QUARTERLY JOURNAL
OF THE
ROYAL METEOROLOGICAL SOCIETY

Vol. 131 OCTOBER 2005 Part B No. 612

Q. J. R. Meteorol. Soc. (2005), **131**, pp. 2961–3012 doi: 10.1256/qj.04.176

The ERA-40 re-analysis

By S. M. UPPALA[1], P. W. KÅLLBERG[1], A. J. SIMMONS[1]*, U. ANDRAE[1], V. DA COSTA BECHTOLD[1], M. FIORINO[2], J. K. GIBSON[1], J. HASELER[1], A. HERNANDEZ[1], G. A. KELLY[1], X. LI[3], K. ONOGI[4], S. SAARINEN[1], N. SOKKA[1], R. P. ALLAN[5,11], E. ANDERSSON[1], K. ARPE[6], M. A. BALMASEDA[1], A. C. M. BELJAARS[1], L. VAN DE BERG[7], J. BIDLOT[1], N. BORMANN[1], S. CAIRES[8], F. CHEVALLIER[1], A. DETHOF[1], M. DRAGOSAVAC[1], M. FISHER[1], M. FUENTES[1], S. HAGEMANN[6], E. HÓLM[1], B. J. HOSKINS[9], L. ISAKSEN[1], P. A. E. M. JANSSEN[1], R. JENNE[10], A. P. MCNALLY[1], J.-F. MAHFOUF[1], J.-J. MORCRETTE[1], N. A. RAYNER[11], R. W. SAUNDERS[11], P. SIMON[12], A. STERL[8], K. E. TRENBERTH[10], A. UNTCH[1], D. VASILJEVIC[1], P. VITERBO[1] and J. WOOLLEN[13]

[1]*European Centre for Medium-Range Weather Forecasts, Reading, UK*
[2]*Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, USA*
[3]*Institute for Atmospheric Physics, Chinese Academy of Sciences, Beijing, China*
[4]*Japan Meteorological Agency, Tokyo, Japan*
[5]*Environmental Systems Science Centre, University of Reading, UK*
[6]*Max-Planck-Institut für Meteorologie, Hamburg, Germany*
[7]*European Organisation for the Exploitation of Meteorological Satellites, Darmstadt, Germany*
[8]*Koninklijk Nederlands Meteorologisch Instituut, De Bilt, the Netherlands*
[9]*Department of Meteorology, University of Reading, UK*
[10]*National Center for Atmospheric Research, Boulder, Colorado, USA*
[11]*Met Office, Exeter, UK*
[12]*Météo-France, Toulouse*
[13]*NOAA/NWS/National Centers for Environmental Prediction, USA*

(Received 3 December 2004; revised 14 June 2005)

SUMMARY

ERA-40 is a re-analysis of meteorological observations from September 1957 to August 2002 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with many institutions. The observing system changed considerably over this re-analysis period, with assimilable data provided by a succession of satellite-borne instruments from the 1970s onwards, supplemented by increasing numbers of observations from aircraft, ocean-buoys and other surface platforms, but with a declining number of radiosonde ascents since the late 1980s. The observations used in ERA-40 were accumulated from many sources. The first part of this paper describes the data acquisition and the principal changes in data type and coverage over the period. It also describes the data assimilation system used for ERA-40. This benefited from many of the changes introduced into operational forecasting since the mid-1990s, when the systems used for the 15-year ECMWF re-analysis (ERA-15) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) re-analysis were implemented. Several of the improvements are discussed. General aspects of the production of the analyses are also summarized.

A number of results indicative of the overall performance of the data assimilation system, and implicitly of the observing system, are presented and discussed. The comparison of background (short-range) forecasts and analyses with observations, the consistency of the global mass budget, the magnitude of differences between analysis and background fields and the accuracy of medium-range forecasts run from the ERA-40 analyses are illustrated. Several results demonstrate the marked improvement that was made to the observing system for the

* Corresponding author: European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK. e-mail: adrian.simmons@ecmwf.int

southern hemisphere in the 1970s, particularly towards the end of the decade. In contrast, the synoptic quality of the analysis for the northern hemisphere is sufficient to provide forecasts that remain skilful well into the medium range for all years. Two particular problems are also examined: excessive precipitation over tropical oceans and a too strong Brewer–Dobson circulation, both of which are pronounced in later years. Several other aspects of the quality of the re-analyses revealed by monitoring and validation studies are summarized. Expectations that the 'second-generation' ERA-40 re-analysis would provide products that are better than those from the first-generation ERA-15 and NCEP/NCAR re-analyses are found to have been met in most cases.

KEYWORDS: Data assimilation Numerical weather prediction Observing system

1. INTRODUCTION

Atmospheric data assimilation comprises a sequence of analysis steps (or cycles) in which background information for a short period, typically 6 h, is combined with observations for the period to produce an estimate of the state of the atmosphere (the 'analysis') at a particular time. The set of observations usually comprises several types of measurement, each with its own accuracy and distribution. The analysis is nevertheless complete in terms of the chosen meteorological variables, domain and resolution. The background information essential to produce the complete representation comes from a short-range forecast initiated from the most recent previous analysis in the sequence. The observations and background forecast are combined using statistically based estimates of their errors; in variational assimilation this is achieved by minimizing the sum of error-weighted measures of the deviations of analysed values from the observed and background values. The background forecast carries forward in time and spreads in space the information from the observations used in earlier assimilation cycles. The resulting sequence of initial states provides a record of the evolving atmospheric state that is based on a synthesis of the available observations; it depends implicitly on the dynamics and physics of the background-forecast model and on any dynamical or physical relationships built into the error statistics. The degree of dependence on the model varies with the density and relative accuracy of the observations (the error statistics), and in general differs from place to place and from variable to variable (e.g. from wind to humidity).

The First Global Experiment of the Global Atmospheric Research Programme, FGGE*, was held in 1979. Data assimilation was used by two centres, ECMWF and GFDL, to produce global analyses of the FGGE observations (Bengtsson *et al.* 1982; Ploshay *et al.* 1992). These analyses were utilized in many research studies, reviewed at a sequence of workshops 6 years later (ECMWF 1985; WMO 1985). By then, however, global data assimilation had become quite widely used to provide initial conditions for operational weather forecast models. Given the limitations of the 1-year sampling period of FGGE, the analyses produced by the operational global systems soon became a mainstay of atmospheric research.

Use of the operational products for research was not without its problems, however. Deficiencies in the analysis method or assimilating model could introduce significant biases in the resulting analyses, and could invalidate the conclusions drawn from them. Many of these deficiencies were remedied over time, but this introduced long-term trends or discontinuities in the operational analysis products that inhibited their use in studies of low-frequency variability and climate change (e.g. Trenberth and Olson 1988; Trenberth and Guillemot 1995). Problems were compounded by difficulties experienced by many users of the analyses in knowing what was changed and when, what the impact was, and also what the impact of changes in the observing system was over the period of study.

* Acronyms used in this paper are given in appendix A.

These considerations led Bengtsson and Shukla (1988) and Trenberth and Olson (1988) to propose re-analysis of the record of past atmospheric observations using fixed, up-to-date data assimilation systems. Their proposals met with positive responses, and led to three major re-analysis projects:

- A 15-year re-analysis starting from 1979, ERA-15 produced by ECMWF (Gibson *et al.* 1997);
- A re-analysis from 1948, which is continued in close to real time, produced by the US NCEP in collaboration with NCAR (Kalnay *et al.* 1996; Kistler *et al.* 2001);
- A 16-year re-analysis from March 1980 produced by the Data Assimilation Office of the NASA, USA (Schubert *et al.* 1995).

These first-generation re-analysis projects were largely successful and their products have become very widely used. The products nevertheless exhibit a number of problems and limitations. Several deficiencies in the original NCEP/NCAR re-analysis were addressed in a second version of the re-analysis run from 1979 onwards by Kanamitsu *et al.* (2002), who stress that this version should be regarded as an update of the original re-analysis with some significant improvements, rather than a new next-generation product. Specific deficiencies in ERA-15 listed by Kållberg (1997) include:

- Surface temperatures generally too cold in winter, and spring temperatures too cold in boreal forests;
- Grossly erroneous Antarctic orography;
- Use of unrepresentative data from island stations influencing surface exchanges and precipitation;
- Severe drying of the western Amazonian land surface, until corrected half way through the period;
- Shifts in temperature and humidity that were subsequently related to problematic assimilation of satellite data (Trenberth *et al.* 2001).

ERA-40 is a new, 45-year second-generation re-analysis carried out by ECMWF with the goal of producing the best possible set of analyses, given the changing observing system and the available computational resources. It begins in September 1957, when the observing system had been enhanced in preparation for the IGY, and runs until August 2002. It benefits from many of the changes made recently to the operational ECMWF data assimilation system, several of which in turn benefited from what was learnt from ERA-15. ERA-40 provides fields with higher horizontal resolution and higher vertical resolution in the planetary boundary layer and stratosphere than provided by the earlier re-analyses. It has been supplied with more observations, and in particular makes more comprehensive use of satellite data, re-processed from raw measurements where possible. A wider range of analysis and forecast fields is also available, including ozone and ocean-wave conditions. ERA-40 provides an important second source of re-analysis data for the period 1957–78 covered previously only by the original NCEP/NCAR re-analysis.

This paper gives a general specification of ERA-40, discusses the quality of the analyses and draws inferences as to changes in the quality of the observing system. The types, sources and distributions of observations are discussed in section 2. Section 3 describes the assimilation system, both its model and data analysis components, comparing it with the versions used for ERA-15 and for operational analysis and forecasting at ECMWF. Boundary and forcing fields, most notably the externally produced SST analyses, are also specified. Some general aspects of the production and archival of the analyses are summarized in section 4. Section 5 presents and discusses a number of results indicative of the overall performance of the data assimilation system, and implicitly of the observing system. It covers: fits of background and analysis fields to observations; the consistency of the global mass budget; analysis increments; and the accuracy of short- and medium-range forecasts run from the ERA-40 analyses. Section 6 discusses two particular problems experienced: excessive precipitation over tropical oceans and too strong a Brewer–Dobson circulation; both of these were pronounced in later years. Several other aspects of the quality of the re-analyses revealed by the monitoring and validation studies undertaken as part of the project are summarized in section 7. Conclusions are presented in section 8.

2. Observations

(*a*) *Acquisition and pre-processing*

The observations used for ERA-40 include data from the operational archives of ECMWF supplemented by operational data archived by NCEP and the Japan Meteorological Agency. Data were also supplied to ECMWF by other institutions specially for use in the re-analysis. The principal such supplier was NCAR, which provided copies of its extensive holdings of *in situ* and satellite data. As a special contribution to ERA-40, EUMETSAT re-derived wind products from the Meteosat-2 and Meteosat-3 satellites for the period 1982–88 (van de Berg *et al.* 2002; Bormann *et al.* 2003). A complete list of data suppliers and the types of data they provided is given in appendix B.

ERA-40 directly assimilated VTPR radiance data from 1973 to 1978 that had been little used since the original retrieval of temperature and humidity profiles from these data by NOAA/NESDIS. It was thus necessary to make a special effort to recover as much as possible of the good quality radiance data and convert them into a modern level-1c dataset (Li *et al.* 2005b). SSM/I radiance data from 1987 to 1998 were obtained from Remote Sensing Systems. Gaps in the TOVS and ATOVS sets of radiance measurements that remained after combining the NCAR and ECMWF holdings were largely filled with bulk data supplied by NASA and LMD, and completed with data from NOAA/NESDIS's on-line Satellite Active Archive. ERA-40's collection of raw (level-1b) TOVS data from October 1978 to December 2002 has been processed to generate an archive of calibrated (level-1c) radiances (Hernandez *et al.* 2004). TOMS and SBUV ozone retrievals were provided by NASA and NOAA, respectively.

All data used in ERA-40, conventional and satellite, had to be converted from their various original formats into the standard WMO FM 94 BUFR format before they could be ingested by the data assimilation system. NCEP, through its own re-analysis activities, had the software to process the *in situ* measurements from NCAR and carried out the BUFR conversion of newly supplied versions of the NCAR data as a contribution to ERA-40. These versions supersede those used in the original NCEP/NCAR re-analysis. NCEP and ECMWF also exchanged copies of their archives of operational *in situ* data for the period 1980–94.

Many conventional observations appeared in more than one of the data sources. After organizing the data into 6-hourly slots, all non-satellite data from the different sources were loaded into a database (Saarinen and Sokka 2002). A combined 6-hourly observation dataset was created from the multiple sources. Most duplicates were identified and removed, a number of other basic checks were made and an analysis pre-processing step was carried out. This enabled most technical data problems to be

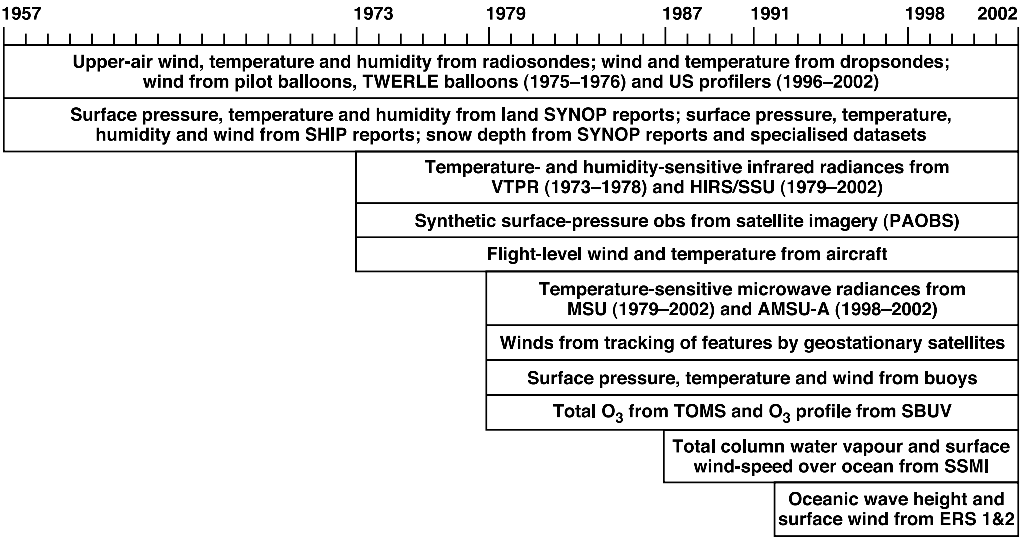

Figure 1. Chronology of types of observations assimilated in ERA-40 from 1957 to 2002. (See appendix A for acronyms.)

detected in advance, without slowing the actual production of the analyses which was carried out later.

Using multiple sources for data brought some clear improvements in observation counts. One surprise was that, although NCEP's and ECMWF's holdings of operationally received data for the period 1980–94 largely overlapped, NCEP generally held significantly more data than ECMWF. The inclusion of NCEP's radiosonde data resulted in 24 015 additional 12 UTC soundings for 1994, an increase of more than 10%. On the other hand ECMWF's archive held just 479 soundings that were not in the NCEP database. Illustrations of this and several other aspects of ERA-40 that are mentioned but not illustrated in this paper can be found in Uppala *et al.* (2004).

A new comprehensive radiosonde dataset (IGRA, Durre *et al.* 2005) became available after ERA-40 was completed. Haimberger (2005) has compared the number of observations in the quality-controlled IGRA dataset with the number of observations accepted by the ERA-40 data assimilation system; he found more observations in ERA-40 for the 1960s and 1970s, but more in IGRA for the 1990s. Combining the two datasets and removing duplicates leads to a collection with more data than in either of the single datasets. Over the period of the re-analysis the combined dataset has between 5 and 10% more 500 hPa data than used by ERA-40.

(*b*) *Coverage*

Figure 1 lists the basic types of data assimilated in ERA-40, and shows when observations of each type first became available in significant numbers. Appendix B includes the periods covered by the individual datasets supplied for use in ERA-40.

The global observing system changed considerably between 1957 and 2002. The ever-present observation types are the synoptic surface observations from land stations and ships, and the soundings from radiosonde and pilot balloons. The accuracy of radiosonde measurements improved over the period, but geographical and temporal coverage declined. Figure 2 shows the distribution and frequency of the soundings from radiosondes available to ERA-40 for 1958, 1979 (the FGGE year) and 2001.

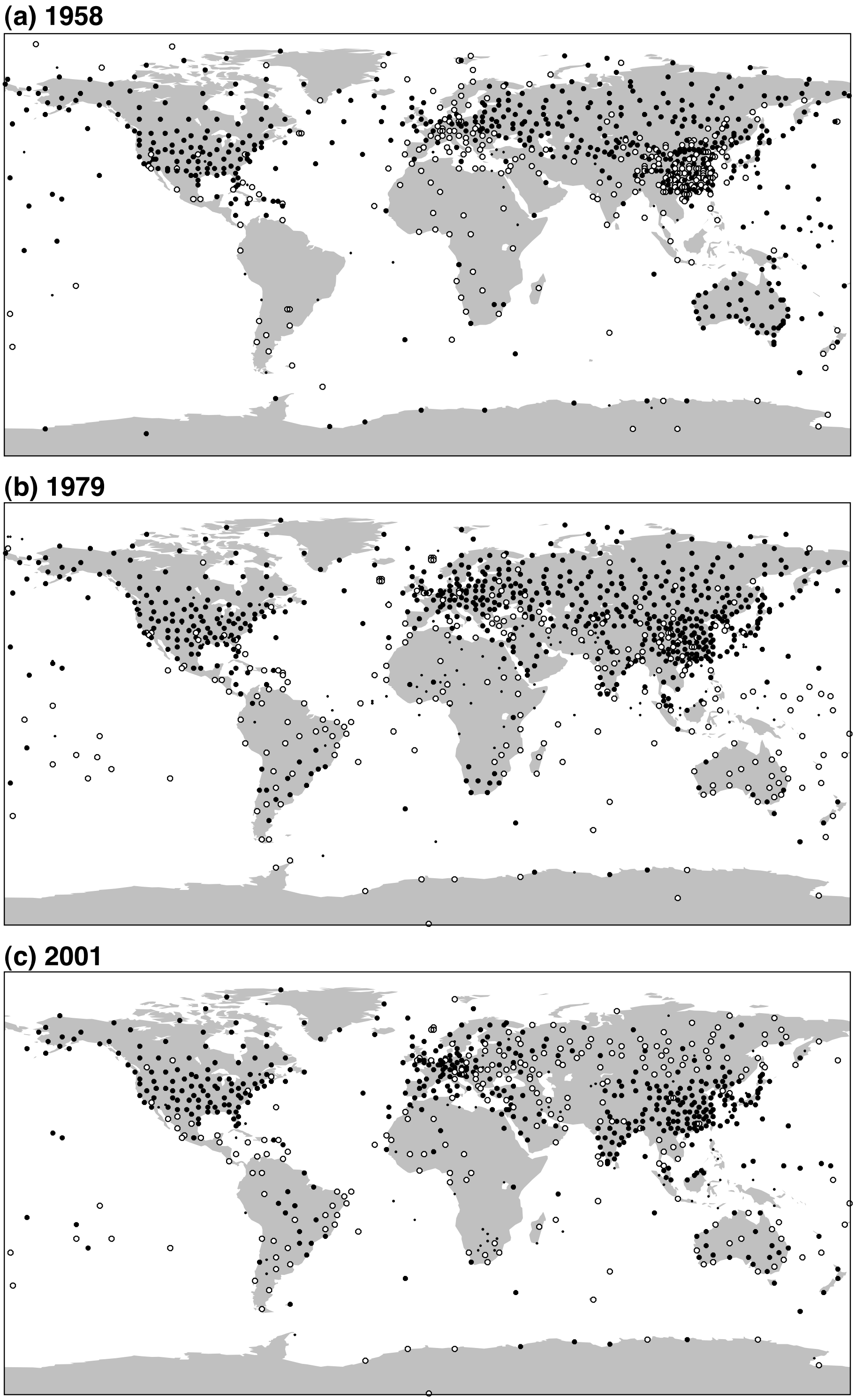

Figure 2. Frequency of radiosonde reports for: (a) 1958, (b) 1979 and (c) 2001. Solid circles denote stations from which at least three reports are available every 2 days on average, open circles denote other stations reporting at least once every 2 days, and small dots represent stations reporting at least once per week.

TABLE 1. AVERAGE DAILY COUNTS OF VARIOUS TYPES OF OBSERVATION SUPPLIED TO THE ERA-40 DATA ASSIMILATION, FOR FIVE SELECTED PERIODS

Observation type	1958–66	1967–72	1973–78	1979–90	1991–2001
SYNOP/SHIP	15 313	26 615	28 187	33 902	37 049
Radiosondes	1 821	2 605	3 341	2 274	1 456
Pilot balloons	679	164	1 721	606	676
Aircraft	58	79	1 544	4 085	26 341
Buoys	0	1	69	1 462	3 991
Satellite radiances	0	6	35 069	131 209	181 214
Satellite winds	0	0	61	6 598	45 671
Scatterometer	0	0	0	0	7 575
PAOBs	0	14	1 031	297	277

Average daily numbers are 1609 for 1958, 1626 for 1979 and 1189 for 2001. In 1958 fixed ocean weather ships provided regular data over the North Atlantic and (to a lesser degree) the North Pacific, continuing a network established in 1946 with ten ships in the Atlantic and three in the Pacific. The number of ships had declined by 1979 and only the *Polarfront* (known also as '*Mike*', located off the coast of Norway) remained in service in 2001 (and continues to the present day). General radiosonde coverage at high northern latitudes was also much better in 1958 and 1979 than in 2001. Southern hemisphere coverage was generally poor in 1958, and this was compounded by a lack of data from Brazil in the holdings from NCAR supplied to ERA-40. Australasia is an exception. Coverage was also relatively good around the Antarctic coast in 1958, because of a special effort to establish stations there for the IGY. The distribution of soundings in the southern hemisphere was more uniform in 1979, with data available from Brazil and more from the rest of South America, from southern Africa and from many island stations, though with fewer ascents from Australia and Antarctica. By 2001 the number of soundings available over the former Soviet Union was much reduced, due to closure of some stations and less frequent ascents from many others. There were also fewer soundings from island stations and numbers elsewhere were generally down. A small number of automated soundings from moving ships were, however, available by then. These are not shown in Fig. 2, but are included in the complete set of data coverage maps showing radiosonde (and other) observation frequencies month by month that can be viewed on the project web site (http://www.ecmwf.int/research/era/) under the section on monitoring.

The other observation types specified in Fig. 1 have more than compensated for the decline in radiosonde coverage, at least over oceanic areas and at higher levels in the atmosphere. Table 1 shows average daily counts of the different types of observation used in ERA-40's analysis of the primary meteorological variables. Averages are shown for five different epochs spanning the re-analysis period, each representative of a particular state of the observing system.

The differences over time in these observation counts are mostly due to a continuously changing and at most times improving observing system. 1973 was a key year that saw radiances available from the first of the VTPR instruments flown on the early NOAA series of operational polar orbiting satellites. A major enhancement of the observing system was in place by the beginning of 1979 for FGGE: VTPR data were replaced by data from the three (MSU/HIRS/SSU) TOVS instruments on new NOAA platforms; winds derived by tracking features observed from geostationary satellites first became available in significant numbers; drifting ocean buoys were deployed in the southern hemisphere; and there was an increase in the number of aircraft data available. Ozone data also become available from the satellite-borne TOMS and SBUV instruments at about the same time; ozonesonde data were not assimilated, but used for validation (Dethof and Hólm 2004). Observation counts in general declined for a while after FGGE, but recovered during the 1980s. Coverage and quality of data from the TOVS system improved considerably from 1979 to 2002 (Hernandez *et al.* 2004). The density of wind and temperature measurements from aircraft, and of winds from geostationary satellites, increased substantially in the 1990s. Newer satellite instruments from which data were assimilated in ERA-40 are: SSM/I from 1987 onwards; the ERS altimeter (for the ocean-wave analysis) from 1991; the ERS scatterometer from 1993; and AMSU-A (the MSU/SSU replacement) from 1998.

Factors other than basic changes to the observing system also cause variations from epoch to epoch in the numbers reported in Table 1, especially for *in situ* data prior to 1979. Among them are:

- Missing or limited collection of SYNOP data from many countries prior to 1967;
- Incomplete data records, for example missing information on flight pressure-level in many aircraft reports prior to 1973;
- Assignment of a radiosonde identifier to non-radiosonde data, for example the TWERLE balloon data (1975–76; Julian *et al.* 1977);
- Coding of significant-level wind data from some radiosonde ascents, and some early wind data from geostationary satellite images, as if they were from pilot balloons (1973–78);
- Failure to recognize and remove some of the duplicated radiosonde ascents, especially from US-operated stations between 1973 and 1976 due to non-standard station identifiers in one data source.

The limited supply of SYNOP data prior to 1967 is identifiable in the quality of the early ERA-40 2 m temperature analyses (Simmons *et al.* 2004), the corresponding humidity analyses and the soil moisture analyses (Betts *et al.* 2003b). In the absence of any other change in observational coverage, assimilation of duplicate radiosonde ascents would cause the analysis to fit the radiosonde data more closely than intended. In practice, however, other changes in observation occurred at the beginning of 1973. No significant general impact of failure to remove duplicate ascents has been detected, although local effects cannot be ruled out.

The observation counts for SYNOP data in Table 1 include observations of snow depth. These were limited to Canada for the early years of ERA-40. Data covering the former Soviet Union were available from 1966 onwards, but data from other countries could be used only from 1976 onwards.

The values for radiosondes and pilot balloons in Table 1 relate to the number of ascents, rather than the number of individual measurements that were accepted by the data assimilation system. Examination of counts of these measurements provides a more positive view of changes over time in the use of these observation types in ERA-40. Table 2 provides average counts of the accepted temperature and wind measurements for selected atmospheric layers, for the same five epochs as before. Values are shown separately for soundings from the extratropical northern and southern hemispheres and from the Tropics. Aside from changes in the numbers of ascents, these measurement numbers may increase in time due to increased reporting of significant-level values, more balloons reaching the higher levels or fewer rejections by the assimilation system's quality-control procedures. These procedures reject observations that differ significantly from background-forecast equivalents; fewer rejections may result either from lower measurement errors or from lower background-forecast errors due to overall improvement of the observing system.

TABLE 2. AVERAGE DAILY COUNTS OF TEMPERATURE AND WIND OBSERVATIONS FROM RADIOSONDES AND PILOT BALLOONS ACCEPTED BY THE ERA-40 DATA ASSIMILATION: FOR FIVE PERIODS, FOR THE EXTRATROPICAL NORTHERN AND SOUTHERN HEMISPHERES AND TROPICS[1], AND FOR SPECIFIED ATMOSPHERIC LAYERS

		Layer (hPa)	1958–66	1967–72	1973–78	1979–90	1991–2001
Temperatures	N Hem.	40–60	1098	1536	2276	1381	1499
		450–600	2905	3587	5432	3122	3007
	Tropics	40–60	132	276	390	167	249
		450–600	325	629	939	427	554
	S Hem.	40–60	40	90	174	162	257
		450–600	77	189	372	325	421
Winds	N Hem.	40–60	901	1090	2027	1606	1796
		450–600	2355	2479	4537	3109	2347
	Tropics	175–225	206	326	476	258	290
		775–925	1049	846	1858	1226	1077
	S Hem.	40–60	36	58	118	118	270
		450–600	137	223	469	485	478

[1]The equator to 20°N and 20°S.

Table 2 shows a general increase in the numbers of measurements accepted by the data assimilation system from 1979–90 to 1991–2001 at the upper layer shown, and a substantial decline only for mid-tropospheric winds in the northern hemisphere. Numbers for the southern hemisphere are considerably higher on average for the period since 1979 than prior to 1972. This is seen also for the number of surface pressure observations accepted: the number of data used from southern hemisphere land stations increased from a daily average of 1077 for 1967–72 to 3484 for 1991–2001. Corresponding figures for the northern hemisphere are 20 806 and 27 563.

There was a substantial drop in the amount of data used from January to July 2002 for types other than radiances. This was due to a technical problem that resulted in the loss of most data types at times other than those of the main synoptic hours. It resulted in some degradation of the quality of the analyses for this period, but this was not judged to be sufficient to prevent release of the analyses for general use. For example, short-range forecast verifications against radiosondes for these months show some degradation compared with results for corresponding months from the preceding decade of ERA-40 (as illustrated later in Fig. 13), but were not invariably poorer than corresponding values from the final years of ERA-15 or from ECMWF operations prior to the late 1990s. Medium-range forecasts for the period did not drop to pre-1979 levels of performance.

3. DATA ASSIMILATION SYSTEM

(*a*) *Introduction*

Ideally, re-analysis is the analysis of past observational data using a fixed, tried-and-tested, data assimilation system. In practice, a number of issues have to be addressed and a number of compromises have to be made. For a multi-decadal re-analysis such as ERA-40, the computational cost of producing the analysis for a single day has to be substantially less than for an advanced operational data assimilation system. Choosing an earlier, affordable version of the data assimilation system would mean foregoing a number of desirable recent developments. Thus, a new configuration that incorporates as many of the recent operational improvements as possible has to be developed, including adaptations to use data from older observing systems that are not catered for in the current operational version.

The computational cost of ECMWF's operational four-dimensional variational (4D-Var) data assimilation system was too great for it to be used for ERA-40. An updated form of the 3D-Var analysis used operationally at ECMWF between January 1996 and November 1997 (Andersson *et al.* 1998) was thus adopted. A form of 3D-Var was also used for the NCEP/NCAR re-analysis (Parrish and Derber 1992; Kalnay *et al.* 1996). The spectral T159 model resolution used for ERA-40, although substantially lower than the T511 resolution operational at the time, is higher than the T62 resolution used for the NCEP/NCAR re-analysis and the T106 resolution used for ERA-15.

The IFS forecasting system software developed jointly by ECMWF and Météo-France was used for ERA-40. An earlier version of the atmospheric model component of the IFS was used for ERA-15. This version was employed operationally by ECMWF from April to November 1995, though with T213 rather than T106 horizontal resolution. Since then there have been between one and four operational changes to the ECMWF system each year. ERA-40 was based on the version of the IFS operational from June 2001 to January 2002, though with some modifications. Simmons and Hollingsworth (2002) discuss the substantial improvement in medium-range forecast accuracy that resulted from changes to the forecasting system made up to 2001. A summary of those changes relevant to ERA-40 and of other changes made specifically for ERA-40 is given below. A general on-line documentation of the IFS can be found at http://www.ecmwf.int as can further details specific to ERA-40.

As 3D-Var does not treat differences between analysis and observation time as consistently as 4D-Var, a 6-hour assimilation period was used for ERA-40 instead of the 12-hour period used in ECMWF's operational 4D-Var system. Analyses of atmospheric temperature, horizontal winds, humidity and ozone, and of a number of surface variables, were produced for the main synoptic hours of 00, 06, 12 and 18 UTC, using observations in 6-hour periods centred on the analysis times. Background forecasts to 9 hours ahead were required for each analysis time, and fields from them were archived 3-hourly. Background values interpolated to the location and time of each datum were also archived. The forecasts from 00 and 12 UTC were run to 36 hours ahead with comprehensive archiving, and later extended to a 10-day range with more limited archiving.

(*b*) *The assimilating model*

The assimilating model used for ERA-40 had a reduced Gaussian grid (Hortal and Simmons 1991; Courtier and Naughton 1994) with an almost uniform spacing of about 125 km, the same as for ERA-15. It differed from the ERA-15 model in that it used the so-called 'linear grid' option made possible by semi-Lagrangian advection (Côté and Staniforth 1988). One consequence of this is a very marked reduction in the amplitude of unrealistic spectral ripples (the Gibbs phenomenon) in the model orography over oceans or flat land close to major mountain ranges. Figure 3 shows the ERA-15 and ERA-40 orographies for South America, using a logarithmic contour interval to emphasize the reduced amplitude of spectral ripples for ERA-40. This can be seen not only over the Pacific Ocean to the west of the Andes, but also over the Amazon basin.

The 60-level vertical resolution and hybrid vertical coordinate (Simmons and Burridge 1981; Simmons and Strüfing 1983) used for ERA-40 are the same as used operationally at ECMWF since October 1999. In Fig. 4 the distribution of the 60 levels is compared with that of the 31 levels used for ERA-15. Resolution has been added in the stratosphere and lower mesosphere, with the top ERA-40 model level raised from 10 to 0.1 hPa, and a vertical layer spacing close to 1.5 km over much of the stratosphere (Untch and Simmons 1999). Resolution has also been increased in the

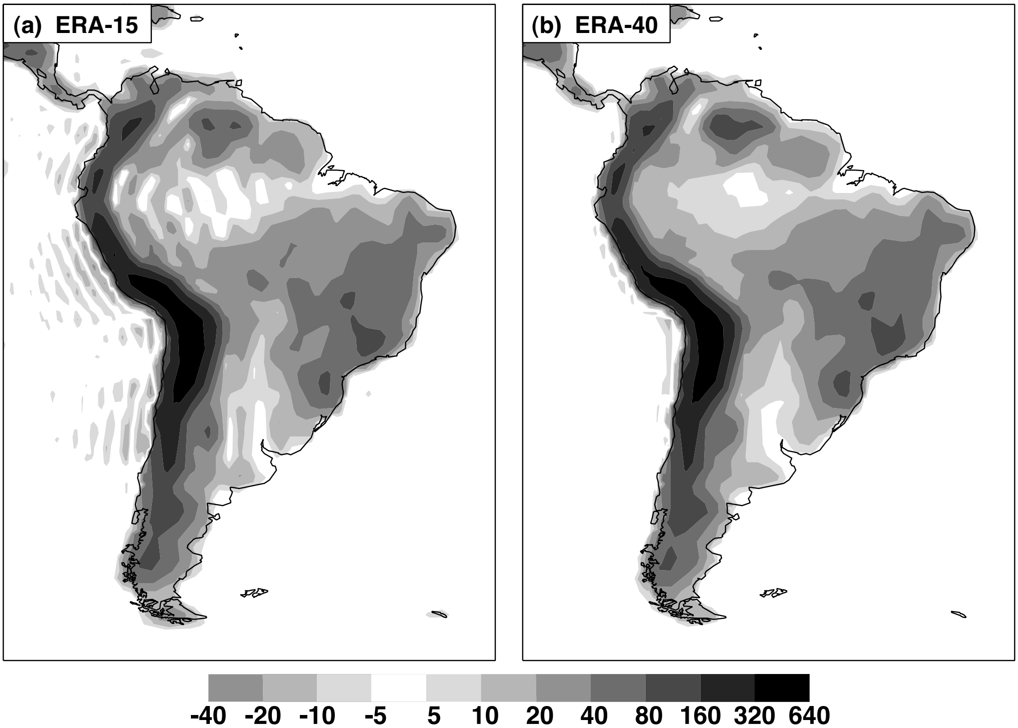

Figure 3. Model orographies for: (a) ERA-15 and (b) ERA-40, plotted with contour values of ±5, ±10, ±20, 40, 80, 160 and 320 dam.

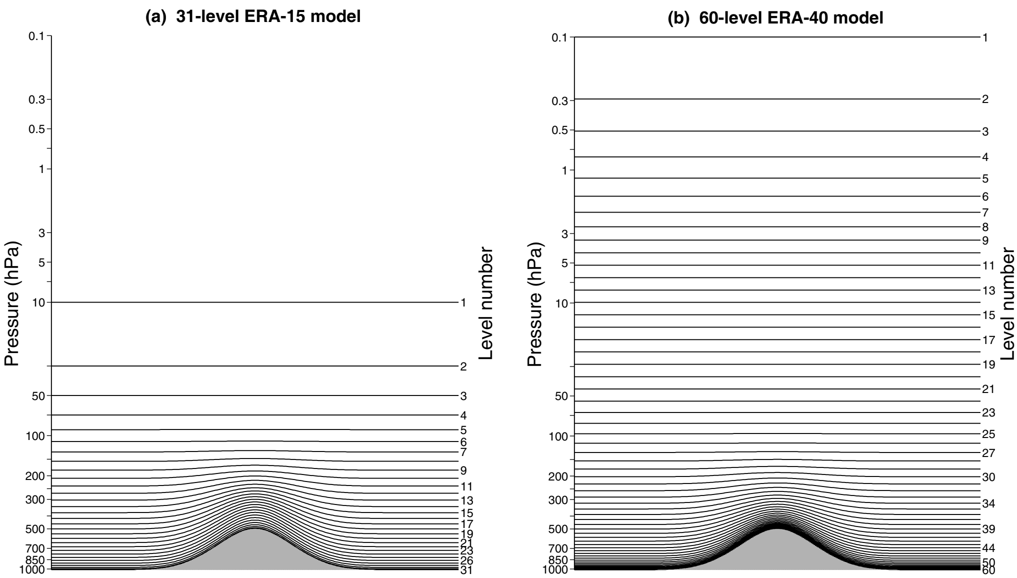

Figure 4. The distribution of full model levels at which the basic prognostic variables are represented for: (a) ERA-15 and (b) ERA-40.

planetary boundary layer, where the height of the lowest level has been reduced from 33 to 10 m (Teixeira 1999). Mid- and upper-tropospheric resolution is similar for ERA-40 and ERA-15, ranging from about 0.5 km in mid-troposphere to about 1 km near the tropopause. The precise locations of levels are provided in the specification of the ERA-40 archive (Kållberg *et al.* 2004).

The ERA-40 model used a two-time-level semi-Lagrangian advection scheme (Temperton *et al.* 2001; Hortal 2002), and a finite element scheme for its vertical discretization (Untch and Hortal 2004). The model included improvements to the parametrizations of deep convection, radiation, clouds and orography, introduced operationally since ERA-15 (Gregory *et al.* 2000; Jakob and Klein 2000; Jakob *et al.* 2000; Morcrette *et al.* 2001). It also included important changes to the parametrizations of the stable boundary layer and land surface, introducing the freezing of soil moisture and a land-cover-dependent albedo for snow-covered areas (Viterbo *et al.* 1999; Viterbo and Betts 1999; van den Hurk *et al.* 2000), and a new sea-ice representation that was developed under advice and using buoy observations supplied by the WCRP/ACSYS Working Group on Polar Products through Re-analysis (Ignatius Rigor, personal communication). The coupling of the model physics and dynamics was revised (Wedi 1999). In addition, ozone was introduced as a prognostic model variable (Dethof and Hólm 2004), although without interaction with the radiation parametrization. Ozone was advected using the same quasi-monotone semi-Lagrangian scheme as applied to specific humidity, with gas-phase chemistry parametrized following Cariolle and Déqué (1986) and a simple representation of ozone loss due to heterogeneous chemistry, developed at Météo-France. A parametrization of the high-level moisture source due to methane oxidation was also added (Untch and Simmons 1999). The atmospheric model was coupled with a 1.5°-resolution ocean-wave model (Janssen *et al.* 2002).

The changes to parametrizations of the land surface and stable boundary layer were the primary cause of substantial improvements of near-surface temperature in ERA-40 compared with ERA-15 over most high-latitude land areas in wintertime; the albedo change in particular gave better temperatures for boreal-forest areas in springtime. Figure 5 shows differences in 2 m temperature for January and July 1989 for the mid- and high-latitude northern hemisphere and for Antarctica. In addition to the effect of the parametrization changes, there are differences due to the ERA-40 analysis of screen-level temperature measurements (see subsection 3(d) below, and Simmons *et al.* 2004). Surface and low-level atmospheric temperatures for Antarctica also differ because the main permanent ice shelves were treated as land rather than sea-ice in ERA-40, and a new definition of the model orography removed a gross error over Antarctica present in the versions used previously in ERA-15 and ECMWF operations (Bromwich, personal communication; Genthon and Braun 1995). The ERA-40 analysis is substantially warmer (and more realistic) over the Antarctic plateau in both seasons, by up to 22 K in July, generally cooler by a few degrees over sea-ice, and substantially colder (by up to 15 K) over the permanent ice shelves.

(*c*) *The variational analysis*

In January 1996, OI (used for ERA-15) was replaced by 3D-Var (Andersson *et al.* 1998) as ECMWF's operational analysis method. It was subsequently extended in the areas of observation screening (Järvinen and Undén 1997), quality control (Andersson and Järvinen 1999), calculation of background-error variances (Fisher and Courtier 1995) and the formulation of the background-forecast error constraint (Derber and Bouttier 1999). In the OI system, specific humidity in the stratosphere was set at each analysis cycle to the value 2.5×10^{-6}; in the version of 3D-Var used in

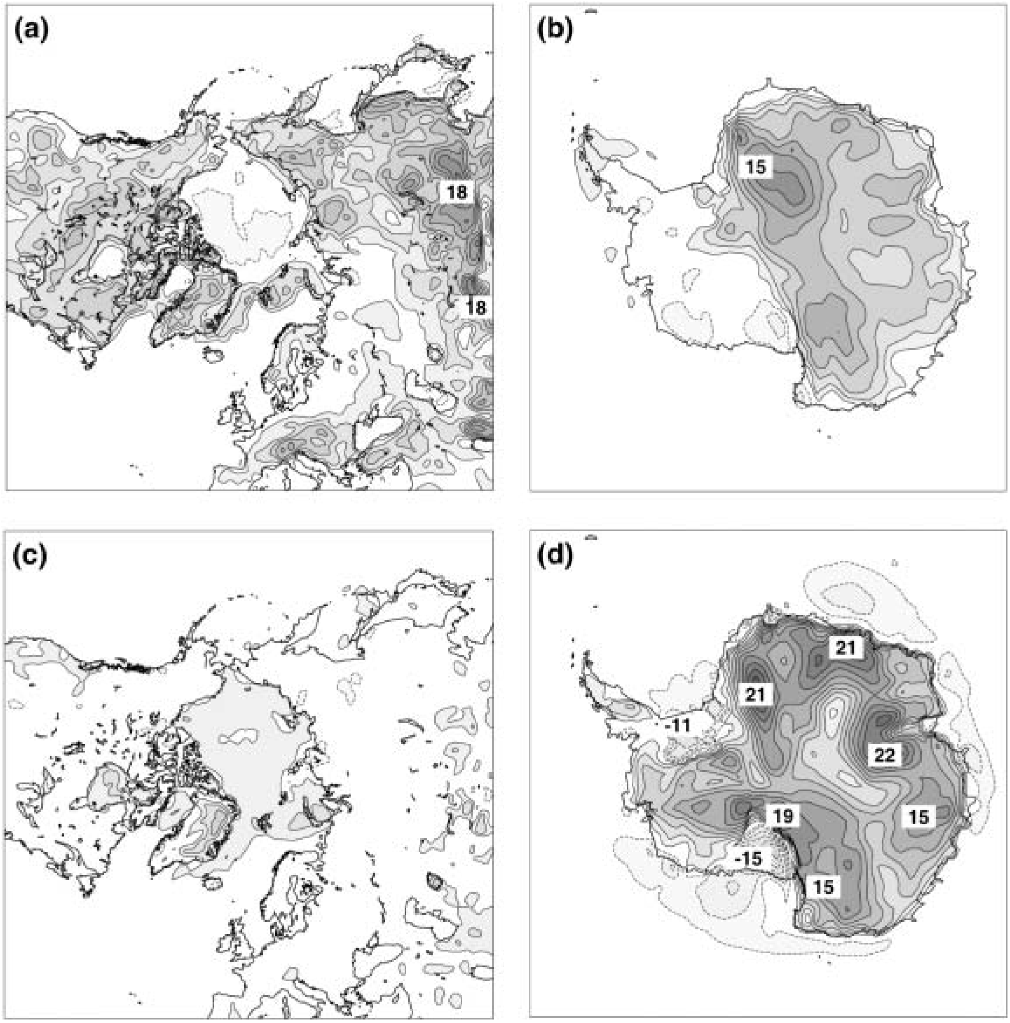

Figure 5. Differences in 2 m temperature (K) between ERA-40 and ERA-15 analyses, averaged for January 1989, for: (a) the mid- and high-latitude northern hemisphere, and (b) Antarctica; (c) and (d) are as (a) and (b) but for July 1989. The contour interval is 2 K and the zero contour is suppressed. Solid contours and solid shading indicate where ERA-40 analyses are on average warmer than ERA-15 analyses.

ERA-40, stratospheric humidity was allowed to evolve through data assimilation cycles (Simmons *et al.* 1999) with analysis increments suppressed above a diagnosed tropopause. In November 1997, 3D-Var was replaced by 4D-Var for operational use at ECMWF (Mahfouf and Rabier 2000; Rabier *et al.* 2000), but most of the subsequent operational changes also affect the 3D-Var system used for ERA-40. Amongst these, observation- and background-error variances were revised in the light of the performance of the new 4D-Var system; also the use of radiosonde data was changed: assimilating temperature rather than height data, assimilating significant-level as well as standard-level data, and correcting an error in the derivation of specific humidity from reports of temperature and dew-point. The assimilation was extended to include data from US wind profilers.

Kållberg (1997) discussed the spin-up/spin-down characteristics (increases/ decreases during short-range forecasts) of oceanic 10 m winds and surface fluxes in ERA-15. He inferred that the analysed winds were substantially too low in places due to assimilation of 10 m wind observations from island stations that were unrepresentative of winds over surrounding open seas, and that marine winds were likely to be too high elsewhere because of assignment of ship wind observations to a height of 10 m. These analysis-induced biases weakened during the short-range forecasts. Both analysis deficiencies were subsequently corrected by changes to the assimilation system. Unrepresentative island wind observations were no longer used, and ship winds were applied at the anemometer height where known and otherwise at a more representative height* than 10 m. Figure 6(a) presents an example of differences in wind speed between the ERA-40 and ERA-15 analyses, showing stronger winds near Pacific islands for ERA-40, and lower winds elsewhere. Ramos Buarque *et al.* (2003) confirm that there is less spin-up of fluxes in ERA-40 than ERA-15. Consistent with this, Fig. 6(b) shows that differences between oceanic ERA-40 and ERA-15 wind speeds are smaller in 24 h forecasts than in the analyses. Surface winds in the later years of ERA-40 also benefit directly from the assimilation of scatterometer and SSM/I data, and indirectly from interaction with the ocean-wave model that in turn benefits from the assimilation of altimeter measurements of ocean-wave height. The smaller spin-up in ERA-40 is linked with analysis increments (changes made to the background fields by the analysis process) that are generally smaller in ERA-40 than ERA-15, as discussed in subsection 5(c) below.

Several developments or parameter adjustments within the 3D-Var assimilation system were made specifically for ERA-40. The so-called ‘first-guess at the appropriate time’ approach was used: background and observed values were compared at the actual observation time rather than the analysis time, and the differences applied at analysis time. The 3D-Var analysis was adapted to use the linear grid employed in the model, allowing analysis increments to be derived at the full T159 resolution of the assimilating model. The background error variances used in the variational analysis were increased by about 30%, a decision based both on synoptic examination of trial analyses, which indicated that the original system was not drawing as closely to observations as was desirable, and on the argument that the standard error variances had been set to be appropriate for the more accurate background fields of the operational high-resolution 4D-Var assimilation. These developments enabled the analysis to fit observations more closely, both in space and time. In addition, the time step of the assimilating T159 model was reduced to 30 minutes from its default setting of 1 hour, primarily to reduce deficiencies in the analysis of the atmospheric tides.

Radiosonde temperatures were corrected for estimated biases from 1980 onwards. As sufficiently comprehensive supplementary data on sonde usage were not generally available, stations were separated into groups defined to represent different countries or areas that were assumed to use similar types of sonde at any one time. Mean differences between background forecasts and observations were accumulated for each group of stations over at least twelve months for different classes of solar elevation. The mean error for all classes was subtracted from the bias computed for each class to provide a correction for radiation effects. It was decided manually for each group whether to apply a correction, and if so whether to adjust for the complete bias or (more commonly) only for the radiation error. The corrections applied were reassessed and

* A fixed height of 25 m was used, based on averaging heights in a recent WMO list of reporting ships. No allowance was made for a tendency for anemometer heights to increase over the period of ERA-40, which may have caused a slight spurious drift in the ocean winds over the course of the re-analysis.

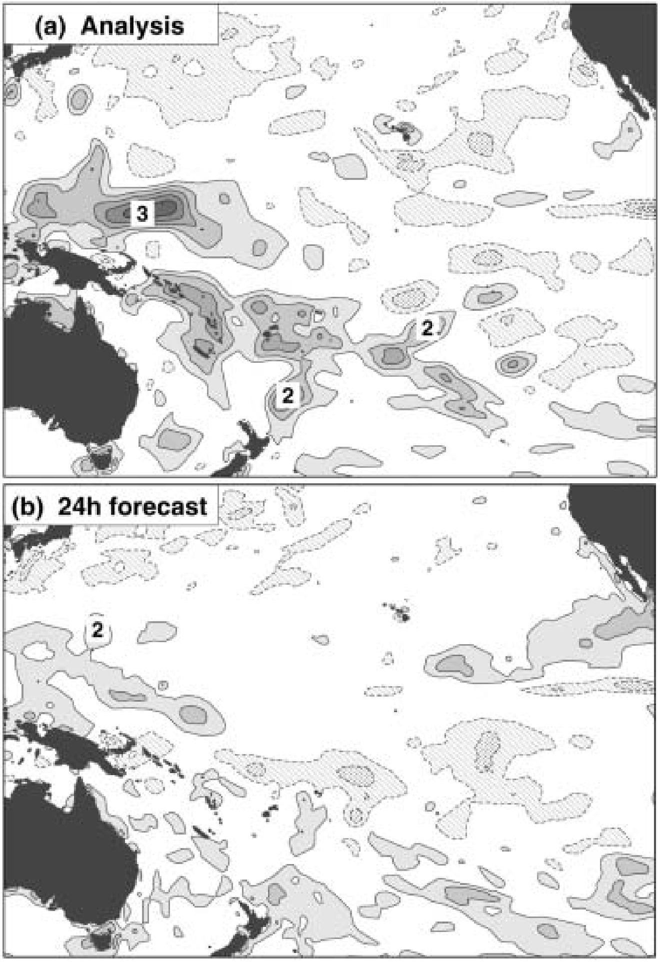

Figure 6. Differences in 10 m wind speed over the Pacific Ocean between ERA-40 and ERA-15 for: (a) analyses and (b) 24 h forecasts, averaged over 00 UTC and 12 UTC data for January 1989. Solid contours and shading indicate faster winds in ERA-40. The threshold for shading is a difference of 0.5 m s^{-1} and the contour interval is 0.5 m s^{-1}.

revised as necessary from time to time. The correction applied for the complete bias reached in excess of 0.5 K in the lower stratosphere for Chinese data averaged over the period 1980–2002. The corresponding average radiation correction applied to Alaskan data likewise exceeded 0.5 K. Details have been reported by Onogi (2000) and Andrae *et al.* (2004).

Biases in the older radiosonde data tend to be larger and more variable in time and space. Correcting them would have required a concerted monitoring effort and frequent breaks in production for updating corrections, and would have carried a greater risk of error, especially when satellite data were not available to provide a control on the analysis. Since ERA-40 was the first comprehensive analysis of the pre-1979 data carried out by ECMWF it was decided that the best approach for these years was not to apply corrections but to accumulate departure statistics that could be used to derive the corrections for future re-analyses. Humidity measurements from radiosondes were known also to suffer from biases, but it was not feasible to develop a scheme to correct them.

(*d*) *Surface analysis*

One of the products of ERA-40 is a set of analyses of temperature and humidity at a height of 2 m. These analyses were produced as part of the ERA-40 data assimilation, but not directly by the primary 3D-Var analysis of atmospheric fields. Instead, a separate analysis of measurements of dry-bulb temperature and dew-point was made using OI (Douville *et al.* 1998). The background field for this analysis was derived from the background forecast of the main data assimilation, by interpolating between the surface and the lowest model level. The interpolation made use of Monin–Obukhov similarity profiles consistent with the assimilating model's parametrization of the surface-layer part of the planetary boundary layer (Beljaars and Viterbo 1999). The 2 m temperature and humidity analyses were not used directly to modify the atmospheric fields used to initiate the background forecast for the next analysis in the data assimilation sequence. They nevertheless influenced this background forecast, since they were used as input to an OI analysis of soil temperature and moisture for use in the background model (Mahfouf *et al.* 2000; Douville *et al.* 2001). *In situ* measurements of snow depth (limited in number in earlier years as discussed previously) were analysed using the successive correction method, with an adjustment applied that relaxed the analysis towards climatology in the absence of measurements; it differed from the scheme used in ERA-15 through the use of the background snow density and snow water equivalent, and also an improved snow-depth climatology.

(*e*) *Use of satellite data*

The principal change from ERA-15 in ERA-40's use of satellite data was its direct variational assimilation of raw radiances, in which basic model variables were adjusted to improve jointly the fits of simulated 'model equivalent' radiances to measured radiances, and the fits of the model to other types of observation. Radiances from the VTPR, HIRS, MSU, SSU and AMSU-A instruments were assimilated in this way, following the approach implemented operationally for assimilation of data from AMSU-A, MSU and a small number of HIRS channels (McNally *et al.* 1999, 2000). AMSU-A provides microwave temperature-sounding data with greater vertical resolution than MSU, but has been flown only since 1998. The operational raw-radiance assimilation scheme was thus extended for ERA-40 to process data from additional HIRS channels to provide extra tropospheric resolution, and from the SSU (Pick and Brownscombe 1981) to provide stratospheric coverage. This was the first time the SSU radiances had been used in multivariate data assimilation. The use of the additional HIRS data also compensated for the absence of microwave humidity data prior to the launch of SSM/I in 1987.

In contrast, ERA-15 assimilated temperature and humidity profiles below 100 hPa that were mostly generated by a 1D-Var physical retrieval of pre-processed HIRS and MSU radiances that had been adjusted to a nadir view and cloud-cleared by NOAA/NESDIS. Above 100 hPa it used the operational temperature retrievals produced by NOAA/NESDIS, except within the tropical band from 20°N to 20°S where no satellite data were used (Gibson *et al.* 1997).

In ERA-15 new satellite bias adjustments had to be calculated at the end of each month and applied the following month. In ERA-40, the bias tuning for each channel was much more stable. In most cases a single bias adjustment was applied for the lifetime of a satellite. Establishment of the adjustments for a new satellite was more straightforward when there was an overlap between satellites, as this allowed 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 new data. Differences in bias from one satellite to the next could be quite substantial. For example, the global-mean adjustment applied to brightness temperatures from channel 4 of the MSU instrument was about 1.5 K for the NOAA-11 satellite and 0.2 K for NOAA-12; the difference in these adjustments is of the same order of magnitude as the warming seen in the MSU-4 measurements due to the eruption of Mt Pinatubo, which occurred at the beginning of the lifetime of NOAA-12 in mid-1991. Time series illustrating this are presented by Uppala *et al.* (2004).

Several factors contributed to the stability of the bias adjustment in ERA-40. The method of determining adjustments was better. Scan-angle corrections were made latitudinally dependent, and background fields instead of radiosonde measurements were used as predictors of air-mass-dependent biases, with regression coefficients determined from background values close to radiosonde stations (Harris and Kelly 2001). The use of level-1c radiances itself reduced the magnitude of scan-dependent biases. Furthermore, it removed the need to change bias corrections in response to changes introduced by NESDIS in its operational production of cloud-cleared radiances and stratospheric retrievals. Satellite height and navigation were taken into account in the ‘forward’ radiative transfer calculation used to produce model equivalents of the measured radiances (Saunders *et al.* 1999), eliminating the need to adjust explicitly for the main effects of orbital drift.

Deciding when to start and when to stop using data from a particular channel or instrument can be important in re-analysis. The global nature of the coverage by a polar-orbiting satellite means that grossly erroneous data can quickly cause global corruption of analyses. This occurred, for example, in ERA-15 early in November 1986, when tropospheric temperatures exhibited a sudden jump to warmer values in the lower troposphere and colder values in the upper troposphere. This was especially apparent in the Tropics. The sudden changes were caused by a shift in radiances from the MSU-3 channel on NOAA-9, believed to be due to a solar flare. Effects were perpetuated in later ERA-15 analyses, primarily by the monthly bias-adjustment procedure (Trenberth *et al.* 2001).

Prior to production of the ERA-40 analyses, time series of brightness temperatures from the TOVS and ATOVS instruments were generated for three scan-position bands and six latitude bands, and examined for temporal consistency. A decision whether or not to use data was made accordingly. This was often a straightforward matter, as in the case of the MSU-3 data from NOAA-9 that were blacklisted from 25 October 1986. It was less clear cut, however, in cases of gradual degradation of data from instruments with significant impact, for example the deterioration of SSU data due to leakage of gas from the pressure-modulated cell. Examples are presented by Hernandez *et al.* (2004) who also document the decisions that were made for each instrument. In addition to the pre-production data monitoring, the background fits to radiance data were monitored during production, and use of data from a particular instrument or channel was halted in the case of jumps or drifts for which a satisfactory compensatory bias-correction change could not be found.

From August 1987 onwards ERA-40, unlike ERA-15, also assimilated 1D-Var retrievals of TCWV and surface wind speed over sea from SSM/I radiances (Gérard and Saunders 1999). Its assimilation of surface winds over sea from the scatterometers on the ERS-1 and ERS-2 satellites from 1993 onwards is discussed by Isaksen and Janssen (2004). Altimeter data from the ERS satellites were used in ERA-40’s ocean wave analysis (Caires and Sterl 2005a). Dethof and Hólm (2004) give an account of the assimilation of SBUV and TOMS ozone retrievals.

(*f*) *Boundary and forcing fields*

SSTs and sea-ice cover were taken from two main sources: the HADISST1 dataset of monthly values produced by the Met Office (Rayner *et al.* 2003), which was used up to November 1981; and the weekly NOAA/NCEP 2D-Var dataset (Reynolds *et al.* 2002), which was used thereafter until June 2001. Both used the same sea-ice analysis which was developed collaboratively for use in ERA-40 (Rayner 2002). Both also used the same method of specifying SST in grid boxes with partial ice-cover. Interpolation was used to produce daily values from each dataset. Other NCEP products were used after June 2001. Further detail and discussion have been given by Fiorino (2004).

Trends in the amounts of specified radiatively active gases (CO_2, CH_4, N_2O, CFC-11, CFC-12) were applied, based on values given in the 1995 scientific assessment of the International Panel on Climate Change (Houghton *et al.* 1996). A trend in chlorine loading was used in the parametrization of ozone loss due to heterogeneous chemistry. The model did not include any aerosol trend or temporal variations, due to volcanic eruptions for example, and there was no interaction between its radiation scheme and variable ozone fields. Instead, a fixed geographical distribution of aerosol and a climatological ozone distribution were used for the radiation calculation. There was also no variation over time in the model's land-cover characteristics.

4. Testing, production, monitoring and archiving

Production of the ERA-40 analyses was preceded by an extensive experimentation programme during which the analysis and model improvements developed for operations since ERA-15 or developed specifically for ERA-40 were tested over different periods. In parallel, assessments were made of the performance and impact of observations not previously used at ECMWF; these had come from different sources than usual, or were going to be used in a different way than hitherto. They included pre-1979 conventional data and VTPR, TOVS, SSM/I, and ERS satellite data. In total some 25 years of test data assimilation were completed. Preparatory work and testing were also carried out for the externally produced SST/sea-ice datasets. The suite of tasks forming the production control system was based on ECMWF's existing framework for the execution of research experiments, which was extended to include monitoring tasks and monthly tasks such as the preparation of mean fields and other climatological diagnostics.

Production of the ERA-40 analyses had to be completed to a deadline determined by external factors. Initially production proceeded slowly as problems were investigated and solutions tested, and to meet the deadline it was organized into three streams. The first covered 1989–2002, the second 1957–72 and the third 1972–88. Completion of the planned production* was ensured by initiating a small number of parallel-running sub-streams to bridge gaps between the main streams. Examination of overlaps between the streams shows few signs of problems associated with this production strategy. Small jumps in mean temperatures in the troposphere result from differences in satellite bias correction. Larger jumps in temperature are seen in the upper stratosphere, where discontinuities also occur in the otherwise slowly varying water-vapour fields.

* Analyses to the end of 2001 were completed by 31 March 2003 as originally planned. Continuation of the analyses to the end of August 2002 was possible because computing resources were available for a few weeks longer than expected.

Monitoring of ERA-40 production was carried out both by ECMWF and by external validation partners. It enabled several problems to be detected and corrected. For example, unrealistic hydrological behaviour over several land areas in early analyses from 1957 onwards was traced to miscoded screen temperatures in one of the observational datasets, and this production stream was restarted from the beginning with correctly coded data. This also enabled corrections to be made to radiosonde data that had been assigned to the wrong time of day. Other problems were detected, that either could not be corrected due to lack of an immediate solution or could be corrected only for subsequent analyses as there was insufficient time to rerun the analyses that had already been completed. These are discussed in subsequent sections.

Enhanced sets of post-processed products were developed for ERA-40 in collaboration with members of the user community. Examples are: vertically integrated fluxes and energetics; fields from the physical parametrization for support of chemical-transport modelling; fields evaluated on surfaces of constant potential temperature and potential vorticity; and special grid point and catchment-basin diagnostics. A complete list of the analysed and diagnosed fields produced by ERA-40 is given in the archive specification (Kållberg *et al.* 2004). In addition, cloud-affected VTPR, TOVS and ATOVS radiances and their model equivalents were processed passively through the assimilation system, in order to enable production of a range of diagnostic information on clouds using CO_2-slicing (Chevallier *et al.* 2001, 2005).

Data produced by the ERA-40 project are available through:

- Public internet access to a comprehensive set of 2.5° resolution products held online at ECMWF (http://data.ecmwf.int/data);
- Direct access to ECMWF's Meteorological Archival and Retrieval System by users from authorized institutions in the ECMWF Member and Co-operating States;
- ECMWF Data Services (http://www.ecmwf.int/products/data);
- Several data centres in Europe that have built up data holdings for supply to national users (e.g. http://www.mad.zmaw.de/, http://climserv.lmd.polytechnique.fr, http://badc.nerc.ac.uk/data/);
- NCAR for supply to members of UCAR and other research and educational institutions in the USA (http://dss.ucar.edu/pub/era40/);
- The ISLSCP Initiative II Data Archive, which offers a set of near-surface data (Betts and Beljaars 2003; http://islscp2.sesda.com).

Climatological information from ERA-40 has also been presented in the form of atlases of the atmospheric general circulation (Kållberg *et al.* 2005; http://www.ecmwf.int/research/era/ERA-40_Atlas) and of ocean waves (Sterl and Caires 2005; http://www.knmi.nl/waveatlas).

5. Overall performance of the ERA-40 data assimilation system

(*a*) *Background and analysis fits to data*

Information on the quality of the analyses and observations can be inferred from the comprehensive feedback statistics of observation-minus-background and observation-minus-analysis differences (the background and analysis fits to data) that have been produced and archived for each cycle of the ERA-40 data assimilation. Uppala (1997) used statistics of these measures from ERA-15 to demonstrate a gradual but significant improvement in the performance of the composite observing system from 1979 to 1993.

Figure 7 shows time series of background and analysis fits to SYNOP and SHIP surface-pressure measurements for the extratropical northern and southern hemispheres.

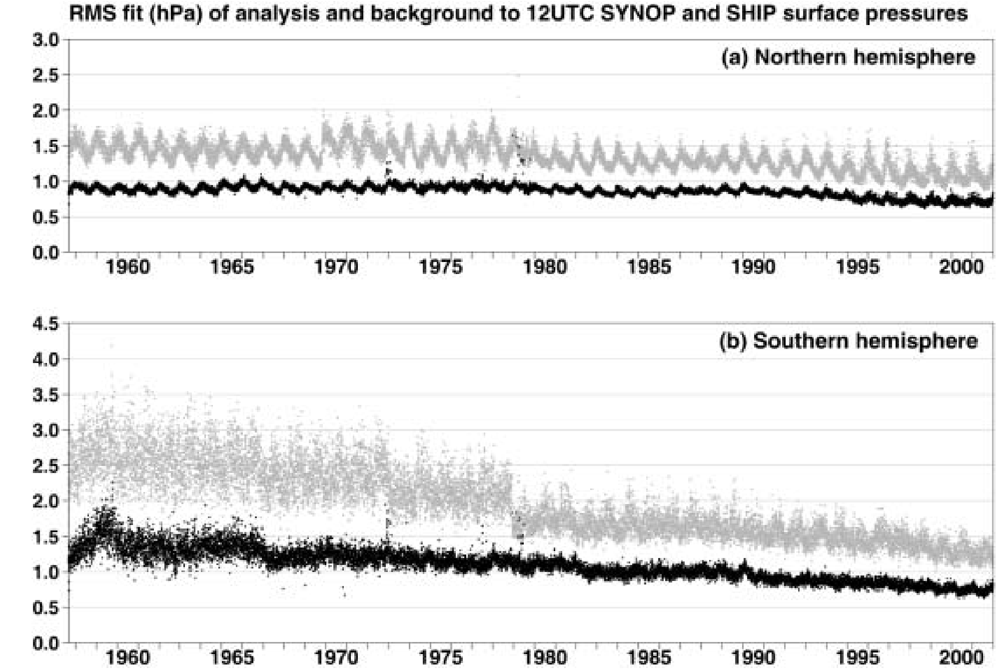

Figure 7. Daily values of the ERA-40 RMS background (grey) and analysis (black) fits to extratropical 12 UTC SYNOP and SHIP measurements of surface pressure (hPa), for: (a) the northern hemisphere; (b) the southern hemisphere.

A general improvement in the fit occurs over the period of ERA-40. Changes in data coverage can affect this, as increased coverage in the subtropics, where variance is lower, tends to reduce values in plots such as these in which no area-weighting is applied. This probably explains the shift for the southern hemisphere at the beginning of 1967, for example. However, the improvement in the background fit at the end of 1978 is almost certainly a consequence of the major improvement of the overall observing system that took place then. It is particularly marked in the southern hemisphere, where a distinct improvement can also be seen at the beginning of 1973 when satellite data were first used. The fits improve gradually from 1979 onwards, more so for the southern than the northern hemisphere, and become similar for the two hemispheres by the end of the period. These and other results presented in this paper indicate a general improvement over time of the post-FGGE observing system, especially for the southern hemisphere.

Figure 8 shows corresponding fits to 500 hPa radiosonde temperatures. A general improvement over time in the background fit can again be seen, more so for radiosonde temperatures than for surface pressure observations; this may include a component directly due to decreasing error in the measurements that are fitted. The RMS background fit drops from around 1.4 to 1 K over the period for the northern hemisphere, and from around 2 to 1.2 K 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 in the later years. However, the fit of the background field is slightly better in the 1980s than in the 1970s for the northern hemisphere, and improves sharply at the end of 1978 for the southern hemisphere; this is a clear sign of analyses that have been improved overall by the availability of the new data. A similar effect for the VTPR data introduced in 1973 may have been masked

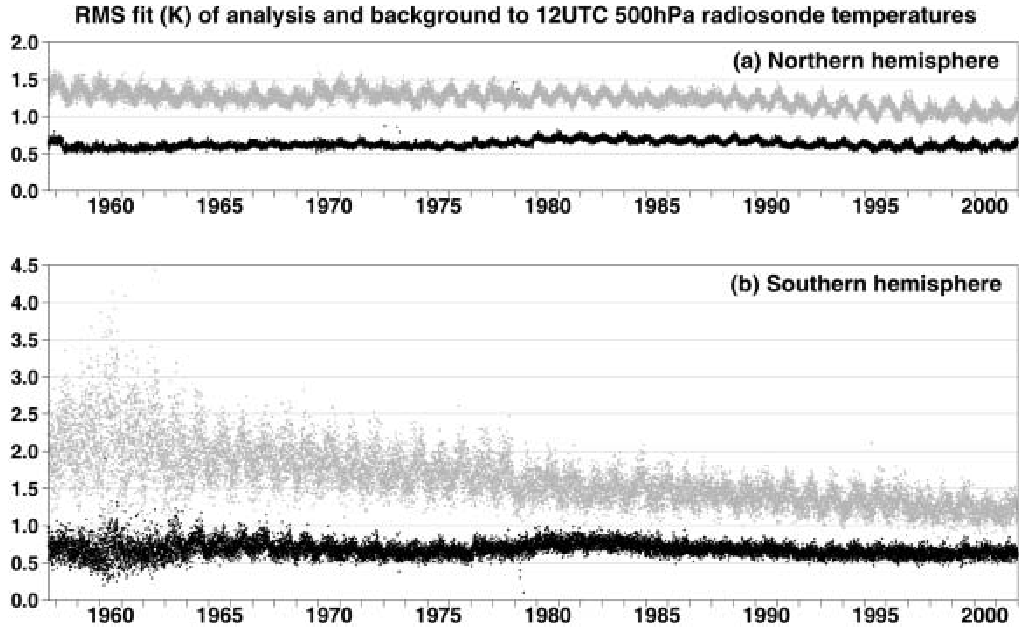

Figure 8. Daily values of the ERA-40 RMS background (grey) and analysis (black) fits to extratropical 12 UTC 500 hPa radiosonde measurements of temperature (K), for: (a) the northern hemisphere; (b) the southern hemisphere.

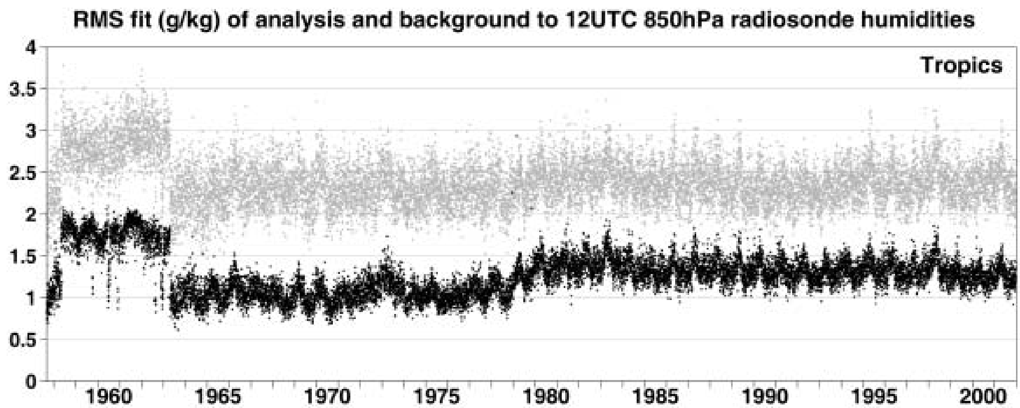

Figure 9. Daily values of the ERA-40 RMS background (grey) and analysis (black) fits to 12 UTC 850 hPa radiosonde measurements of specific humidity (g kg^{-1}) over the Tropics.

by the assimilation of the duplicate radiosonde observations from 1973 to 1976 noted earlier. The fit of the analysis to the radiosonde data does indeed worsen slightly at the beginning of 1977.

Fits to 850 hPa specific humidity from radiosonde measurements in the Tropics are presented in Fig. 9. They are especially poor from early 1958 to early 1963. This has been traced to an error made in the conversion of humidity measurements in one of the early sets of radiosonde data. A corrected dataset has been created for use in future re-analyses. Assimilating the erroneous humidity data caused widespread mean drying increments and lower precipitation from 1958 to 1963; this is seen, for example, in hydrological studies for North America reported by Betts *et al.* (2003b) and Hagemann

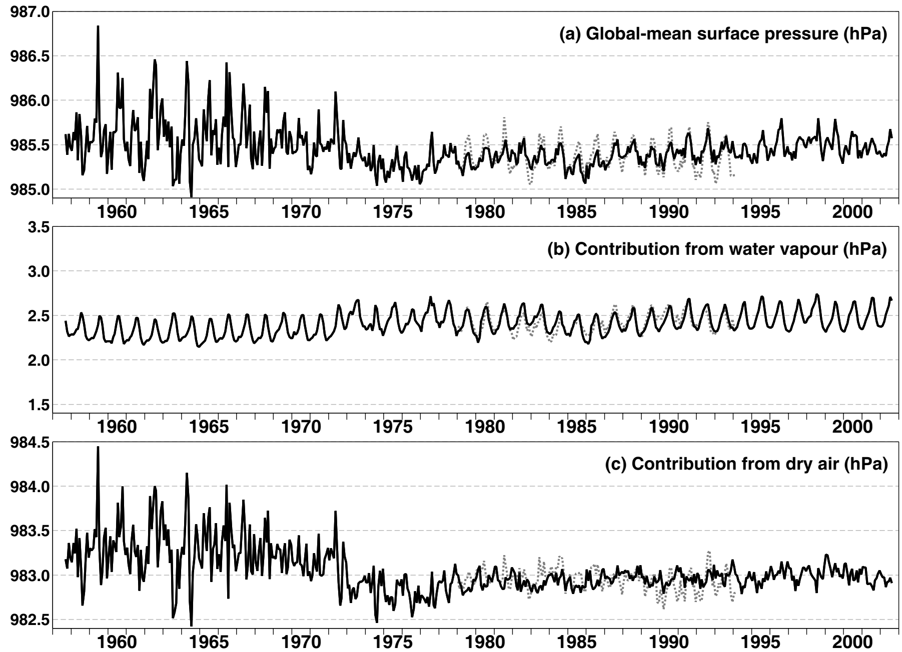

Figure 10. Global means of: (a) analysed surface pressure (hPa), (b) the contribution from water vapour as deduced from the humidity analyses, and (c) the difference between the two, which provides an estimate of the contribution from dry air. Monthly mean values from ERA-40 (black solid) and ERA-15 (grey dotted) are plotted; ERA-15 values are adjusted to give zero mean difference over the period for which they are available.

et al. (2005). As in the case of radiosonde temperatures in the extratropics, the fit of the analysis to the radiosonde measurements of tropical humidity worsened when assimilation of TOVS radiances started at the end of 1978. There is, however, a smaller change at this time in the background fit, and there is a slight improvement in this fit following 1987, when SSM/I radiance data were first assimilated. Short-term variations can also be discerned in Fig. 9; for example, fits are poorer early in 1983 and 1998 when strong El Niño events were in progress.

(*b*) *Global mass*

Examination of global mass statistics provides further clear-cut evidence of improvement over time in the quality of the surface pressure analyses, and indicates a measure of consistency over time of the analysed water content of the atmosphere for the latter half of the re-analysis period (Trenberth and Smith 2005). Figure 10 shows time series of the global-mean analysed surface pressure, the contribution from atmospheric water vapour (derived from the humidity analyses) and the difference between the two. The latter is a good approximation to the surface pressure of dry air, and should be almost independent of time. Results are shown for both ERA-40 and ERA-15. Monthly means of the 6-hourly analyses are plotted. To facilitate comparison, mean values for ERA-15 have been adjusted so that they match those for ERA-40 over the period from January 1979 to February 1994; raw values differ due to differences in model orography.

Prior to 1973, the diagnosed pressure of dry air from ERA-40 shows relatively large fluctuations over time, with a standard deviation of about 0.3 hPa, and a mean value that is about 0.3 hPa higher than for subsequent years. The latter is due both to a higher mean analysed surface pressure (with the largest contribution from the data-sparse Southern Ocean) and to a lower mean analysed humidity. Fluctuations are much smaller from 1973 onwards, and smaller still from 1979 onwards. Not only is there a degree of consistency over the final two decades of ERA-40 between the directly analysed annual cycle in net atmospheric water-vapour content and the analysed annual cycle in global-mean surface pressure, there is also a degree of consistency in the analyses of longer-term variations. The analysed total surface pressure and the analysed humidity content decrease to a minimum at the end of 1985, and rise thereafter. The least-squares linear trends from September 1985 to August 2002 are 0.12 hPa per decade for the total analysed surface pressure and 0.09 hPa per decade for the contribution derived from the analysed humidity. Such agreement as there is must come from the analysis of observations, as the assimilating model's governing equations do not account for changes in surface pressure due to imbalance between precipitation and evaporation, and the model would thus give uniform global-mean total surface pressure were it not for truncation error.

The ERA-15 results available from 1979 onwards are clearly superior to the pre-1973 ERA-40 results, but ERA-15 values do not show the same consistency as contemporary ERA-40 values. The standard deviations of the time series of inferred monthly values of the global-mean pressure of dry air are 0.121 hPa for ERA-15 and 0.082 hPa for ERA-40. The ERA-40 value does not change (to the accuracy quoted) if the calculation is repeated for total atmospheric water (vapour plus cloud, a quantity not available for ERA-15) rather than water vapour. Trenberth and Smith (2005) include comparisons with the NCEP/NCAR re-analyses. The results from ERA-40 are clearly superior from 1973 onwards.

(*c*) *Analysis increments and short-range forecast accuracy*

The improvement in the observing system over the past four decades is reflected in a marked reduction over time in the general magnitude of analysis increments—the analysis-minus-background differences that measure the extent to which the background forecast is changed by the observations assimilated at a particular analysis time. Smaller increments do not mean that the observations play a less important role, but rather that the observations influence the assimilation more through relatively small adjustments that provide better background forecasts for subsequent analyses than through more substantial corrections to poorer background forecasts.

Figure 11 presents maps of the RMS increments to 500 hPa height computed over all 12 UTC analyses for the years of 1958 and 2001. Increments are much smaller in 2001 over land and coastal regions where there are marked increments in 1958. Isolated small-scale maxima over the oceans in 1958 indicate where radiosonde data from islands and the fixed weather ships correct the background forecast. Local impact still occurs in 2001 for isolated radiosonde stations over Antarctica and northern Russia, but is of smaller magnitude. Increments are particularly large along the west coast of North America in 1958, where a background forecast error that developed over the poorly observed Pacific Ocean is corrected on its first encounter with the North American radiosonde network. Larger increments occur in 2001 than in 1958 over oceanic regions that are almost devoid of observations in 1958, due to assimilation of the satellite, buoy and aircraft data that today provide coverage of such regions. Smaller increments in 2001 over regions well covered by radiosonde data in both 1958 and 2001 can arise both from more accurate background forecasts and from more accurate radiosonde measurements.

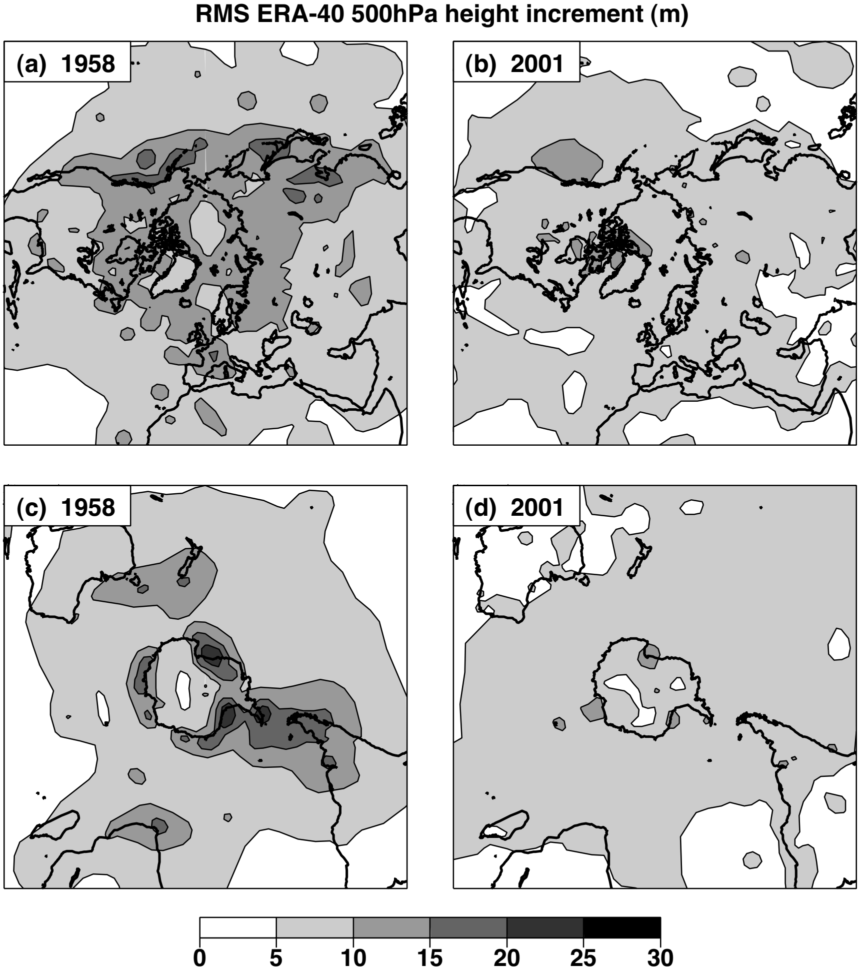

Figure 11. RMS 12 UTC analysis increments in 500 hPa height (m) from ERA-40, for: (a) 1958, and (b) 2001, for the northern hemisphere; (c) and (d) are as (a) and (b), but for the southern hemisphere.

Analysis increments are generally smaller in ERA-40 than in ERA-15. A clear example of this is provided in Fig. 12, which shows RMS 500 hPa height increments for the 12 UTC ERA-15 and ERA-40 analyses for 1979. Evident over the southern hemisphere are larger local increments in ERA-15 caused by data from individual radiosonde stations around the Antarctic coast, at the South Pole and southern tip of South America, and on islands in the southern oceans. There are also generally larger increments over the oceans due to satellite and other data.

Corresponding increments for the years 1958 and 1996 from the NCEP/NCAR re-analysis have been presented by Kistler *et al.* (2001). The ERA-40 increments for 1958 are generally smaller than the NCEP/NCAR increments for that year. The ERA-40 increments for both 1979 and 2001 are likewise generally smaller than the NCEP/NCAR increments for 1996.

For a given set of observations, smaller increments can result from a better background forecast (due to a better model and/or a better preceding analysis), from specifying a larger ratio of observation-error to background-error variances in the analysis, and from tighter quality control of the observational data. The smaller increments seen for

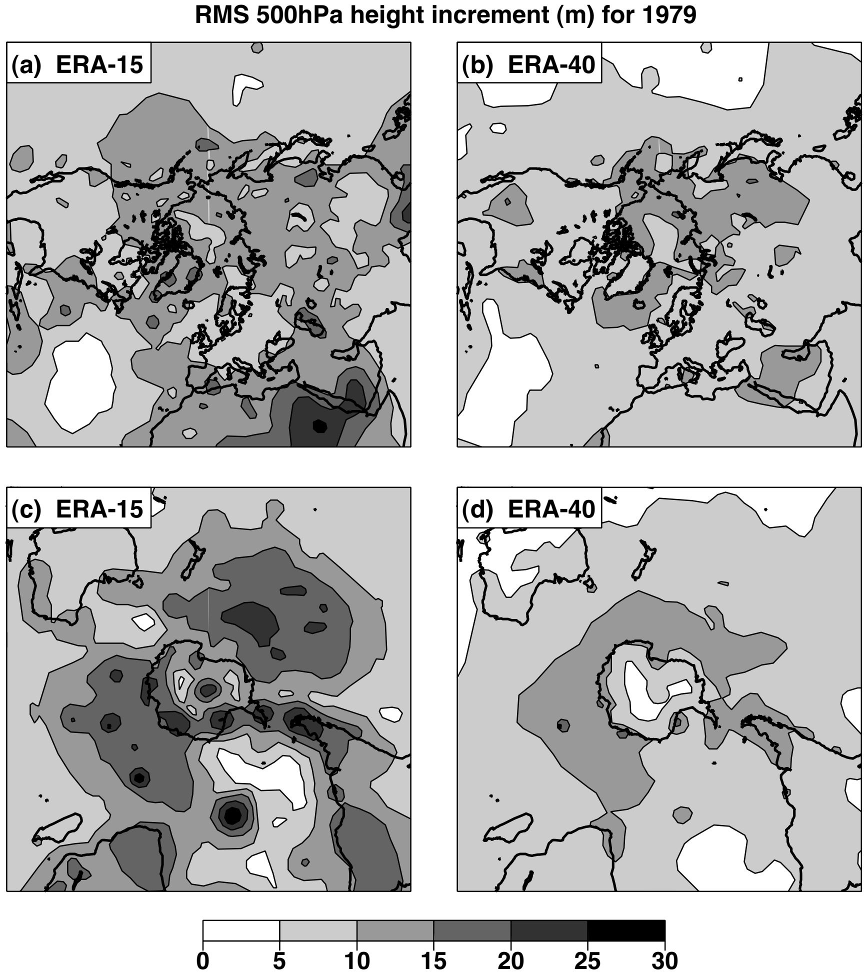

Figure 12. RMS 12 UTC analysis increments in 500 hPa height (m) for 1979 for: (a) ERA-15 and (b) ERA-40, for the northern hemisphere; (c) and (d) are as (a) and (b), but for the southern hemisphere.

ERA-40 are a welcome result provided they do not stem from a failure of the analysis to draw appropriately to observations. An acid test is whether short-range forecasts run from the ERA-40 analyses fit observations better. This is indeed the case.

One-day forecasts from ERA-40 have been verified against radiosonde measurements and compared with corresponding results from operational ECMWF and ERA-15 forecasts. The verification is that used by ECMWF to produce its contribution to the statistics that forecasting centres exchange monthly under the auspices of the WMO; it involves verifying against data from a fixed set of stations that have a recent history of reporting regularly. A selection of results from 1991 onwards is compared in Fig. 13, which presents RMS differences between the forecasts and the observations for temperature and vector wind at 50, 200 and 850 hPa, for the extratropical northern hemisphere, where coverage of verifying observations is best. Monthly means for 12 UTC are plotted.

Figure 13 shows that the ERA-40 forecasts are closer than the ERA-15 forecasts to the radiosonde data. They are also generally closer than (or as close as) the operational forecasts to data up to 1999. After that the advantages of the higher operational

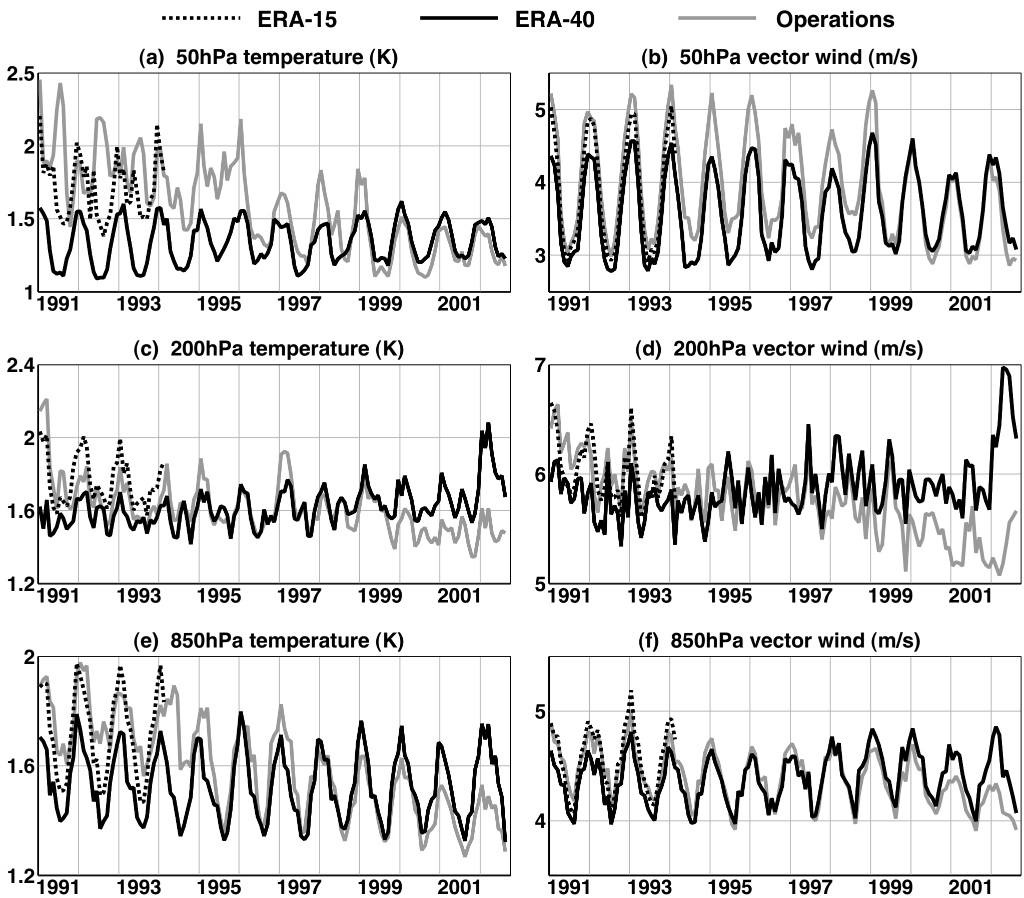

Figure 13. RMS fits to radiosonde data of 24 h forecasts from ERA-15 (black dotted), ERA-40 (black solid) and ECMWF operations (grey solid) for the extratropical northern hemisphere. Monthly means of daily values for 12 UTC forecasts are plotted, for: (a) temperature (K) and (b) wind (m s^{-1}) at 50 hPa; (c) and (d) are as (a) and (b) but for 200 hPa; (e) and (f) are as (a) and (b) but for 850 hPa. (See appendix A for acronyms.)

resolution and 4D-Var analysis predominate. The marked improvement in the fit of 50 hPa temperatures seen for operations after January 1996 is due to the operational change from the OI used for ERA-15 to the 3D-Var used for ERA-40 (Andersson *et al.* 1998); much smaller improvement is seen for the wind field. The 3D-Var analysis drew less closely than the OI to wind measurements, but gave forecasts that fitted the wind measurements a little better and the temperature measurements a lot better. It also produced smoother, more coherent, derived potential-vorticity fields.

The distinct degradation in the fit of the ERA-40 forecasts to radiosonde data seen at 200 hPa in 2002 is almost certainly due to the technical failure to use most data types at times other than the main synoptic hours. Failure to use the asynoptic data from aircraft and from upper-level satellite winds makes 200 hPa a level where detrimental impact is likely to be relatively large. Very little sign of a problem can be seen at 50 and 850 hPa in these northern hemispheric statistics. Some deterioration in 2002 is evident at these levels in corresponding plots for the southern hemisphere, but it merely offsets an improvement in fit that occurs for the three preceding years, most likely due to the assimilation of data from AMSU-A.

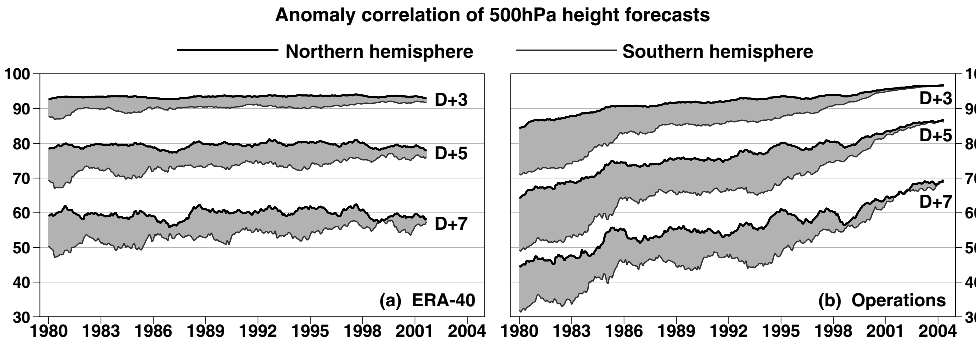

Figure 14. Twelve-month running mean anomaly correlations (%) of 3-, 5- and 7-day 500 hPa height forecasts for the extratropical northern and southern hemispheres: (a) 12 UTC ERA-40 forecasts from January 1980 to August 2002; (b) operational 12 UTC ECMWF forecasts from January 1980 to April 2005. The shading shows the difference in scores between the two hemispheres at the forecast ranges indicated. (See appendix A for acronyms.)

(*d*) *Medium-range forecast accuracy*

The accuracy of the medium-range forecasts run to 10 days ahead from each of the 00 and 12 UTC ERA-40 analyses provides a further indication of the quality of the analyses and of the observing system on which they are based. Short-term variations in accuracy over periods in which little change to the observing system occurred provide indications of natural variations of atmospheric predictability.

Figure 14 presents 12-month running mean verification scores for 12 UTC forecasts run from 1 January 1980 onwards. This covers the post-FGGE period in which reasonable confidence may be placed on the accuracy of the verifying ERA-40 analyses over southern as well as northern oceans, and it is also a period for which there is a complete record of corresponding verification statistics from operational forecasting at ECMWF. Anomaly correlations of 500 hPa height forecasts are shown at 3-, 5- and 7-day ranges for the extratropical northern and southern hemispheres, with shading indicating the differences in accuracy between the hemispheres. Results from ERA-40 are shown in Fig. 14(a) and from ECMWF's operational forecasts in Fig. 14(b). The plot for the operational forecasts is an update for the period up to August 2001 presented by Simmons and Hollingsworth (2002). It shows continuing general improvement of these forecasts.

The plot for ERA-40 shows much less trend than that for the operational forecasts, indicating that most of the improvement in operational forecasts since 1980 has been due to better data assimilation, better modelling techniques and higher resolution (supported by substantial increases in computer power) rather than to net improvement of the observing system. Some increase in skill of these post-FGGE ERA-40 forecasts is evident for the southern but not the northern hemisphere. Additions and refinements to the satellite-based component of the observing system are expected to have had greater impact for the southern hemisphere, because much more extensive use is made of satellite data over sea than land (Simmons and Hollingsworth 2002). Moreover, benefit in the northern hemisphere from better satellite systems, extra aircraft and buoy data, and better radiosonde quality, may have been masked by the decline in radiosonde coverage. It should also be noted that use of 4D- rather than 3D-Var for the ERA-40 assimilation might have resulted in more improvement over time, as 4D-Var is particularly suited to exploitation of the primarily asynoptic data provided by the newer observing systems. In addition, some of the very recent improvement in operational forecasts has come from use of types of satellite data that were not assimilated in ERA-40: frequent water-vapour radiance data from geostationary satellites (Köpken *et al.* 2004); high-latitude winds derived by tracking features in images from polar-orbiting satellites (Bormann and Thépaut 2004); and radiances from the first in a new generation of high-resolution infrared sounders (McNally *et al.* 2005).

The 5-day ERA-40 forecast scores shown in Fig. 14 can be compared with scores presented by Kistler *et al.* (2001) for forecasts from the NCEP/NCAR re-analyses. The correlations from ERA-40 are about 10 percentage points higher than from NCEP/NCAR for the northern hemisphere, and they are about 15 percentage points higher in the early 1980s for the southern hemisphere, with the difference decreasing to about 10 percentage points in the late 1990s. Correlations show a more distinctive upward trend since 1979 for the NCEP/NCAR re-analysis than for ERA-40, especially for the southern hemisphere. This may be explained by a better capability of the newer ERA-40 assimilation system to extract useful information from the somewhat poorer observing system of the early and mid-1980s, especially through its assimilation of raw radiances rather than the retrievals produced at the time. For the southern hemisphere the performance of the NCEP/NCAR re-analysis is likely to have suffered to some degree from mis-specifying locations of PAOB data from 1979 to 1992, although Kistler *et al.* (2001) argue that the impact of this error is relatively small. Moreover, improvement over time of medium-range ERA-40 forecasts for the extratropics may have been inhibited by increasing error-propagation from the Tropics, arising from the increasingly excessive short-range tropical oceanic precipitation discussed in the following section.

Figure 15 presents anomaly correlations of 3-, 5- and 7-day 500 hPa height forecasts from ERA-40 for the whole re-analysis period. They are shown for four regions for which the availability of radiosonde data throughout the period gives confidence in the accuracy of the verifying ERA-40 analyses. Corresponding operational results are also shown for the second half of the period. Forecast quality is relatively high throughout for the three northern hemisphere regions chosen, with levels of skill for the ERA-40 forecasts that from the outset are higher than or similar to those of the operational ECMWF forecasts from the early 1980s. The accuracy of the ERA-40 forecasts is most uniform over time for east Asia, where the effects of improvements in some components of the observing system are most likely to have been obscured by the decline in radiosonde coverage upstream over the former Soviet Union and by the limited use made of satellite data at low levels over land. Improvement over time is a little more evident for Europe and clearer still for North America, which, lying downstream of the broad expanse of the Pacific Ocean, benefits more than the other two regions from improvements in oceanic data coverage.

The consequence of improved oceanic data coverage is seen most strikingly in the results shown for the Australasian region. Here, the accuracy of the forecasts is very much poorer than elsewhere prior to establishment of the observing system for FGGE in 1979. Forecast scores, in fact, decline early in the period, which may be a consequence of a degradation of observational coverage after the IGY. They begin to pick up only in the 1970s, most likely due to the assimilation of VTPR radiance data backed up by PAOBs. Scores subsequently jump substantially when data from the enhanced FGGE observing system are first assimilated at the end of 1978; the improvement amounts to approximately a 2-day gain in practical predictability in the medium range.

The ERA-40 data assimilation system was largely the same as that used operationally at ECMWF in the second half of 2001, but with lower horizontal resolution and 3D rather than 4D-Var analysis. The medium-range forecasts for 2001 from ERA-40 are accordingly not as accurate as the corresponding operational forecasts. Improvement of the operational system has, however, occurred at such a pace that the ERA-40 forecasts are similar in skill to the operational forecasts of the late 1990s.

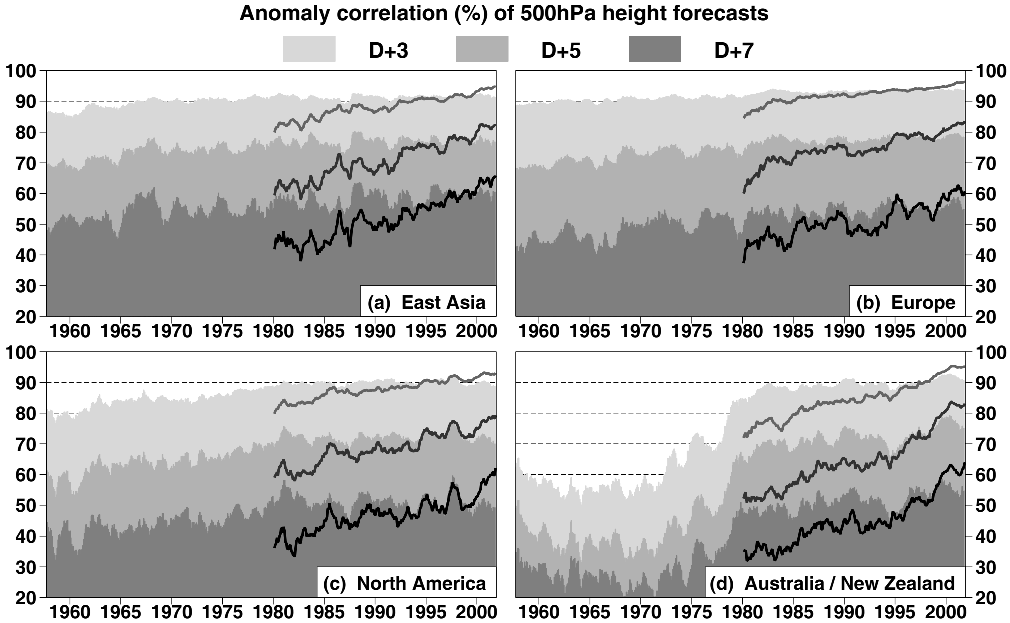

Figure 15. Twelve-month running-mean regional anomaly correlations (%) of 3-, 5- and 7-day 500 hPa height forecasts from 12 UTC ERA-40 forecasts for the whole period of the re-analysis (denoted by shading limits), and from operational 12 UTC ECMWF forecasts for the period from January 1980 onwards (denoted by lines), for: (a) east Asia (25–60°N, 102.5–150°E); (b) Europe (35–75°N, 12.5°W–42.5°E); (c) North America (25–60°N, 120–75°W); (d) Australia/New Zealand (45–12.5°S, 120–175°E). (See appendix A for acronyms.)

Figure 15 shows very similar interannual variations in skill between the ERA-40 and operational forecasts at this time, and similar short-period fluctuations in the two sets of forecasts scores can be seen more generally in Figs. 14 and 15. This indicates that the fluctuations in operational performance were not related primarily to changes to the operational forecasting system, but rather were due to fluctuations in predictability associated with interannual variations in the atmospheric circulation or possibly with variations in the observing system. The ERA-40 analyses and forecasts provide a basis for the study of such fluctuations in predictability.

6. TWO DIFFICULTIES IN DATA ASSIMILATION

The ERA-40 data assimilation system was designed to produce analyses of atmospheric temperature, horizontal winds, humidity and ozone, and a number of surface variables. The system did not impose any overall hydrological balance, and the dynamical balance imposed on the analyses (Derber and Bouttier 1999) was not designed to ensure correct long-term balance of atmospheric circulations driven by diabatic heating and small-scale wave-breaking. Two of the most serious problems diagnosed in ERA-40 products are excessive tropical oceanic precipitation in short-range forecasts run from the analyses and a too strong Brewer–Dobson circulation. Neither quantity is directly analysed from observations, but each influences the quality of the data assimilation through degradation of some aspects of the background forecast. For both, problems are reduced if products are taken from further into the forecast range than the first 6 hours, when adjustment of the model to the imbalance introduced by assimilating observations is strongest.

(*a*) *Humidity analysis and rainfall over the tropical oceans*

Andersson *et al*. (2004) discuss how the ERA-40 analyses were generally moistened over tropical oceans by the assimilation of satellite data. The infrared VTPR and HIRS data were assimilated only in regions judged to be cloud-free, and SSM/I data were assimilated only in regions judged to be rain-free. Background forecasts in these regions were drier than indicated by the data, and moistening increments resulted. The problem of excessive rainfall arose in part from the way the humidity analysis spread increments in the horizontal, which not only moistened regions that the data indicated were too dry, but also added moisture in neighbouring regions that were already close to saturation, increasing rainfall there. It is also likely that the resulting excess latent heating in moist regions increased the tropical circulation, producing additional drying in regions of descent that in turn led to additional moistening by the data assimilation. As rainfall was enhanced where it tended to occur naturally, the overall patterns of wet and dry regions appear to be realistic, both climatologically and for seasonal anomalies (Betts and Beljaars 2003). The global average, however, shows an unrealistic excess of precipitation over evaporation (Hagemann *et al.* 2005).

Larger rainfall rates from the second half of 1991 onwards in ERA-40 were due in part to effects of volcanic aerosols on HIRS infrared radiances following the eruption of Mt Pinatubo. These effects were not included directly in the forward radiative transfer model used in the variational analysis. Instead they needed to be absorbed into the bias corrections applied to the radiance measurements. This was a particular problem for data from the NOAA-12 satellite as it became operational close to the time Mt Pinatubo erupted. Inadequately corrected infrared radiance biases tend to result in humidity changes in the tropical troposphere, since the relatively low background errors in temperature force analysis changes to be predominantly in humidity. 1991 was a difficult year in this regard because there were no data available from two SSM/I channels, which reduced a control on the humidity analysis. In the light of experience, a revised thinning, channel selection and quality control of HIRS radiances was implemented from 1997 onwards in the first production stream, and this was also used for assimilation of all HIRS data prior to 1989 in the third stream.

Comparisons of ERA-40 products with retrievals from microwave data available since 1979 are presented in Fig. 16. It shows time series of analysed and 24-hour forecast values of TCWV averaged over the tropical oceans, and corresponding mean precipitation rates derived from forecasts to 6 hours ahead (from 00, 06, 12 and 18 UTC start times) and from forecasts from 24 to 36 hours ahead (from 00 and 12 UTC). Also plotted are corresponding tropical oceanic averages of gridded monthly mean retrievals from SMMR data for the period 1979–84 (Wentz and Francis 1992) and SSM/I data from July 1987 onwards (Wentz 1997; Wentz and Spencer 1998). SMMR data were not assimilated in ERA-40. Some of the radiance data from rain-free regions used to produce the SSM/I retrievals were assimilated in ERA-40 but via quite different processing. Estimates of precipitation rates from the GPCP (Adler *et al.* 2003) are also plotted.

Figure 16 shows very similar month-to-month and year-to-year variations in the analyses and SSM/I retrievals of TCWV, but the analyses are moister than the retrievals from 1991 onwards. The fit to retrievals is as good for the 24 h forecasts as for the analyses prior to 1991, and is clearly better thereafter for the forecasts. There is an 88% correlation between the time series of the 24 h forecasts and SSM/I retrievals of TCWV, and an 83% correlation between the analyses and retrievals. ERA-40 values are also in quite good agreement with the SMMR retrievals. Analysed values are larger than

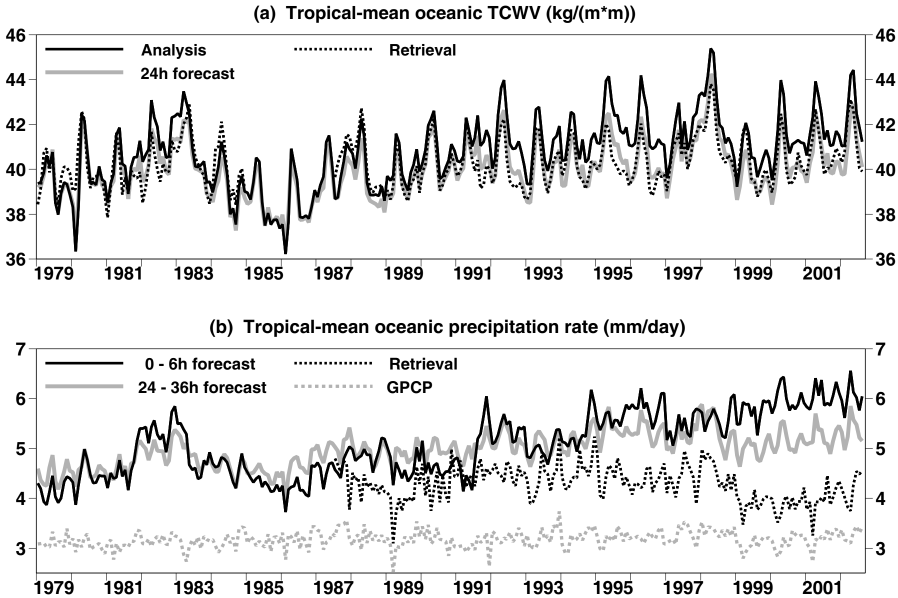

Figure 16. Monthly averages of: (a) TCWV (kg m^{-2}), and (b) precipitation rate (mm d^{-1}) averaged over oceans in the tropical belt from 23.5°N to 23.5°S from January 1979 to August 2002. Values for TCWV are presented for the ERA-40 analysis (black; based on averaging fields for 00, 06, 12 and 18 UTC) and 24 h forecasts (grey solid; based on values available for 00 and 12 UTC). Corresponding precipitation rates are based on accumulations from four-times daily forecasts from 0 to 6 h ahead (black) and from twice daily accumulations for the forecast range 24 to 36 h (grey solid). Also plotted are: retrievals from SMMR data (black dotted, from 1979 to 1984; downloaded from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology); SSM/I data (black dotted, from July 1987 onwards; all-satellite averages of version-5 retrievals downloaded from Remote Sensing Systems); and GPCP estimates (grey dotted). (See appendix A for acronyms.)

SMMR values for much of 1982 and the first half of 1983, which may be related to an uncorrected effect of aerosol from the volcanic eruption of El Chichón on the HIRS radiances. The 24 h forecasts fit the SMMR data well during this period. Both analysed and forecast values are lower than SMMR values for a spell beginning in mid-1979 and in 1984. Further discussion of the comparison of TCWV analyses and retrievals is given by Allan *et al.* (2004).

The precipitation rate for the 24–36 h forecasts remains at about 5 mm d^{-1} throughout the SSM/I period, whereas the rate for the 0–6 h forecasts increases from below 5 mm d^{-1} prior to mid-1991 to around 6 mm d^{-1} towards the end of the period. The time series of the 24–36 h forecast precipitation has a 35% correlation with the corresponding times series of SSM/I retrievals; the correlation is –9% for the 0–6 h forecasts. The 0–6 h and 24–36 h precipitation rates are similar for a while following the change in usage of HIRS radiances at the beginning of 1997, but the 0–6 h rate increases in 1998 when radiances from a third HIRS instrument begin to be assimilated, followed by use of data from a second SSM/I instrument from 1999 onwards.

The precipitation rate from the 24–36 h forecasts, though generally smaller than from the 0–6 h forecasts beyond 1991, is nevertheless higher than from the SSM/I retrievals. TCWV accordingly drops to lower values later in the 10-day forecasts that have been run from the ERA-40 analyses, as precipitation rates become more similar to the retrieved values. TCWV averaged over all 10-day forecasts from 1996 to 2001 is 39.4 kg m^{-2}. The corresponding mean precipitation rate over the final

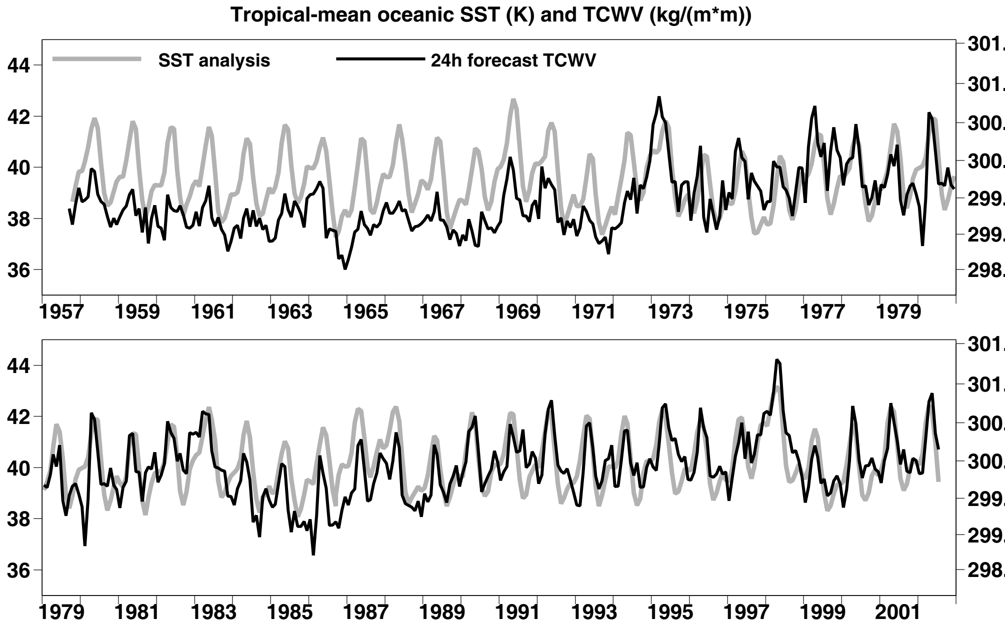

Figure 17. Monthly averages from 1957 to 2002 of 24 h forecast TCWV (black; kg m^{-2}; left-hand scale) averaged over tropical oceans, and the mean tropical SST used in ERA-40 (grey; K; right-hand scale). The temperature scale is linear in saturation specific humidity for a reference surface pressure of 1013.25 hPa, and chosen to make the mean and standard deviation of the two time series equal for the SSM/I period from July 1987 onwards. (See appendix A for acronyms.)

12 hours of the forecasts is 4.4 mm d^{-1}, similar to the SSM/I retrievals though higher than GPCP rates. The correlation between the GPCP and SSM/I time series is 65%. The 24–36 h rate from ERA-40 has a 34% correlation with GPCP, similar to that with SSM/I.

Variations in the 24 h forecast TCWV averaged over tropical oceans during the SMMR and SMM/I periods correlate well with variations in the tropical-mean SST analyses used in ERA-40. This is shown in Fig. 17, where time series are presented for the whole of the re-analysis period. The figure shows that relatively low values of TCWV occur prior to assimilation of the first satellite data at the beginning of 1973, and the comparison of these values with the SST time series and with TCWV later in the period suggests that the amplitude of the annual cycle of TCWV is underestimated in the early period, with particularly low values from March to May each year. The TCWV time series matches the SST series well from 1973 to 1978, giving some confidence in ERA-40's extraction of humidity information from the VTPR radiances. TCWV is lower than suggested by SST in late 1979, early 1980 and in 1984, consistent with the comparison with SMMR data. The comparison with SST suggests that too dry ERA-40 values extend from 1984 until 1988.

The conclusion from the results presented here and by Andersson *et al.* (2004) is that the assimilation of satellite data improves the water-vapour content over tropical oceans in ERA-40, particularly as depicted by the short-range forecasts. This comes at the expense of high initial precipitation rates and lack of balance between precipitation and evaporation as the forecast model shifts to its preferred, drier state. Bengtsson *et al.* (2004a) concluded, from an observing system experiment for single winter and summer seasons, that the ERA-40 assimilation system was able to generate a credible global

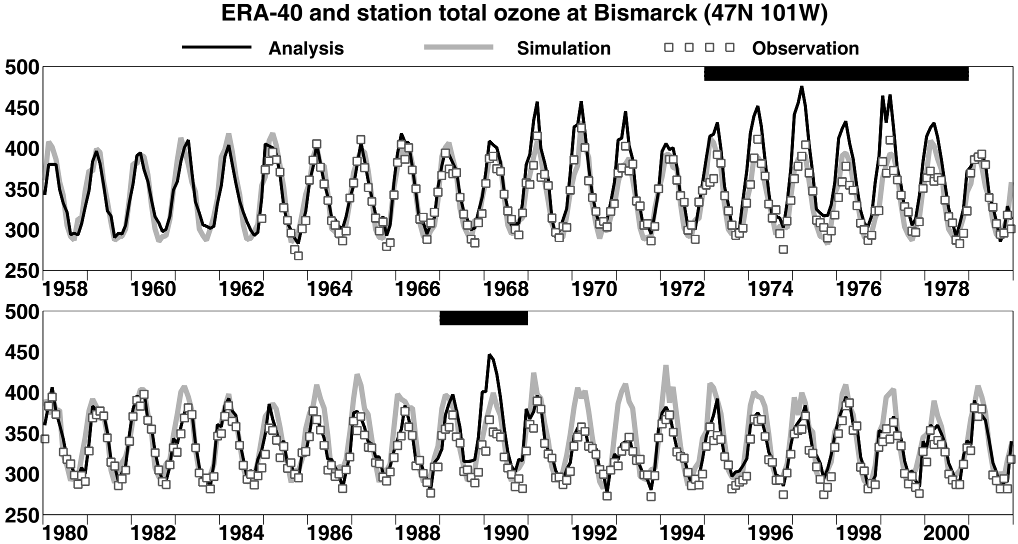

Figure 18. Monthly mean values from 1957 to 2002 of total column ozone (Dobson units) computed from ground measurements (squares) at Bismarck, North Dakota (47°N, 101°W; data from NOAA/CMDL), with corresponding values from the ERA-40 analysis (black) and simulation (grey). Horizontal bars indicate periods when VTPR or TOVS radiance data, but no ozone data, were assimilated. (See appendix A for acronyms.)

hydrological cycle without the use of humidity observations. Whilst the hydrological cycle of the 6 h ERA-40 forecast would have been closer to physical balance from 1973 onwards had humidity observations not been assimilated, this would have been achieved with an atmospheric water-vapour content that was biased low in the Tropics, especially in boreal spring. This has been confirmed by several observing-system experiments. For example, repeating 1992 without HIRS radiances (but still using SSM/I data) gave the largest impact in April, when the mean analysed TCWV over the tropical oceans was reduced by 1.1 kg m^{-2}. Bengtsson *et al.* (2004b) show that removing satellite data results in drier analyses that are in poorer agreement with independent ground-based GPS measurements.

(*b*) *Stratospheric biases and the Brewer–Dobson circulation*

Use of the 3D velocity fields from ERA-40 to drive long-term chemical transport models has been found to produce an ‘age of air’ in the stratosphere that is much too young (van Noije *et al.* 2004), indicating that the Brewer–Dobson circulation in the ERA-40 data assimilation is considerably too strong. Examination of several of the ERA-40 products confirms this.

Figure 18 compares time series of total column ozone from (non-assimilated) ground-based measurements at Bismarck, North Dakota, with two sets of values from ERA-40. The latter are the analysed values and values from a free-running ‘AMIP-style’ simulation of the atmosphere over the ERA-40 period, which was carried out using a model version identical to that used for the ERA-40 data assimilation apart from suppression of the trend in chlorine loading in the parametrization of ozone depletion by heterogeneous chemistry. Ozone retrievals from TOMS and SBUV satellite measurements were assimilated in ERA-40 from 1979 to 1988 and from 1991 to 2002; for these years the ERA-40 analyses match well the independent ground-based measurements, capturing interannual variability although with a small general underestimation of summertime minima. The simulation produces higher winter maxima than analysed or observed from 1986 onwards, with the exception of 1989 and 1990.

The observations made at Bismarck in the 1960s and early 70s (when no ozone data were assimilated) are also reproduced well, by the simulation as well as the analysis in this case, with a slight overestimation of maxima in the analyses from 1968 onwards. The largest observed value in the sequence occurs in 1970, and is matched quite well by both the analysis and the simulation. Analysed SST and sea-ice distributions as used in the ERA-40 data assimilation were specified in the simulation, which accordingly reproduces some aspects of interannual variability (Simmons *et al.* 2004). Braesicke and Pyle (2004) have shown in a modelling study that stratospheric extremes in dynamics and ozone can be associated with anomalous SST.

Figure 18 shows that the analyses overestimate late-winter maxima at Bismarck for the period from 1973 to 1978 and in 1989/90, when either VTPR or TOVS radiance data were assimilated to adjust stratospheric temperatures but no ozone data were assimilated. The analysed values for these years are also higher than seen in the simulation. Dethof and Hólm (2004) show similar overestimation of late-winter maxima at Barrow, Alaska, for these years. The indication from these results is that wintertime ozone transport is too strong in the ERA-40 assimilation cycles when radiance data influence the stratospheric analysis, but that its effect is compensated when the TOMS and SBUV retrievals are assimilated (at least as regards the total column value).

The too strong Brewer–Dobson circulation is seen more directly in a too rapid 'tape-recorder' effect in tropical stratospheric humidity (Oikonomou and O'Neill 2005). No change to the stratospheric humidity was made by the ERA-40 analysis other than removal of any supersaturation, so its distribution was determined primarily by tropospheric exchange, by the upper-level moistening due to parametrized methane oxidation and by advection in the sequence of 6 h background forecasts, with some loss due to precipitation in the cold polar night. Relatively dry air introduced at the tropical tropopause in boreal winter, and relatively moist air introduced in boreal summer, were transported upwards in data assimilation cycles to reach above 10 hPa in well under a year. Simulations with the ECMWF model, using either an earlier version (Simmons *et al.* 1999) or the ERA-40 version, tend to produce rather fast upward transfer in the Tropics, but transfer is much faster still in the ERA-40 data assimilation, and the annual cycle is much less attenuated in the vertical. Again, the problem is most marked for years when radiance data were assimilated.

Figure 19(a) shows time series from 1987 to 2001 of monthly mean specific humidity at the equator for the model level closest to 30 hPa, from the analyses and the simulations. Stronger ascent in the data assimilation than in the simulation gives rise to a generally drier analysed lower and middle stratosphere, a larger annual cycle and a shift of 3 to 4 months in the phase of the annual cycle. Confirmation that it is stronger upward transport, rather than small-scale mixing of humidity, that causes this behaviour is presented in Fig. 19(b), which shows the 12-month running mean of the analysed equatorial humidity and the corresponding running mean of the analysis increment in temperature. If ascent is too strong, the associated cooling (if not balanced radiatively) must be balanced in the data assimilation cycles by a net warming from observations. This is indeed the case, with a yearly average temperature increment every 6 hours that varies between 0.1 and 0.3 K over the period shown. Moreover, there is a tendency for the temperature increment to be out of phase with the humidity; when ascent is relatively strong the stratosphere at this level is drier, and there are larger balancing temperature increments. An exception occurs in 1997 and 1998 when the variation in humidity at

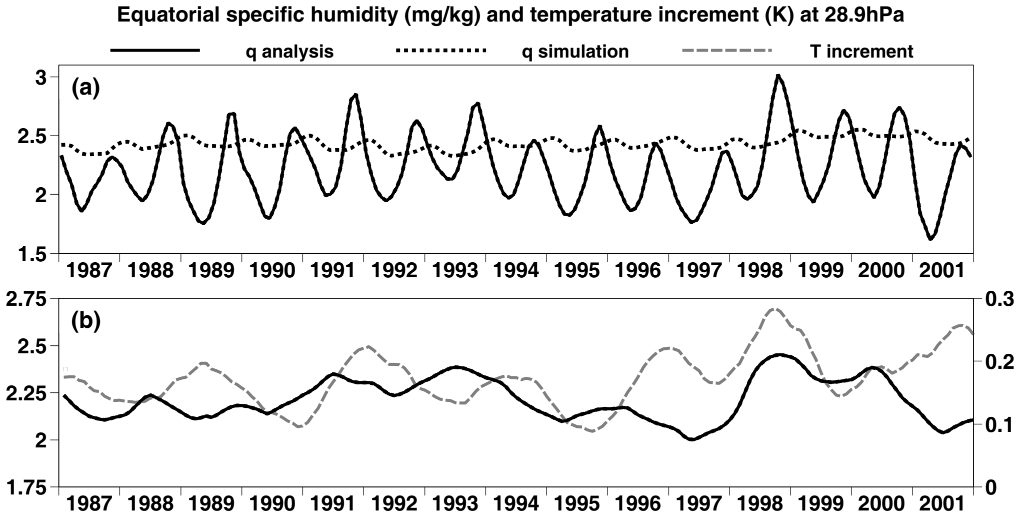

Figure 19. Time series from 1987 to 2001 for model level 19, located close to 28.9 hPa, showing: (a) monthly mean ERA-40 analysed (black solid) and simulated (black dotted) values of specific humidity (q, mg kg^{-1}), and (b) 12-month running means of the analysed specific humidity (black solid, left-hand scale) with temperature analysis increments (T, grey dashed; K, right-hand scale).

30 hPa follows unusually strong drying then moistening of the lowermost stratosphere. This may be a response to the strong El Niño event that occurred at the time, but it appears to be unrealistic, as it is not confirmed by satellite measurements (Oikonomou and O'Neill 2005). The excessive precipitation in background forecasts is in any case likely to limit the realism of moisture transport into the stratosphere from the tropical troposphere.

Underestimation of the age of stratospheric air when using winds from a data assimilation system, rather than from a free-running version of the assimilating model, is not unique to the ERA-40 system. For example, it has been discussed in some detail by Douglass *et al.* (2003), Schoeberl *et al.* (2003) and Tan *et al.* (2004) for a NASA Goddard system. In particular, Tan *et al.* (2004) concluded that the problem arose in the NASA system through unrealistic eddy motion originating locally from the assimilation of radiosonde observations in the tropical lower stratosphere. In ERA-40 the problem becomes particularly pronounced when satellite radiance data are assimilated, and it is likely that the too strong meridional circulation is forced primarily by the large temperature corrections made repeatedly to compensate for bias in the background model at upper levels. Further diagnosis has not been carried out for the ERA-40 system; instead the issue is being investigated in the context of a revised version of the data assimilation system being developed for future re-analysis activities.

7. Some other aspects of the quality of the ERA-40 analyses

Several other aspects of the quality of the ERA-40 analyses merit discussion. The summaries presented below are largely based on ECMWF's monitoring of production and on the results of validation studies carried out either by ECMWF's formal partners in the ERA-40 project or by collaborators from the polar and stratospheric research communities.

TABLE 3. PERCENTAGE DETECTION RATE FOR TROPICAL CYCLONES, COMPARING ERA-40 ANALYSES WITH A BEST-TRACK DATASET FOR DIFFERENT EPOCHS OF THE OBSERVING SYSTEM

	1958–66	1967–72	1973–78	1979–90	1991–2001
Northern hemisphere	94	95	94	93	96
Southern hemisphere	75	82	91	95	97

(*a*) *Synoptic systems*

Reassurance as to the basic synoptic quality of the ERA-40 analyses for the extra-tropical northern hemisphere early in the period was provided by subjective comparison of synoptic maps from ERA-40 analyses and forecasts with published contemporary analyses, such as those for conditions at the time of the Windscale nuclear accident in October 1957 (Crabtree 1959) and the launch of the first meteorological satellite in April 1960 (Fritz and Wexler 1960). Jung *et al.* (2004, 2005) present specific examples for the devastating Hamburg storm of February 1962, and from an additional assimilation using the ERA-40 system for a period leading up to the even more destructive North Sea storm that occurred on the night of 31 January to 1 February 1953.

Objective tracking was applied by Hodges *et al.* (2003) to fields indicative of mid-latitude storm-tracks, using data from ERA-15, later operational ECMWF analyses and re-analyses from other centres. One surprising result was the small number of upper-tropospheric tracks found in winter in the western North Pacific in fields such as vorticity and potential vorticity from ERA-15. Results from the later operational analyses showed behaviour more similar to that in the other datasets, and it has been confirmed (following encouraging first results reported by Hodges *et al.* (2003)) that the ERA-40 version of the analysis system has performed much more satisfactorily than the ERA-15 version in this region. ERA-40 has also been found to give much more coherent tracks of African easterly waves from their source region near the Ethiopian Highlands. The merging, near the West African coast, of the deep moist cyclonic structures with shallow heat-lows from North Africa is also well captured. Other regions of the Tropics also show significant improvements in the coherence between the consecutive analyses in ERA-40. Hoskins and Hodges (2005) report new insights from application of ERA-40 data to characterize storm tracks in the southern hemisphere.

Table 3 summarizes results of a comparison of the tropical cyclones in ERA-40 with those in an independent best-track dataset (Neumann 1993). It shows a detection rate above 90% in the northern hemisphere throughout the period. The figure for the southern hemisphere exceeds 90% from 1973 onwards, after PAOB and VTPR radiance data begin to be assimilated.

(*b*) *Temperature trends*

The utility of re-analyses for helping to document and understand climatic trends and low-frequency variations is a matter of some debate. Problems arise partly because the atmospheric models that carry the assimilated observational information forward in time have biases. If observations are abundant and unbiased, they can correct the bias of a background model when assimilated. In reality, however, observational coverage varies over time, whilst observations are themselves prone to bias and these biases change over time. This introduces trends and low-frequency variations in analyses that are mixed with the true climatic signals. ERA-40 is no exception, as shown for example by Simmons *et al.* (2004), who present a variety of evidence pointing to a cold tropospheric bias in the ERA-40 analyses for the extratropical southern hemisphere in the pre-satellite years, contributing to the too large global-mean warming trend noted by Bengtsson *et al.* (2004b).

The ERA-40 analyses, nevertheless, clearly have a role to play in studies of trends and low-frequency variations, especially for the period from 1979 onwards. Simmons *et al*. (2004) compare monthly mean anomalies in surface air temperature from ERA-40 with values from station climate data, and discuss some aspects of consistency of analyses in the vertical. Santer *et al*. (2004) show reasonable agreement between estimates of layer-mean tropospheric and lower-stratospheric temperature changes from ERA-40 and independent processings of the microwave radiance record (see also Bengtsson *et al.* 2004b). They also show consistent evolution of tropopause height between ERA-40 and climate-model simulations that include anthropogenically influenced change. These studies have also shown a clear improvement of ERA-40 over the earlier NCEP/NCAR re-analysis. Simmons *et al*. (2004) also discuss how both re-analyses have helped identify erroneous station data in the near-surface temperature climate record. For radiosondes, Haimberger (2005) has used inhomogeneities in the fit of the ERA-40 background forecasts to data from individual stations to derive corrections for biases in the earlier data, improving the radiosonde database both for direct analysis of trends and for use in future re-analyses.

(*c*) *Other aspects of the hydrological cycle*

In contrast to the situation over tropical oceans discussed earlier, precipitation in the 0–6 h ERA-40 forecasts tends to be lower than GPCP values over the extratropical oceans, and increases (spins up) as the forecast range increases (Kållberg 2002; Betts and Beljaars 2003; Hagemann *et al.* 2005). Biases and spin-up over land and sea-ice vary from region to region and over time as the observing system evolves. Specific examples can be found in studies for French Alpine stations (Martin 2004), for polar regions (Bromwich *et al*. 2002; Genthon 2002; Serreze and Etringer 2002) and for the Mackenzie (Betts *et al.* 2003b), Mississippi (Betts *et al.* 2003a) and Amazon (Betts *et al.* 2005) river basins. Results for a wider set of river basins are presented by Hagemann *et al.* (2005), who note that evapotranspiration is higher than estimated from precipitation and discharge measurements for many of the catchments. Realistic inferred changes in terrestrial water storage for the Mississippi basin derived from analysed water-vapour fluxes and changes in atmospheric water content are discussed by Seneviratne *et al.* (2004), while Déry and Wood (2004) use ERA-40 data to identify a linkage between the Arctic oscillation and variations in the river discharge into Hudson Bay. Li *et al*. (2005a) report comparisons of soil moisture with data for China, showing generally better results from ERA-40 than from either the original NCEP/NCAR re-analysis or the second version carried out from 1979 onwards (Kanamitsu *et al.* 2002). For the atmosphere, 7-day back-trajectories derived from ERA-40 wind analyses have been shown to give consistent pictures for the origins of dry tropospheric layers identified in tropical radiosonde ascents (Cau *et al.* 2005), while back trajectories from the 400 K surface have been used to study the upward transfer of moisture across the tropical tropopause (Fueglistaler *et al*. 2005).

(*d*) *Stratospheric temperature and wind structure*

Biases in the background model fields are relatively large at the highest model levels; at these levels there is also marked inhomogeneity over time in data coverage, with no data assimilated early in the period and increasing coverage and data quality subsequently from the VTPR, SSU and AMSU-A instruments. The effect of an error in the bias correction of the VTPR data from the NOAA-4 satellite during 1975 and the first half of 1976, seen in studies of tropospheric and lower-stratospheric temperature trends (Santer *et al.* 2004; Simmons *et al.* 2004), is particularly evident in upper-stratospheric temperatures. Assimilation of upper-stratospheric temperature information was also especially problematic in those periods (from 1987 to 1997 in particular) when data were available from only one SSU instrument in sun-synchronous orbit, as it was difficult for the data assimilation system to distinguish a background error in the semi-diurnal tide from an overall bias in the background forecast. Compared with the consensus of climatologies examined by Randel *et al.* (2004), the upper-stratospheric temperatures from ERA-40 are generally biased warm by several K early in the re-analysis period, then oscillate substantially in the middle of the period as data availability varies and radiance-bias adjustments change, and are biased cold by up to 5 K later in the period. There is also a pronounced ($\sim$10 K) cold bias in winter and springtime analyses in the Antarctic lower stratosphere in the early years, evident from comparison with later ERA-40 analyses and other climatologies. Later in the period there is an unrealistic oscillatory temperature structure in the vertical in polar regions, predominantly in winter and spring, and especially strong in the final years when both SSU and AMSU-A data were assimilated. Although the core problems lie in the biases of the background model and the inadequacy of data coverage for much of the period, inadequacies of the data bias-correction and analysis system also contribute to the deficiencies of the end product.

Despite these problems, radiosonde coverage over the northern hemisphere appears to provide analyses of sufficient accuracy for quite skilful prediction of stratospheric warming events throughout the period, beginning with the case in January 1958 as judged by comparison with the contemporary analyses of Teweles and Finger (1958) and Scherhag (1960). The observations collected for ERA-40 and the resulting analyses have also helped place in context the remarkable split of the Antarctic polar vortex that occurred in September 2002 (Simmons *et al.* 2005). Verification of the tropical wind fields shows a consistent representation of the QBO throughout the period, with good fit to the assimilated radiosonde data and generally coherent longitudinal structure. For example, Randel *et al.* (2004) show that the amplitude of the QBO in the ERA-40 analyses for 1989–95 matches radiosonde observations from Singapore and rocketsonde data better than other processed datasets. ECMWF's own monitoring for the earliest years showed that the analyses, both locally and in the zonal mean, closely fitted the radiosonde data from Canton Island (Simmons 2004), the earliest of which had in fact helped lead Ebdon (1960) and Reed (1962) to discover the QBO. Randel *et al.* (2004) also show reasonable agreement between the ERA-40 analyses and a climatology of rocketsonde data for the semi-annual oscillation of winds at 1 hPa.

(*e*) *Upper-stratospheric humidity*

The stratospheric humidity fields from the first few years of ERA-40 production (from 1989 onwards) were found to be generally drier than the short-term climatology derived from UARS data by Randel *et al.* (1998). This arose not only from the excessive transport of dry air from the tropical troposphere discussed previously, but also from insufficient high-level moistening by methane oxidation. The parametrization of this process used in the assimilating model was based on relaxation towards a value of 6 ppmv for water vapour around the stratopause, and this was held fixed as it was felt premature to introduce a trend in methane in this relatively new parametrization. The value of 6 ppmv was based on publications earlier than that of Randel *et al.* (1998), whose results clearly indicate that a value more than 10% higher would have been appropriate for recent years. As tropospheric methane is estimated to have increased by 6% over the decade 1984–94 (Houghton *et al.* 1996) the value of 6 ppmv used for ERA-40 appears to have been a reasonable compromise, being appropriate to the middle years of the re-analysis period. The early results from ERA-40 were nevertheless used to justify a change to ECMWF's operational system, in which the relaxation value was increased to 6.8 ppmv in April 2002.

(*f*) *Snow cover*

Time series of global-mean snow mass exhibit low values from 1992 to 1994 due to an error in the snow analysis. Analyses from 1989 to 1997 suffer to a lesser degree from a miscoding by ECMWF of Canadian snow-depth observations that moved some observation dates to later within the month of observation. Limitations in observational coverage prior to 1976 have been noted in section 2.

(*g*) *Arctic analyses 1989–96*

A cold bias from 1989 onwards in the lower troposphere over ice-covered oceans in both the Arctic and the Antarctic was identified by Bromwich *et al.* (2002) in the analyses from the first production stream. This was subsequently found to have arisen from the assimilation of HIRS radiances. The changes to the thinning, channel-selection and quality control of the infrared data introduced to reduce the tropical precipitation bias also virtually eliminated these cold polar biases. This was effective for the analysis of HIRS data from 1997 onwards in the first production stream, and from 1979 to 1988 in the third production stream.

(*h*) *Radiation budget*

A specific component of the validation activities was devoted to aspects of the radiation budget. Allan *et al.* (2004) show that the clear-sky radiation budget simulated by ERA-40 compares well with independent satellite data, especially when effects of satellite sampling are taken into account. This provides independent overall validation of the temperature and humidity analyses. The agreement in TCWV between ERA-40 and microwave satellite data, discussed earlier, indicates that surface downwelling clear-sky long-wave fluxes are likely to be of high quality. While observed cloud fields away from stratocumulus regions are reasonably well captured, the radiative properties of cloud, which relate more to model parametrization than to the quality of the basic re-analysis fields, are not as well simulated, leading to a poor all-sky radiation budget. In particular, there is a net cooling imbalance at the top of the atmosphere of about 7 W m^{-2}, most likely due to over-reflective model cirrus clouds. Nevertheless, careful use of dynamical fields from ERA-40 to sub-sample observed all-sky radiation fields from satellite data offers a powerful tool for evaluating cloud properties in climate models (Ringer and Allan 2004). 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 but also because the clear-sky sampling inconsistency between models and data would be circumvented.

(*i*) *Ocean waves*

ERA-40 provides the first re-analysis dataset in which an ocean-wave model has been coupled to the atmospheric model. Moreover, it provides the longest and most complete wave dataset available. The ocean-wave products were thus another specific

TABLE 4. CORRELATION (%) BETWEEN ALTIMETER MEASUREMENTS AND MODEL VALUES OF SEA LEVEL FROM 1 JANUARY 1993 TO 31 DECEMBER 2001

	West Pacific	East Pacific	Atlantic Ocean	Indian Ocean
ERA-40	85	96	70	79
ERA-15/Operations	76	93	43	73

Results are shown for model values forced by fluxes from ERA-40 and from a combination of ERA-15 and ECMWF operations, for four tropical regions.

area chosen for validation and exploitation studies. Comparison with other ocean-wave re-analyses are reported by Caires *et al.* (2004); differences in recent years occur mostly in the Tropics, and they are also significant in the southern hemisphere prior to the mid-1980s. The ERA-40 wave data are of lower quality from December 1991 to May 1993; this was found to be due to the assimilation of faulty 'Fast Delivery Product' ERS-1 wave height data extracted from the ECMWF archives.

Comparisons of significant wave height and wind speed from ERA-40 with buoy, ERS-1, and TOPEX altimeter measurements, show that the ERA-40 products underestimate high values of significant wave height and to a lesser extent wind speed (Caires and Sterl 2003). A corrected version of the significant wave height dataset has been derived using a non-parametric method that estimates the bias between significant wave height ERA-40 data and TOPEX altimeter measurements. Comparing the corrected data with measurements both from buoys and global altimetry shows clear improvements in bias, scatter and quantiles across the whole range of values (Caires and Sterl 2005b). Corrections based on buoy data were implemented by Caires and Sterl (2005a) in estimating 100-year return values, including examination of decadal variability. A variety of maps based on these studies are included in the web-based ocean-wave atlas referred to earlier (Sterl and Caires 2005).

(*j*) *Ocean circulation and seasonal forecasting*

Production of the ERA-40 analyses enabled Palmer *et al.* (2004) to carry out an extensive study of seasonal prediction in a collaborative EC-funded project (DEMETER) in which output from a number of coupled atmosphere–ocean models was combined. The ERA-40 analyses provided the initial atmospheric and land-surface conditions for the forecasts, and also the ocean-surface fluxes used to force the ocean models to produce initial ocean conditions for the forecasts. ERA-40 also provided data for the validation of the predictions, both directly in terms of meteorological fields and via crop-yield and disease models driven by ERA-40 and forecast products. Initial tests of the ECMWF coupled system used in DEMETER compared the use of ERA-15 and ERA-40 ocean-forcing fluxes; better results were found for ERA-40.

A quantitative indication of improved ocean analysis using fluxes from ERA-40 is given in Table 4. The ocean-model component of the ECMWF seasonal forecasting system has been forced using fluxes from ERA-40 for the period from January 1993 to December 2001, and the resulting analyses of sea level have been compared with independent satellite altimeter data for the period. The same has been done but with forcing from a combination of fluxes from ERA-15 for the beginning of the period and ECMWF operations for the remainder. Table 4 shows that correlations with altimetry are higher in the case of forcing by ERA-40 fluxes across the equatorial oceans. Correlations are higher for other regions also; the ERA-40 fluxes produce a poorer estimate of sea level only over the South Atlantic.

8. CONCLUSIONS

The data assimilation system used for ERA-40 was based on the software version of the ECMWF data assimilation and forecasting system that was made operational in mid-2001, although it included some changes and components that did not become operational until 2002. Some developments had to be made specifically for ERA-40: to adapt the system for 3D- rather than 4D-Var data assimilation and for the lower horizontal resolution of the assimilating model; to cater for assimilation of older types of data; and to introduce a more extensive range of output products. The changes made to the operational system over the 6 years since it formed the basis for the ERA-15 re-analysis brought significant improvements to the accuracy of operational analyses and forecasts (Simmons and Hollingsworth 2002), and many of these changes apply to ERA-40. Several results presented in this paper, or in studies cited here, have demonstrated that the ERA-40 re-analysis does indeed provide products that are better, in most respects, than those from the first-generation ERA-15 and NCEP/NCAR re-analyses.

Monitoring the ERA-40 data assimilation was a critical task. It enabled many problems to be detected and corrected during production. Others could not be corrected, either because they were not detected quickly enough to rerun the problematic period of assimilation, or because a solution to the problem was not available at the time. Two major problems in the latter category—excessive precipitation over tropical oceans and a too strong Brewer–Dobson circulation—have been discussed in this paper. They may be remedied to a degree by choosing to work with forecast products for ranges beyond 6 hours, and bias correction may be a further option for some applications, as discussed, for example, by Troccoli and Kållberg (2004).

Many results from ERA-40 show that there has been a long-term improvement in the observing system, confirming the picture provided by the NCEP/NCAR and ERA-15 re-analyses. This is especially so for the southern hemisphere, where analyses clearly benefited from introducing satellite data in 1973 and improved more substantially due to the changes made to the observing system late in 1978 in the build-up to FGGE. This is shown not only by results such as the fits to surface data and forecast verification presented here, but also by other comparisons of ERA-40 and station data and by closer agreement between the ERA-40 and NCEP/NCAR re-analyses from 1979 onwards (Bromwich and Fogt 2004; Simmons *et al.* 2004; Sterl 2004). Improvement since 1979 has also been larger for the southern than the northern hemisphere. Analyses for the northern hemisphere benefit from the availability of radiosonde data from the ocean weather ships in the pre-satellite years, and more generally from the extent of radiosonde data coverage over the continental land masses. They are sufficiently accurate throughout the re-analysis period to yield forecasts that remain skilful well into the medium range.

Simmons *et al.* (2004) discuss how ERA-40 suffers from significant gaps in the coverage of synoptic screen-level data available for assimilation prior to 1967. Additional retrieval of pre-1967 data from national or other holdings would be of benefit to future re-analyses. Benefit is also likely to be derived from better correction of biases in the earlier radiosonde data and from the collection of additional such data. Nevertheless, much of the increase in operational analysis and forecast accuracy over the past 25 years has stemmed not from improvements to the observing system but from improvements to data assimilation, both in the model and the analysis components. Better data assimilation enables more information to be extracted from observations already available for re-analysis, and was a key factor in the improvement of ERA-40 over earlier re-analyses. It is known from the performance of ECMWF's current operational system that better analyses than those produced in ERA-40 are already achievable given sufficient computational resources; further improvement of data assimilation, including better handling of biases, remains a priority for numerical weather prediction centres. Future advances in the quality of re-analyses for the past four or five decades are more likely to arise from better data assimilation systems than from collecting additional data. Analyses that go further back in time may well require alternative approaches to assimilation (Whitaker *et al.* 2004) as well as efforts to recover more data.

Effort is not being invested in the maintenance needed to keep the ERA-40 data assimilation system running on newer computer systems and with newer observations. It is being devoted instead to development of a new re-analysis system derived from the latest operational version of the ECMWF assimilation system. Tests to date indicate that several of the problems experienced in ERA-40 will be eliminated or significantly reduced, most notably the too strong tropical oceanic precipitation and Brewer–Dobson circulation. This new re-analysis system will not be used for a comprehensive extended new re-analysis, but will be used to produce an 'interim' re-analysis that will be run from 1989 onwards and carried into the future in close to real time. This interim re-analysis will provide the basis for testing new versions of the assimilation system in the re-analysis context and, in particular, will provide the basis for extending the assimilation system to produce analyses of additional atmospheric constituents. Allied with further work on the older conventional observational data, this should lead to a capability for an extended re-analysis to succeed ERA-40 towards the end of this decade. Until then, ERA-40 will be the main ECMWF re-analysis product, to be compared with emerging products such as those from JRA-25, the 25-year re-analysis currently being carried out in Japan (see http://www.jreap.org).

Many of the known strengths and weaknesses of ERA-40 have been outlined in this paper. Appreciation of them is required in order to exploit products to the full. Despite some shortcomings, the ERA-40 analyses and related forecast information have considerable potential to contribute to studies of atmospheric, oceanic and land-surface processes, and to studies of the variability and predictability of climate, especially for the period from 1979 onwards for which there is good global observational coverage. Examples have been given of how this potential is beginning to be realized.

Acknowledgements

ERA-40 benefited from the work of many people not included in the list of authors, some active at ECMWF in the general development of the forecasting system and others active elsewhere in the validation of experimental and production analyses. Others helped with advice and data during the planning of the project. The production phase of ERA-40 received significant funding from the European Commission through contract EVK2-CT-1999-00027. ERA-40 was supported by Fujitsu Ltd through provision of computational resources and by WCRP and GCOS through partial funding of planning and progress meetings. The Japan Meteorological Agency, the Institute for Atmospheric Physics of the Chinese Academy of Sciences and the US Program for Climate Model Diagnosis and Intercomparison seconded staff to work at ECMWF on ERA-40. NCAR is sponsored by the US National Science Foundation. Glenn White provided a constructive review of this paper.

APPENDIX A

Acronyms used

ACSYS	Arctic Climate System Study
AMIP	Atmospheric Model Intercomparison Project
AMSU	Advanced Microwave Sounding Unit
ATOVS	Advanced TIROS operational vertical sounder
BUFR	Binary Universal Form for Representation
COADS	Comprehensive Ocean Atmosphere Data Set
COARE	Coupled Ocean–Atmosphere Response Experiment
DEMETER	Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF Re-Analysis
ERA-15	A 15-year ERA starting from 1979
ERA-40	A 45-year ERA from September 1957 to August 2002
ERS	European Remote Sensing Satellite
ESA	European Space Agency
EUMETSAT	European organization for the Exploitation of Meteorological Satellites
FGGE	First GARP Global Experiment
GARP	Global Atmosphere Research Programme
GATE	GARP Atlantic Tropical Experiment
GCOS	Global Climate Observing System
GFDL	Geophysical Fluid Dynamics Laboratory
GMS	Geostationary Meteorological Satellite
GPCP	Global Precipitation Climatology Project
GTS	Global Telecommunication System
HIRS	High-resolution Infrared Spectrometer
IFS	Integrated Forecasting System
IGRA	Integrated Global Radiosonde Archive
IGY	International Geophysical Year
ISLSCP	International Satellite Land Surface Climatology Project
JRA	Japanese Re-Analysis
LMD	Laboratoire de Météorologie Dynamique
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OI	Optimal interpolation
PAOBS	Pseudo Surface Pressure Observations produced by Australia
QBO	Quasi-Biennial Oscillation
RMS	Root-mean-square
SBUV	Solar Backscattered Ultra Violet
SMMR	Scanning Multichannel Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
SST	Sea surface temperature
SSU	Stratospheric Sounding Unit
SYNOP	Surface Synoptic Observation
TAO	Tropical Atmosphere and Ocean
TCWV	Total column water vapour
TIROS	Television Infrared Observation Satellite
TOPEX	Topography Experiment
TOGA	Tropical Ocean Global Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
TWERLE	Tropical wind energy conversion and reference level
UARS	Upper Atmosphere Research Satellite (NASA)
VTPR	Vertical Temperature Profile Radiometer
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
xD-Var	x-dimensional variational analysis

APPENDIX B

The suppliers of observational data for ERA-40, the type of data, the original source where appropriate, and the period covered by the data are given in Table B.1. See appendix A for acronyms.

TABLE B.1. OBSERVATIONAL DATA SOURCES FOR ERA-40

Data supplier	Data type and suppliers' identifiers	Period
ECMWF	Operational GTS data: surface, radiosonde, pilot, dropsonde, profiler, aircraft and cloud motion winds	1979–2002
	FGGE Final Level 2b data	1979
	ESA/ERS scatterometer and altimeter data	1991–2002
	Level 1b radiances	
NCAR, ECMWF, LMD, NASA, NOAA	NOAA TOVS/HIRS/MSU/SSU	1979–2002
	Level 1c radiances	
NCAR	NOAA VTPR	1972–1978
ECMWF	NOAA ATOVS	1998–2002
Remote Sensing Systems, ECMWF	Defense Meteorological Satellite Program SSM/I	1987–2002
	Additional satellite cloud motion winds	
Japan Meteorological Agency	Separate supply of operational GMS data	1980–1993
EUMETSAT	Reprocessed Meteosat	1982–1988
NCAR/NCEP	Radiosonde and pilot	
	China	1957–1962
	Raobs	1957–1967
	Countries, US Control, France, Misc.	1957–1978
	Russia	1960–1978
	TD52	1960–1971
	TD53	1957–1969
	TD54	1957–1968
	ON20	1962–1972
	US Navy	1966–1973
	GATE/TWERLE	1974–1976
	USAF, ON29	1973–1978
	Surface	
	TD13, TD14, USSR	1957–1973
	USAF	1967–1976
	ON124	1976–1978
	Aircraft	
	Australian	1971–1978
	US Navy	1970–1978
	ON20	1962–1972
	Sadler	1960–1973
	Rean–1	1957–1961 1973–1978
	Cloud Motion Winds	
	ON20	1967–1972
	Rean–1	1973–1978
NCAR	COADS	1950–1999
	Snow dataset from former USSR	1966–1990
	Automatic Antarctic stations from Wisconsin University	1980–1998
Japan Meteorological Agency	Operational GTS data: radiosonde, pilot and aircraft	1975–1978 1980–1997
NCEP	Operational GTS data: surface, radiosonde, dropsonde, pilot, aircraft and cloud motion winds	1980–1994
US Navy	Surface, radiosonde, pilot and aircraft	1985–1996
Environment Canada	Canadian snow depths	1946–1995
British Antarctic Survey	Antarctic surface data	1947–1999
Australian Bureau of Meteorology	Australian Antarctic surface and radiosonde data	1947–1999
	PAOBs, derived from surface-pressure analyses for 1972–1978	1972–1993
Woods Hole Institute for Oceanography	Subduction buoys	1991–1993
Center for Ocean Atmospheric Prediction Studies	TOGA COARE dropsondes and radiosondes	1992–1993
Pacific Marine Environmental Laboratory	TAO-buoy array	1993–1995
NASA, NOAA, ECMWF	TOMS and SBUV ozone retrievals	1978–2002

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