Bias correction of radiosonde observations

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ABSTRACT

This paper is tries to give an overview of methods available for bias correction of radiosonde temperature measurements. Radiosonde temperatures are an important data source for detecting climate change in the upper atmosphere. However, they contain a number of time-varying biases that need to be removed in order to exploit the full potential of this dataset. The availability of innovation statistics (observation minus background forecast) from the ECMWF re-analysis (ERA-40) and from the operational ECMWF data assimilation system allows the estimation of biases for the whole radiosonde network.

Two methods based on innovation statistics are examined. One method tries to remove the temperature biases caused by direct solar radiation on the radiosondes or by cooling of the instrument during nighttime, using innovation statistics for groups of similar radiosonde stations. The other method tries to detect and adjust breaks in the temperature time series of individual radiosonde stations. For this purpose it uses time series of ERA-40 innovations.

It is demonstrated that the overall spatial and temporal consistency of radiosonde temperatures is significantly improved by both adjustment methods. For single stations the adjustments can be rather different, however. There are also significant differences in the adjustment of the global mean bias, particularly before ca. 1990.

The innovation statistics are useful for correcting radiosonde records but also reveal problems of the usage of satellite data in ERA-40. Examples are given showing that the usage of innovation statistics before 1979 for the correction of radiosonde biases is not straightforward because of major changes in the satellite observing system.

1 Introduction

Radiosondes are an essential component of the global atmospheric observing system from the 1940s onwards. While the influence of the radiosonde observations on operational analysis has decreased in recent years, since more and more satellite observations are assimilated, they are still regarded as a valuable reference for estimating the quality of operational analyses and forecasts.

The importance of radiosonde observations for upper air climatology and reanalyses such as ERA-40 (Uppala et al. 2005) is even larger. They reach farther back than satellite records and they also provide relatively high vertical resolution compared to satellite instruments such as the Microwave Sounding Unit (MSU). As such they are a unique source of information about the upper air climate. While radiosondes measure temperature, humidity and wind, the analysis here is restricted to temperature.

The quality of the radiosonde instrumentation has been constantly improved. While this is a positive development, the artificial shifts that inevitably occur when changing the instrumentation can easily distort any climate signal in the data. Fig. 1 shows time series of mean day-night differences of composites of radiosondes located between 30W and 40E as well as between 120E and 120W at the 50 hPa level. The differences, which exceed 1K in the 1960s are gradually reduced at this altitude to practically zero in recent years. This reduction is caused by improved shielding of the temperature sensors as well as by improved radiation correction software.

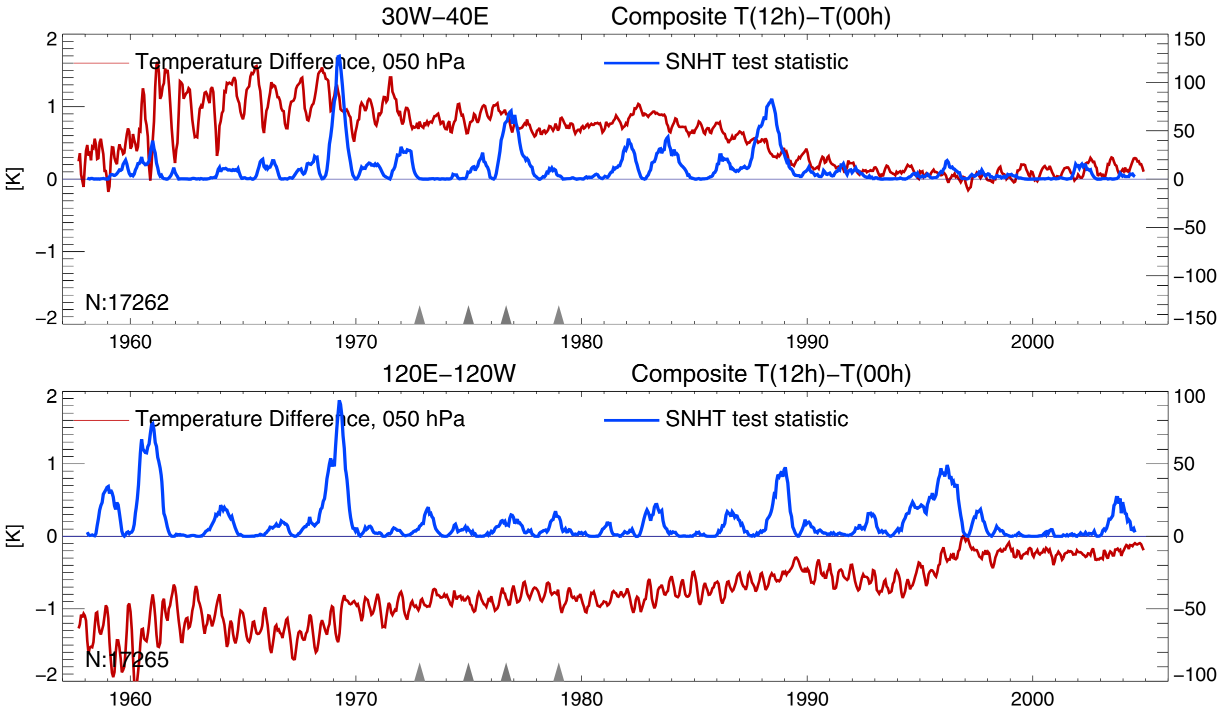

Figure 1: Time series of composite mean 12GMT-00GMT differences from radiosondes, a) between 30W and 40E, b) between 120E and 120W. Only stations and days with both 00GMT and 12GMT data have been included in composite (about 80 radiosondes in a), 90 radiosondes in b), much less in the early 1960s). Thin curve is 12GMT-00GMT difference, thick curve is time series of SNHT test statistic. Peaks in SNHT test statistic indicate abrupt changes in the mean 12GMT-00GMT difference. The peak in a) in 1988/1989 is probably caused by the change to Vaisala RS80 radiosondes at many places. The peak in b) in 1996 is caused by the degradation of the Russian radiosonde network, which had relatively large day-night differences. The breaks in 1969 are caused mainly by changes in the Russian and French radiosonde networks

The resulting trend is purely artificial and must be removed before the radiosonde data can be recommended as input for climate change detection or for reanalysis.

Fig. 2 provides a different view of the same problem for the years 1989/1990 which will be the beginning years of the forthcoming "interim" reanalysis at ECMWF. One can see the large regional differences in the 12GMT-00GMT differences related to political boundaries. If a relatively homogeneous observing system is used, as is the case over the US, the functional dependence of the radiation error on longitude (and thus solar elevation) is obvious. According to recent findings by (Seidel and Free 2005) the diurnal cycle at 50 hPa should have an amplitude of less than 0.3K except in the inner tropics. The situation has improved since 1989, but there are still large biases at some sites.

A bias correction for radiosondes should ideally satisfy the needs of both operational and climate data assimilation systems. For an operational data assimilation system, the biases of all current radiosonde observations should be estimated and corrected. At present the biases are estimated before the data assimilation process by reading in static tables that have been prepared in advance. The tables for the operational bias correction are based on recommendations of the radiosonde vendors or on results from the literature. A revised operational bias correction with tables based also on analysis feedback information is under development at ECMWF and is not discussed further here.

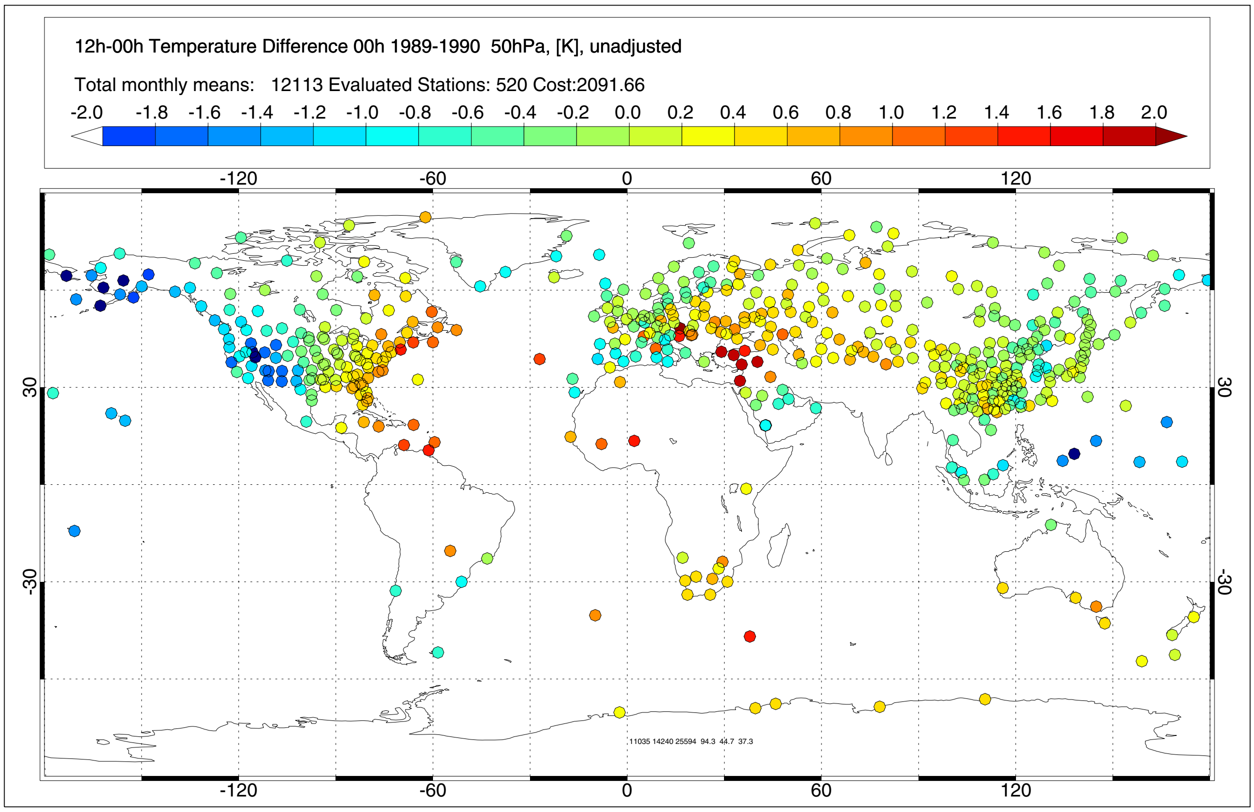

Figure 2: 12GMT-00GMT radiosonde temperature differences at 50 hPa averaged over period 1988-1990. Each bullet denotes a radiosonde station with more than 30 out of 36 months of data; Indian radiosondes are excluded in this and all following calculations. Colour of bullets indicates the difference. Differences above ca. 0.5K are considered spurious except in the Tropics.

In this report the emphasis is on historical radiosonde records and climate data assimilation. For this purpose the temporal homogeneity of the analysis product is much more important than for operational purposes. A bias correction procedure in a climate data assimilation system should remove any shifts in the biases of the assimilated observations.

Efforts to generate a homogenized radiosonde temperature dataset started in the 1990s, when radiosonde observations as well as information about the observation practice in use (metadata) were collected in the Comprehensive Aerological Reference Data Set (CARDS, Eskridge et al. 1995). Some authors attempted to use the data and metadata available in CARDS to provide homogenized temperature datasets. While physically based corrections as described by Luers and Eskridge (1995) based on metadata and detailed knowledge of the instruments are potentially the most satisfying approach, they need detailed information about equipment and launch times that is often not available. Therefore such an approach can be applied only at selected sites but not for the global radiosonde dataset.

Homogeneity adjustments based on statistical methods, metadata and expert judgement have been published by Lanzante et al. (2003a); Lanzante et al. (2003b), referred to as LKS, and recently by Thorne et al. (2005). While these datasets are important achievements that have been used for intercomparisons with satellite data and with climate model results, they are not suitable for future reanalyses since only a fraction (87 stations by LKS, 477 (678) stations by (Thorne et al. 2005)) of the available radiosonde records is adjusted and since only shifts in the anomalies are adjusted but not a possible bias of the whole time series.

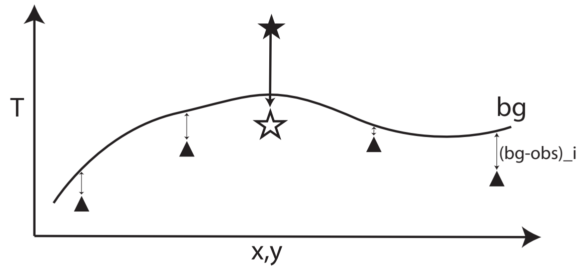

Figure 3: Adjustment of the mean of the most recent part of radiosonde time series. bg is background temperature field averaged over most recent 4 years of tested time series. Triangles are corresponding time means of neighbouring radiosonde temperatures. Filled star is mean of unadjusted time series, open star is mean that would be expected from bg-obs of ensemble of neighbouring stations. Adjustment applied is difference between filled star and open star.

There are also concerns regarding the homogenization method used. The corrections by LKS do not involve neighbour intercomparisons and therefore may be influenced by real climate shifts. The correction method employed by Thorne et al. (2005) uses neighbour intercomparisons but is applied to seasonal means and without distinguishing between daytime and nighttime ascents. The daytime biases are, however, rather different from the nighttime biases as may be seen from Fig. 1. Therefore they need to be adjusted separately, as has been emphasized recently also by Sherwood et al. (2005). Further, none of these datasets has been created by automatic procedures. Therefore it may be difficult to reproduce the decisions that led to some of the applied adjustments.

The adjustment procedures mentioned so far are based purely on radiosonde observations and metadata. In this report results from two methods that use innovation statistics for bias corrections are presented. The innovations are defined as $\mathbf{y} - H(\mathbf{x})$, where $\mathbf{y}$ is the vector of observations available for the assimilation system, $\mathbf{x}$ is the model state vector and H is the observation operator. In the present context we refer to the innovations as *obs-bg*, where *obs* is the actual radiosonde temperature measurement and *bg* is the background state mapped to the observation location by the observation operator H.

2 Radiosonde bias correction methods based on innovation statistics

For ERA-40 a bias correction method that removes the radiation error of radiosondes, which is caused by direct solar heating of the temperature sensor as well as infrared heat loss, has been developed and implemented (Andrae et al. 2004). This is achieved by estimating the dependence of the temperature innovations on the solar elevation angle and pressure. This dependence is considered largely spurious and is therefore removed. For this purpose innovations from one year are collected for calculating adjustment tables valid for this year. The tables are calculated for groups of stations which are similar in terms of geographic region and radiosonde type. The fundamental assumption in this method is that *the diurnal cycle of the background temperature forecasts is realistic*.

Application of this correction method in ERA-40 reduced the number of rejected radiosonde observations and had an overall positive impact on the analyses. The adjustment method can use innovation statistics from an operational assimilation system as well. At present ERA-40 analysis feedback data are used for the period 1958-2001 and operational feedback data are used from 2002 onwards.

However there is room for improvement as well. No special effort is undertaken to ensure the temporal con-

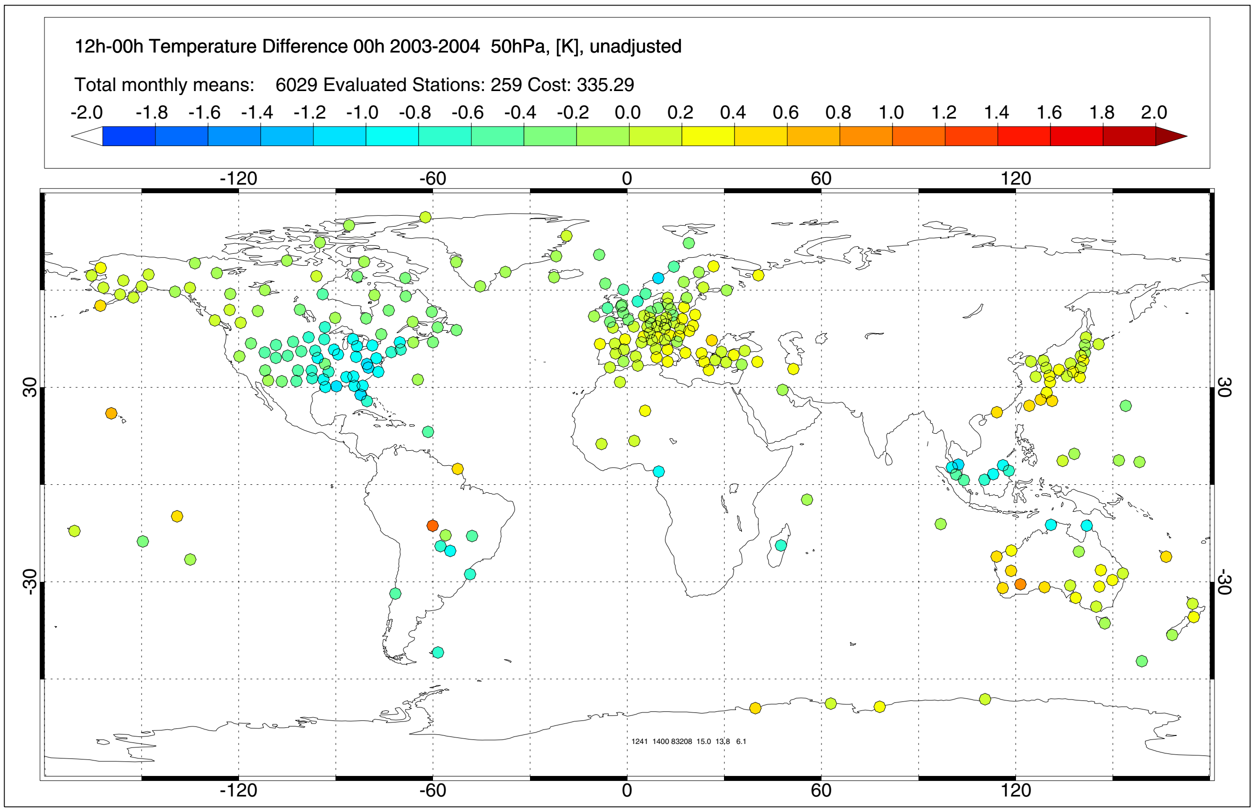

Figure 4: 12GMT-00GMT temperature differences at 50 hPa averaged over period 2003-2004 at "trusted" radiosonde sites. At these sites twice daily ascents exist and their most recent four years of data are assumed to be unbiased because high quality radiosonde equipment has been used according to the radiosonde type specifier in the GTS messages. Homogenized time series of these sites are used for interpolation to sites that need adjustment of the most recent part of their time series.

sistency between years. As such the bias estimates may vary from year to year. The adjustment procedure also only adjusts the radiation error but not a possible mean bias that is independent of solar elevation, since it cannot be assumed that the daily or annual mean background forecasts are unbiased.

Recently a second bias correction method called RAdiosonde OBservation COrrection using REanalyses (RAOBCORE) has been developed by Haimberger (2005). It is uses innovation statistics from ERA-40 (1958-2001) and operational analysis (from 2001 onwards) as well, but in a completely different way as the bias correction used in ERA-40. Its most important characteristics are:

- It uses *time series* of radiosonde temperature innovation statistics for individual radiosonde stations, not composites of station groups. This is possible only since the existence of the so-called ERA-40 analysis feedback dataset, which contains long enough time series of innovation statistics from 1958-2001, together with other useful diagnostic information. The method uses the bg time series as reference and the radiosonde temperatures at individual sites as test series. A jump in the obs-bg time series is attributed to a change in the observation practice at the radiosonde site. The fundamental assumption of this method is that *the time series of ERA-40 bg forecasts are temporally more homogeneous than the individual radiosonde temperature records*.
- The method is capable of detecting changes of the mean radiosonde temperature bias, since it is not necessary to assume that the bg is unbiased.

- It uses time series of individual launches, not monthly or seasonal means, for break detection and adjustment, and it analyzes daytime and nighttime launches separately. Since it does not use compositing, the method needs relatively long time series for estimating the breaks. At present at least 2 years of data are required for detecting a breakpoint.

- Not only breaks of long records are adjusted but also the biases of the most recent parts of the records. A record with no breaks may still have a large constant bias, which is not problematic for climate change studies but is detrimental for reanalysis efforts. A method using a combination of neighbour composites and ERA-40 innovations addresses this problem (see next section and Fig. 3).

Adjustments have been applied by RAOBCORE to 1184 radiosonde records which had at least half a year of observations, i.e. to more than 95% of the available radiosonde data. Shorter time series have not been adjusted since the adjustment method applied is useful mainly for the annual mean bias. RAOBCORE in its present form is not capable of adjusting deviations of the radiation error from the annual mean.

Both methods prepare static adjustment tables that can be read in by the ECMWF data assimilation system. A possible third method would be an adaptive variational bias correction technique as described by Dee (this volume). This method uses the innovations for estimating parameters of a bias model, which could be, in the case of radiosonde temperatures, the radiation error as function of pressure and solar elevation for each radiosonde type. The ratio between the number of available observations and bias parameters to be estimated is, however, much less favorable than for most satellite observing systems. Therefore radiosondes are not the first candidate for the application of variational bias correction techniques and development of such a scheme for radiosondes is left for the future.

To illustrate how the two static methods work, the radiosonde station Bethel (Alaska, 70219) is examined. This is a particularly difficult station for several reasons. Firstly, different radiosonde types have been used at Alaskan stations during the early 1990s. Therefore any composite over Alaskan stations is a mixture of radiosondes with different (and large) radiation errors. Secondly, the solar elevation angle has a strong annual cycle and is often close to zero, where the radiation error is most sensitive to the solar elevation angle.

Fig. 5 shows time series of the temperature innovations (obs-bg) at 00GMT at this radiosonde site at 50 hPa. According to the digitized station history of Aguilar (2000) VIZ-sondes have been used at Bethel until 1989, then Space Data radiosondes have been introduced. In 1995 there was another change to Vaisala RS80 radiosondes. Several other radiosondes in Alaska have similar station history, but not all of them.

Fig. 6 shows the different character of the two adjustment methods. The solar angle dependent correction generates adjustment tables from innovation statistics of Alaskan composites for each year. The compositing helps to gather enough data within a year to be able to calculate bias estimates for four different solar elevation classes($<$-7.5°,-7.5°-7.5°,7.5°-22.5°, $>$22.5°). Through a year Bethel lies in different solar elevation classes, which causes the approximate seasonal cycle of the corrections (Fig. 6-a)

RAOBCORE first tries to accurately detect the dates of shifts in the time series using a variant of the Standard Normal Homogeneity Test (Alexandersson and Moberg 1997). The breakpoint detection also makes use of digitized station history information, if available (see Haimberger 2005 for details). In many cases it is possible to locate the data of the instrument with an accuracy of one month. After the break detection, the means of the older parts of the series are adjusted by the difference of the innovations before and after the breakpoint (Fig. 6-b). The adjustments between breakpoints are constant, i.e. they do not have seasonal variations. The size of the abrupt temperature shifts is well determined, however, and therefore it is possible to adjust the annual mean temperature bias more aggressively than with the radiation error correction.

Since RAOBCORE adjusts only breaks in time series, the whole time may still be biased after the adjustment if the most recent temperatures of the radiosonde record are biased. In order to remove this bias, it is estimated

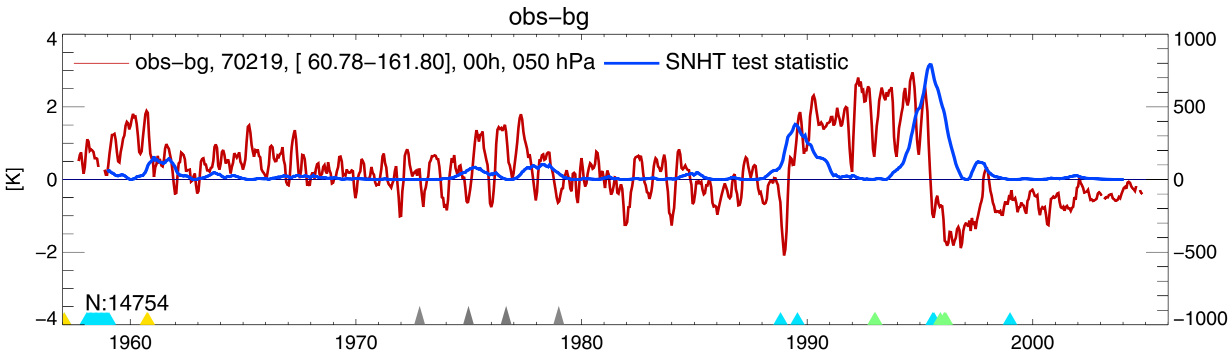

Figure 5: Time series of innovations at radiosonde station Bethel (70219, Alaska) at 00GMT. Red curves are differences between observed temperature and the ERA-40 background forecast. Blue curve is SNHT test statistic. Peaks in SNHT test statistic indicate abrupt changes in the mean difference. Blue/green triangles indicate changes of radiosonde type and on-site radiation correction, as documented by (Aguilar 2000). At Bethel the most prominent peaks coincide with the introduction/removal of Space Data radiosondes. Black triangles indicate start and end of VTPR (1973-1978) and NOAA-4(1975-1976) periods.

by comparing the innovations of the most recent part of the tested time series with innovations of a composite of ”trusted” neighbouring radiosondes such as Vaisala RS80/90/92 or the most recent Japanese radiosondes. Fig. 3 indicates this. The adjustment of the most recent part works quite well in general. Only in data sparse regions the interpolation distances are large and the quality of the adjustment is more questionable, of course. Fig. 4 shows the distribution of trusted radiosondes in 2003/04 together with their 12h-00h differences.

Both adjustments reduce the effect of the radiosonde changes from VIZ to Space Data in 1989 and from Space Data to Vaisala in 1995, as can be seen from Fig. 7. At this high latitude the radiation error has a strong annual cycle which is strongly damped by the solar elevation dependent correction. The large mean error in the early 1990s is only partly removed, however. RAOBCORE efficiently removes the annual mean error but the strong annual cycle remains after the adjustment. It should be noted that Alaska is a particularly difficult example that clearly reveals the limits of both adjustment methods in their present implementation. At most other sites, both adjustment methods work more satisfactorily, particularly from the 1990s onwards, which is the period of the interim reanalysis. The example should highlight that both bias corrections can only be interim solutions that need to be improved before the next major reanalysis starts.

Another difficulty is that the fundamental assumptions of both feedback-based bias correction methods are questionable during some periods of ERA-40, especially the VTPR period (1973-1978, Kelly and Li (2006)). Fig. 8 shows a time series of 12h-00h differences of the ERA-40 bg. This time series should be very close to stationary apart from a possible constant annual cycle. There are, however, relatively large fluctuations from 1973-1978 which contradict the assumption of a temporally homogeneous bg. One should further note that before 1973 the 12GMT-00GMT difference of the bg is positive whereas it is close to zero after 1979. This effect is caused before 1979 by the too warm daytime radiosonde temperatures at high altitudes which lead to a too warm nighttime bg temperature 12 hours later since no other data are available to constrain the bg during the early years. As a result the bias corrections based solely on ERA-40 innovations before 1979 must be interpreted with caution.

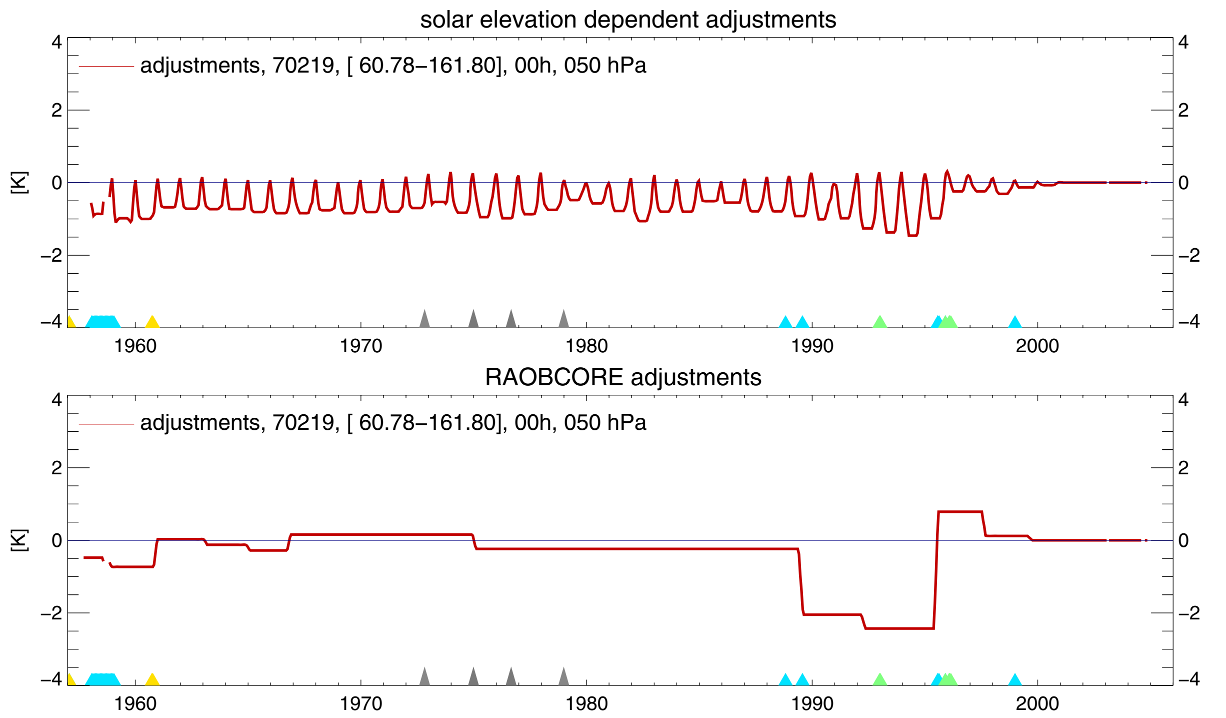

Figure 6: Adjustments applied to the radiosonde temperatures in 50 hPa at Bethel, a) by the solar angle dependent correction, b) by RAOBCORE.

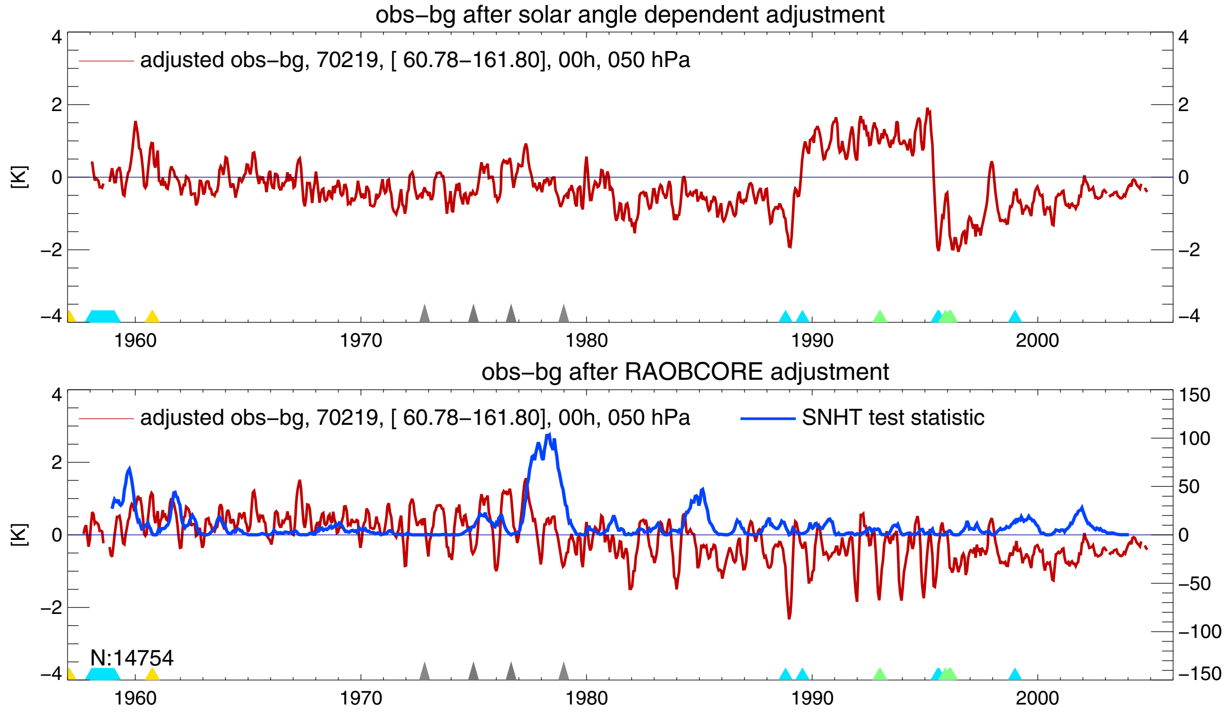

Figure 7: Time series of difference between observed temperatures and the bg, a) after adjustment of the observations with the solar elevation dependent bias correction b) after adjustment with RAOBCORE. Compare with Fig. 5.

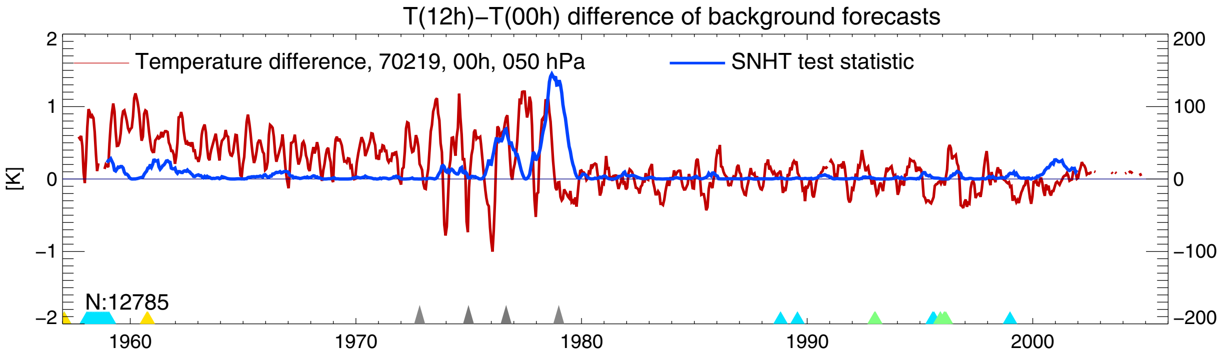

Figure 8: Time series of 12h-00h difference of the ERA-40 bg at Bethel. Note problematic VTPR period 1973-1978. and positive 12h-00h differences before 1973. Note smaller temperature scale compared to figures above.

3 Effects of the adjustments on global mean radiosonde temperatures

Despite these caveats both adjustment methods perform well at least for the period of the interim reanalysis, as may be seen from Fig. 9. It shows the 12h-00h differences after adjustment with a) the solar angle dependent correction and b) RAOBCORE. The spuriously strong dependence of the 12GMT-00GMT difference on longitude apparent in Fig. 2 is strongly reduced by the solar angle dependent adjustment and almost completely removed by RAOBCORE. The heterogeneity of the Alaskan station network visible in Fig. 2 is reduced in Fig. 9 as well.

Both adjustments seem to be reasonably robust since there are only very few stations that still have obviously erroneous day-night differences after adjustment. The overall spatial consistency of the 12h-00h differences is substantially better in Fig. 9 compared to Fig. 2.

The positive impact of both bias corrections may be seen also from Figs. 10 and 11. The day-night differences over Europe and the Pacific regions are temporally more stable after both corrections, at least from the late 1980s onwards, which is sufficient for the interim reanalysis. Again one can see that the solar angle dependent adjustment in Fig. 10 reduces annual variations of 12GMT-00GMT differences. RAOBCORE makes the annual mean 12GMT-00GMT differences practically constant (Fig. 11), as it should be, but the seasonal variations remain.

While the regional day-night differences are a good consistency check, they do not reveal how the daily mean temperatures are affected by the adjustments. Fig. 12-a) shows that the solar angle dependent adjustment has little effect on the global mean radiosonde temperature at 12GMT, apart from the annual cycle that is changed more or less strongly. The global mean temperature trend remains practically unchanged by this adjustment.

RAOBCORE in Fig. 12-b) adjusts the early global mean temperatures downward by about 0.5K. This appears reasonable since the large 12GMT-00GMT differences in the early years in the European and Pacific longitude belts can be attributed mainly to local daytime biases. The downward adjustment is also more consistent with the findings of (Seidel et al. 2004). Given the size of the differences of about 1K shown in Fig. 1, the adjustment by RAOBCORE still seems relatively weak.

There is much additional verification work with independent datasets necessary before one can fully trust one of these global mean adjustments. Such work has been partly performed by regional studies such as (Haeberli 2005) and may come from comparisons with MSU records and data from international radiosonde intercomparisons as well.

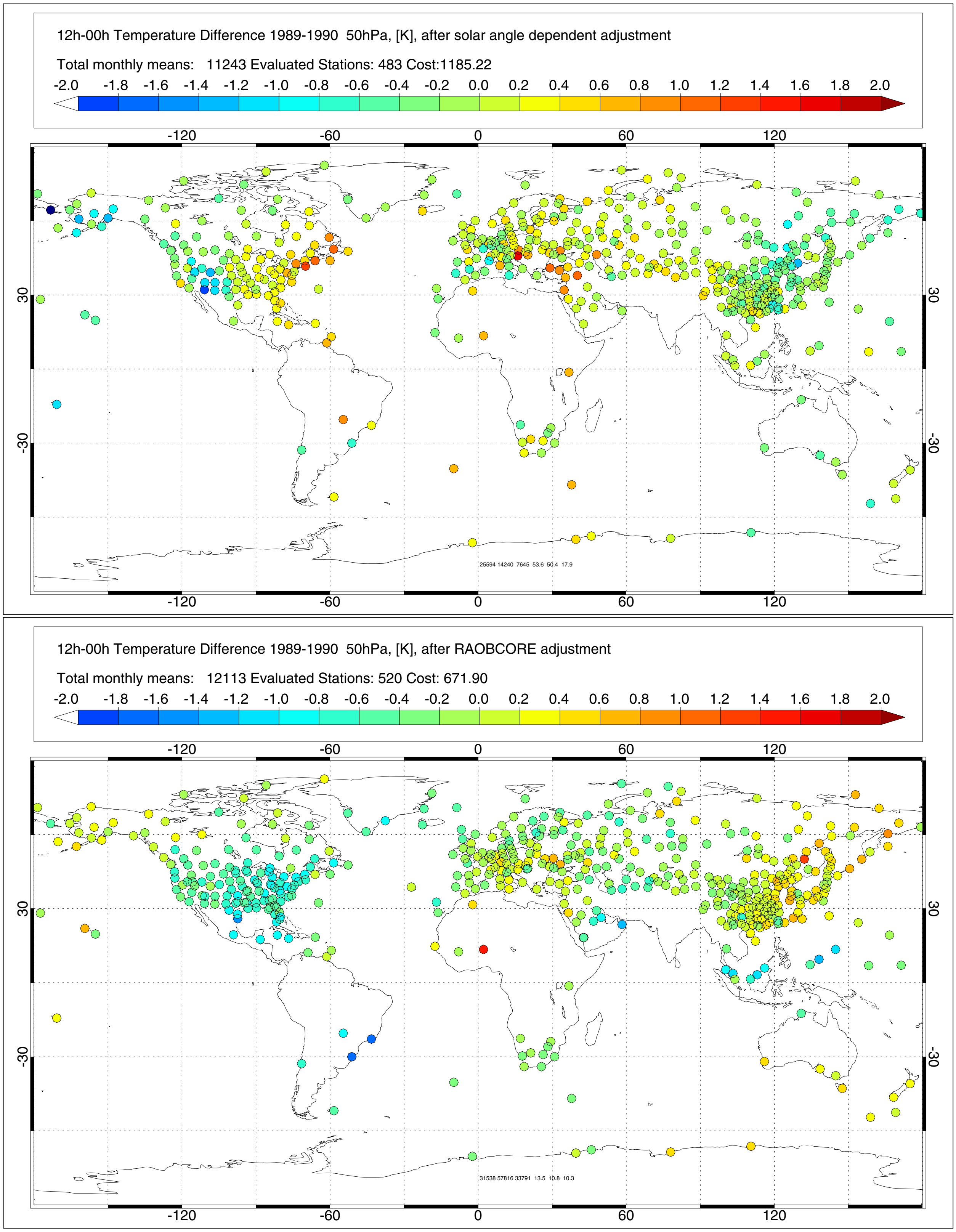

Figure 9: Adjusted 12GMT-00GMT temperature differences at 50 hPa averaged over period 1989-1990. Upper panel shows the difference after adjustment with solar angle dependent bias correction, lower panel shows difference after adjustment with RAOBCORE.

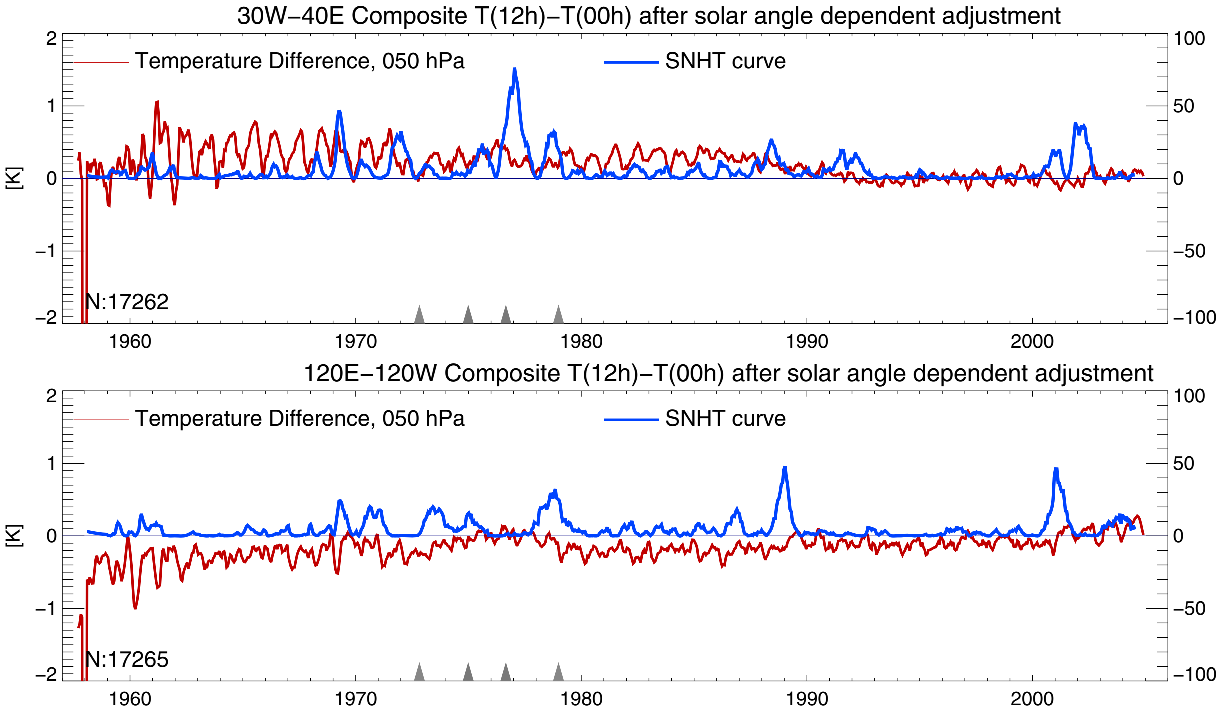

Figure 10: Time series of composite mean 12GMT-00GMT differences from radiosondes, adjusted with solar angle dependent bias correction, a) between 30W and 40E, b) between 120E and 120W. Compare with Fig. 1

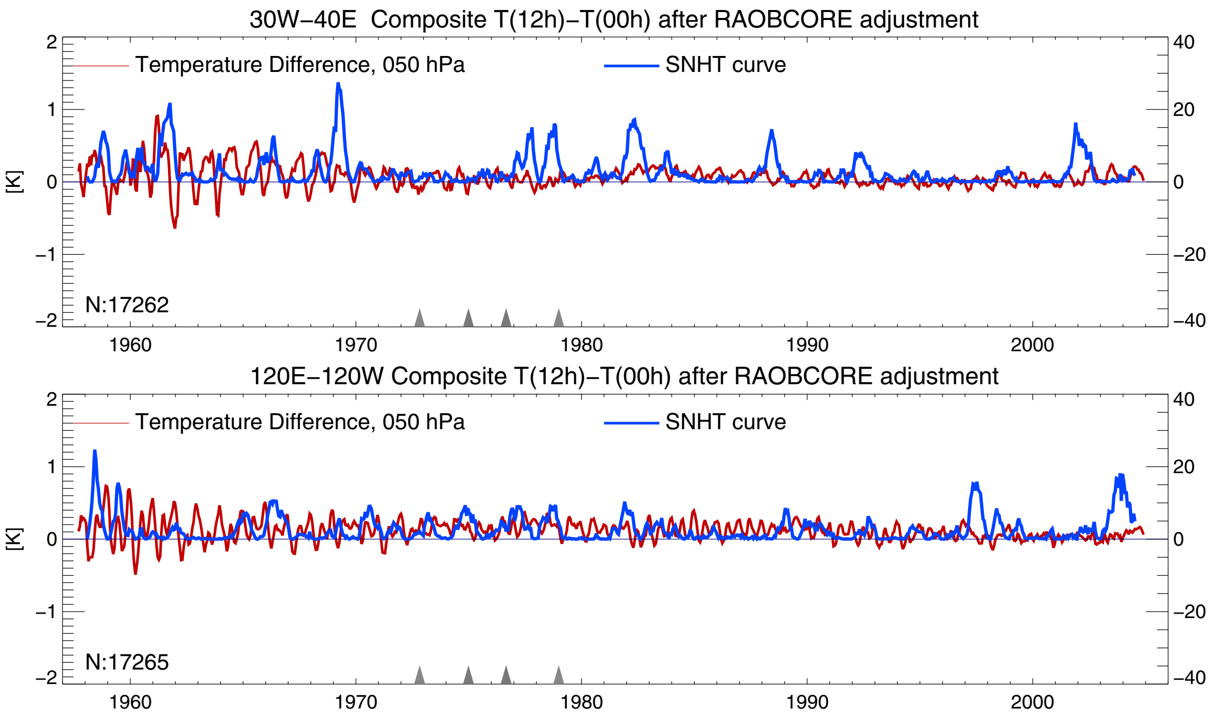

Figure 11: As Fig. 10, but after adjustment of radiosonde temperatures with RAOBCORE

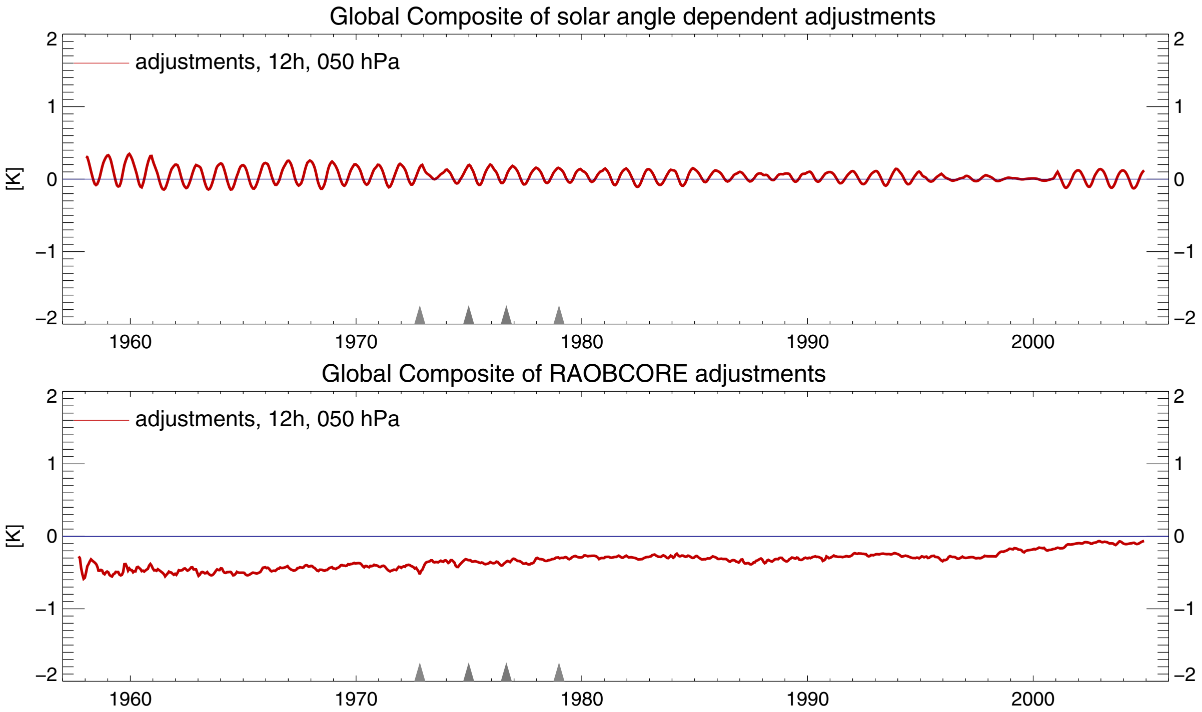

Figure 12: Global mean (now averaged over all longitude belts) adjustments at 12GMT at 50 hPa applied a) by the solar angle dependent bias correction, b) by RAOBCORE.

4 Conclusions

In this report two radiosonde temperature bias correction methods using ERA-40 and operational innovation statistics have been briefly described and intercompared. While one method focuses on adjusting the solar elevation dependent radiation error, the other is a homogeneity adjustment method that tries to re-establish the temporal consistency of the radiosonde temperature time series.

It is shown that it is insufficient to adjust only the annual mean bias since the radiation error has a large annual cycle at high latitudes and near 90W/90E. On the other hand it is shown that with an homogeneity adjustment method the temporal stability of the day-night difference, which should be constant even during a climate change, can be better re-established than with a pure radiation error correction.

Both bias corrections have shown the potential that lies in the innovation statistics and have been able to remove parts of the radiosonde temperature biases. Both bias correction methods work better than the original bias correction method used in ERA-40. However neither method works completely satisfactory yet, particularly before 1980. It seems necessary to build a combined bias correction procedure that produces nearly bias-free radiosonde temperatures from the 1960s up to recent times before the next complete reanalysis.

Both correction approaches would greatly benefit from a reassimilation of the radiosonde data in the pre-TOVS era (-1979), perhaps at low resolution. The basic assumptions of an unbiased diurnal cycle of the bg and of a temporally homogeneous bg are not valid for ERA-40 data during this period. A reassimilation with a 12h 4DVAR data assimilation system should improve the quality of the innovation statistics since the longer assimilation window, which contains both 00h and 12h ascents, should damp the spurious diurnal cycle caused by radiosonde radiation errors and by the assimilation of VTPR radiances in ERA-40 (Kelly and Li 2006).

Despite all these problems one should note than only ERA-40 innovation data allow such in-depth error tracking of both assimilation system and observations (see also article by Uppala in this volume). The generation of the ERA-40 analysis feedback dataset was a major step toward systematic improvement of input data quality. In this context it seems highly desirable to assimilate upper air input data from the pre-1958 period at least once well before the next major complete reanalysis. This would allow for a thorough investigation and bias correction of these early data. Such a first assimilation with a 4D-VAR data assimilation system seems particularly useful since the radiosonde ascents before 1958 took place at asynoptic times at many stations which makes bias correction without innovation statistics extremely difficult.

It is technically possible and in the long term desirable to use adaptive bias correction techniques as described by Dee, Vasiljevic and Auligné (all in this volume) for radiosonde homogenization, because they are conceptually elegant and require less human intervention. However, their performance in terms of the long term temporal homogeneity of a bias-corrected radiosonde dataset has yet to be investigated.

At present it seems more reasonable to prepare a bias corrected radiosonde dataset in advance that may serve as an ”anchor” for an adaptive satellite bias correction scheme. This seems possible since the static bias corrections, while not perfect, are computationally cheap and can be repeated several times until the adjustments are satisfactory. The quality may be measured in terms of internal consistency, as has been tried in this report, and in terms of consistency with independent bias estimates, e.g. from radiosonde intercomparisons. If this consistency can be achieved, the bias correction will add substantial value to the input for the next major reanalysis.

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