Experience in estimation of biases in ECMWF reanalyses

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1. Introduction

The reanalyses projects are designed to produce long sequences of analyses by applying modern assimilation techniques to the historical observations. The aim at ECMWF has been to maximize the analysis quality at any analysis time by using all the available observations. At the same time actions have been taken to maintain analysis continuity and homogeneity as much as possible.

In order to detect the climate signals "cleanly" recommendations have often been made for the creation of a homogenized (in space and time) observation dataset to support the conclusions from the reanalyses, e.g Workshop on Re-analysis (2001). It is hoped that by eliminating the changes in the observing systems the true climate signal would be revealed. This target is very difficult (and maybe even impossible) to achieve, since the common "homogeneous" part of the observing system is sparse in space and short in time.

The handling of observational biases in the data assimilation is still in an early stage and the model biases are not yet accounted for. Advanced bias correction schemes are becoming important tools in maximizing the reanalysis homogeneity.

The reanalysis data assimilation system has to be affordable, which means that the latest, best and computationally expensive data assimilation schemes cannot be applied. Satellite data in the latest ERA-40 reanalysis (Uppala et al (2005) are used in the form of calibrated Level-1c radiances. The increasing quality of the data assimilation system (including the radiative transfer model) enables extraction of more detailed information than previously possible from the observations. The greater sensitivity of data-assimilation to the observations has increased the importance of the bias handling in ERA-40 and has improved the homogeneity of the reanalysis products. Many of the applications are sensitive to biases in the reanalyses products.

In general the quality of reanalyses is affected by:

- **The quality of the assimilation system**

  The assimilating model (atmosphere, ocean waves, land state)

  The analysis system

- **The characteristics of the observing system**

  The type, accuracy and coverage of observations, changes over time in particular

- **The prescribed boundary conditions**

  Sea-surface temperature and sea-ice distribution

  Land-surface state (vegetation, lakes, etc)

- **The specified atmospheric composition**

  Greenhouse gases, aerosols

2. Reanalyses in general

Prior to reanalyses operational analyses were successfully used in general circulation studies. However due to the improvements in the forecasting system it was difficult to study interannual variations and it was impossible to study the climate change.

There has been an increasing need to understand trends in the global atmosphere. In the late 1980s TOVS data, in particular MSU Channels 2 and 4, has successfully been used to study trends in the troposphere and the lower stratosphere. They have been also used to reveal discrepancies between observations and the operational analyses, Hurrell and Trenberth (1991) and Oort and Liu (1992). In this sense high expectations were expressed concerning the proposed reanalyses projects in the late 1980s.

Several global reanalyses have since been performed: the US NCEP/NCAR 1948-present and NCEP/DOE 1979-present, the ECMWF ERA-15 1979-1993 and ERA-40 1957-2002, and the Japanese JRA-25 1979-2004.

There are significant differences between these reanalyses. The data assimilation systems and the input data to the analysis are different. The same also applies to the bias correction schemes. While NCEP/ NCAR reanalysis is using the NESDIS temperature retrievals, ERA-15 used 1D-Var retrievals based on Cloud Cleared Radiances below 100hpa and NESDIS retrievals above, John Eyre et al (1992). ERA-40 has made use of the Level-1c radiances from all TOVS instruments HIRS/ MSU/ SSU Hernandez et al (2004), VTPR Li et al (2006) and SSM/I radiances through 1D-Var retrievals of TCWV and wind speed.

Use of radiances always includes the use of a bias correction model. NCEP reanalysis makes use of the NESDIS temperature and moisture retrievals Kalnay et al (1996). Since the use of radiances in ECMWF operations started around 1996 in ECMWF the information and experience on instrument biases/ drifts in the historical radiance data hardly existed before ERA-40. In ERA-15, Gibson et al (1997), and in ERA-40 productions, Uppala et al (2005), the radiance monitoring was a critical activity for the quality of analysis products and to find out radiance characteristics. The benefits of the direct use of radiances can be seen in more realistic time variability in ERA-15 than in NCEP reanalysis, Engelen et al (1997), but the analyses have also become prone to the biases in observations. The monitoring results and experience from ERA-15 users have been utilized in the ERA-40 bias treatment and in the blacklisting of erroneous data.

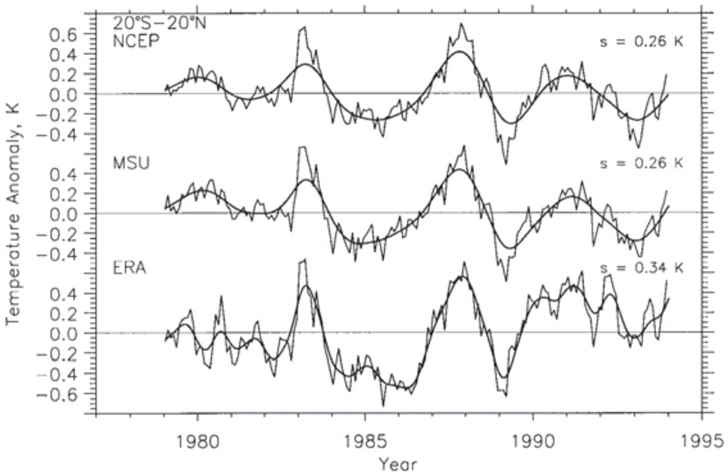

Figure 1 Time series of the monthly mean tropical (20N-20S) 2LT temperatures from NCEP, MSU, and ERA-15. The standard deviation of each is given in the insets. A low-pass smoothing spline has been fitted to the data to show the decadal variations, Trenberth et al (2001).

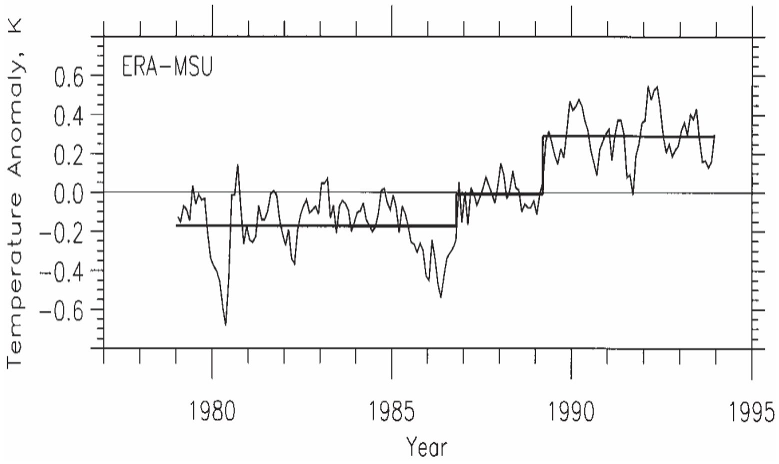

Figure 2 Difference in time series of the monthly mean tropical (20N to 20S) 2LT temperatures Trenberth et al (2001).

As an example of the effects and importance of the bias correction Figures 1 shows time series of lower tropospheric temperature (2LT) anomalies for MSU data, NCEP and ERA-15 reanalyses, Trenberth et al (2001). MSU and NCEP are in better agreement while ERA-15 seems more different from mid 1980s onwards. Figure 2 shows the difference between MSU and ERA-15. Until the end of October 1986 ERA-15 is slightly colder from then on ERA-15 is warmer. The failure of MSU-3 onboard NOAA-9 in the beginning of November 1986 was not noticed and the bias correction, which used observed values as predictors, compensated for the cold observed temperatures from then on. Therefore, ERA-15 could not be recommended for trend studies, also due to its short period.

3. Bias estimation in ERA-15 and ERA-40

If the observational biases had been known, schemes to remove them could have been developed. Well known biases are the instrument dependent upper level temperature biases in radiosondes due to short wave radiation. Also the ERS scatterometer wind speeds are corrected for biases. The bias in the Atmospheric Motion Vector zonal wind speeds is known (too slow in the strong jet stream winds), but they are not corrected since no correction method exists. Reprocessing of these winds, as carried out by EUMETSAT, Leo Van de Berg et al (2006), for the Meteosat winds and by JMA for the GMS winds, is possibly the best method to improve these winds and reduce the bias.

In ERA-15 the radiosonde heights were corrected using statistics of observation-minus-background departures (OB-FG) in different solar elevation angles over the previous year. In ERA-40 the same was done for the temperature measurements Andrae et al (2004). For some radiosonde types also the mean error was corrected. Identification of different radiosonde instruments is not possible in the old data records and therefore stations are grouped by countries and regions in the earlier periods.

A summary of the bias corrections applied to the radiance data in ERA-15 and ERA-40 is given in the table below. The main difference between ERA-15 and ERA-40 is in the input data and in the use of predictors. Much more data and closer to the source has been used in ERA-40, Level-1c radiance instead of CCR. The use of a better assimilation system, a better radiative transfer model and the use of the model values as predictors meant that the bias corrections were much more stable in ERA-40 than in ERA-15. Also, all the known periods with instrument problem during ERA-15 were blacklisted in ERA-40. The bias correction of VTPR was more demanding for two reasons. Each of the four satellites carried two instruments, which were turned on/ off several times before 1975. This is a challenge for the static bias correction. Also the set of filter functions was applied to all instruments. SSU radiances do control the stratospheric data-assimilation and it is important to notice that until 1997 and before the introduction of AMSU there is only one instrument operating for most of the time during the six hour analysis window.

	ERA-15	**ERA-40**
Input radiance	Cloud Cleared and nadir corrected Radiances HIRS/ MSU	Level-1c calibrated at ECMWF from Level-1b VTPR/HIRS/MSU/SSU/ AMSU-A&B SSM/I from Frank Wentz
Method	Static J. Eyre (1992) based on W. Smith & H. Woolf	Static B. Harris & G. Kelly (2001)
Scan bias	Global offset with 0 at center	18 latitude bands
Air-mass dependent bias predictors	Observed values Data selected in 5 latitude bands MSU-2,3 and 4, which are unaffected by clouds	Model values DZ(1000-300)hPa DZ(200-50)hPa Tskin and TCWV 10m WS and TCWV for SSM/I
Update frequency	Monthly	Once per satellite life time or after a jump in instrument

ERA-40 has made much wider use of observations than the other reanalyses, see schematic presentation of the systems in Figure 3. Red indicates data not used in ERA-15.

1957-1972	No satellites
1973-1978	VTPR
1979-	TOVS(HIRS,MSU,SSU), AMV
1987-	TOVS(HIRS,MSU,SSU), AMV, SSM/I
1991-	TOVS(HIRS,MSU,SSU), AMV, SSM/I, ERS
1998-	TOVS(HIRS,MSU,SSU), AMV, SSM/I, ERS, ATOVS(AMSU)

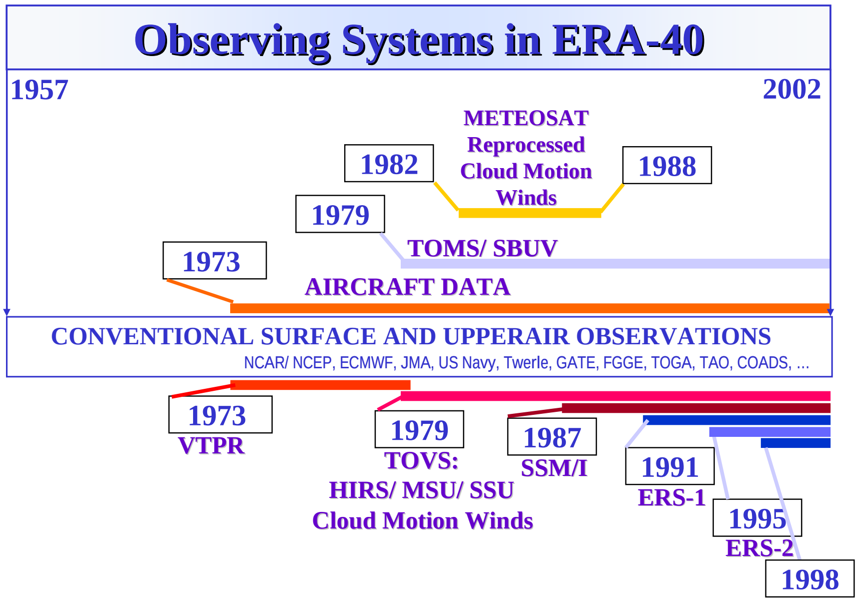

Figure 3 The observing system components in ERA-40 schematically, for details see Table5, Uppala et al (2005).

4. Success of bias handling in ERA-40

The success of bias correction can be technically evaluated within the bias correction scheme. The ultimate test however is how cleanly the reanalysis user can detect the physical signals in the reanalysis products. In the following this is demonstrated with a few examples.

The correct handling of biases will remove the bias and enable the data-assimilation to extract the physical information in the data. Figure 4 demonstrates the quasi-biennial oscillation in the monthly mean temperature anomaly. The regular oscillations seem to be captured well through the full ERA-40 period. In the troposphere the anomaly does not show any marked jump in 1973 or in 1979 when the VTPR and TOVS instruments, respectively were introduced. There are however large anomalies below 100 hPa level during the El Nino events, the strongest such anomaly can be seen in 1998. Even apart from the 1998 El Nino, one can note a warming trend in the entire troposphere. The bias correction of radiances has therefore worked well to homogenize the ERA-40 temperature analyses.

However above the 10hPa level we can see a strong warm anomaly for the period 1975 through to mid 1976. This has resulted in application of incorrect biases for the NOAA-4 VTPR instrument. We can also see a clear cooling trend above 10hPa over the period with TOVS data from 1979 onwards. Validation of the stratospheric wind analysis with independent rocketsonde data is shown later.

Satellite radiances from different platforms are not consistent and this is demonstrated in Figure 5 for the MSU Channel-4 radiances onboard NOAA-11 and NOAA-12. The blue curves represent the mean uncorrected departures (observation-minus-background), for NOAA-11 ~-1.5K and for NOAA-12 ~-0.2K. The mean corrected departures, the pink curve, indicate close fit and the black curve shows the observed anomaly. The effect of Pinatubo is a ~1K warm anomaly. Therefore the large inconsistency between the two satellites is harmonized and the signal from the radiances is well absorbed into the analyses. The fit to the radiosonde temperatures indicates (not shown here) that a relatively good time homogeneity has been achieved.

The data-assimilation performance can be measured by the mean departure of background and analysis from the radiosonde temperatures. Figure 6, shows that in the Northern Hemisphere the analysis is fairly unbiased with only a small scatter through the period. The background instead has small but time varying bias during the satellite period from 1973 onwards. In general, the spread of bias is much wider in the Southern Hemisphere, especially before 1973. In the Southern Hemisphere, the VTPR bias correction problem in 1975 and early 1976 has introduced a clear jump, which can also be seen in the Northern Hemisphere, but is much smaller here.

A striking similarity can be seen between the anomalies in the global lower tropospheric temperatures calculated directly from MSU-4 data (Mears et al. (2003)) and the equivalent from ERA-40 analyses, Ben Santer et al. (2004). This proves that the use of radiances in ERA-40 including their bias correction has produced high quality lower stratospheric analyses. This is useful in trend studies.

The improving skill of 10-day forecasts over the years is presented in Figure 8 for the both hemispheres. Southern Hemisphere is represented by Australia/ New Zealand since over this area the verifying analysis has sufficient quality over the whole period 1958-2001. Over the Northern Hemisphere the combination of the Ocean Weather Ships (before 1980s), satellites (after 1979) and the land based observations have been able to produce good quality forecasts throughout the period. We can see the skill to improve steadily through the period. In the Southern Hemisphere the improvement due to the use of satellite data is clear in 1973 and dramatic in 1979.

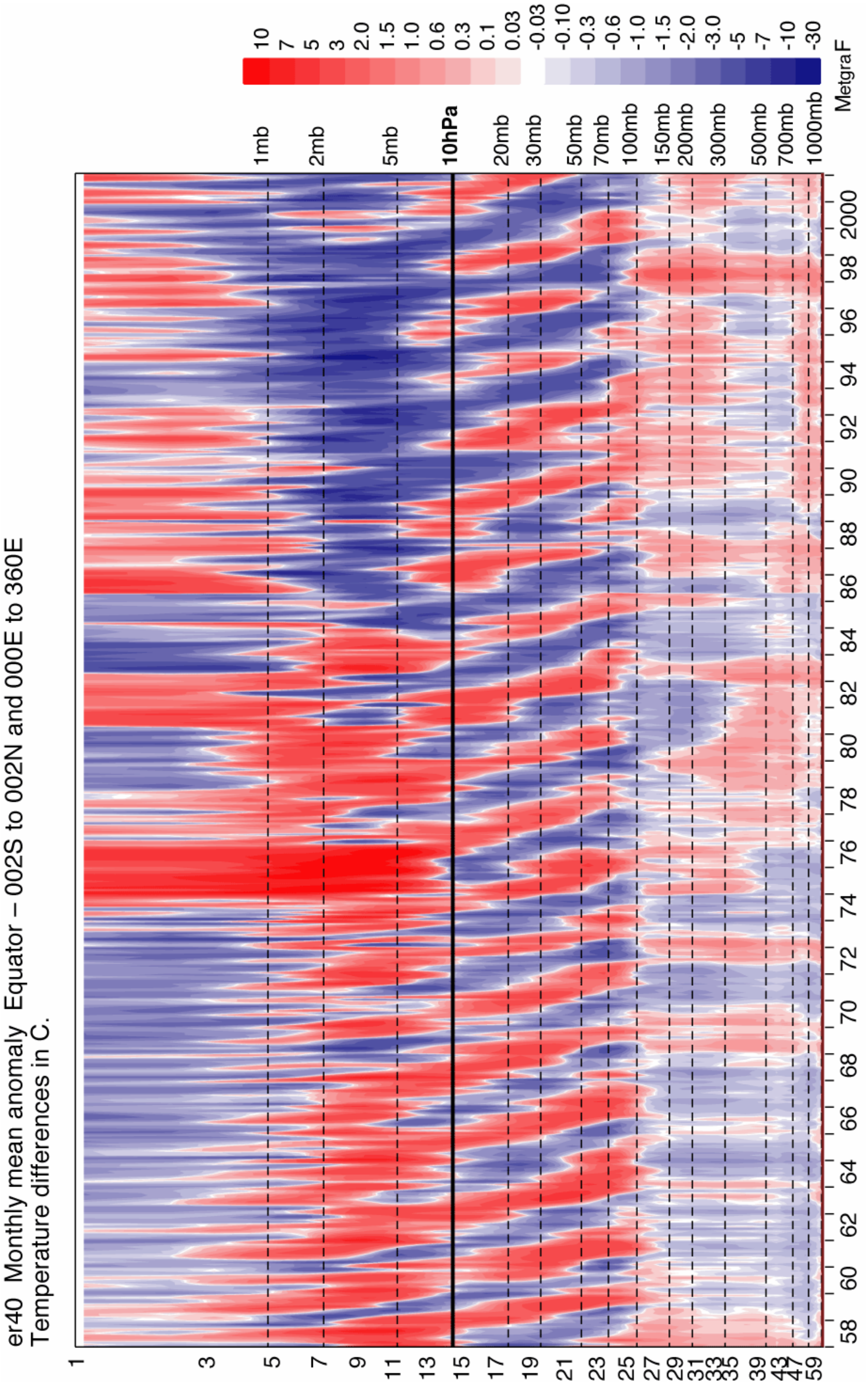

Figure 4 The monthly mean temperature anomaly over the Tropical band 2S-2N.

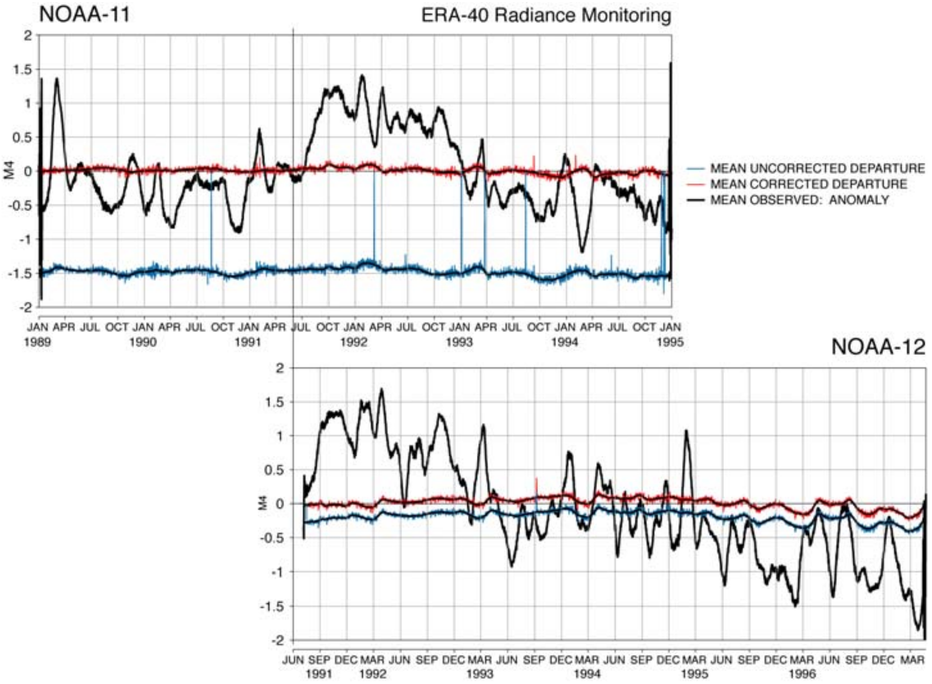

Figure 5. Departure of background simulated brightness temperatures for MSU Channel-4, without bias correction (blue) and with bias correction (red), from the NOAA-11 (upper) and NOAA-12 (lower) satellites. The measured brightness temperature anomaly as seven day moving averages is shown in black.

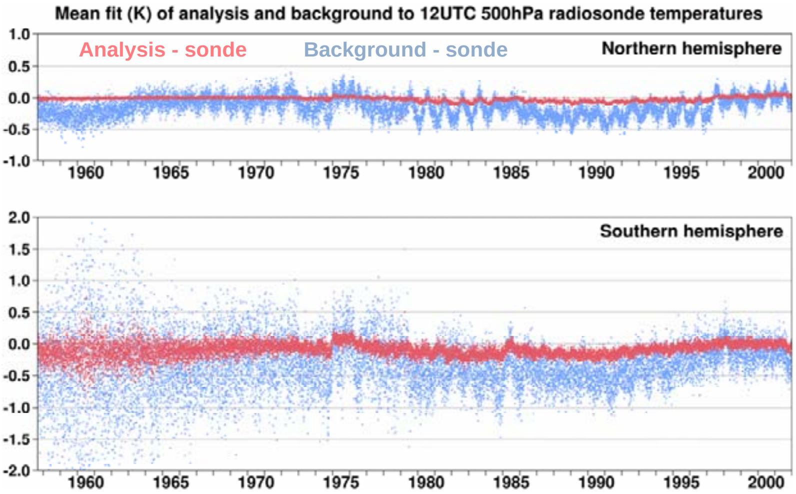

Figure 6 The mean fit of radiosonde temperatures at 500hPa to the analysis and background in both hemispheres.

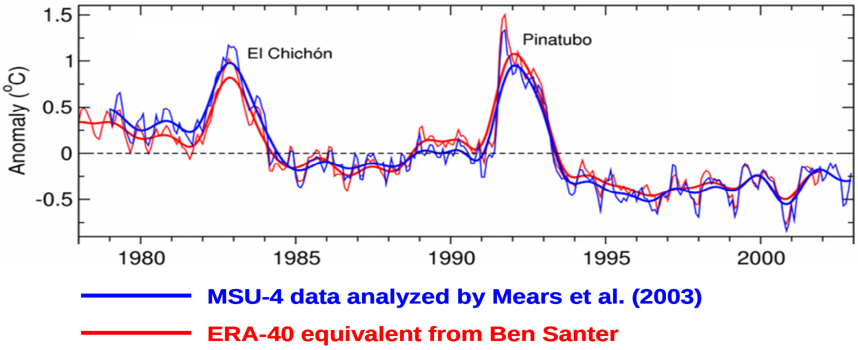

Figure 7 Time series of global mean anomalies in lower stratospheric temperatures.

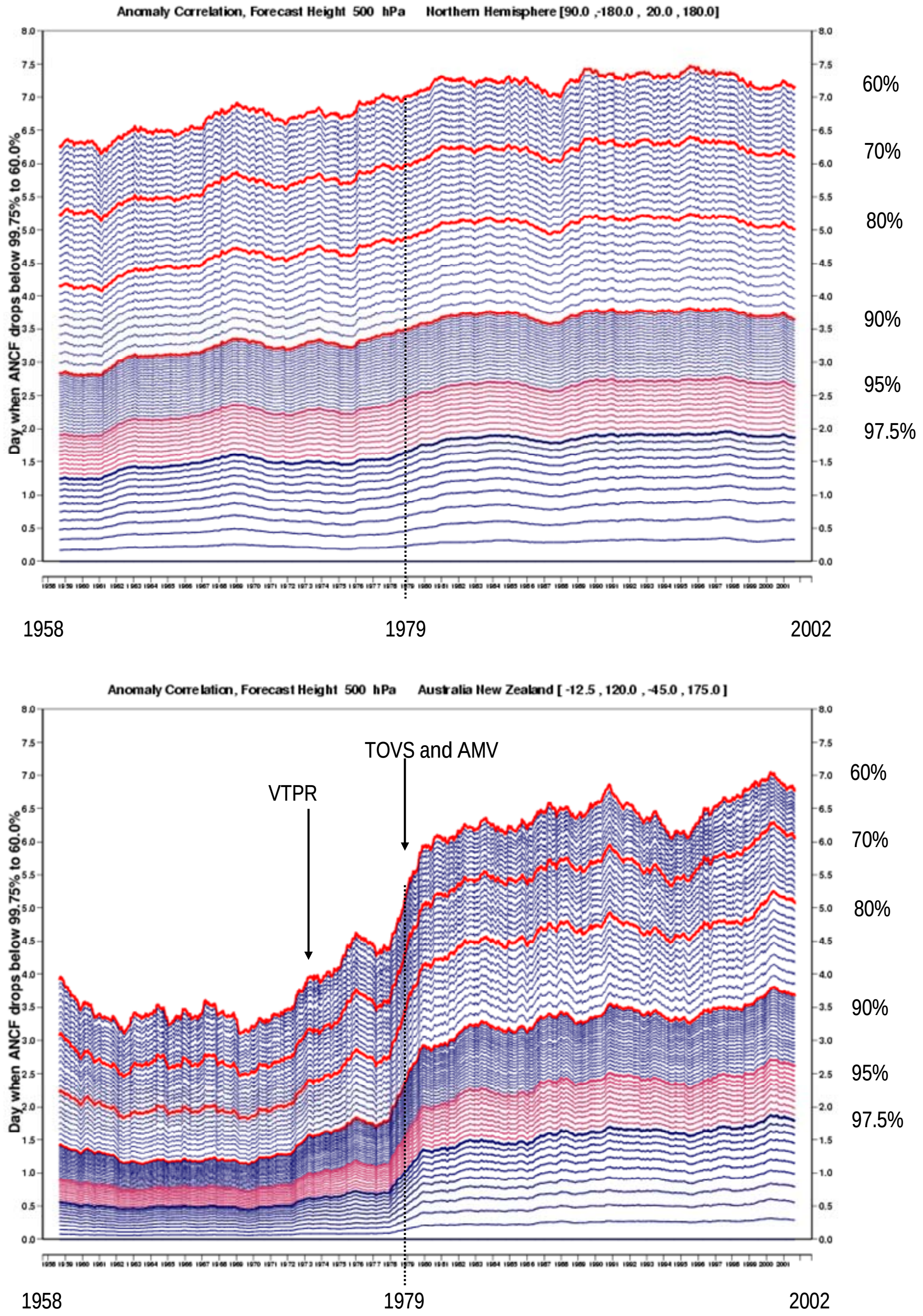

Figure 8 Timeseries (1958-2001) of the two year moving average of the length of daily 10-day 500 hPa height forecasts reaching anomaly correlations 97.5, 95, 90, 80, 70 and 60 % (and levels in between). Northern Hemisphere (top), Australia/ New Zealand (below).

5. Signals of TOVS instrument behaviour in ERA-40

In the following the bias corrected brightness temperatures for a selection of channels are compared with the background and the analysis through the period over the whole globe, Figs 9 → 15. These results should be interpreted as a preliminary indication of the power of data-assimilation to detect inconsistencies in radiance data. Much more could and should be done based on the existing departure data from ERA-40.

In general, we can see that for the channels HIRS-11, HIRS-12, MSU-2 and MSU-4 the behaviour between satellites is fairly stable. Before 1987, the channels SSU-2, SSU-3, MSU-3 and HIRS-4 are noisier and there is a drift in SSU-2 and MSU-3 onboard NOAA-6. There is a opposing drift in MSU-3 and HIRS-4 departures on NOAA-14. Comparison in ECMWF operations: AMSU-A/ NOAA-16 with NOAA-14/ MSU-3 and MSU-2 in Figure 17 shows that NOAA-14/ MSU-3 and MSU-2 are drifting, while AMSU-A is stable. The detection of a drifting channel is easier during multi-satellite periods.

In a period of two or more instruments the mean background departures often mirror each other, e.g. SSU-2 between NOAA-7 and NOAA-6 and MSU-3 between NOAA-10 and NOAA-11.

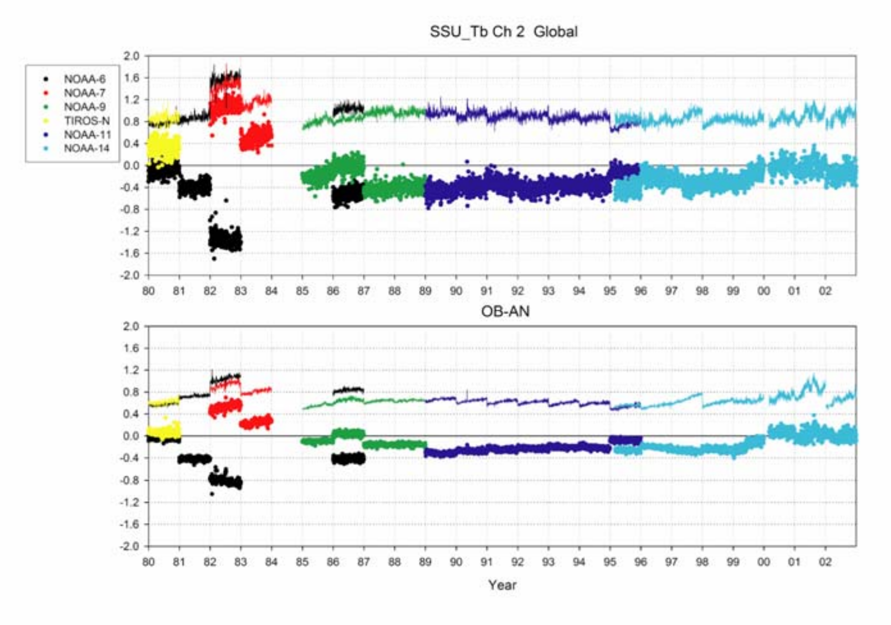

Figure 9 SSU Channel-2 peaks at 4 hPa: global observation-minus-background (top) and observation-minus-analysis (below) statistics (STD and bias) over two months (May and June) from each year 1980 → 2002 and satellite NOAA-6 → NOAA-14. Each dot corresponds to a six hour period.

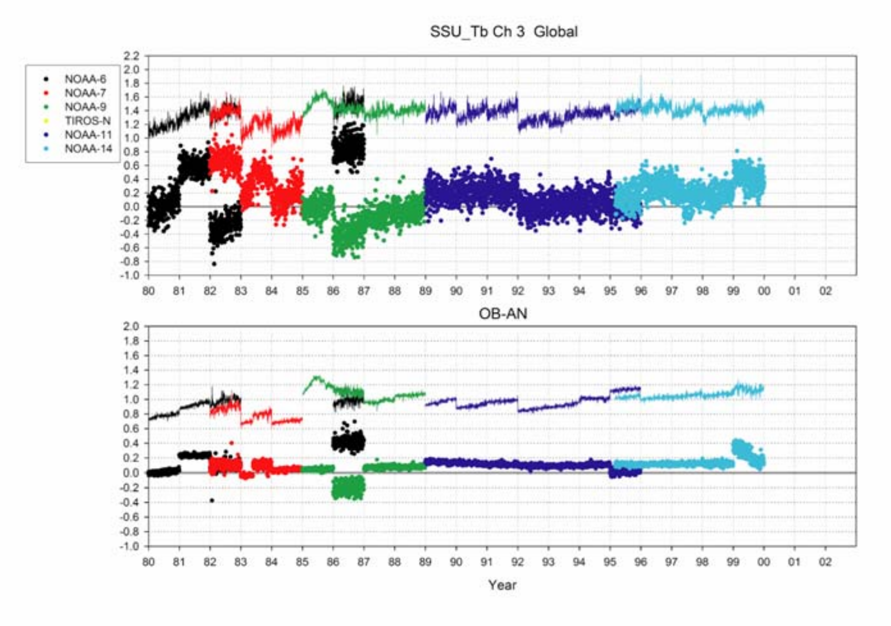

Figure 10 The same as in Figure 9 but for SSU Channel-3, which peaks at 1.5 hPa.

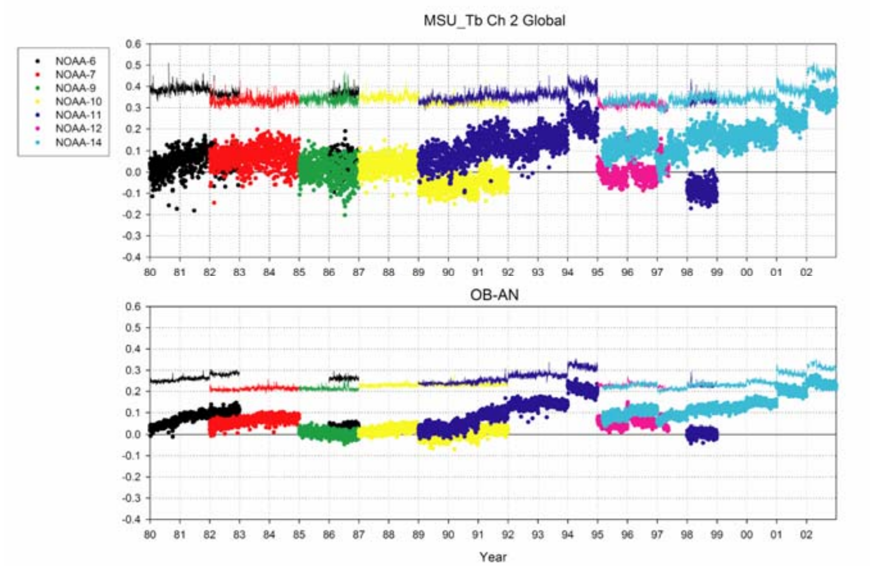

Figure 11. The same as in Figure 9 but for MSU Channel-2, which peaks at 700 hPa.

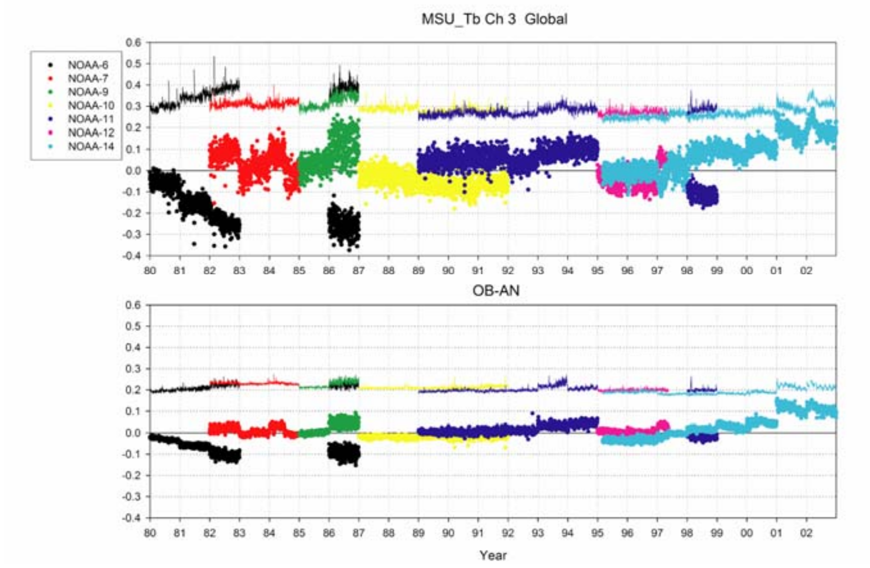

Figure 12. The same as in Figure 9 but for MSU Channel-3, which peaks at 300 hPa.

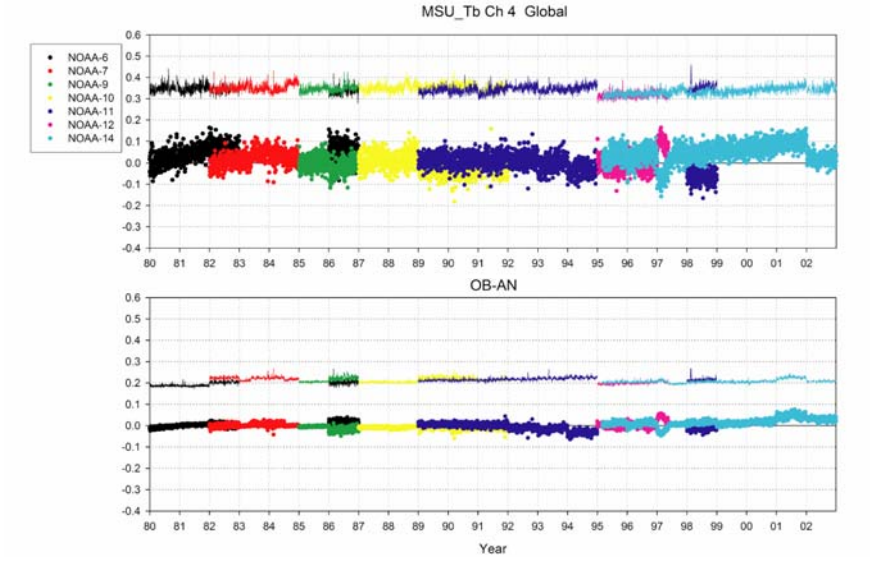

Figure 13. The same as in Figure 9 but for MSU Channel-4, which peaks at 90 hPa.

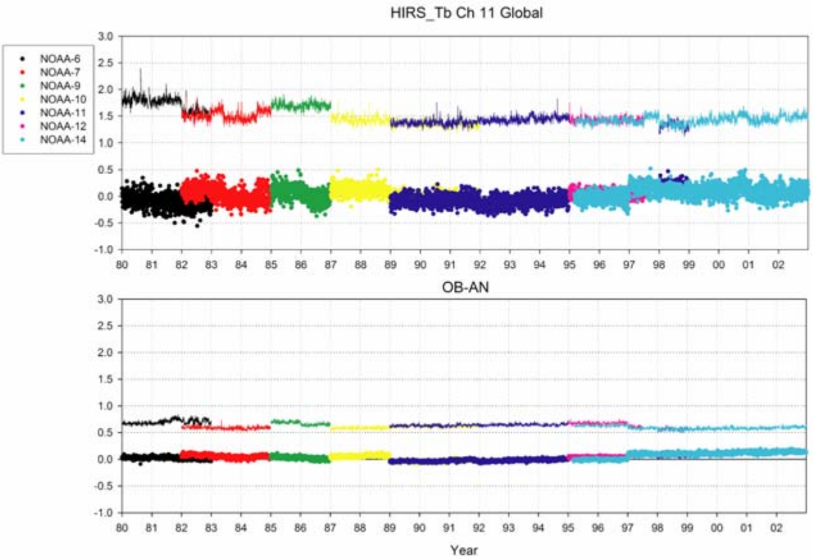

Figure 14. The same as in Figure 9 but for HIRS Channel-11, which peaks at 500 hPa.

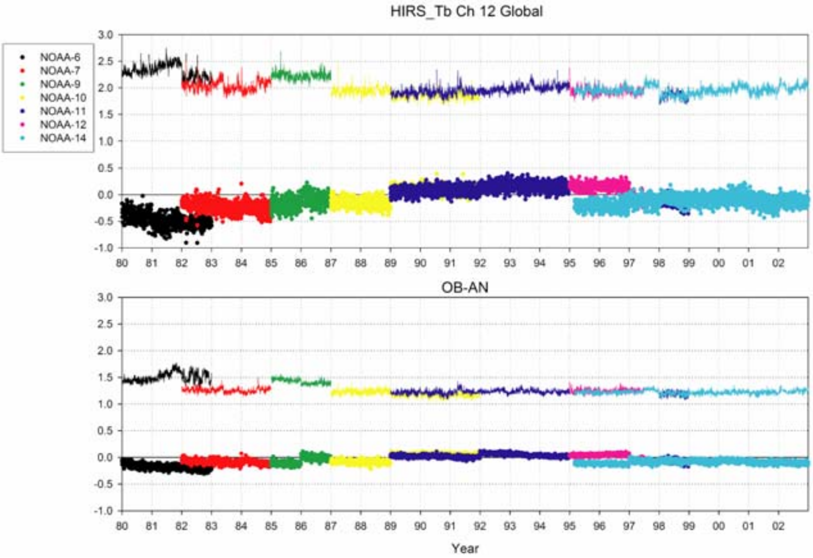

Figure 15. The same as in Figure 9 but for HIRS Channel-12, which peaks at 500 hPa.

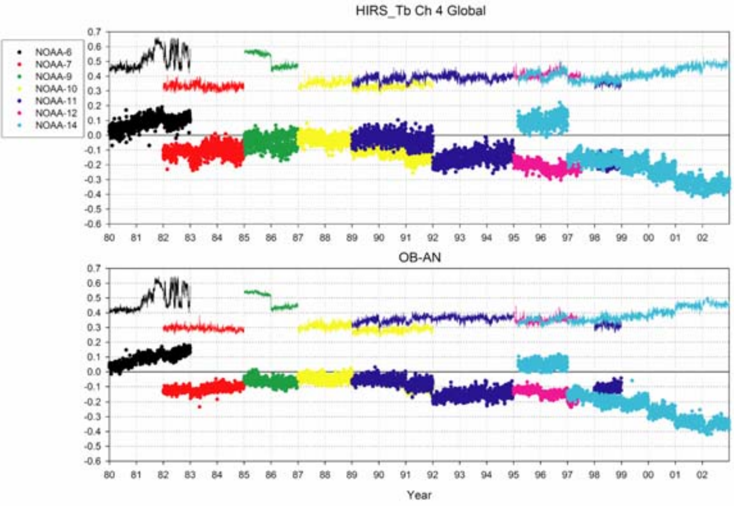

Figure 16. The same as in Figure 9 but for HIRS Channel-4, which peaks at 400 hPa.

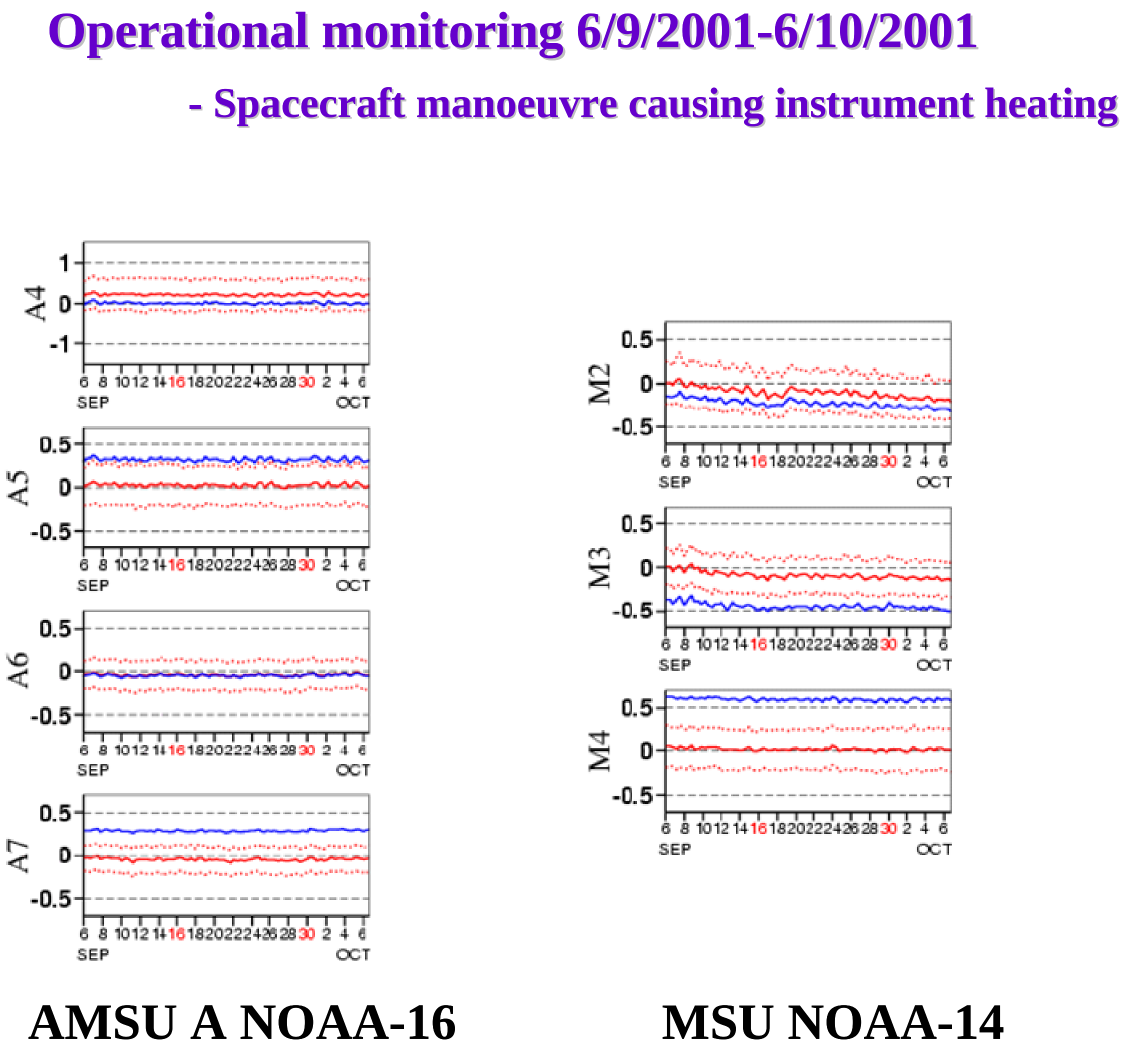

Figure 17. Operational monitoring of AMSU-A/ NOAA-16 and MSU/ NOAA-14

6. Validation of ERA-40 with rocketsonde winds

The ERA-40 stratospheric wind analyses have been verified against independent rocketsonde data at Ascension Island (8S, 14W) over two periods 1973 → 1977 and 1979 → 1984 in Figure 18. Despite the problem of VTPR bias correction in 1975 and the instrument behaviour shown in the previous section, the quasi-biennial oscillation (QBO) in the ERA-40 analysis is remarkably consistent with the rocketsonde data. For a more thorough validation against independent rocketsonde and dependent radiosonde data of the tropical stratospheric winds in ERA-40 see Baldwin and Gray (2005).

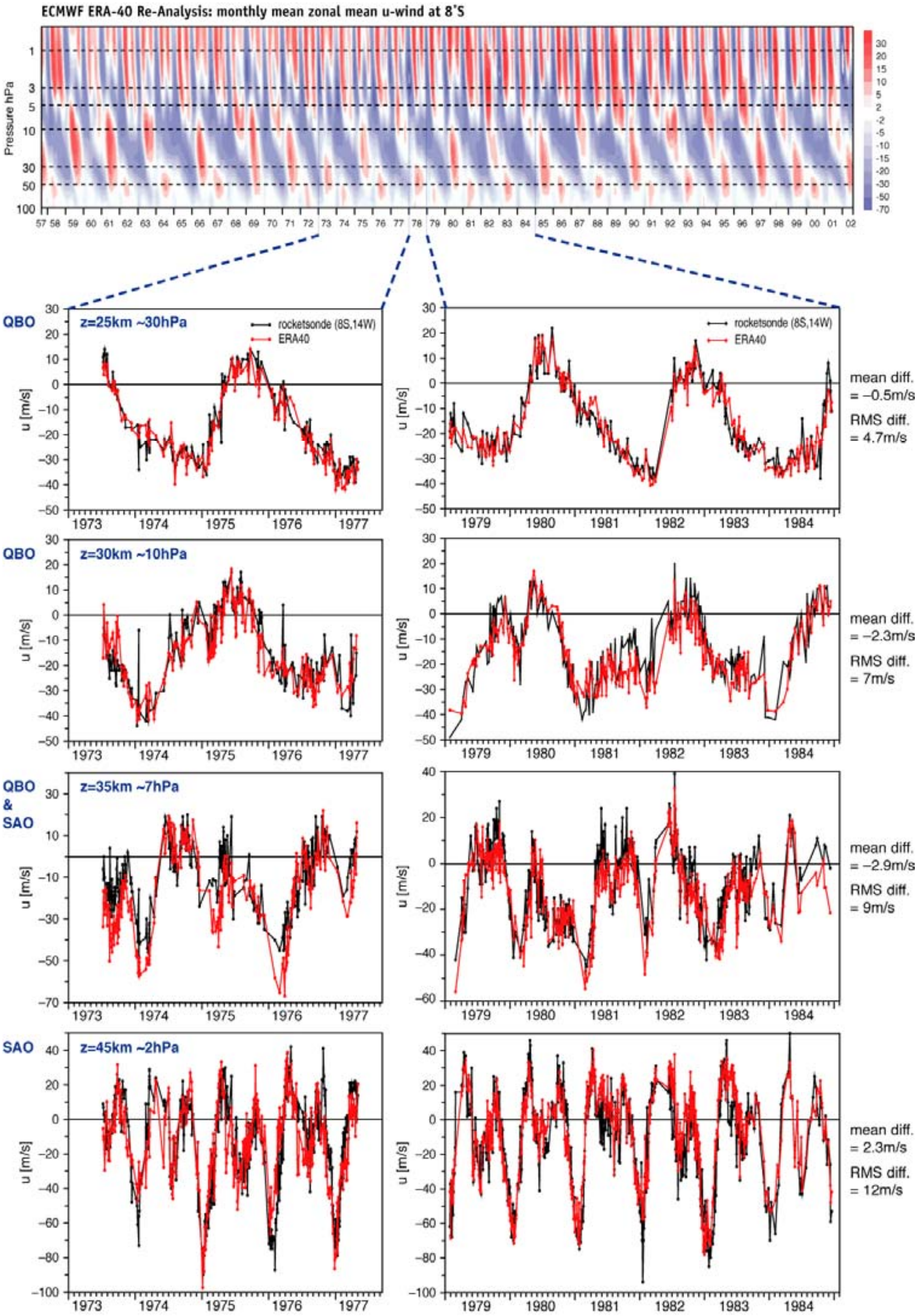

Figure 18. Comparison of individual rocketsonde measurements at (8°S, 14°W) (black) with ERA-40 analysis interpolated to the station location (red). The analysis cycle closest to the measurement time has been used (i.e. no time interpolation of ERA-40).

7. Handling of biases in ERA-Interim

ECMWF’s plan is to start soon an “Interim” global reanalysis from 1989 onwards with an upgraded data-assimilation system using 12h 4D-Var. Early test results show that the deficiencies identified in ERA-40 have to a large extent been addressed and the global hydrological balance has been improved, Figure 19. A positive signal has also been seen in the stratospheric analysis, the “age of air” now being older over the polar areas and in much better agreement with observations. The input data for the Interim Reanalysis will be largely as used for ERA-40, but will include newly reprocessed Meteosat winds from EUMETSAT, reprocessed altimeter height data for ocean waves and new GOME ozone profile retrievals from RAL.

Radiosonde bias correction will be refined and the radiosonde time series are homogenized as described by Leopold Haimberger in these proceedings and in Haimberger (2005). Bias correction will also be introduced for surface-pressure data according the presentation by Drasko Vasiljevic in these proceedings. Use of TOVS data will benefit from quality monitoring undertaken by JMA for JRA-25.

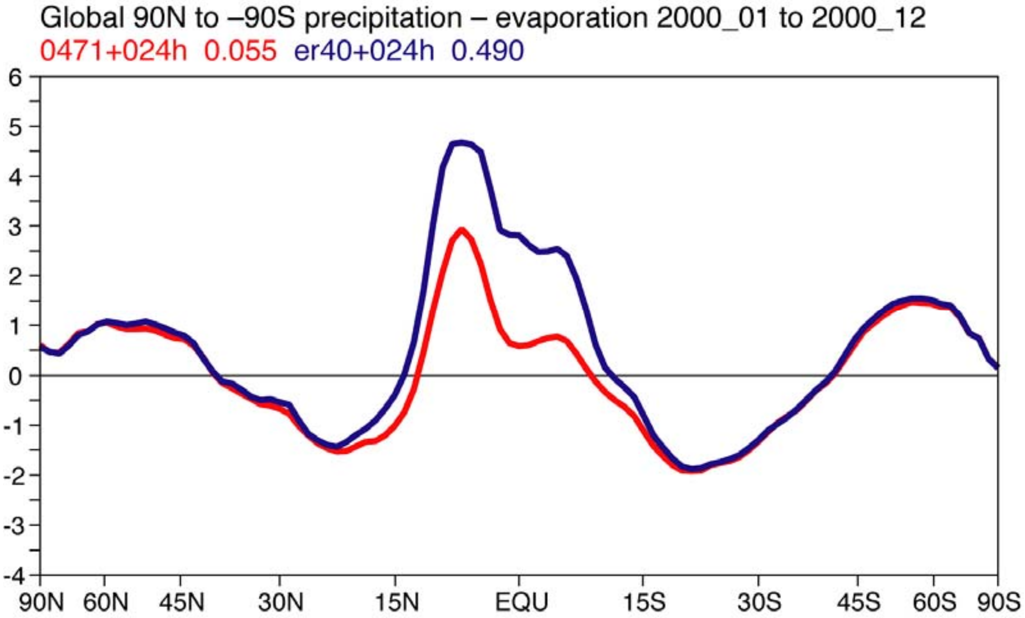

Figure 19. Annual zonal mean of precipitation minus evaporation for ERA-40 (blue) and for a 12 hour 4D-Var test assimilation (red) averaging to 0.49 mm and 0.06 mm/ day respectively.

ERA-Interim will use the adaptive bias correction, see the presentations by Dick Dee and Thomas Auligne in these proceedings, for all radiance data. Long assimilation experiments have proven the technical and scientific benefits of the scheme. Figure 20 illustrates how the adaptive scheme is able to adapt quickly to a sudden jump in the SSM/ I radiances. With multi-instrument observing system jumps in the raw data are common and adaptive scheme can handle them correctly.

A data-assimilation is currently running from 1989 onwards using only conventional observations and atmospheric motion vectors but including all the radiance data passively for monitoring purposes. This will support the understanding of the biases between satellites and instruments and also the assimilation of radiances in the aerosol contaminated period after the Pinatubo eruption in June 1991. The assimilation is also hoped to reveal possible instrument/ channel drifts more objectively.

Figure 21 shows that the mean vertical temperature structure is smoother in the adaptive assimilation, since the increments in the stratosphere are smaller in the adaptive scheme and their effects do not propagate into the troposphere. It has been seen that globally as well as over the Arctic areas the number of accepted and used radiosonde temperatures is slightly larger in the adaptive than in the static assimilation.

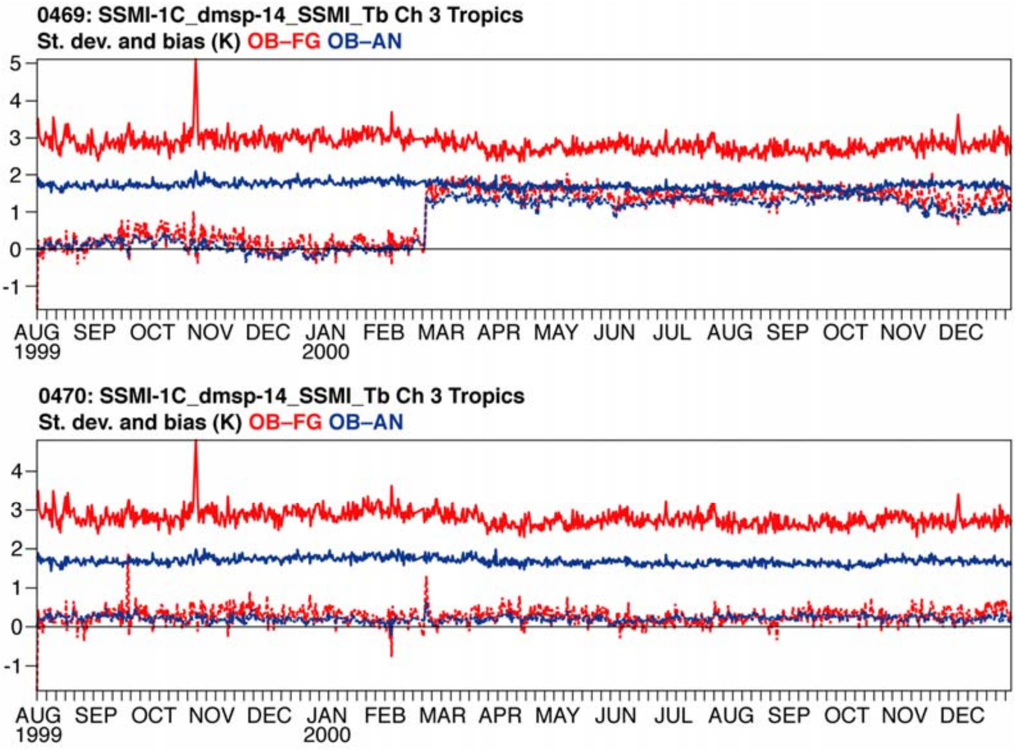

Figure 20. Bias correction of SSM/I/ Dmsp-14 Channel-3 radiances in the static experiment (top) and the adaptive experiment (below). The sudden jump in the radiances went unnoticed in the static assimilation while the adaptive assimilation quickly responded to the jump.

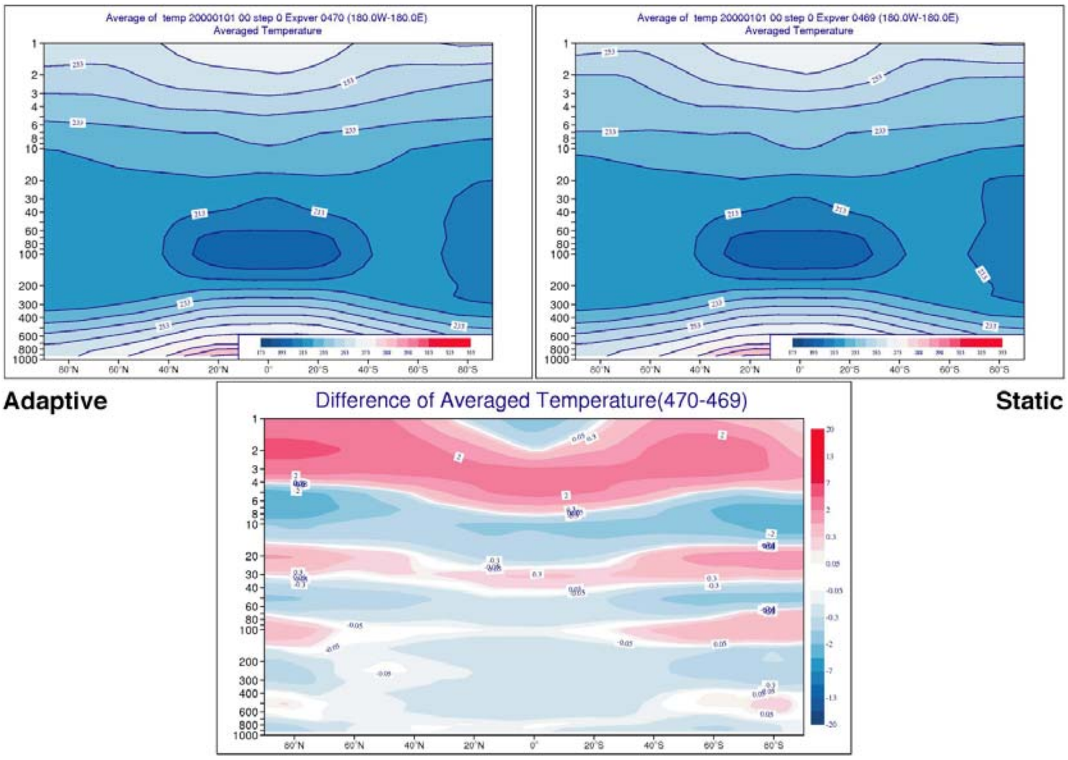

Figure 21. The zonal annual mean temperature structure in the adaptive (top, left) and static (top,right). The difference of the mean temperatures adaptive - static is shown below.

8. Conclusions

In ERA-40, for the first time, satellite radiances have been extensively assimilated including data from the first operational sounder instrument VTPR. The ERA-40 bias correction has benefited from the ERA-15 experience of assimilating the CCR radiances.

The use of Level-1c radiances and the use of model values as predictors produced corrections which could be applied often through the lifetime of the instrument. The quality of the ERA-40 analyses allows studies of climate change. The trends from ERA-40 agree well with the climate trends from independent analysis of the observed values. However reanalysis users should be encouraged to use departure statistics in order to better understand uncertainties in the reanalysis products and feedback towards improvements in the future reanalyses. Independent validation data should be included in the input data for faster intervention based on the monitoring activities.

Adaptive bias correction method offers technical and scientific advantages for radiance bias correction in the reanalyses and extended experiments show that analyses do not “drift”, since other observing systems are acting as anchors. The technical advantages from the adaptive schemes are important, since the historical radiance data have frequent undocumented anomalies, which have to be taken into account.

As the quality of data-assimilation improves the bias handling becomes even more important for reanalyses. There is further potential to improve the bias correction especially during the early data sparse periods by using a longer assimilation window and accounting for the model biases.

A passive radiance assimilation is considered an important tool in identifying the relative biases between satellites and instruments and the possible instrument drifts. It also helps to understand how to assimilate the aerosol contaminated radiance data.

The radiance departure data from reanalyses is still underutilized and could help to understand instrument problems/ drifts as well as to help the satellite data producers to create metadata for future reanalyses.

Integration of different bias handling schemes and the monitoring activities should have high priority. Expert system would be very important in the future to detect automatically signals in the atmosphere but also in the instrument behaviour.

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