TECHNICAL MEMORANDUM

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Performance of TOVS data in the ECMWF reanalysis 1979-1993

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PERFORMANCE OF TOVS DATA IN THE ECMWF REANALYSIS 1979-1993

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ABSTRACT

The purpose of the Reanalysis project at ECMWF was to create a time consistent set of global analyses for 1979-1993 using a fixed optimised data assimilation system. During the reanalysis period, the global observing system experienced constant changes. The TOVS radiances in the form of NESDIS Cloud Cleared Radiances provided however a time consistent and high quality global data source with only a few significant gaps over the reanalysis period. For the major gaps cloud clearing was done during the data-assimilation from the 1b data. One dimensional physical retrieval (1DVar) with its built in quality control methods was applied to the radiances after they were tuned with the first guess forecast. In general the quality of the global observing system improves towards the end of the reanalysis period. A positive signal in the quality of the first guess forecast can be seen when two polar orbiters are available instead of one. The 1DVar humidity retrievals are the main global upper air moisture data used in the reanalysis. Through the use of temperature and humidity channels the TOVS data have provided valuable data for the whole of reanalysis period especially in the Tropics and Southern Hemisphere.

1. INTRODUCTION

Operational analyses are affected by the changes in models, analysis technique, assimilation, and data usage contributing to the continuous improvement of the forecast system. The way in which TOVS data are used now is very different from earlier years. Operationally only those data which become available within near real time are used. The ECMWF Re-Analysis (ERA) project objective was to produce a new, validated time consistent 15 year set of analyses for the period 1979 to 1993 using a fixed optimised data assimilation system. Studies of the general circulation, atmospheric low-frequency variability, the global hydrological and energy cycle, predictability, coupled ocean-atmosphere modelling, and observing system performance will benefit from the reanalyses.

Before starting the ERA production a series of experiments was completed to evaluate different aspects of the intended assimilation system. Due the use of computer resource requirements the horizontal spectral resolution was pre-determined to be T106 corresponding to about 125 km. Questions relating to the choice of vertical resolution (19 or 31 hybrid levels), whether to use the mean or envelope orography and which cloud and soil moisture schemes to use in the reanalysis were experimented. The selected system included:

- a 1DVar physical retrieval scheme to utilise TOVS Cloud Cleared Radiances globally
- a statistical Optimum Interpolation scheme with 6 hour cycling
- ECMWF's Integrated Forecasting System, T106L31
- Normal Mode Initialisation
- prognostic cloud scheme
- prognostic soil scheme
- mean orography

The main source for observations has been the ECMWF real-time data collection from the Meteorological Archive and Retrieval System (MARS). Additional sources include:

- NESDIS Cloud Cleared Radiance data (CCR);
- Ship and buoy observations from the Comprehensive Ocean Atmosphere Data Set (COADS);
- First GARP Global Experiment (FGGE) and Alpine Experiment(ALPEX) II-b data;
- GMS satellite cloud winds made available by the JMA;
- PAOBS (synthetic surface pressure observations) data from NMC Melbourne;
- supplementary radiosonde and aircraft data from JMA' archive;
- Subduction and TOGA buoy data.

The CCR data constitute a relatively consistent data set for the entire re-analysis period. Figure 1 shows, for each NOAA satellite, the periods when they were actively used in the re-analysis. For NOAA-6 MSU channel 3 was not available 1.1-31.5.1980. The CCR data have been processed from NESDIS 1b data using the Wisconsin ITPP package (1995) to supplement gaps in the archive. For details concerning the ERA system see Gibson et. al (1997).

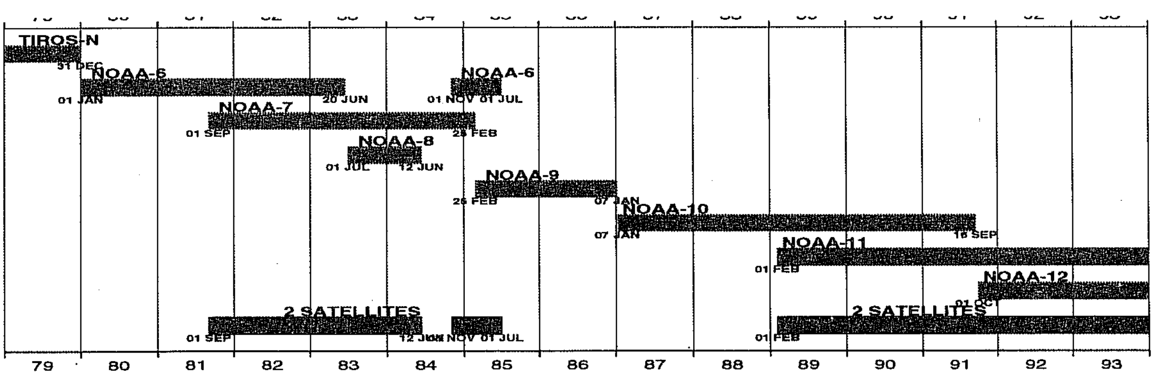


Fig 1. TOVS Cloud Cleared Radiance data used in the ECMWF reanalysis

2. THE USE OF TOVS DATA IN ERA

2.1 1DVar-retrieval and quality control

The ECMWF reanalysis used the NESDIS TOVS Cloud Cleared Radiances (CCR) (Smith and Woolf, 1976 and McMillin and Dean, 1982) through the 1DVar temperature and humidity retrieval system (Eyre, 1989). An integral part of the 1DVar scheme is the radiative transfer model (Eyre, 1993) and a radiance bias tuning and monitoring scheme (Eyre, 1992). In the reanalysis 1DVar is applied globally including the use of the three stratospheric channels of the Stratospheric Sounding Unit.

A "manual" quality control was carried out on the CCR data as a preliminary check. For each satellite and channel a monthly time series of the global mean six hour brightness temperatures was plotted together with the corresponding number of data. Both the radiance bias tuning and also the calculation of the retrievals need to know which channels are available. A sudden jump in the global mean brightness temperatures reveals possible problems either in the data location or in the preprocessing. The NOAA/NESDIS report: Polar Orbiter Archived TOVS Sounding Data Change and Problem Record (NESDIS internal document) provided a useful list of the most important errors and changes in the software used to preprocess the raw radiances. Most of these events are difficult to identify from brightness temperatures alone, since their effects in global averages are usually small.

The variational method finds the atmospheric temperature and humidity structure (1DVar-retrieval) which best fits the measured radiances. This 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 the background profile and to other information. The method of Newtonian iteration is used to minimize the penalty function starting from a 6 hour forecast as the initial profile. TOVS channels used by the 1DVar are: 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. If a sounding has not converged within 5 iterations it is rejected. A sounding is also rejected even if the minimization converges and if the " measurement cost" for any channel exceeds its threshold value. A sounding is 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 also rejected. Finally the accepted retrievals are thinned to a spacing of about 250 km (Eyre et al., 1993).

2.2 Radiance bias tuning

During reanalysis a correction for systematic errors in radiosonde temperature and geopotential is applied to sets of selected stations. The correction is based on observation-minus-first guess departure statistics at different solar elevation angles. The bias correction was more important during the first half of the reanalysis and the correction had progressively less importance with the improving quality of radiosondes at the end of the period.

With the implementation of the 1DVar it turned out also to be necessary to apply a bias correction to the CCR data for several reasons (Eyre 1992). As pointed out by Eyre 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. 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, the measured-minus-calculated brightness temperatures contain components from errors in the preprocessing of raw radiances, radiative transfer model and forecast model. The bias tuning is aimed to correct air-mass dependent errors in the forward modelling. 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-retrievals were"actively" produced for a new satellite, the 1DVar processing was done in "passive" mode for about a month to derive the bias tuning statistics. This guaranteed a smooth transition to new satellites.

For quality control purposes the mean corrected and uncorrected measurement-minus-first guess departures for each six hour period were plotted against time 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 was about to happen, these graphs revealed satellite problems that had occurred during the previous month. Often NESDIS had listed a change (e.g. a change in the water vapour attenuation coefficients), but it was only afterwards that it could be seen whether or not this change had 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.

In studies, where a radiative model is applied to the reanalyses 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 suprising to see differences of the order of the correction.

2.3 The use of retrievals in the analysis

In the Optimum Interpolation analysis the 1DVar-temperature and humidity retrievals are used globally below 100hPa and only over sea areas. In the Tropics only "clear" retrievals are used. The NESDIS-temperature retrievals are used in both hemispheres above 100hPa except in the Tropics, where no retrievals are used. The retrievals are further quality controlled within OI together with all other observations.

3. THE TOVS PERFORMANCE

3.1 First guess statistics

Through the whole reanalysis period and for every six hour cycle the departures observations-minus-first guess and observations-minus-analysis were calculated for each datum. Fig 2 shows the time evolution of the 91-day running mean of the daily Root Mean Square, 1DVar retrieval-minus-first guess layer mean temperature through the reanalysis period over the Northern Hemisphere. In the mid troposphere the values vary between 0.5 and 1.1 degrees and in the upper troposphere between 0.4 and 0.8 degrees. In the stratosphere where NESDIS retrievals are used the values range from 0.6 to 2.1 degrees. A strong seasonal fluctuation can be seen through the atmosphere; there are higher first guess errors in the winter period from November to March and smaller errors in the summer periods. During the periods with two satellites the RMS values are smaller than during the periods of one satellite. The time evolution of radiosonde-minus-first guess height RMS in Fig 3 illustrates the general improvement in radiosonde quality. It also reveals that during the two satellite periods a slightly closer fit on levels above 300 hPa is obtained. The improved quality of first guess is thus confirmed by an independent observing system.

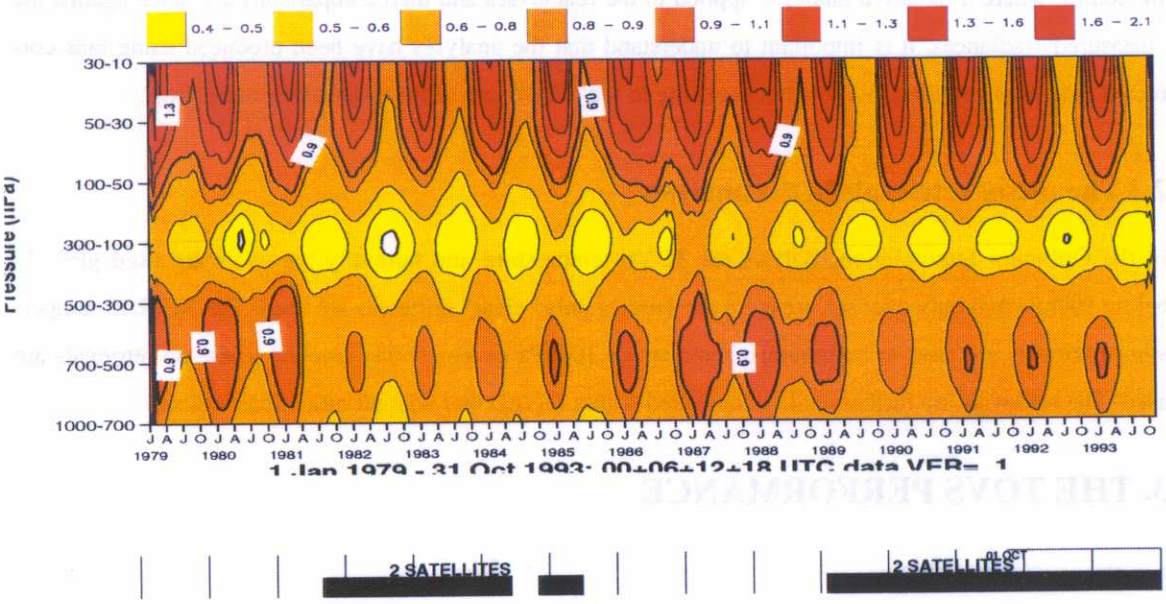


Fig 2. Time evolution of the time averaged daily RMS of first guess-minus-1DVar retrieval layer mean virtual temperatures in the Northern Hemisphere, 1979-1993

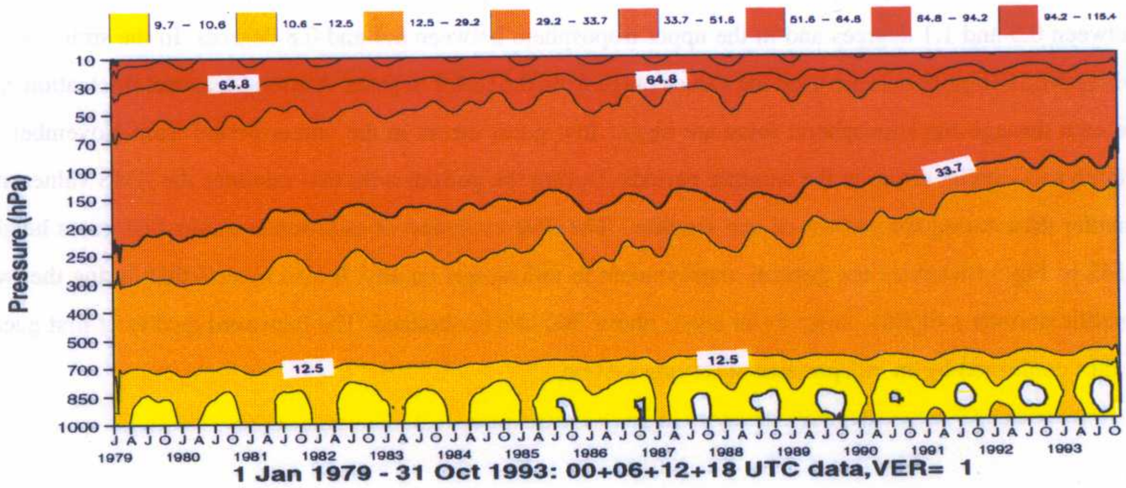


Fig 3. Time evolution of the time averaged daily RMS of first guess-minus-radiosonde heights in the Northern Hemisphere, 1979-1993

The analysis fit to the 1DVar temperature retrievals is globally nearly unbiased through the years, while the first guess is colder than the retrieval by about 0.1 to 0.3 degrees below 300 hPa in midlatitudes, in the Southern Hemisphere slightly more (not shown). The bias also has a seasonal signal. In theTropics the first guess is consistently colder than the retrievals below 500hPa and warmer above .The analysis draws close to the

1DVar moisture profiles in terms of relative humidity for example in the Tropics within 2%, but there is a bias in the first guess-minus-1DVar retrieval and in the extra tropics it has a seasonal signal. For example below 500 hPa in summer, autumn and winter the first guess has up to 10% and in spring up to 4% lower relative humidity than the 1DVar retrievals in the Northern Hemisphere. In the Tropics the first guess is more humid except in the layer 700-500 hPa, where it agrees with the first guess. From the beginning of 1989 and with the introduction of NOAA-11 the low level humidity bias is greatly reduced. In terms of the RMS, first guess-minus-1DVar humidity retrieval the quality of first guess is better during periods with two satellites in the extra tropics. In the Tropics this signal can be seen above 500 hPa, but in layers below 500 hPa the RMS values have increased generally after 1986. A part of the explanation for this is the better quality first guess temperature during periods of two satellites. Since relative humidity is a function of water vapour pressure and temperature, we have to compare the integrated water vapour amounts in order to know if the retrieval or first guess is moister in absolute terms.

3.2 Collocation statistics

Collocation statistics provide a powerful tool to assess the relative characteristics of data from different sources. Radiosonde ascents, first guess profiles and satellite retrievals describe different scales of the atmosphere and they have different error characteristics. Radiosonde types have changed during the years and they have smaller systematic errors in later years. However when we study long term statistics this should not prevent us drawing conclusions. In the following the main results concerning mean layer virtual temperature and integrated layer Total Column Water vapour (TCW) retrievals are presented. As collocation criteria 200km and 2hours are used. The collocated radiosonde and first guess profile are first interpolated to 40 NESDIS temperature and 15 specific humidity levels. Often the radiosonde data do not contain a full set of levels and consequently interpolation/extrapolation is needed leading to uncertainties especially at the top levels.

Zonal mean temperature profiles of the collocated data were calculated over the whole reanalysis period. The difference of the zonal mean temperature profiles over sea : radiosonde-minus-1DVar is shown in the Fig 4. In general the 1DVar retrievals are slightly colder than the radiosondes following the pattern of the radiosonde-minus-model structure (not shown here). As an example Fig 5 shows the horizontal distribution of the bias in 5*5 degree boxes. In the mid latitudes 1DVar is slightly cooler and in the Tropics it is slightly warmer than the radiosondes.

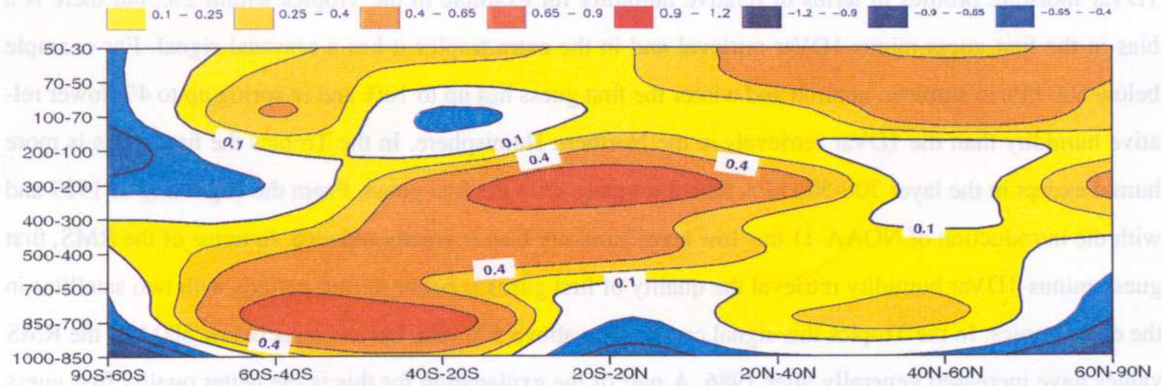


Fig 4. Zonal mean radiosonde-minus-zonal mean 1DVar virtual layer mean temperature retrieval difference from collocated data. Period 1979-1993, collocation criteria (200km and 2hours).

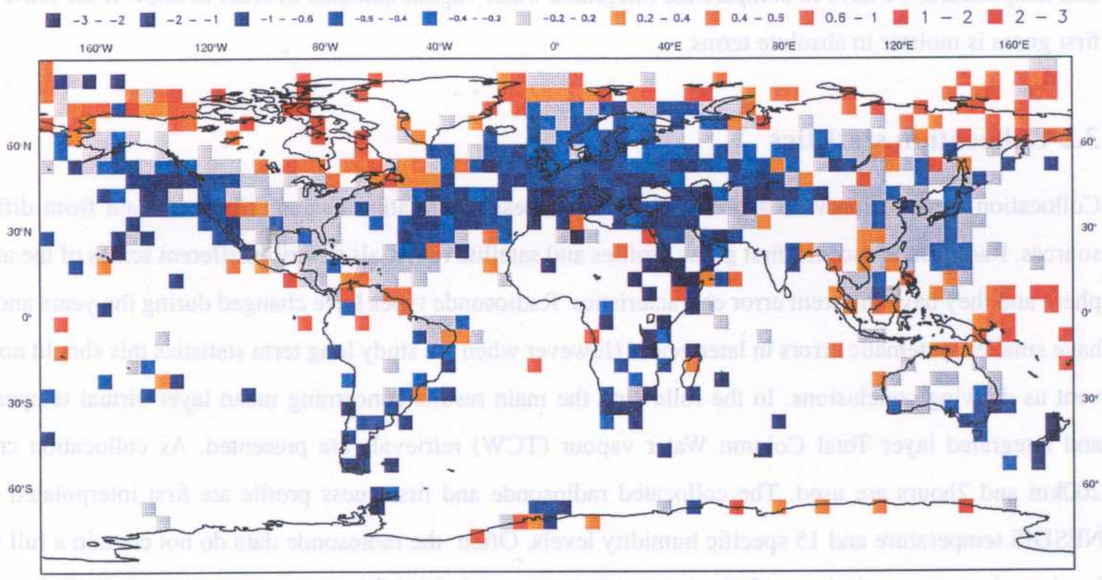


Fig 5. 1DVar-minus-radiosonde Layer Mean Temperature bias 850-700 hPa from collocated data. Unit degrees.

The Stardard Deviation of radiosonde-minus-1DVar calculated in latitude bands shows the smallest values, 1.0-1.2 C, in the tropical troposphere increasing poleward up to 2.0 C, Fig 6. The time evolutions of the global Standard Deviation of radiosonde-minus-1DVar and radiosonde-minus-NESDIS virtual layer mean temperature, Fig 7, show that the 1DVar performs very steadily and has smaller values than the NESDIS retrievals through the troposphere. Both retrievals improve slightly from 1990 onwards.

Zonal mean layer PWC profiles of the collocated radiosonde data were also calculated over the reanalysis period. The difference of the zonal mean layer PWC profiles over sea (radiosonde-minus-1DVar) is shown in Fig 8. It indicates that in absolute terms the 1DVar is moister than the radiosonde by upto ~2 kgm^{-2} in the layer 1000-700 hPa and by .1-.4 kgm^{-2} in the top 700-300 hPa layer. In the NESDIS retrievals (figure not

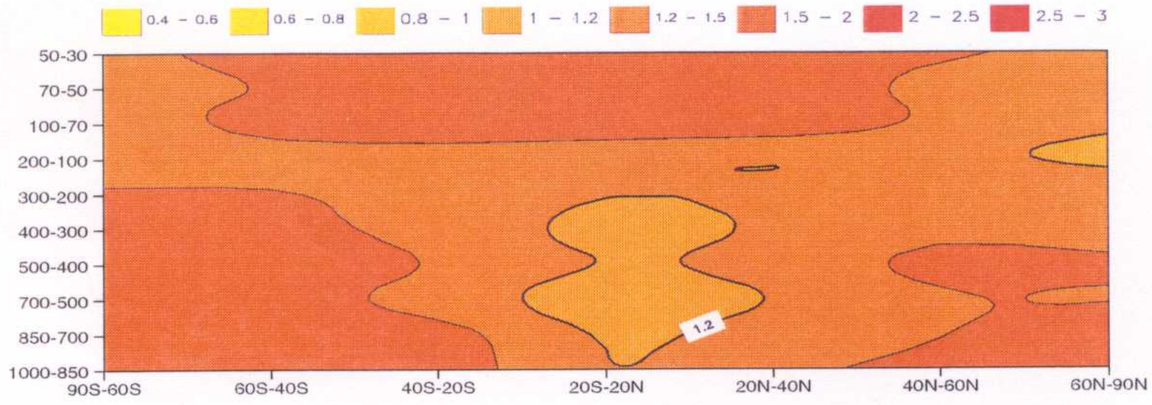


Fig 6. Zonal mean STD (radiosonde-minus-1DVar virtual layer mean temperature retrieval from collocated data. Period 1979-1993, collocation criteria: 200km and 2 hours.

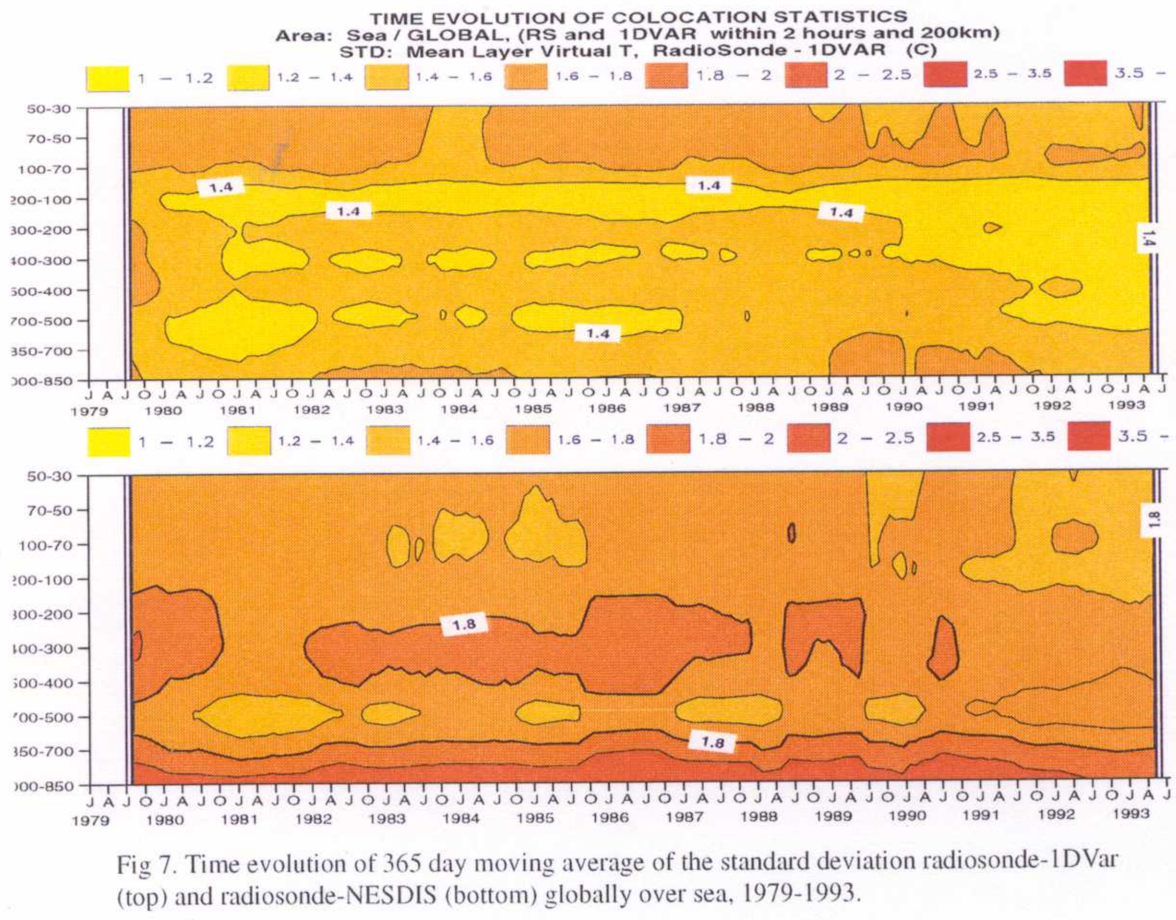


Fig 7. Time evolution of 365 day moving average of the standard deviation radiosonde-1DVar (top) and radiosonde-NESDIS (bottom) globally over sea, 1979-1993.

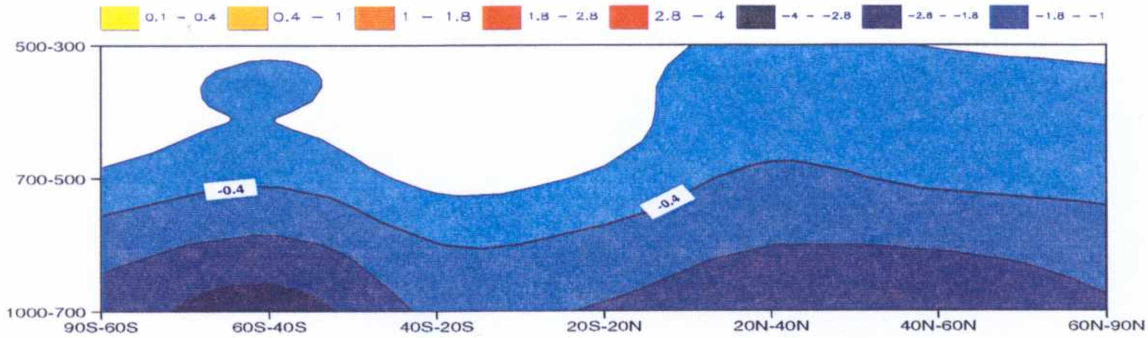


Fig 8. Difference of zonally averaged layer PCW (kgm^{-2}) of collocated data over sea (2 hours, 200km); radiosondes-minus-1DVar retrievals, 1979-1993.

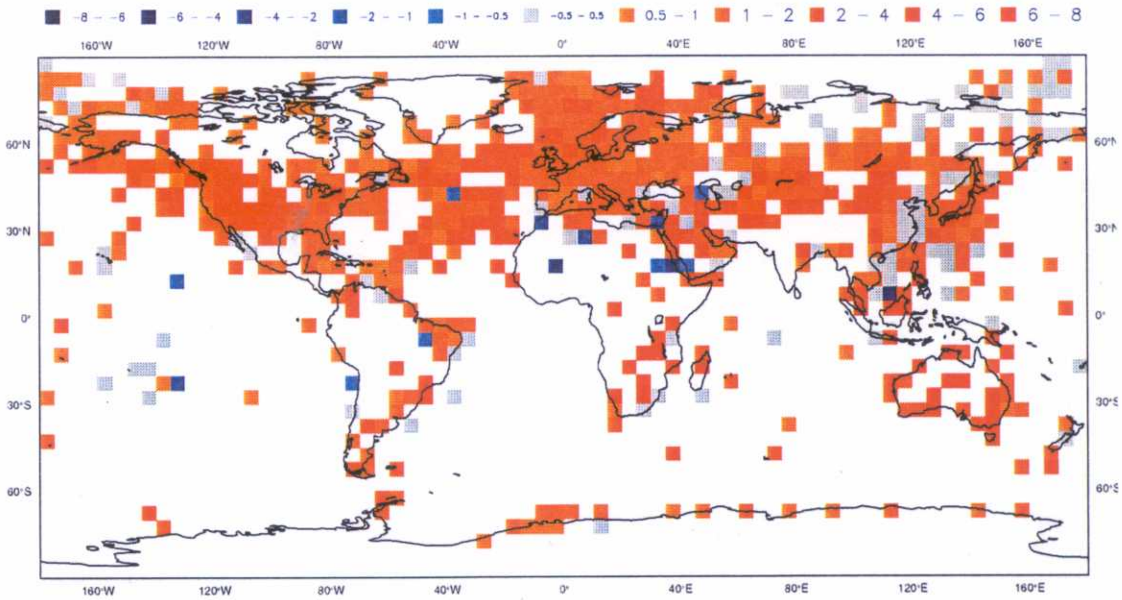


Fig 9. The mean difference of 1DVar-minus-radiosondes PWC (kgm^{-2}) of layer 1000-700hPa in 5*5 degree boxes, 1979-1993

shown here) the layer 1000-700 hPa in the band 40S-40N is moister upto ~2 kgm^{-2} than that of radiosondes, elsewhere NESDIS is dryer than the radiosondes. As seen in Fig 9 the 1DVar retrievals are moister than the radiosondes nearly everywhere. Fig 10 shows the previous as scatterograms for the TCW through 15 years. Each point represents a 5*5 degree box, which has had collocations (hundreds) with 1DVar and NESDIS retrievals and with first guess. It indicates that the first guess and radiosonde (middle) agree fairly well, the first guess has only a small moist bias. The NESDIS retrievals have too little moisture in the midlatitude columns (below 20 kgm^{-2}) and too much moisture in the tropical high water content atmosphere in comparison with the radiosondes. The 1DVar columns have slightly higher values throughout.

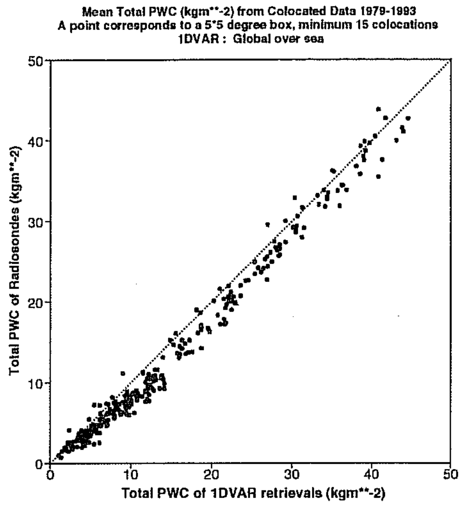
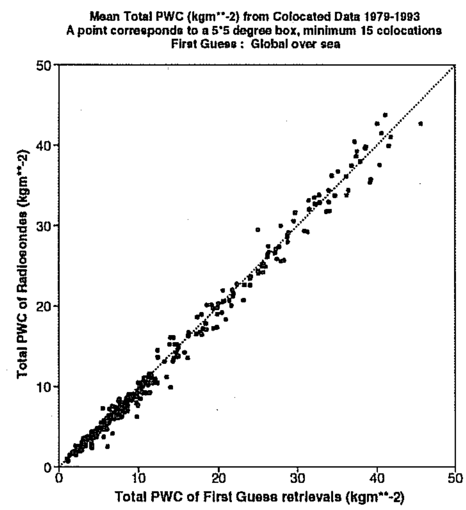


Fig 10a. The mean total column water content (kgm^{-2}) in 5x5 degree boxes, calculated from colocated radiosondes (y-axis) and from 1DVar retrievals (x-axis) 1979-1993. Each point has collocations with 1DVar and NESDIS retrievals so that the same boxes are represented in figures a,b and c. The collocation criteria: 2 hours, 200km.

Fig 10b. The mean total column water content (kgm^{-2}) in 5x5 degree boxes, calculated from colocated radiosondes (y-axis) and first guess profiles (x-axis) 1979-1993.



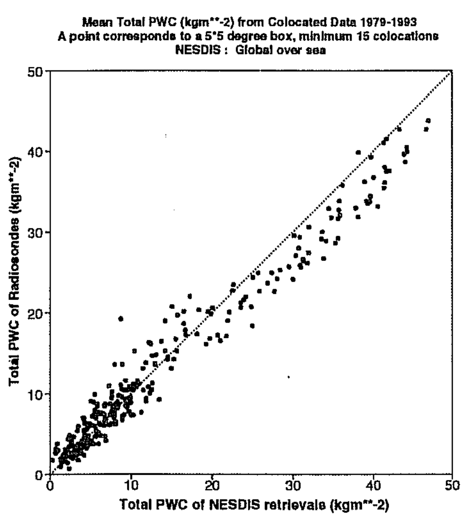


Fig 10c. The mean total column water content (kgm^{-2}) in 5x5 degree boxes, calculated from colocated radiosondes (y-axis) and NESDIS retrievals (x-axis) 1979-1993.

4. SUMMARY

ECMWF reanalyses have successfully assimilated the TOVS radiances 1979-1993. TOVS data represents a time consistent global dataset through the reanalysis period. Transition from satellite to satellite was achieved smoothly by the radiance bias tuning. Due to the overlap in the TOVS channels, the 1DVar system was able to perform reasonably well even if a channel or combination of channels was not available.

The comparison between the first guess and 1DVar retrievals through the period shows that in a RMS sense the performance of TOVS data in the presence of two satellites is better than during periods with one satellite. This can be seen in midlatitudes both with the temperature and humidity retrievals. A limited sample of ten day forecasts run from the ERA analyses each month does not however have improved skill in medium range forecasts during the two satellite periods. This can be due to the small sample size of 4-5 forecast per month, model resolution, or to the dominance of other error sources in longer model integrations. The important fact however is that the two satellite signature can be seen in the equivalent 6 hour statistics with the radiosondes. On the other hand this indicates that the medium range forecasts of today may not yet benefit of the full potential from the TOVS data. This naturally applies also to other data types.

The comparisons between collocated radiosonde and 1DVar retrievals the 1DVar shows a very steady performance through the years, which from the climate point of view is essential. From 1990 onwards the consistency of 1DVar with radiosondes is slightly higher.

The 1DVar retrievals in relation to the radiosondes overestimate the total column water vapour content fairly uniformly through all the latitudes. Thus the TCW is relatively more accurate in the Tropics. The NESDIS TCW has a distinct latitudinal feature, too moist in the Tropics and too dry in the mid and high latitudes. Since NESDIS has improved their retrieval system during years, this might not reflect their todays retrieval quality.

To complement this statistical study further work is needed to establish how well the termodynamic structures of individual cyclones and fronts have been analysed over areas dominated by TOVS data.

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Land-Atmosphere Studies (COLA), the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP) and Cray Research Incorporated.

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