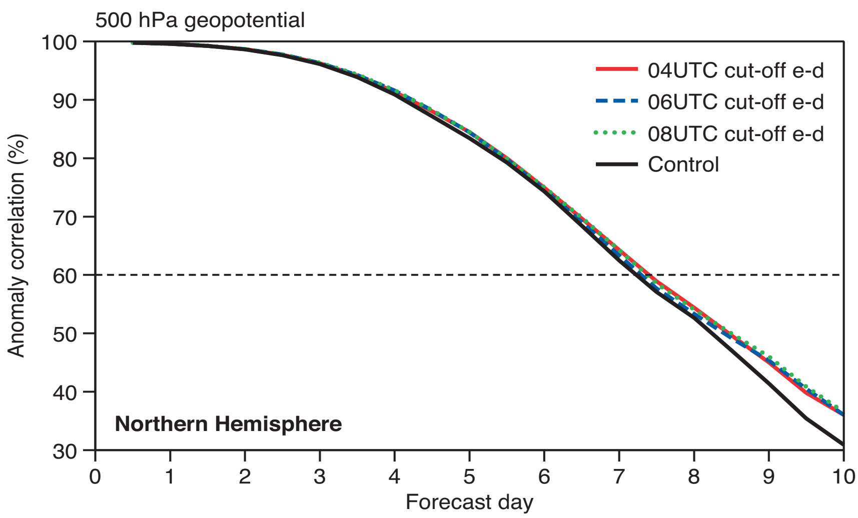


Fig. 7 Anomaly correlation for the 500 hPa geopotential-height forecast error for the Northern Hemisphere extratropics, averaged over 30 days from 0000 UTC 1 September 2003, for the forecasts from the early-delivery analysis with an observation cut-off time of 0400 UTC (red), 0600 UTC (blue) and 0800 UTC (green) and for the control forecasts (black).

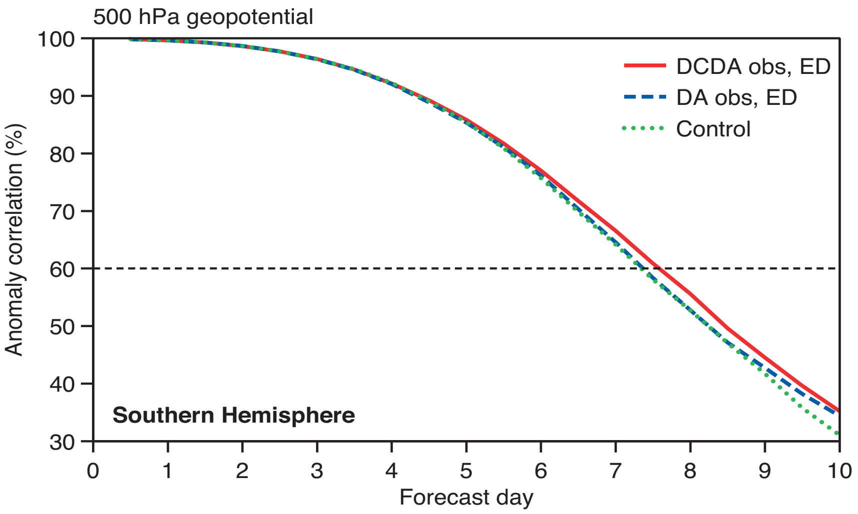


Fig. 8 Anomaly correlation for the 500 hPa geopotential-height forecast error for the Southern Hemisphere extratropics, averaged over 60 days from 0000 UTC 1 February 2004, for the forecasts from the early-delivery analyses (red and blue) and the control analyses (green). In the red experiment, the shifted window 12-hour 4D-Var analyses used the delayed-cut-off observation stream, while in the blue experiment the operational observations were used.

quality of the forecasts from the early-delivery analyses in the two experiments was compared. In the Southern Hemisphere, at all levels, there was a small improvement in the early-delivery forecast scores when the delayed-cut-off observation stream was used for the shifted-window 12-hour 4D-Var analyses. The Southern Hemisphere 500 hPa geopotential-height scores are shown in Figure 8. In the Northern Hemisphere, changing the shifted-window 12-hour 4D-Var assimilation observation stream had no impact on the quality of the forecasts from the early-delivery analyses. Over the two-month period, the experiment with the new delayed-cut-off stream used 0.1% more TEMP winds and 1% more AMSU-A brightness-temperature data than the experiment with the operational observations.

Data coverage

The extraction of the observations for the 0000 UTC early-delivery analysis is done at 0400 UTC. For the 0000 UTC analysis on 25 March 2004, which uses observations for the time interval 2101 UTC 24 March - 0300 UTC 25 March 2004, the table below shows which observations arrived early enough to be used by the early-delivery analysis, i.e. before 0401 UTC, and which were used by the operational analysis but arrived too late to be used by the early-delivery analysis, i.e. they were received between 0401 and 0800 UTC. Data-coverage plots are also presented for TEMPs and NOAA ATOVS data, showing the geographical coverage of the on-time and late observations. (As long as the observations arrive by 1345 UTC, they are still used by the delayed-cut-off analysis, even if they arrive too late to be used by the early-delivery analysis.)

Observation departure statistics

Statistics of the departures of observations from the background field and the analysis are presented for a three-week period at the beginning of February 2004. Statistics for both the delayed-cut-off 12-hour 4D-Var and the early-delivery analyses are compared with a control analysis, which has the original 12-hour 4D-Var configuration. Due to the changed window geometry, the delayed-cut-off 12-hour 4D-Var experiment has more late-arriving data at 0000 and 1200 UTC, and fewer data at the end of its observation windows, at 0600 and 1800 UTC. Total numbers of observations presented to the delayed-cut-off and the control analyses over the three-week period are similar. The totals for the delayed-cut-off 12-hour 4D-Var and the control assimilation are within 0.5% for radiosondes, AIREPs, profilers, SYNOPs, AMV winds and scatterometer data and within 1% for geostationary radiances and DMSP data. There are 1% extra data from the NOAA polar-orbiting satellites, 2% less dropsonde data and 3% less DRIBU reports in the delayed-cut-off 12-hour 4D-Var compared with the control assimilation.

Observation type	Number of reports received before 0401 UTC	Number of reports received 0401 - 0800 UTC
SYNOP	13243	323
SHIP	1396	34
Aircraft	52219	239
BUOY	2785	708
TEMP	541	35
PILOT	278	8
Profilers	583	42
ATOVS/AMSU-A	254520	63445
ATOVS/AMSU-B	1705625	487260
ATOVS/SSU and MSU	4	0
ATOVS/HIRS	440017	126560
AIRS	65546	15081
Geostationary radiances	730763	24900
SSM/I	986496	0
Scatterometer	353394	143226
AMV	216465	46047

Table 2 Observations for the timeslot 2101 UTC 24 March – 0300 UTC 25 March 2004, showing the number of reports for each observation type that were received before 0401 UTC (i.e. early enough to be used by the early-delivery analysis) and the number received between 0401 and 0800 UTC (i.e. early enough for the old operational analysis, but too late for the early-delivery analysis)

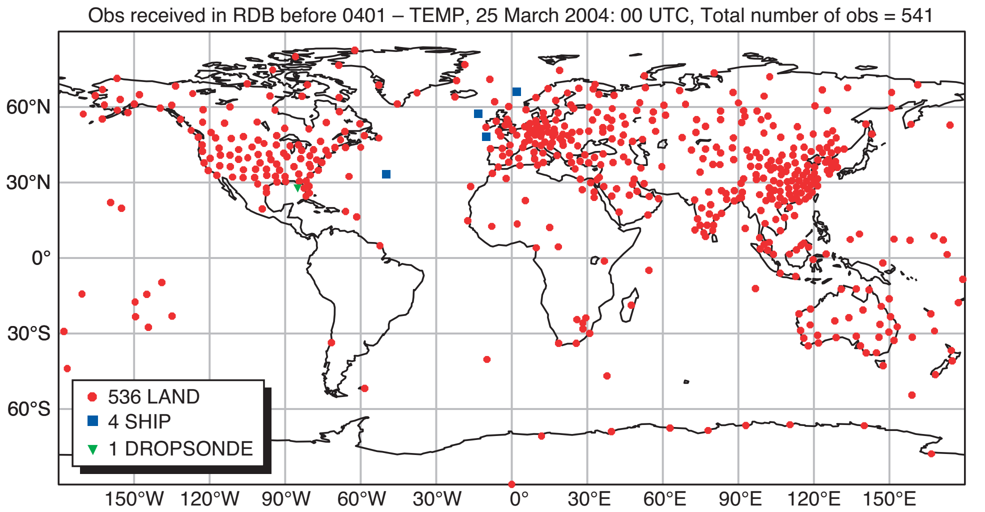


Fig. 9 TEMP reports for land (red) and ship (blue) for the period 2101 UTC 24 March - 0300 UTC 25 March 2004 which were received by 0400 UTC.

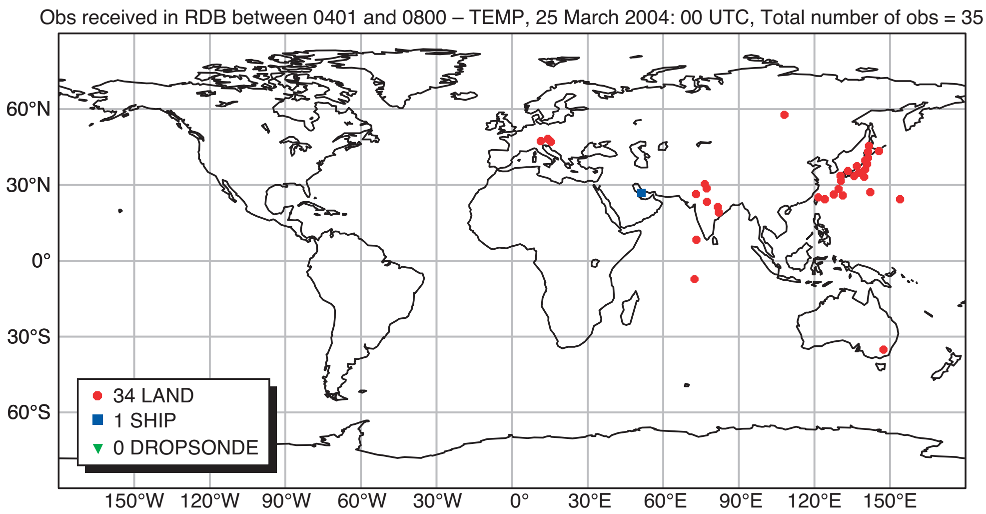


Fig. 10 TEMP reports for land (red) and ship (blue) for the period 2101 UTC 24 March - 0300 UTC 25 March 2004 which were received between 0401 and 0800 UTC.

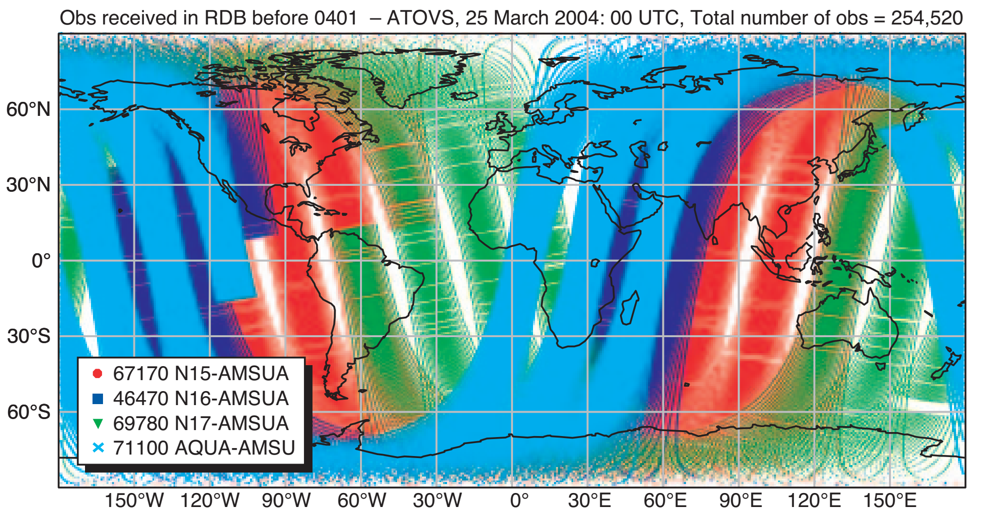


Fig. 11 ATOVS reports from NOAA 15 (red), NOAA 16 (blue), NOAA 17 (green) and AQUA (cyan), for the period 2101 UTC 24 March - 0300 UTC 25 March 2004 which were received by 0400 UTC.

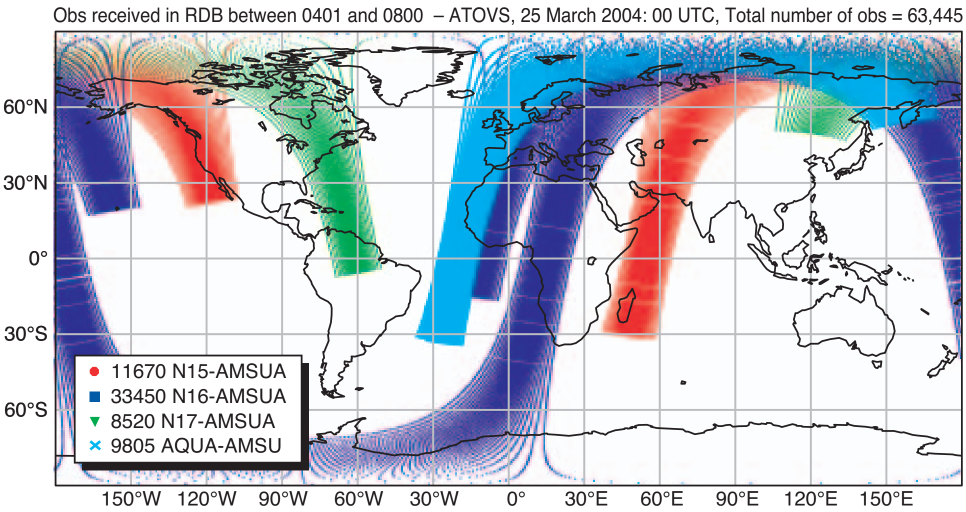


Fig. 12 ATOVS reports from NOAA 15 (red), NOAA 16 (blue), NOAA 17 (green) and AQUA (cyan), for the period 2101 UTC 24 March – 0300 UTC 25 March 2004 which were received between 0401 and 0800 UTC.

The observation statistics for the six-hour 4D-Var early-delivery analyses are accumulated for the three weeks over two six-hour intervals, 2101 - 0300 UTC and 0901 - 1500 UTC. The statistics for the control 12-hour 4D-Var analyses are accumulated over two 12-hour intervals, 1501 - 0300 UTC and 0301 - 1500 UTC. For an observation type that reports evenly over the data-assimilation window, and where all the observations arrive before the early-delivery cut-off time, the total number of observations accumulated for the six-hour 4D-Var early-delivery analysis statistics should be approximately 50% of the total accumulated for the 12-hour 4D-Var control-analysis statistics. For TEMPs, where most of the observations report at 0000 UTC or 1200 UTC and most arrive promptly, the proportion accumulated for the early-delivery statistics is significantly greater than 50%. For AIREPs, where the observations are distributed fairly evenly in time, but some arrive after the cut-off time, the proportion accumulated is less than 50%.

AIREP 'u' winds

Figure 13 shows the standard deviation and the bias for the AIREP east-west (*u*) component winds which were used by the analysis in the Northern Hemisphere extratropics (north of 20°N) for the delayed-cut-off 12-hour 4D-Var (black) and the control (red). The departures from the background field are shown with a solid line, while a dotted line is used for the departures from the analysis. Over the three-week period, 1,612,502 AIREP *u* winds were used by the delayed-cut-off 12-hour 4D-Var, and 1,610,327 were used by the original analysis, a 0.13% difference. The observations are distributed evenly in time and the impact of shifting the assimilation window by six hours is seen to be neutral.

Figure 14 shows the standard deviation and the bias for the AIREP u winds which were used by the analysis in the Northern Hemisphere extratropics for the early-delivery analysis (black) and the control (red). The standard deviation of the departure from the background field is smaller for the early-delivery system than for the control above 700 hPa, while the standard deviation of the departure from the analysis is smaller for the early delivery at all levels. Bouttier (2001) showed that the distance of the analysis from the observations is greater for 12-hour 4D-Var than for six-hour 4D-Var. Since the early-delivery analysis uses six-hour 4D-Var and the control analysis uses 12-hour 4D-Var, this may explain the closer fit of the early-delivery analyses to the observations. The early-delivery analyses used 49% fewer

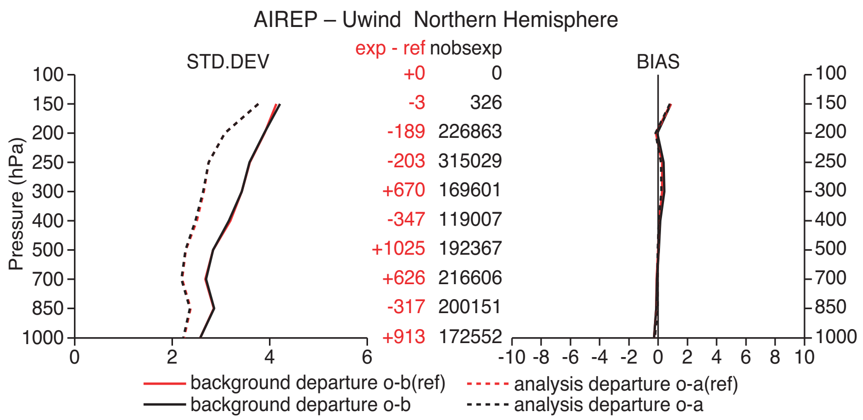


Fig. 13 Standard deviation (left) and bias (right) for the departures of used AIREP u-wind components in the Northern Hemisphere extratropics from the background (solid) and analysis (dotted) for delayed-cut-off 12-hour 4D-Var (black) and control (red), accumulated over the period 0000 UTC 1 February – 1200 UTC 20 February 2004.

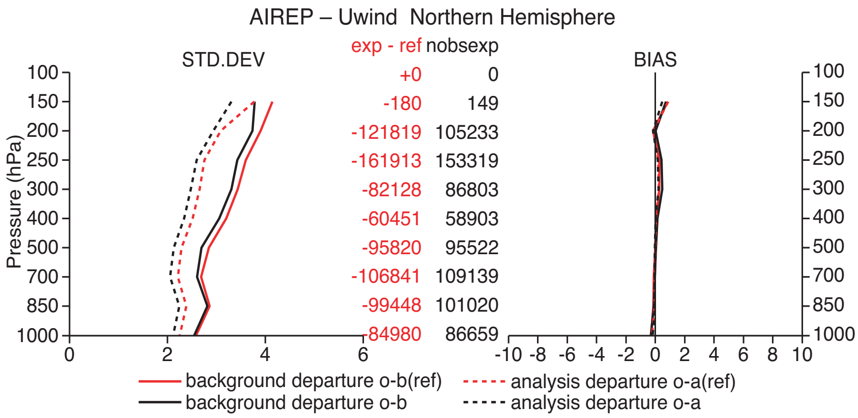


Fig. 14 Standard deviation (left) and bias (right) for the departures of used AIREP u-wind components in the Northern Hemisphere extratropics from the background (solid) and analysis (dotted) for the early delivery (black) and control (red), accumulated over the period 0000 UTC 1 February – 1200 UTC 20 February 2004.

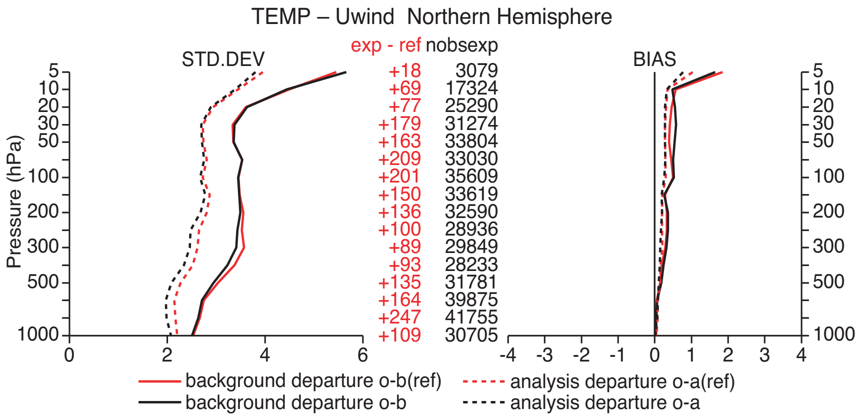


Fig. 15 Standard deviation (left) and bias (right) for the departures of the used TEMP u-wind components in the Northern Hemisphere extratropics from the background (solid) and analysis (dotted) for delayed-cut-off 12-hour 4D-Var (black) and control (red), accumulated over the period 0000 UTC 1 February – 1200 UTC 20 February 2004.

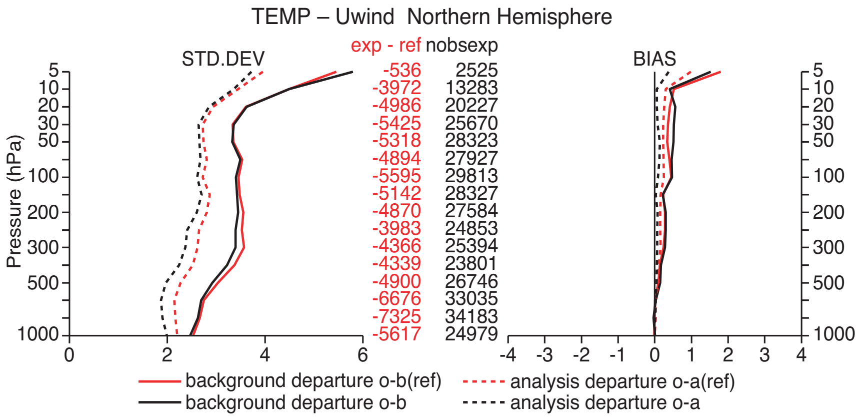


Fig. 16 Standard deviation (left) and bias (right) for the departures of used TEMP u-wind components in the Northern Hemisphere extratropics from the background (solid) and analysis (dotted) for the early delivery (black) and control (red), accumulated over the period 0000 UTC 1 February - 1200 UTC 20 February 2004.

AIREP u winds than the control analyses in the Northern Hemisphere and 63% less in the Southern Hemisphere. (It should be emphasised that observations that arrive too late to be used by the early-delivery analysis are not lost, since they are included in the delayed-cut-off cycling component of the suite.)

TEMP 'u' winds

Figure 15 shows the standard deviation and the bias for the TEMP *u* winds that were used by the analyses in the Northern Hemisphere extratropics for the delayed-cut-off 12-hour 4D-Var (black) and the control (red). The standard deviation of the departure from the background field is smaller for the delayed-cut-off 12-hour 4D-Var than for the control in the region 500 - 200 hPa, while the standard deviation of the departure from the analysis is smaller for the delayed-cut-off 12-hour 4D-Var in the region 1000 - 150 hPa. The explanation is that the background-error standard deviation for component wind increases most rapidly with time in the upper troposphere, as shown by Järvinen (2001). In the delayed-cut-off 12-hour 4D-Var, the TEMP reports, with an observation time of 0000 or 1200 UTC, are used three hours after the start of the background forecast, rather than nine hours in the control analysis. The departure statistics indicate the analysis is able to draw more closely to the TEMP *u* winds if they are used closer to the start of the 4D-Var window when the background errors are smaller.

Figure 16 shows the standard deviation and the bias for the TEMP *u* winds that were used by the analysis in the Northern Hemisphere extratropics for the early-delivery analysis (black) and the control (red). The standard deviation of the departure from the background field is smaller for the early-delivery system than for the control in the region 500 - 200 hPa, while the standard deviation of the departure from the analysis is smaller for the early delivery in the region 1000 - 50 hPa. During this three-week period, 17% fewer TEMP u winds were used in the Northern Hemisphere extratropics by the early-delivery six-hour 4D-Var analyses than by the control 12-hour 4D-Var analyses. (Again, it should be noted that any late arriving TEMP reports were not lost, since they were still used by the delayed-cut-off analysis.)

NOAA brightness temperatures

Overall, there were 1.1% more used brightness temperature observations from NOAA polar-orbiting satellites for the delayed-cut-off 12-hour 4D-Var analyses than for the control analyses, with more data for NOAA-16 and NOAA-17, and slightly fewer data for NOAA-15, AQUA and AIRS. The early-delivery analyses used 62% fewer brightness-temperature observations than the control analyses.

Figure 17 shows the standard deviation and bias for the NOAA-16 AMSU-A brightness temperatures that were used by the analysis in the Northern Hemisphere extratropics for the early-delivery analysis (black) and the control (red). The early-delivery analysis has a larger bias for channels 12-14, reaching -0.6 K for the departure of the channel-14 brightness temperatures from the background field, compared with 0.1 K for the control. The standard deviation is of similar magnitude for the early-delivery analysis and the control, reaching 1.4 K for the departure of channel 14 from the background field, and 0.8 K for the departure from the analysis. In the tropics and the Southern Hemisphere extratropics, the early-delivery analyses have a smaller bias than the control analyses, while the standard deviation is neutral. The delayed-cut-off 12-hour 4D-Var analyses also show an increase in bias for NOAA-16 AMSU-A channels 12-14 in the Northern Hemisphere extratropics, but with the smaller magnitude of -0.4 K. AQUA AMSU-A brightness temperatures show the same signal as NOAA-16 AMSU-A. Channel 14 of NOAA-15 AMSU-A is blacklisted, but channel 13 hints at the same signal, though with reduced magnitude.

Future Developments

There are various plans for more timely reception of satellite data. ECMWF is already receiving and passively monitoring EUMETSAT ATOVS Retransmission Service (EARS) data. Ground stations download and process ATOVS data as the NOAA polar-orbiting satellites pass overhead, and the information is posted on the GTS by EUMETSAT within 30 minutes. The EARS data currently cover Europe and the North Atlantic, and there are plans to extend the cover to the whole of the Northern Hemisphere. MetOp, the first European polar-orbiting weather satellite, is scheduled to be launched in 2005. Although initially the data will be available 2.25 hours after observation time, there are plans to provide it more quickly. By 2010, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) is planned to replace the current NOAA satellites, and its processed data should also be available within 30 minutes. Faster reception of satellite data may make it possible to further reduce the observation cut-off time of the early-delivery data assimilation.

ECMWF currently runs the Boundary Condition (BC) suite, to provide boundary data for certain Member State limited-area models. The BC suite runs four six-hour 3D-Var assimilations, and reinitializes twice per day, at 0600 UTC from the operational 0000 UTC forecast and at 1800 UTC from the operational 1200 UTC forecast. Investigations are under way to see if the early-delivery system could be extended to provide better boundary-condition data.

By providing the best possible first guess from the delayed-cut-off 12-hour 4D-Var analyses, it has proved to be possible to perform 4-hour-cut-off analyses without any significant reduction in forecast quality. As a result, the early-delivery suite became the operational data assimilation system on 29 June 2004, and the ECMWF forecast products are now available up to four hours sooner than with the previous operational schedule.

Acknowledgements

I would like to thank David Burridge for his support of this project from its inception through to its operational implementation. I would also like to thank Erik Andersson, Adrian Simmons, Lars Isaksen, Milan Dragosavac, Manuel Fuentes and Antonio Garcia-Mendez for help, advice and software.

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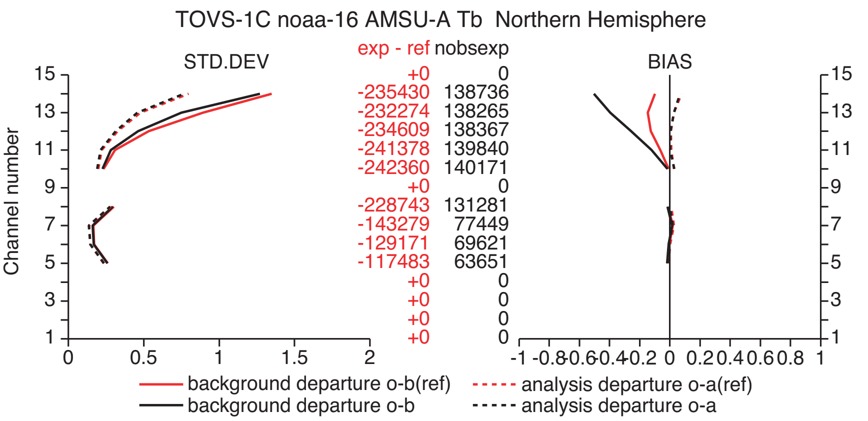

Fig. 17 Standard deviation (left) and bias (right) for the departures of used NOAA-16 AMSU-A brightness temperatures in the Northern Hemisphere extratropics from the background (solid) and analysis (dotted) for the early-delivery (black) and control (red), accumulated over the period 0000 UTC 1 February-1200 UTC 20 February 2004

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Jan Haseler

European Flood Alert System

Co-operation agreement between ECMWF and the JRC

Every year, on average, 100 European citizens die in floods. Over the period 1998-2002 alone, 100 major floods comprised 43% of all disaster events, causing 700 fatalities, the displacement of about half a million people, and at least 25 billion Euro in insured economic losses.

The Directors of ECMWF and the European Commission's Joint Research Centre (JRC), on 31 August 2004, signed a Cooperation Agreement providing the JRC with real-time access to ECMWF weather forecast products for use in the European Flood Alert System (EFAS). Both organizations will work together to develop a system for early flood warnings up to ten days in advance. An increased warning time could help to avoid casualties and reduce flood damages.

The European Flood Alert System (EFAS)

The JRC is currently testing and refining the pan-European Flood Alert System. Based on the computer model LISFLOOD, combining both medium-range weather forecasts from ECMWF and hydrological data from water authorities, this system will simulate the flow in many large European rivers with a lead-time of three to ten days. This will allow more time for appropriate action to prevent human casualties and reduce material losses. The system has a particular focus on large, trans-boundary river basins.

Since numerical forecasts of rainfall several days ahead are progressively more accurate, the aim is to provide national water authorities with an early warning capability for a developing flood disaster and greater knowledge about its likely extent and development over time.

During the test period, the results of the system will be evaluated in real time by selected flood warning agencies in several European countries. Subject to positive results, the system will be made operational, probably in 2008.

Added value of cooperation between ECMWF and the JRC

Joint research by the JRC and ECMWF has already demonstrated that, for example, the large floods on the Meuse/Rhine (1993 and 1995) and Po (1994 and 2000) rivers could have been forecast several days earlier if a system like EFAS had been available.

The new agreement will give the JRC greater access to the medium-range weather forecasts of ECMWF. The Ensemble Prediction System will supply 50 different ten-day forecast scenarios twice per day. These will be used to simulate river flow scenarios. It is anticipated that this system will be able to predict the risk of floods more accurately in most large European rivers from three to ten days in advance.

Manfred Kloeppel

A simple false-colour scheme for the representation of multi-layer clouds

The representation of model clouds on weather charts is an increasingly attractive option due to the efforts spent in recent years on improving their realism (*Jacob and Klein* 1999; *Hogan et al.* 2000; *Morcrette* 2001). Clouds are three-dimensional, while, although 3D-visualisation techniques are available, most of our representations (printouts or plots for the web) still are 2-dimensional. One way to solve this apparent contradiction is to make use of colours to mark the difference between clouds from different layers. A first proposal was implemented at ECMWF some 10 years ago, initially covering the Meteosat domain. It was later applied to the Euro-Atlantic domain and is still in use for plots on display in the Entrance Hall at ECMWF and, until recently, on the web (for Member States only). An example is in Figure 1. The principle is simple: each of three layers (Low, Medium and High) is attributed one colour (orange, magenta and cyan respectively). The cloud cover in each layer is represented by the density of dots in each grid cell. The printing order is important: if the last layer to be printed has full cloud cover, the information coming from other layers will be lost as they are entirely overlaid. The choice made has been to plot the high, middle and finally low clouds - the idea being that for an observer at ground level, dense low clouds would obscure the other layers.

Although the use of dots is efficient in terms of colour-printer resources, it does not convert efficiently into postscript; a single chart such as the one shown in Figure 1 is around 10 Mbytes. The CPU resources needed to generate the plot are also non-negligible. Therefore, when the time and geographical ranges of plots on offer on the web were recently extended, it was decided to go for a more efficient colour coding. This note describes the new method used.

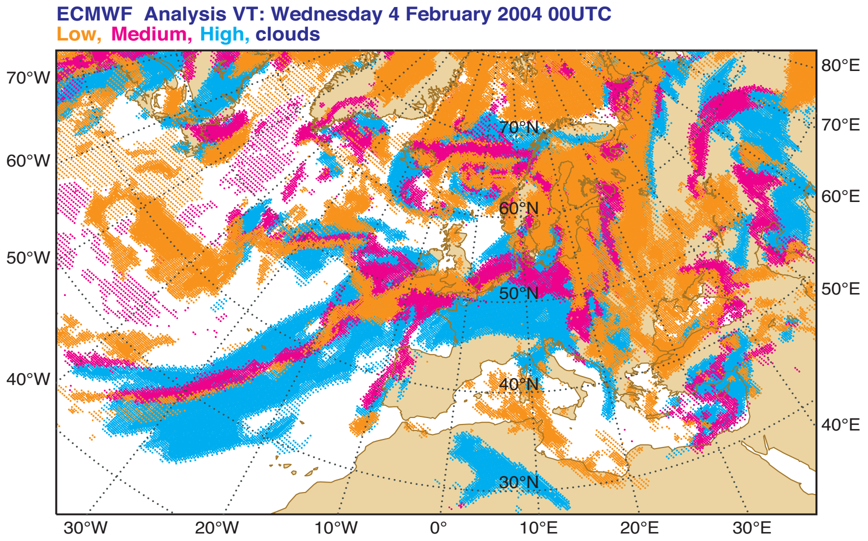

Fig. 1 Cloud chart in its original format (0000 UTC 4 February 2004).

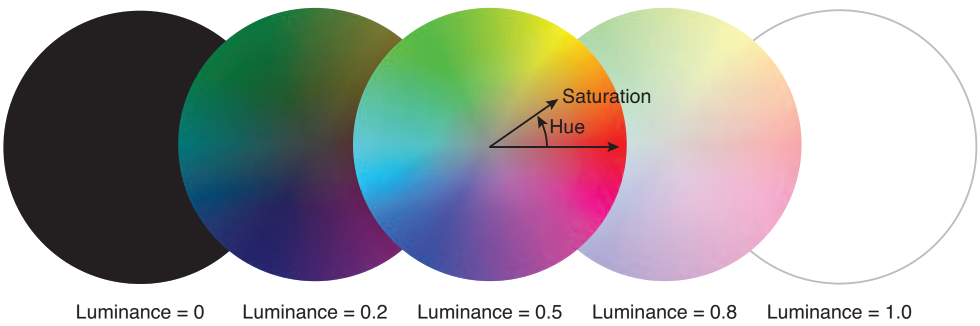

Fig. 2 The HSL representation of colours.

The proposed use of the HSL colour representation for multi-layer clouds

The most commonly used digital representations for colours are the following two:

- RGB (Red Green Blue) affects a weight (usually between 0 and 1) to each of the three basic colours; (0, 0, 0) is black, (1, 1, 1) is white
- HSL (Hue Saturation Luminance) also represents colours with three numbers; 'hue' is an angle between 0 and 2π (0 is red, $2\pi/3$ is green, $4\pi/3$ is blue); 'saturation' and 'luminance' go from 0 to 1 (see Figure 2 for a schematic representation of this colour coding convention).

Algorithms exist, of course, that convert from one representation to the other. Because the cloud cover is usually coded from 0 (no cloud) to 1 (fully overcast), it is natural to combine the three layers as three vectors in HSL space, each of them having an amplitude (or 'saturation') that is proportional to its cloud cover. The 'hue' and maximum 'saturation' are defined for each of the three layers once for all in a way that for any equipartition of clouds in all three layers the colour code is neutral (zero saturation). A simple way to achieve this would be to use three 'complementary' colours, i.e. colours within $2\pi/3$ from each other in 'hue space'. It was, however, preferred to keep the same basic colours as in the original product (orange for low-level clouds, magenta for mid-level clouds and cyan for high-level clouds (see Figure 1), although these are not complementary ones (Figure 3). Finally, luminance is associated with the sum of low-cloud cover (LCC), middle-cloud cover (MCC) and high-cloud cover (HCC); no cloud will show in white, and the maximum cloud cover will be dark grey.

The corresponding algorithm has been encoded as a Metview macro – among the new features supported by Metview3 is the possibility of specifying colours either in RGB or HSL representation. Four classes have been defined for each layer of clouds ($< 1/6$, $[1/6, 1/2]$, $[1/2, 5/6]$, $> 5/6$). A 'synthetic' cloud field has then been defined as the combination of the three LCC, MCC and HCC fields, and a 64-colour table was then associated to it using the association between cloud cover in each layer and the HSL code described above.

The resulting table can be represented as a kind of Rubik's cube always offering a smooth transition from one element to the next (Figure 4)

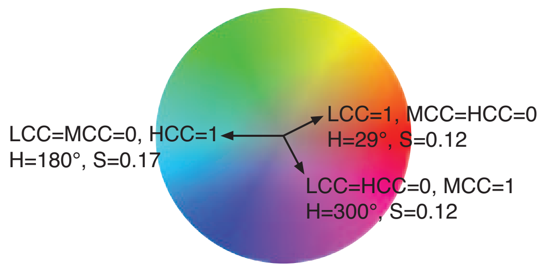

Fig. 3 The HSL colours used for clouds.

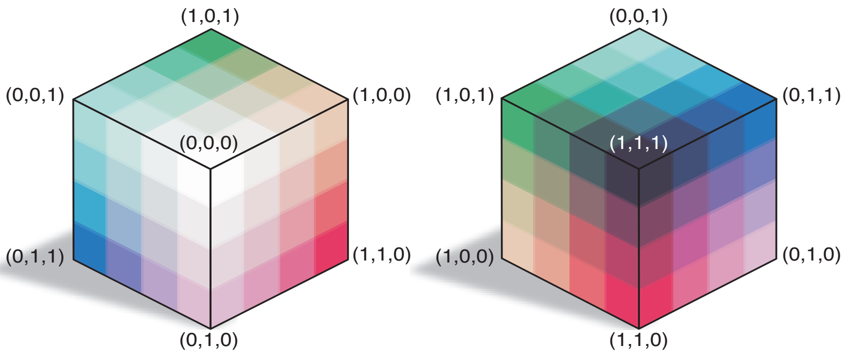

Fig. 4 The 'Rubik's cube' representation of the colour table used for the different categories of clouds cover (triplets are for the cover in each of the low, middle and high layers, respectively). Thanks are due to Rob Hine for having generated this diagram.

New false-colour cloud charts

The same meteorological situation as used for Figure 1 (1200 UTC 15 January 2004 analysis over Europe) is displayed in Figure 5, where the different level of clouds can be recognised, even when overlaid (making it possible to look through the upper-level clouds, in a sense). The form of display is particularly convenient for locating active fronts in the forecast, as they show up nicely as dark grey bands (e.g. the one located from the subtropical Atlantic up to Ireland in Figure 5). In order to help identify the colour codes, a figure caption (Low, L+M (for Low+Medium), Medium, etc.) is printed using the relevant colour coding for each category. Rather than aiming at an accurate representation of the precise amount of clouds in each layer, the scheme should be seen as one offering natural overlaying. It is relatively easy, for example, to follow the low-cloud covered areas, even when they start being overlapped by higher clouds.

Any colour display can be discussed at length in terms of how pleasant it is to the eye. This one is not particularly appealing, but this is almost by construction; in order to maximise the discrimination between different categories of superposition, almost all colours are used (something that any conventional artist would reject at once as not being aesthetic!) By reducing the saturation and enforcing the use of orange, magenta and cyan as the base colours, the visual 'shock' is, however, reduced compared with what would be the case using complementary colours at full saturation; Figure 6 is an example that has been constructed in this way, using yellow (hue = $\pi/3$) for low clouds, magenta (hue = $5\pi/3$) for mid clouds, and cyan (hue = π) for high clouds.

It may be of interest to compare the product introduced here with one that has been developed in a somewhat different context, while offering interesting similarities. As part of the development of the Meteosat Second Generation Satellite Application Facility, a cloud-type product (CT) has been developed by Météo-France to support nowcasting and very-short-range forecasting (SAFNWC 2004). The product generated for the same date and only a few hours after that of the other figures (0345 UTC 4 February 2004) is reproduced in Figure 7. Here, the colour codes again cover a wide palette, making the product informative rather than aesthetic. More importantly, it offers some validation of the ECMWF clouds that are shown in Figure 5. The low clouds over the Mediterranean Sea, Libya, the Black Sea and Ukraine are reasonably well represented in the model, even if the low clouds east of Gibraltar or in the Ebro valley are not. A definite advantage of the model over the satellite, however, is its knowledge, not only of the cloud tops, but also of the underlying layers; this allows discrimination between deep-cloud areas and ones only covered by dense high clouds.

Summary

A new simple scheme to display model clouds using three layers and four different cloud-cover ranges in each layer has been introduced. By allowing colours attributed to each layer to be combined rather than overlaid, it has been possible to show

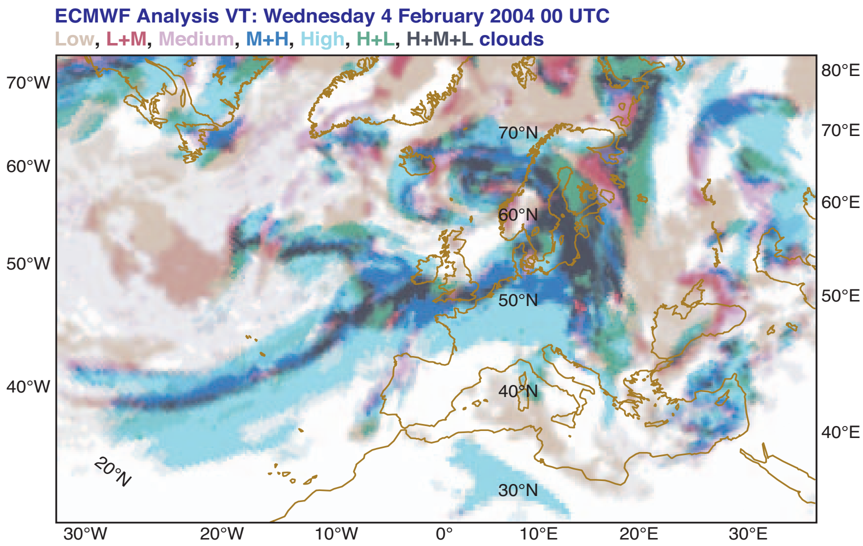

Fig. 5 New false-colour multi-layer cloud charts (0000 UTC 4 February 2004).

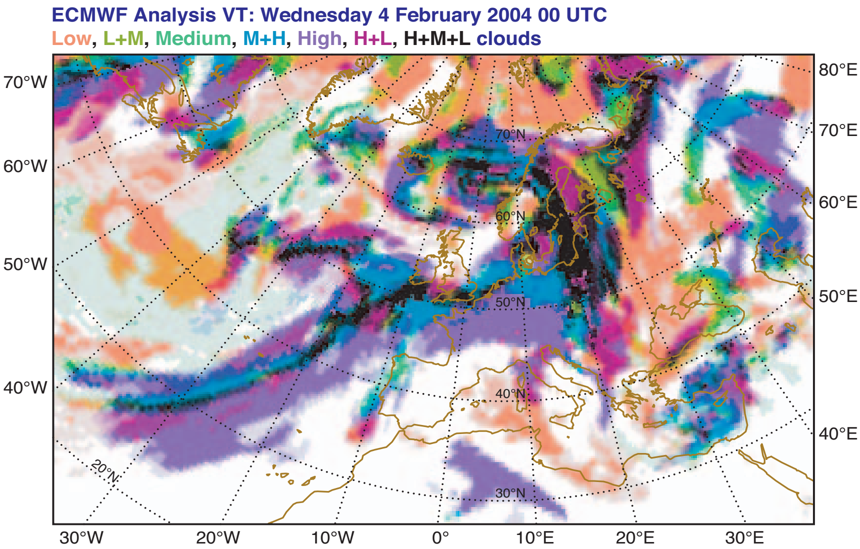

Fig. 6 An alternative false-colour scheme with full saturation and complementary colours (0000 UTC 4 February 2004).

maps where the user can see through the upper-level clouds, and where deep clouds can be identified as dark grey areas.

Users may perceive such maps negatively as they are not really eye-catching. The reasons why the decision has been taken to let them go on the ECMWF web server, even if they are not 'beautiful', can be summarised as follows:

- The resulting postscript output is about ten times smaller than in the previous representation (compression for the PDF files is even larger – about 30 times smaller); this is due to the 'cell shading' used instead of 'dot shading' before; the saving in terms of production time is also significant;
- The information relating to different layers of cloud is added instead of being substituted; full cloud cover at low levels will result in different colour codes depending on what is above (up to black when layers above are also fully covered)
- The continuous table in all three dimensions ensures that, when going from single to multiple-layer clouds, the edge can still be easily recognised.

These maps have been included in the new release of the web service (http://www.ecmwf.int/products/forecasts/d/charts/medium/deterministic/range/cloud/) on 15 June 2004.

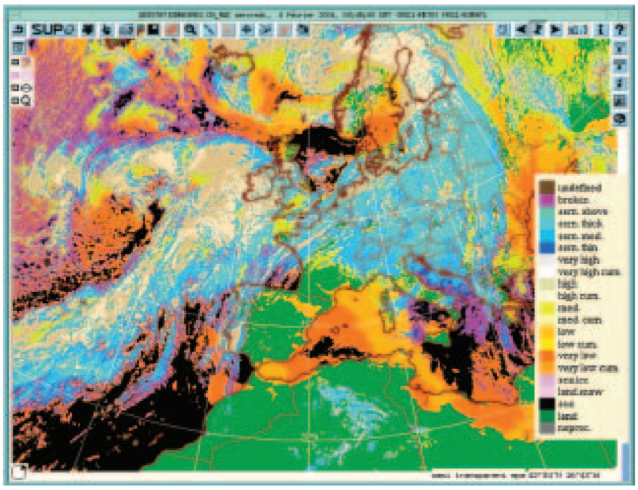

Fig. 7 The cloud-type (CT) product developed as part of the EUMETSAT SAFNWC (0345 UTC 4 February 2004).

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François Lalaurette, Claude Gibert and Jan-Erik Paulsen

Retirement of David Burridge

David Burridge retired on the 17th June 2004 after 13½ years as Director of ECMWF (nearly half the lifetime of the Centre itself).

David graduated with a first class honours degree in Mathematics from Bristol University in 1966 and was awarded a PhD later for research in fluid dynamics undertaken with Dr Philip Drazin. He then spent a year as an Assistant Professor in the Geophysical Fluid Dynamics Institute of Florida University working with Prof T. N. Krishnamurti.

David was appointed to the Forecasting Research Branch of the Met Office in 1970 as a research scientist, and this was

Dr. David Burridge CBE

when I first got to know him – he did not give the impression of being a typical civil servant! "Who is this wild Welshman", I thought to myself, "I can't see him staying here very long". But I was wrong. His enthusiasm was infectious in both his scientific research and in activities outside the workplace (as Chairman of the Sports and Social Committee, he set out to liven up the Met Office by organising events from fun-runs to five-a-side football).

When David arrived in the Met Office, we were heavily involved in developing the new forecasting model (a 10-level explicit primitive-equation model) for the new IBM 360-195 computer that had just been ordered; this involved frequent visits to Poughkeepsie NY (David was to lead a similar exercise a few years later to Minneapolis to develop the first operational ECMWF model on the Cray-1 computer). David, however, turned his efforts towards developing a more efficient version of the model using a new 'split semi-implicit' scheme, whereby the two fastest-moving gravity waves were integrated implicitly while the remaining terms were integrated explicitly. Dave's new scheme was tested and was found not only to be four times faster to run but also to give more reliable forecasts, and it was quickly made operational. However, when it was announced that a new European centre was going to be set up a few kilometres away, I was not surprised that David left to become a founder member of ECMWF – and the rest, as they say, is history.

David was initially appointed as Head of the Numerical Aspects Section and was responsible for developing the first successful global semi-implicit model of the atmosphere. In 1979 he was promoted to Head of the Modelling Division responsible for the formulation of long-term strategies for atmospheric modelling and for the supervision of research in numerical methods and parametrization of subgrid-scale processes. This led to further promotions: to Head of Research in 1982, and then to Deputy Director of ECMWF in 1989 and to Director in 1991. David's easy-going friendliness to everyone at whatever level in the Centre has been the hallmark of his management style throughout his career, and it has underpinned his achievements and his influence with colleagues.

David has a distinguished record of leadership and achievement across a broad spectrum of work in operational weather forecasting. He has contributed to the scientific literature on numerical methods, physical parametrization, global modelling, data analysis and the diagnosis of atmospheric processes. He has been particularly active in promoting meteorology both within the UK and internationally, and he has participated in many working groups and committees covering satellite remote sensing and supercomputers, as well as meteorology. Within the UK, he was Chairman of the UK Universities' Global Atmospheric Modelling Programme's Scientific Steering Group from 1992 to 1996, and he has been an active supporter of the Royal Meteorological Society (Member of Council 1975-1978, Vice President 1990-1992 and 1999-2000, President 2000-2002). In 1995 he achieved national recognition through his appointment as a Commander of the Order of the British Empire (CBE) by Her Majesty Queen Elizabeth II, for services to meteorology.

Several articles are printed below from people around the world who have known David personally and are well placed to appreciate his many contributions to meteorology and weather forecasting during his time at ECMWF.

Peter White (Deputy Director of the Met Office 1985-1995)

During the conference on spectral transform models in Copenhagen in August 1974, a lively red haired young man was sitting behind me in the audience. Following several intelligent and humorous remarks I believed he would be a suitable person for the Centre. I turned around and asked him if he was interested. He was and this was the way he was hired. As a formality he later went through an interview but that only enhanced the first impression. For a number of bureaucratic reasons it took a longer time than expected for Dave to join the Centre but finally he arrived the following year.

Dave was given the overall responsibility for the numerical aspects of the first model. We had a long discussion about whether we should go for the spectral transform technique from the beginning, but we both felt it was too early to make such a decision, as we needed a model suitable for operational use. However, there were many important decisions to take, including the type of Arakawa grid to use. Dave proposed the C-grid, which turned out to be very efficient when using the semi-implicit time integration. This approach was disliked by many who argued that the E-grid was much better and the right thing to use. That was, of course, not the case as was clearly demonstrated. Another difficulty was to convince the Director that the semi-implicit time integration also was the right thing to use, but finally he agreed as we could make a forecast with the same quality at about 20% of the computer time. It was a great day in 1976 when the first global 10-day integration was carried out on the CDC 6600 - a bit slower than the Centre's present computer! (It took almost a month of almost continuous calculation using a 2° resolution). Some time later, Dave also agreed to replacing the grid-point model with a spectral one, although a bit reluctantly. I believe he never liked the spectral model.

When, some years later, I was promoted to Director, Dave was an obvious choice as Head of Research and I was very happy that Council supported that recommendation. We had, over the years, an excellent cooperation including an ability of almost instant communication. This was very useful, as we could always understand each other without too much discussion, although some of our other colleagues did not share that ability. That was sometimes frustrating. The ultrafast communication between us was most helpful as there were a number of tricky problems to address in the early years, including political and personal ones. As Dave showed a capability of extending his good judgement to areas outside science, including helping me to produce a Fortran program for the handling of the Centre's overdraft debt-I was accused at one time by a delegation that I had poisoned the Centre's accounts through this procedure-he showed that he also had the right personal gifts to further extend his responsibilities. So, when I left ECMWF for the Max-Planck Institute for Meteorology in Hamburg, Dave succeeded me as Director. I was very happy with this decision, as it would guarantee that the Centre would continue on its successful path. This has proven to be the case as Dave has done such a sterling job as Director. The staff and the Member States should be proud of having had such a fine man at ECMWF who has given such an excellent contribution over a period of almost 30 years.

Thanks Dave for the fine cooperation over the years and for your great contribution to meteorology and to European cooperation

Lennart Bengtsson (Director of ECMWF 1982-1990, Professor, University of Reading, Director Emeritus, Max-Planck Institute for Meteorology)

Dr. David Burridge has been Director of ECMWF since 1991. He has worked at the Centre since its start in 1975, and he is one of the most influential pioneers in numerical weather prediction. As Head of the Model Division he was responsible for the development of the forecast model during the first years of the Centre's existence; later he became Head of the Research Department and finally the Centre's Director.

David Burridge, along with a few colleagues, developed ECMWF's first explicit grid-point model. He immediately realized that the Centre should use the most efficient numerical techniques and the most powerful computers available to allow for the highest possible spatial resolution. David Burridge has devoted himself to fulfilling this goal ever since. This, in combination with ECMWF's leading role in physical parameterization and data assimilation, is the main reason for the success of ECMWF.

ECMWF started operational forecasts in 1979 and outperformed the resolution used at all other forecasting centres. This was made possible by the introduction of the semi-implicit time integration scheme developed a few years earlier. This scheme allowed time steps up to six times larger than those previously used. There was some dispute at the Centre, however, as to the usefulness of the new scheme because it treated gravity waves inaccurately. David Burridge demonstrated, however, that this had only an effect on spurious gravity oscillations caused by imbalances in the initial fields. When the initial fields were properly initialized, very similar results were obtained from explicit forecasts with small time steps and corresponding semi-implicit forecasts with large time steps.

David Burridge has always pushed for increased efficiency, and several major improvements in the model have resulted. In 1983 the grid-point model was replaced by a spectral model, and this model was improved further over the years. In 1993 the semi-Lagrangian scheme was introduced, at first allowing up to six times larger time steps, and later an even longer time step. It is noteworthy that the improved numerical techniques constitute a significant part of the increase of the total forecasting capability of ECMWF.

David Burridge has always argued for open co-operation in the international research community and with the Member States. ECMWF has organised numerous meetings covering all aspects of its operational and research activities. David Burridge has always taken a very active role in these meetings and at the social events and parties accompanying them. The outcome of such meetings has had a substantial impact on the activities at ECMWF. Furthermore, the importance of the Centre for the international meteorological community can hardly be overestimated and ECMWF is known worldwide as a leading scientific and technical organization. David Burridge has been pivotal in these achievements.

ECMWF has played a major role in the fields of data assimilation, ensemble prediction and seasonal forecasting. During the years with David Burridge as Director, the number of products from the Centre has increased substantially and the quality of these products has steadily improved. The enormous increase in the computer power available at the Centre is, of course, a key factor, and again the achievement of ECMWF in this area is, to a large extent, due to David Burridge. His excellent ability to base his recommendations on solid arguments and, by using these, to convince Council of the current and future needs of the Centre is well known and has been a key to the success of the Centre.

David's loyalty towards the Centre, his passion, enthusiasm, sense of humour and good spirits have influenced the environment at the Centre and will remain to have a positive effect in the years to come.

Lars Prahm (President of ECMWF Council 2001-2003, Director of the Danish Meteorological Institute)

In what might loosely be referred to as the good old days of Southern Hemisphere synoptic meteorology, Southern Hemisphere synopticians were not averse to pouring small amounts of scorn on products emanating from meteorological centres north of the equator. And some of those who were around in the early days of experimental numerical products coming out from the ECMWF for assessment may still recall the patronizing way we drew attention to streamlines spiralling anticyclonically into well-formed tropical cyclones off northern Australia.

All that soon changed as we came to recognise ECMWF as the pace setter for Southern Hemisphere, as well as Northern Hemisphere, analysis and prediction. Much of the good work was, of course, done under the guidance of earlier Directors but it has been consolidated and reinforced many times over during the Burridge years.

Indeed, it is appropriate to note that much of the scientific progress and the very high quality of the ECMWF products derive from Dr Burridge's earlier periods in charge of modelling and of research. Through his influence, the ECMWF has, for most of the past couple of decades, led the way in Southern Hemisphere analysis and prediction, particularly as a result of its superior computing power, its well-formulated models and its well-designed data impact experiments.

As viewed from the Australian Bureau of Meteorology, some indication of the value of ECMWF products in the Southern Hemisphere may be gained from the fact that:

- ECMWF products are now eagerly sought by Australian operational forecasters;
- ECMWF is widely seen as the benchmark for operational performance for all NWP centres;
- ECMWF has paved the way in the development of innovative systems such as 4D-VAR and ensemble prediction systems;
- ECMWF re-analysis is highly regarded and widely seen as setting the standard for all the others;
- ECMWF set standards for data distribution, e.g. GRIB and BUFR codes, GTS products in response to WMO requests;
- ECMWF is now leading the way with assimilation of atmospheric constituents; and
- ECMWF annual workshops promote good practice for operational centres.

The Bureau of Meteorology's links with the ECMWF have been strong and long-standing. Dr Burridge himself has visited Australia three times: in 1980, when he visited the then Australian Numerical Meteorology Research Centre (ANMRC) and delivered a series of lectures on NWP systems and systematic errors; in 1990, for a meeting of the Working Group on Numerical Experimentation (WGNE); and in 1999, when he participated in an external expert review of the Bureau of Meteorology Research Centre (BMRC).

Throughout his time as Director, Dr Burridge has supported strong cooperation with the Bureau of Meteorology through a long series of exchange visits and generous provision of access to major software systems including:

- MARS for data management, which is becoming the main database for Australian operational numerical products;
- MetView for meteorological graphics;
- SMS scheduler software used in the Australian National Meteorological and Oceanographic Operations Centre (NMOC) to schedule and integrate the operational suite;
- A number of ECMWF-based parameterisations used by the Bureau unified atmospheric model; e.g. the land-surface scheme and gravity-wave drag; and
- The development of 1D-VAR systems for the assimilation of satellite soundings.

For these and the many other very tangible products of inter-hemispheric collaboration during David Burridge's Directorship of the ECMWF, Australian and Southern Hemisphere meteorology will remain very much in his debt.

John W Zillman (President of WMO 1995-2003
Director of the Australian Bureau of Meteorology 1978-2004)

It is a great pleasure for me to contribute with words of compliments and thanks to the special article in the ECMWF Newsletter on the occasion of the retirement of Dr. David Burridge as Director of ECMWF. I have known David Burridge for about two decades and I have worked with him when I was President of the German Weather Service (DWD) and, in the recent nine years, as Director-General of EUMETSAT. In those years the collaboration between EUMETSAT and ECMWF became quite intense, also because EUMETSAT took over the operations of the Meteosat satellites from ESA in 1995. In order to steer the cooperation between both organisations in an effective way, David and myself held, once a year, a bi-lateral meeting during which our staff reported on ongoing work, progress and issues of interest and relevance of both organisations. Beyond this, there were continuous interactions between both organisations at various levels reflecting a fruitful cooperation.

There is no doubt that ECMWF is the leading numerical weather-prediction centre on the planet. This unrivalled lead includes the use of satellite data in NWP. ECMWF has always been interested in using new data in their assimilation and has always been willing to explore the utility of data. The use of satellite data became a high priority under the leadership of David Burridge. Ambitious research plans and four-year programme activities show a clear dedication to making use of satellite data in order to improve numerical weather prediction. David Burridge continuously supported the improved use of existing data as well as the preparation for data from new satellite missions, which is why ECMWF is at the leading edge of science and applications in this area.

EUMETSAT benefited from the continuous constructive feedback on product quality from ECMWF. Many improvements to the winds derived from feature tracking in Meteosat images (atmospheric-motion vectors) were a result of rigorous testing and critical feedback from ECMWF. ECMWF pioneered the assimilation of radiances from geostationary satellites and were first in assimilating the Meteosat radiances. I should also mention the highly beneficial EUMETSAT Fellowship Programme with four fellows currently hosted at ECMWF. The Fellowship Programme advances the use of satellite data and provides opportunities for young scientists to become professional in this important and growing field. ECMWF is playing a pivotal role in preparing the NWP community for the use of data from the EUMETSAT Polar System (EPS/Metop), especially in relation to the use of the advanced sounder IASI (Infrared Atmospheric Sounding Interferometer). I have no doubt that ECMWF will again be the leading NWP centre when it comes to demonstrating the positive impact of data from IASI and other new satellite instruments.

Let me conclude with sincere thanks to David Burridge for excellent cooperation, strong leadership and warm friendship. I wish David all the best for his future and hope that he will continue to share his inspiring insight with the meteorological community.

Tillmann Mohr (Director-General EUMETSAT)

I am honoured to be able to write a short piece regarding David Burridge upon his retirement. During his 13½ years tenure, the ECMWF has led the way in data/quality control efforts, advanced data assimilation techniques and weather, climate and ocean modelling, while serving an incredibly diverse community.

I have marvelled how ECMWF continues to excel and set a world standard for all model performance and related model enhancements. The ECMWF is on the cutting edge for the implementation and refinement of 4-dimensional variational data assimilation and is one of the world leaders in the growth of model ensemble forecasting systems. Stopping to look at all that has been accomplished at the ECMWF over the past decade simply takes one's breath away.

As impressive as the accomplishments have been, I am even more pleased to write this note given Dave's approach to leadership and management style. Simply stated, he has been a class act in his interactions with the broad meteorological research and operational communities. From my perspective as a fellow Director of a major international centre, he has been as cooperative and accessible as could be hoped for, and we have both gained. On a personal note, I will always remember how Dave and the rest of ECMWF reacted swiftly to help back up NCEP after the famous Cray fire in 1999. I will also remember that the first phone call I received on the early morning of 9/12/01 after the 9/11 catastrophe was from Dave Burridge. He called to express condolences for our country and to provide whatever support was needed to get us through the aftermath. This call helped me get through those first painful days, and our communication flowed both ways as we learned the extent to which people from Europe were also victims of this horrific act.

So my hat is off to David Burridge. I wish him well with whatever he chooses to do and hope he stays in touch with all of us.

Louis Uccellini
(Director of the National Centers for Environmental Prediction, USA)

60th Council session on 3–4 June 2004

Chaired by the President, Anton Eliassen, the ECMWF Council held its 60th session in Reading on 3-4 June 2004. The main results of this session were:

Amending the ECMWF Convention

Council formally recommended the Member States to accept amendments to the Convention proposed by Norway. The main goal of the amendments is to allow more European States to become Member States of ECMWF.

The primary purpose is confirmed to be *"the development of a capability for medium-range weather forecasting and the provision of medium-range weather forecasts to the Member States"*.

The objectives of the Centre are updated. The new Article 2(2)a reads:

"to develop, and operate on a regular basis, global models and data-assimilation systems for the dynamics, thermodynamics and composition of the Earth's fluid envelope and interacting parts of the Earth-system, with a view to:
i. preparing forecasts by means of numerical methods;
ii. providing initial conditions for the forecasts; and
iii. contributing to monitoring the relevant parts of the Earth-system"

ECMWF strategy

Council requested the Director to prepare a new ten-year strategy with particular focus on the Centre's role in environmental areas.

Co-operation Agreements

Council authorised the Director to conclude Co-operation Agreements with the Slovak Republic, Estonia and Latvia.

A co-operation with the Joint Research Centre of the European Commission on the development and testing phase of the European flood alert system was approved.

Products of the Centre

The maximum charge for real-time products was reduced from 365,000 to 140,000, and now includes the redistribution licence fee. The Council agreed on a unified costing method for products from the Real-time Catalogue and products from the Catalogue of Data and Products. Products from the Monthly Forecasting System will be made available from the Catalogue of Real-time Products.

For further information: http://www.ecmwf.int/products/catalogue/tariffs.html.

Staff Matters

Walter Zwieflhofer was appointed as the new Head of Operations and Gerd Schultes is the new Deputy Director – both from the 18 June 2004.

The Council expressed its thanks to the Director of the Centre, Dr. David Burridge, who was retiring and was therefore attending Council for the last time.

Manfred Kloeppel

ECMWF Calendar 2004

Oct 4-6	Scientific Advisory Committee	33rd
Oct 6-7	Technical Advisory Committee	34th
Oct 8	Joint extra-ordinary session of Finance Committee and Technical Advisory Committee	
Oct 11-12	Finance Committee	73rd
Oct 11-15	Meteorological Training Course for WMO Members – *Use & interpretation of ECMWF products*	
Oct 13-15	Policy Advisory Committee	21st
Oct 20	Advisory Committee of Co-operating States	10th
Oct 25-29	Workshop – *11th workshop on high-performance computing in meteorology*	
Nov 8-11	Workshop – *ECMWF/ELDAS workshop on land-surface assimilation*	
Nov 16-17	Workshop – *First HALO (Harmonised co-ordination of Atmosphere, Land and Ocean) workshop*	
Dec 13-14	Council	61st

ECMWF publications

(see http://www.ecmwf.int/publications/library/ecpublications/)

Technical Memoranda

444 **Drusch, M., E.F. Wood, H. Gao** and **A. Thiele**: Soil moisture retrieval during the Southern Great Plains Hydrology Experiment 1999: A comparison between experimental remote sensing data and operational products. *June 2004*

443 **Drusch, M., D. Vasiljevic** and **P. Viterbo**: ECMWF's global snow analysis: Assessment and revision based on satellite observations. *June 2004*

442 **Meetschen, D., B. v.d. Hurk, F. Ament** and **M. Drusch**: Optimized surface radiation fields derived from METEOSAT imagery and a regional atmospheric model. *July 2004*

441 **Ricci, S., A.T. Weaver, J. Vialard** and **P. Rogel**: Incorporating state-dependent temperature-salinity constraints in the background error covariance of variational ocean data assimilation. *June 2004*

440 **Bourke, W., R. Buizza** and **M. Naughton**: Performance of the ECMWF and the BoM ensemble systems in the Southern Hemisphere. *May 2004*

437 **Nedjeljka Zagar, Erik Andersson** and **Michael Fisher**: Balanced tropical data assimilation based on a study of equatorial waves in ECMWF short-range forecast errors. *April 2004*

436 **Bormann, N., M. Matricardi** and **S.B. Healy**: RTMIPAS: A fast radiative transfer model for the assimilation of infrared limb radiances from MIPAS. April 2004

435 Saetra, O: Ensemble shiprouting. *April 2004*

434 **Palmer, T.N., A. Alessandri, U. Andersen, P. Cantelaube, M. Davey, P. Délécluse, M. Déqué, E. Díez, F. J. Doblas-Reyes, H. Feddersen, R. Graham, S. Gualdi, J-F. Guérémy, R. Hagedorn, M. Hoshen, N. Keenlyside, M. Latif, A. Lazar, E. Maisonnave, V. Marletto, A. P. Morse, B. Orfila, P. Rogel, J.-M. Terres** and **M.C. Thomson**: Development of a European multi-model ensemble system for seasonal to inter-annual prediction (DEMETER). *February 2004*

433 **Brown, A.R.**: Resolution dependence of orographic torques. *February 2004*

429 **Mahfouf, J-F., P. Bauer** and **V. Marecal**: The assimilation of SSM/I and TMI rainfall rates in the ECMWF 4D-Var system. *November 2003*

ERA-40 Project Report Series

18 **Simmons, A.J., P.D. Jones, V. da Costa Bechtold, A.C.M. Beljaars, P.W. Kållberg, S. Saarinen, S.M. Uppala, P. Viterbo** and **N. Wedi**: Comparison of trends and variability in CRU, ERA-40 and NCEP/NCAR analyses of monthly-mean surface air temperature. *April 2004*

16 **Hernandez, A.G. Kelly** and **S., Uppala**: The TOVS/ATOVS observing system in ERA-40. May 2004

15 **Andrae, U., N. Sokka** and **K. Onogi**: The radiosonde temperature bias corrections used in ERA-40. *April 2004*

14 **Martin, E.**: Validation of Alpine snow in ERA-40 *February 2004*

ESA Reports

Abdalla, S. & **H. Hersbach**: The technical support for global validation of ERS wind and wave products at ECMWF. *June 2004*

Workshop Proceedings

ECMWF/CLIVAR workshop on simulation and prediction of intra-seasonal variability with emphasis on the MJO. *3-6 November 2003*

NWP SAF Programme Research Reports

9 **Prigent, C., F. Chevallier, F. Karbou, P. Bauer** and **G. Kelly**: AMSU-A land surface emissivity estimation for numerical weather prediction. *June 2004*

New items on the ECMWF web site

Additional forecast charts

Additional forecast charts and chart archives are now available, including the 00 UTC and 12 UTC operational forecast charts, an increased archive of forecast charts up to 10 days, a greater choice of geographical area and forecast ranges, tropical cyclone deterministic and EPS forecasts, multi-layer cloud forecasts and significant oceanic wave height and direction from the deterministic forecast. This upgrade also required all *'Your Rooms'* to be emptied.

http://www.ecmwf.int/newsevents/sitechange/May04/ms.html

Web site login and access upgrade

The login and access control system of the web site has been replaced with a much more flexible system. The login (available from the top of every page on our web site) is at:

https://www.ecmwf.int/login/

We support enhanced access from Member State Internet domains as well as from registered computer users who may use SecurID or certificate to login.

http://www.ecmwf.int/newsevents/sitechange/May04/ms.html

The 2004 Annual Seminar

The one-week annual seminar in 2004 was on *'Developments in numerical methods for atmospheric and ocean modelling'*. The seminar started on Monday 6 September at 10.00 and finished on Friday 10 September at 13.00. Details of the presentation are on:

http://www.ecmwf.int/newsevents/meetings/annual_seminar/2004/presentations.html

IFS documentation - Cycle 28r1

The scientific documentation for IFS Cycle 28r1 (which became operational on 9 March 2004) is composed of seven sections. The following parts are now available on the web site in html and pdf formats: III *'Dynamics and numerical procedures'*, IV *'Physical processes'*, and VII *'ECMWF wave model'*. The remaining parts will become available later in the year.

http://www.ecmwf.int/research/ifsdocs/CY28r1/

Additions to the ECMWF data server

Data for the Atlantic THORPEX regional campaign (A-TreC) project has been added to the ECMWF data server. The ECMWF data server provides free access, for research use, to publicly released datasets.

http://data.ecmwf.int/data/

Andy Brady

Index of past newsletter articles

This is a list of recent articles published in the ECMWF Newsletter series.
Articles are arranged in date order within each subject category. Articles can be accessed on the ECMWF public web site

http://www.ecmwf.int/pressroom/newsletter/ index.html

Useful names and telephone numbers within ECMWF

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International: +44 118 949 9 + three digit extension
UK: (0118) 949 9 + three digit extension
Internal: 2 + three digit extension

e.g. the Director's number is:
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(0118) 949 9001 (UK) and 2001 (internal).

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The e-mail address of an individual at the Centre is:
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For double-barrelled names use a hyphen
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Internet web site

ECMWF's public web site is: http://www.ecmwf.int

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Deputy Director & Head of Administration Department	
Gerd Schultes	007
Head of Operations Department	
Walter Zwieflhofer	003
Head of Research Department	
Philippe Bougeault	005

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Networking and Computer Security Section Head	
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