MONITORING OF OBSERVATIONS AND ASSESSMENT OF OBSERVING SYSTEM PERFORMANCE IN THE REANALYSIS

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1. CONCEPT OF REANALYSIS

A reanalysis is a long data-assimilation performed with a fixed DA-system and maximum use of observations. The application of reanalyses expand to all areas of atmospheric research, where the accuracy of the numerical analyses is adequate. In operational applications the data-assimilation system experiences changes to its components; the data selection scheme, the analysis procedure or the assimilating forecast model. In normal circumstances a change is an improvement and is part of the "natural evolution" of a good forecasting system in an environment of increasing computer power and large quantities of both conventional and satellite data. A "fixed" DA-system should then reflect the real atmospheric variations. We know intuitively, and it will be shown later by how much, that the observing system undergoes constant changes. We also know that the weather regimes have slowly evolving components. Even if the observing system would be fixed, it is still irregular, and the time consistency of the analyses would not be perfect due to the variations in weather regimes. In reality the variations both in weather regimes and in the observing system occur simultaneously. The principle of using all observations and doing the best possible analysis with them has been adopted at ECMWF. Good quality boundary forcing fields have been used, since through the model physics they have a large influence on the analyses of free atmosphere especially over data sparse areas.

ECMWF has completed a fifteen year reanalysis ERA15, 1979-1993, and has undertaken the task of performing a 40 year reanalysis, 1958 up to the present day. The main features in the observation monitoring performed during the ERA15 production are described and a summary of the observing system performance during ERA15 is given. For more detailed evaluations see Uppala(1997) and Kållberg(1998).

2. ERA15 OBSERVATION MONITORING

2.1 Radiosonde monitoring and bias correction

In ECMWF operations a comprehensive system for the correction of systematic errors in radiosonde temperature and geopotential is used. It is based on the feedback information from the data assimilation and determines the corrections for individual radiosonde observations as a function of the solar elevation and instrument type. A simplified version of the scheme was adapted for ERA. During most of the reanalysis period the actual radiosonde type used is not available in the database. This is why the bias corrections were calculated for those WMO blocks where homogeneous radiosonde equipment were believed to have been used. Measurement-minus-first guess departures from the preceding twelve months were used to cover all the possible solar elevations. Only 20% of the calculated bias is applied to the observed height at 300hPa and 40% and 80% at 250hPa and above 200hPa levels respectively. In order to decide, which stations should be bias corrected, the analysis feedback information and monthly mean analysis increment (An-Fg) fields were monitored. A large mean increment can result from a model problem, from a systematic instrument error or from an error in observational practice. If the local station characteristics are not represented by the model e.g around steep orography, this can also result in large increments on nearby levels. After considering all these effects, areas with suspicious stations were added to the bias correction scheme, and individual stations with very large first guess deviations were added to the blacklist. The monitoring was applied both to the uncorrected and corrected observations so that the stations can be removed from the correction list and from the blacklist, when their quality improves. Consequently there was a continuously evolving radiosonde bias correction and blacklisting. The bias correction was more important during the first half of the reanalysis but then on with the improving quality of radiosondes it had gradually less importance.

2.2 TOVS radiances

2.2.1 1DVAR-retrieval and quality control

The TIROS Operational Vertical Sounder (TOVS) measures multi-spectral radiances, which are related to the temperature and humidity structure in the atmosphere. From these global data NOAA/NESDIS in Washington, D.C. has operationally produced atmospheric temperature and humidity profiles for the international community from 1979 with a similar method described by Smith et al. (1979).

Instead of using these retrievals, the ECMWF reanalysis used the Cloud Cleared Radiances (CCR) through its own temperature and humidity retrieval system. Before any further processing a "manual" quality control was carried out on the CCR data. For each satellite a monthly time series of the mean six hour brightness temperatures for each channel was plotted together with the corresponding number of data. It was necessary to know beforehand, which channels were available both for the radiance bias tuning and also for the calculation of the retrievals. A sudden jump in the global mean brightness temperatures could result from data coverage or a data location problem. The NOAA/NESDIS Polar Orbiter Archived TOVS Sounding Data change and Problem Record provides a useful list of the most important changes or errors as well as changes in the software used in the preprocessing of the raw radiances. Most of these events are difficult to identify from brightness temperatures alone, since their effects can be small.

A scheme developed by Eyre(1989) to make use of the raw TOVS radiances had been adapted at ECMWF to run on cloud cleared radiances Eyre et al.(1993) and is known as "one-dimensional variational analysis" or 1DVAR. An integral part of the scheme is the radiative transfer model Eyre(1991) and by the experience also a radiance bias tuning/ monitoring scheme Eyre(1992). Within 1DVAR process a comprehensive quality control is done on the radiances. In the re-analysis 1DVAR was applied globally including the use of the three stratospheric channels of the SSU.

The variational part is to find the atmospheric temperature and humidity structure, the 1DVAR-retrieval, which best fits the measured radiances. It is done by the minimization of the penalty function with respect to the atmospheric state, which is the fit of the measured radiance vector to the atmospheric state vector in radiance space (calculated by the radiative transfer model), to background profile and to other information. The method of Newtonian iteration is used to minimize the penalty function starting from the first guess as the initial profile. If a sounding has not converged within 5 iterations it was rejected. TOVS channels used by the 1DVAR were: HIRS channels 1-7 and 10-15, MSU channels 2-4 and SSU channels 1-3 are used for "clear" and "partly cloudy" soundings; HIRS channels 1-3, MSU channels 2-4 and SSU channels 1-3 are used for "cloudy" soundings. A sounding was also rejected even if the minimization converges, but if the "measurement cost" for any channel exceeds its threshold value. A sounding was rejected due to residual cloud contamination if the measured-minus-forecast difference for HIRS 10 is below the threshold values over sea, over sea-ice and over land. In the stability check based on the results by Andersson et al.(1991) a number of retrievals with probably erroneous static stability are thrown out. Finally the accepted retrievals were thinned to a spacing of about 250 km Eyre et al.(1993).

The CCR data constitutes a relatively consistent data set for the entire reanalysis period since the TOVS instruments have the same characteristics through the reanalysis period. The main variation within CCR data in the reanalysis was that there are periods with one or two polar orbiters. This has a clear signal on performance of the data assimilation system in respect to TOVS data as is shown later.

2.2.2 Bias correction

The radiosonde geopotentials are corrected or "tuned" with the assimilating model. With the implementation of the 1DVAR it turned out to be necessary to apply a bias correction to the CCR data for several reasons Eyre(1992). The "measurements" (CCR data) have undergone calibration and preprocessing. Any radiative transfer model has random and systematic errors. The systematic errors mainly result from the errors in the spectroscopic data, on which the radiative models are based. Since within the 1DVAR process the radiative transfer model is applied to forecast model profiles, do the measured-minus-calculated brightness temperatures contain components from errors in the preprocessing of raw radiances, radiative transfer model and forecast model. The magnitude of the bias is of the order of a typical forecast error that the radiances try to correct and thus it has to be removed. Before 1DVAR-retrieval are "actively" produced from a new satellite, the 1DVAR processing is done in "passive" mode producing the departure statistics without the final 1DVAR-retrievals to allow the calculation of the initial biases. The passive period is typically 2-4 weeks, and has guaranteed a smooth transition to new satellites. As pointed out by Eyre(1992) it would be preferable to correct these errors at source, but since this is not possible a practical strategy has been adopted. Biases between measured brightness temperatures and those calculated from the six hour forecast profiles are corrected using corrections calculated from the previous months biases close to a selection of reliable radiosonde stations in different parts of the world. The bias corrections are determined for each channel and are then applied during the following month of assimilation.

For monitoring purposes the mean corrected and uncorrected measurement-minus-first guess departures for each six hour period were plotted as a monthly "radgram" for each channel and satellite. Since the first guess itself is independent of any changes in the CCR data, at least when a change is about to happen, these graphs reveal satellite problems that have occurred during the previous month. Often NESDIS has listed a change (e.g. a change in the water vapour attenuation coefficients), but it is only afterwards that it can be seen whether or not this change has caused a significant problem in the data assimilation. In practice full use of this information would require the bias tuning to be done separately during all the abnormal periods, and those periods subsequently re-run with new coefficients. The experience from the bias correction during re-analysis shows, that the scheme itself worked in a consistent way from satellite to satellite and that independent validation by radiosondes has no discontinuities. Collocation statistics between radiosonde, model and 1DVAR retrievals were also calculated are helped to diagnose problems.

In studies, where radiative model is applied to the re-analyses and then comparisons are made against the measured radiances, it is important to understand that the analyses have been produced using bias corrected radiances and therefore it is not surprising to see differences of the order of the correction.

2.3 Drifting buoy monitoring

Drifting buoy data particularly from the earlier parts of the ERA period, suffer from numerous errors in the pressure measurements. Based on experience from FGGE and ECMWF operations a system for blacklisting of questionable buoy reports has been implemented for ERA. It consists of two parts:

- Precheck of monthly pressure traces. Monthly time-series pressure recordings from each buoy is presented in the form of 'barograms' on the workstation. Buoys with questionable readings, typically for random or constant ("stuck"), were included in the blacklist.
- Feedback information from the previous month's analyses. Quality information, in the form of observation fit to the first guess, from the previous month is scanned and buoys with systematic, or random, deviations above certain limits, were added to the blacklist of the following month. Infrequent cases were seen where a buoy has generated monthly mean and rms analysis increments which are larger than normal.

2.4 General monitoring tools

At every analysis cycle and over different geographical areas the Root Mean Square and bias statistics of the departures (Ob-Fg, Ob-An, Ob-In) are calculated from the feedback files for all analysis variables and for different observation types : TEMP, PILOT, AIREP, SATOB, TOVS, DRIBU, SYNOP/SHIP and PAOB. This is complemented by maps of available and rejected observations and maps of selected analysis fields with observations.

Each month vertical profiles of monthly mean and standard deviation of radiosonde height biases (for bias-corrected areas) are produced together with global plots of mean monthly height biases at each radiosonde station on upper levels. The bias correction plot as a function of the solar angle for each area confirms the need to keep an area on the correction list.

Before the start of the assimilation of a month time-series graphs of CCR brightness temperatures for all channels were checked. During the assimilation time-series graphs of CCR brightness temperature departures of model-minus-uncorrected and model-minus-corrected were checked for all channels used in 1DVAR. Mean maps of the geographical distribution of these departures were monitored in the end of each month. Additionally a time series of the global mean analysis increment and its standard deviation are plotted for selected levels and parameters. It has on occasions some errors in satellite processing. Consequently these periods have been rerun.

Most of the daily monitoring during the ERA production, Gibson et al (1997), concentrated on aspects relating to the use of observations in the analysis. This often resulted in actions such as bias-correction of TEMP heights, tuning of the TOVS radiances and blacklisting of problematic data. At the end of each cycle information concerning each datum was saved containing its departures from the first guess forecast and from the analysis. These departure statistics have been analysed throughout the re-analysis period in order to assess the performance of both the observations and the ERA data-assimilation system.

3. ASSESSMENT OF OBSERVING SYSTEM PERFORMANCE IN ERA15

Observations and the forcing fields are the external information through which the data-assimilation system senses the weather patterns. Radiance data (CCR) from TOVS instruments on board one or two NOAA satellites were used throughout the reanalysis. These provided the most time consistent global data source; they were the main data source for the temperature and humidity analysis over the oceans. This can be seen from their departure statistics and from the performance of medium range forecasts. Independent radiosonde statistics confirm that the CCR data were better assimilated during periods with two satellites. Observations from other observing systems experienced both quantitative and qualitative changes during the period. In general the quality of observations improves throughout the re-analysis period. This, together with the multivariate optimum interpolation scheme used in assimilation has been able to produce a time consistent set of analyses, despite large variations in the observing system. It has also enables these variations to be studied in detail. Radiosonde data are known to have improved throughout the years and this has benefited the analyses, despite a marked drop in the data availability after 1990. Cloud Motion

Winds (CMW) are derived at higher latitudes and their quality has been improved by each of the data producers. The CMW slightly underestimate the jet level zonal winds. Despite the long term stability of the ERA analyses they are effected by the quality of observations. It is important that the physical effects of changes in the observational characteristics are fully understood when re-analyses are used in climate change studies.

4. TIME VARYING OBSERVING SYSTEM

The reanalysis appears rather homogeneous if we consider only which observing systems operated during the period. Each observing system however had its own internal variations, which in turn may vary between different reanalysis centres due to the different data sources and ways the observations have entered their database. CCR data were available from one or two NOAA satellites. The two satellite periods with a full global data coverage were 1.9.1981-12.6.1984, 1.11.1984-31.6.1985 and 1.1.1989 onwards. There has been a progressive increase in the number and latitude range of CMW since 1980, figure 1. The First GARP Global Experiment (FGGE) year 1979 still has the largest data amounts and it is the only year when CMW have also been used over the Indian Ocean. Due to its special observations and delayed data collection the FGGE year has the best radiosonde coverage during the years. In the ERA database the number of TEMP data increases slowly from 1980, reaches its maximum 1987-1989 then falls to the lowest level during the period. The areas responsible for the reduction are Europe and Asia. Aircraft data roughly doubled from 1980 to 1993. The SYNOP/SHIP data have steadily increased, while years 1981-1984 are nearly void of tropical and southern ocean drifting buoys. Quantitatively the global observing system is improving towards the end of period, with the exception of radiosondes.

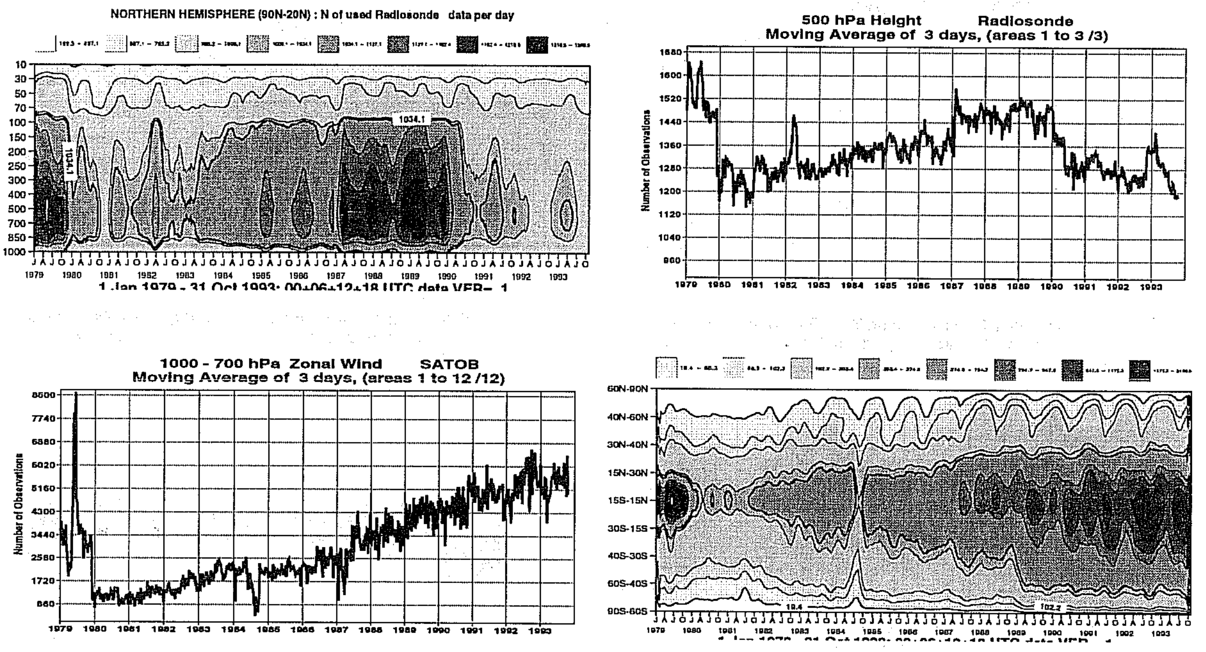

Figure 1. Time evolution of the 91 day moving average of the number of accepted radiosondes per day in the Northern Hemisphere, (top left) and the time evolution of the 3 day moving average of the global number of accepted 500 hPa radiosonde height data per day, (top right). Similarly the 3 day moving average of the global number of accepted low level cloud motion winds per day (bottom, left) with its latitudinal time evolution (bottom right).

5. THE IMPROVING GLOBAL OBSERVING SYSTEM

A general trend of improvement can be seen in the global first guess-minus-observation statistics with the radiosonde heights and temperatures as well as with radiosonde, pilot, cloud motion and aircraft winds, see some examples in figure 2. At the same time the analysis fit gets closer to these data and the net increment analysis-minus-first guess at the position of observation gradually is reduced in time. The reduction is more steady and more marked with the CMW than with radiosonde heights, temperatures and winds. The analysis increment at the locations of aircraft data is reduced clearly after 1989. Thus with the improved observations the quality of analyses have been improved. In the multivariate statistical analysis the improvement in one data source also propagates to the statistics of the other sources. To quantify this observing system experiments are needed.

The CCR data were the most time consistent of the data sources. When the quality of the first guess is measured against the retrievals (during two satellite periods against only retrievals from one satellite), the improved analysis quality is reflected as a smaller analysis increment and closer fit to the first guess, figure 2. Also during the two satellite periods the stratospheric heights of radiosondes fit the first guess slightly better. It is a signal seen by independent data, but can rather be seen as an underestimate of the true impact, since most of the radiosondes are over land, where the CCR data were not used below 100 hPa.

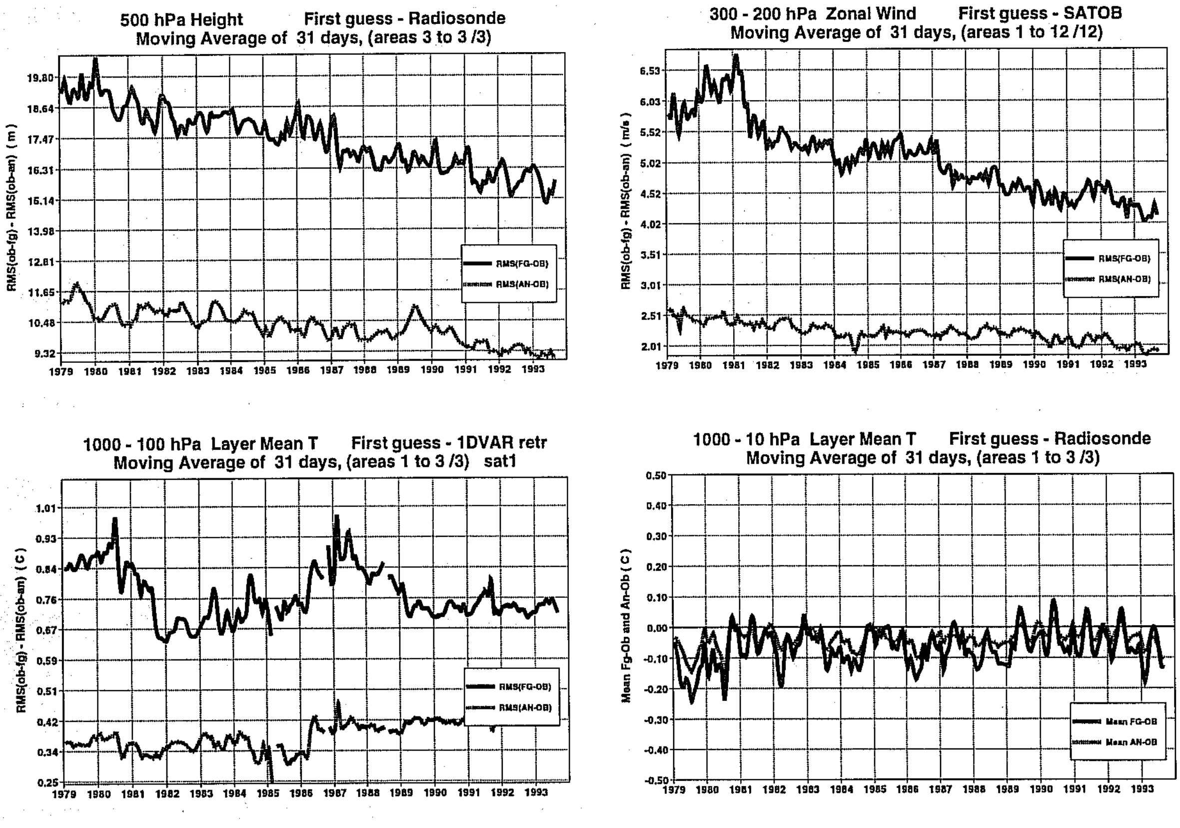

Figure 2. Time evolution of the 31 day moving average of the RMS of: first guess-minus-radiosonde height at 500hPa, (top left), first guess-minus-low level cloud motion zonal winds (1000 to 700hPa),(top right) and first guess-minus-1DVAR retrieval (1000-100hPa) (bottom left). The time evolution of the 31 day moving average of the mean layer (14 layers) temperature bias, first guess-minus-radiosonde is shown bottom right. Dotted line represents the corresponding statistics for the analysis-minus-observation departures.

The humidity structures are well analysed as verified against independent Meteosat water vapour channel data and the first guess fits the radiosonde relative humidity between 1000-300 hPa globally within 15% and analysis within 10%. The first guess is slightly biased moist (1-2%), the analyses are almost unbiased.

The first guess has a small cold bias compared with bias corrected radiosondes at all levels; the mean layer bias varies between 0.0 and 0.1 C, the analysis bias being slightly smaller, figure 2. There is also an indication that the period after 1989, when radiosondes are better, is less biased. The CMW bias underestimating the jet level zonal winds has been reduced but still exists in 1993.

CONCLUSIONS

Monitoring has played a crucial role in the reanalysis. The speed of the production means that more efforts should be made towards automated procedures. Important decisions still have to be taken by manual monitoring, where quality information from various sources can be combined. Special attention in the monitoring has been given to radiosonde data, satellite radiances, cloud motion winds and isolated data in general.

The quality of the observing system, accuracy and coverage, shows clear signals in the first guess statistics. In general the quality of the observing system improves in time and consequently the analyses are more accurate towards the end of the period. However there are areas, for example the Indian Ocean and Southern Hemisphere Oceans, which are data sparse throughout the re-analysis period. Over these areas the biases of the first guess propagate to the analyses. In the same way if an observing system dominates over an area the possible biases in the observations propagate to the analyses and then to the first guess.

Large variability of available data is characteristic for the whole period. The exceptionally good data availability during the FGGE year, due to the delayed data collection and monitoring, stands out. After a decline at the end of FGGE, the global radiosonde availability first improves, then, after 1990, again experiences real losses. Cloud Motion Winds increase in number threefold over the period. Part of this is due the increase of coverage towards higher latitudes. Aircraft data increase dramatically in 1991 due to the introduction of AMDAR. The drifting buoys have large variations especially in the Tropics and Southern Hemisphere where their importance is large. SYNOP and SHIP data steadily increase due to better data collection. TOVS data are available throughout the period either from one or from two polar orbiting satellites.

ECMWF reanalyses have successfully assimilated the TOVS radiances. TOVS data represent a time consistent global data set throughout the reanalysis period. The comparison between the first guess and 1D-Var retrievals through the period shows that in an RMS sense the quality of the analyses better in the presence of two satellites than during periods with only one. This can be seen in mid-latitudes both with the temperature and humidity retrievals. The important fact however is that the two satellite signature can be seen in the equivalent six hour statistics of the fits to the radiosondes heights.

The RMS and bias of the radiosonde height departures from the first guess show a global improvement. The equivalent wind statistics also show an improvement. In general the improvement can be seen throughout the troposphere, but it is more marked at higher levels indicating that the radiation error of the radiosondes has been reduced. In the Northern Hemisphere a positive interaction between the TOVS and radiosonde height data can be seen. The radiosonde heights are better fitted during periods when data are available from two, rather than one polar orbiting satellites. The same is true also over the data sparse areas in the Southern Hemisphere. Comparing the results from different areas, Europe and Central Asia show a steady improvement, stronger in Europe, while East Asia and North America are relatively steady with a small improvement. In absolute terms North America clearly performs best. In the Southern Hemisphere all the areas show improvement.

The improvement of the cloud motion winds from all producers is evident and can be seen globally. The running mean of RMS first-guess fit to low-level cloud motion winds is reduced from just over 4 ms^{-1} in 1979 to about 3 ms^{-1} by the end of 1993. Towards the end of the period the analysis increment is much smaller and cloud motion winds are assimilated better. The improvement in the high level cloud motion and aircraft winds is equally evident. The statistics indicate that there is still a bias in the cloud motion zonal wind throughout the period, the jet-level winds being slightly underestimated.

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