Impact of Balloon Drift Errors in Radiosonde Data on Climate Statistics

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ABSTRACT
Radiosonde data are a valuable resource in the detection of climate change in the upper atmosphere. Long time series of stratospheric temperature data, carefully screened and corrected to remove errors, are available for this purpose. Normal reporting practice usually ascribes a fixed time and position (the station location) to all data reported in the ascent. In reality, the ascent may take around 90 min to complete and the spatial drift of the radiosonde may exceed 200 km. This note examines the magnitude of the errors associated with this practice using simulated radiosonde data generated from the ECMWF reanalysis archive. The results suggest that the temperature errors, while generally small in the troposphere, are locally significant in the stratosphere, particularly in the jet stream areas. However, the impact of the drift errors on global climate statistics is very small. Errors in the wind and humidity data are also examined.

1. Introduction
While the upper-air observing stations were primarily established to support operational weather forecasting, the sounding data they provide are a valuable resource for studying changes in the climate. However, the nature of the observations and the supporting station practices are not conducive to securing a homogeneous sequence of data extending over many years. Changes in the sonde type, inappropriate corrections for radiative heating or cooling of the temperature sensors, or changes in the reporting practice make it a challenging task to identify genuine climate change signals in a sequence of observations. The situation is particularly acute in the stratosphere where the low air density may lead to inadequate sensor ventilation and spuriously high temperatures arising from solar heating. In spite of this, considerable effort has been devoted to identifying and correcting the errors, enabling the construction of homogeneous datasets acceptable for climate investigations (Gaffen 1994; Parker and Cox 1995; Zhai and Eskridge 1996; Luers and Eskridge 1998; Angell 2003; Lanzante et al. 2003; Redder et al. 2004). The Comprehensive Aerological Reference Data Set (CARDS; Eskridge et al. 1995), and more recently, the Integrated Global Radiosonde Archive (IGRA; available from the Climate Analysis Branch at the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center) are the results of such initiatives.

However, it is difficult to eliminate all spurious signals associated with radiative errors or changes in station practices. Comparisons between temperature datasets derived from radiosondes and the satellite-based Microwave Sounding Units (MSU) and Advanced MSU (AMSU) instruments show reasonable agreement, but there is a large spread in the temperature trends estimated from the different datasets (Seidel et al. 2004). Discrepancies between the surface and tropospheric temperature trends may be related to errors arising from the solar heating of the radiosonde sensor (Sherwood et al. 2005).

Here, the practice of treating each radiosonde ascent as fixed in space and time—an interpretative error—is examined to assess its impact on the detection of climate change.

The remainder of this report is organized as follows: in section 2 the scope of the problem is addressed; section 3 describes the generation of simulated radiosonde data to evaluate the errors; sections 4–6 provide esti-
mates of the temperature error for sample stations and climate averages for geographical regions; section 7 examines the wind and humidity errors associated with drift; and a summary with concluding remarks follows in section 8.

2. Drift error related to coding practices for radiosonde data

The data routinely available to researchers are usually based on the products disseminated internationally for Numerical Weather Prediction (NWP). The original station data will normally contain information at significantly more levels in the vertical compared with the disseminated product and will also record the position and time of the balloon at each level. The disseminated subset is usually coded using the World Meteorological Organization (WMO) alphanumerical TEMP code (WMO 1995) and may be unpacked and repacked in the binary BUFR code (WMO 2001) by the National Weather Services for use in NWP or reanalysis projects. For fixed land-based stations the alphanumerically coded product does not include any position information; the user must match a coded station identifier with the entry in a WMO station catalog (WMO 2004) to determine the elevation and position (this information may be available in datasets as metadata). The launch time of the balloon, in hours and minutes, is available in the coded data, but an additional time, rounded to the nearest hour in the report, is traditionally taken to be the official observation time. To facilitate NWP the balloon may be launched approximately 1 h ahead of the main synoptic hours (0000, 0600, 1200, and 1800 UTC) so that the midpoint of the ascent matches the NWP analysis time. However, for some stations one suspects that the official observation time corresponds with the main hours and not with the balloon release time. Regardless of local practices even if the raw data are available, it is clear that ascribing a fixed time to the entire ascent introduces a temporal error at best around 45 min and possibly as much as 90 min over a portion of the ascent. Note, however, that this does not affect radiative corrections performed on the data at the station as the exact time is used to calculate the solar elevation. Note also that the coding practice for the balloon release time was changed in 2000; the launch time is now included in all parts of the TEMP message, not only in Part B, the previous practice.

For climate studies, it is generally assumed that the drift errors are small and do not impact the statistical means and trends over long periods. However, this is not necessarily true: if the mean flow pattern changes, the reported data may show a spurious time trend associated with a change in the mean drift direction.

Recently, WMO have recognized the need for a more accurate coding of upper-air data and plan to introduce a new BUFR code format that will allow the full set of data to be disseminated.

3. Simulated radiosonde observations

a. Rationale and data generation

Even if the original station data are available, it is not possible, without further information, to estimate the data that would have been recorded if the balloon ascent were instantaneous (time $t_{\text{ref}}$) and without horizontal displacement. One possible approach would be to match the observed data with high-quality NWP analyses valid for $t_{\text{ref}}$ and examine the differences, hereafter referred to as drift error. However, the drift error will be susceptible to errors in the observations and errors in the analyses and therefore will be difficult to assess, particularly when looking for trends over several years of data.

Here, a different approach is used. Simulated radiosonde data are generated using 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Simmons and Gibson 2000). For selected locations, a fictional balloon is allowed to rise at 5 m s$^{-1}$ through the atmosphere, starting at time $t_{\text{ref}}$, and the temperature, wind components, and specific humidity are computed at intervals of 30 s using interpolated reanalysis fields (see appendix for details). Note that actual ascent data are usually recorded at a higher sampling frequency (some U.S. datasets have 6-s sampling rates). The 30-s sampling interval, producing around 200 points for an ascent to 10 hPa, was chosen to ensure reasonable accuracy in the interpolation of the data to standard levels; tests with a finer sampling interval did not produce significantly different results.

To mimic actual station data, simulations were generated twice per day at the main synoptic hours, that is, $t_{\text{ref}}$ equal to 0000 and 1200 UTC. Three types of simulated observations were generated:

(a) Full drift simulations: spatial and temporal drift allowed; position and time at each “level” also recorded.

(b) Static simulations: no spatial or temporal drift allowed; the data are simply the vertically interpolated NWP fields valid at $t_{\text{ref}}$ for the (fixed) location.

(c) Static offset simulations: same as (b), but NWP data are for $t_{\text{ref}} +1$ h.
Differences between matching (a) and (b) simulations and between matching (a) and (c) simulations, hereafter referred to as type I and type II data, give a measure of the drift error for actual radiosonde measurements.

Type II data are a gesture to local practices where the radiosondes are launched approximately 1 h in advance of the reported time to ensure that the midpoint of the ascent corresponds approximately with the coded report time. (A positive offset is used here simply to facilitate the data setup in running the simulations; the midpoint of the full drift simulations corresponds approximately to \( t_{\text{ref}} + 1 \) h.)

Simulated observations were generated for 0000 and 1200 UTC each day for the period 1 January 1960 to 31 July 2002 for the locations of the 87 stations used by Lanzante et al. (2003; see appendix for station list and positions) from the CARDS archive. Simulations were also produced using ECMWF operational analyses in place of ERA-40 data for a 3-month overlapping period to quantify the accuracy of the method. For convenience, individual ascent data will be referred to using the WMO identifier of the physical station. All references are to simulated data.

With real ascents, the radiotelemetry system may lose contact with the sonde if the horizontal displacement is excessive. For the simulated observations, the cutoff point was fixed at 250 km. All discussions from hereon refer to the simulated observations generated from this dataset. Furthermore, only the differences between the simulations, as discussed above, are used; positive differences for scalar values (e.g., temperature) imply that the conventional treatment of the ascents (no allowance for drift) overestimates the value at the station. Note that in this application the accuracy of the horizontal gradients in the reanalysis field variables is a key issue for the reliability of the results.

b. Data quality

According to WMO (1996), most modern radiosonde systems measure temperature in the troposphere with a standard error between 0.2 and 0.5 K; in the lower stratosphere the accuracy is similar, but below 30 hPa the errors increase rapidly with decreasing pressure for many radiosonde types. For relative humidity, the error is of the order of 5% in the troposphere above the convective boundary layer but can be much larger at temperatures lower than \(-40\) K. For wind, the suggested standard vector error is of the order of 3 m s\(^{-1}\) in the lower troposphere, increasing to 5 m s\(^{-1}\) in the upper troposphere. These numbers are not intended to be definitive; they are simply listed here to provide a context for the assessment of the errors associated with radiosonde drift.

The quality of the ERA-40 analyses, while generally high, is not homogenous over time: changes in the global observing system and improvements in the quality of the observations over the decades are reflected in the data. The 1970s, for example, were a significant period for the assimilation system: satellite data were unavailable before 1973, prior to which the upper-air analyses are more heavily dependent on radiosonde data, and radiosonde temperatures were bias-corrected after 1979 (Andræ et al. 2004). Based on a consensus of climatologies (Bengtsson et al. 2004; SPARC 2002) the ERA-40 upper-stratospheric temperatures in the 1990s show a cold bias (up to 5 K) and display oscillatory vertical structure, especially over Antarctica; in the lower stratosphere (50–100 hPa) there is reasonable agreement between ERA-40 and the other datasets, except over Antarctica. In the presatellite era the quality of the stratospheric ERA-40 data is more problematic compared with data in the troposphere. Changes in the number of observations have also impacted homogeneity (Bengtsson et al. 2004; Sterl 2004). The lack of homogeneity has been highlighted in studies with other reanalysis datasets [National Centers for Environmental Prediction (NCEP); ERA-15, the first-generation ERA reanalysis project] used in conjunction with the observational records (Pawson and Fiorino 1998, 1999; Santer et al. 1999; Randel et al. 2000). Note that the ERA-40 assimilation system did not allow for drift in the radiosonde data.

While temperature trends derived from radiosonde and MSU datasets are not entirely consistent the estimated global cooling rates in the stratosphere are around 0.5–1.0 K per decade (50–100 hPa) for the period 1979–97 (Free and Seidel 2005). Haimberger (2005), using the ERA-40 background fields to automatically detect breaks in the radiosonde time series, found similar trends in corrected radiosondes for the period 1979–2001; for the later period, 1989–2001, the trend is stronger, exceeding 1 K per decade. The reanalysis fields show similar but reduced cooling trends compared with the corrected observations.

The interpretation of trends in the radiosonde drift difference data is not straightforward. If there is a trend in the temperature but the temperature gradient remains constant in the vicinity of the station, the trend will not be reflected in the difference data. However, this will not be the case if there is a trend in the temperature gradient. Also, if the mean flow pattern is changing with time, the mean trajectory path will change and this could introduce temperature trends in
the difference data that could reduce or enhance genuine climate change signals.

4. Drift error—General considerations

The scatterplot in Fig. 1 shows the temperature drift errors compared with the corresponding horizontal drift at 50 hPa for type I and type II data for station 04018 (Keflavik, Iceland). An examination of individual cases shows that, in general, the largest errors are associated with extreme horizontal drift when the ascent takes place in the vicinity of jet streams. Note that even for modest horizontal drift (less than 50 km) the errors are larger for type I data and occasionally of the order of 1 K. Analyses of data from other sites show similar patterns: the drift errors are largest in meteorologically active regions and generally low in regions with relatively light winds.

![Figure 1. Scatterplot of temperature drift errors at 50 hPa for (a) type I and (b) type II data for station 04018 (Keflavik: 63.97°N, 22.60°W) as a function of the horizontal displacement. Data are for 0000 and 1200 UTC for the period 1960–2002.](image1)

![Figure 2. Temperature drift errors at 50 hPa for type I data: (a) time series for station 30230 (Kirensk: 57.77°N, 108.07°E) using ERA-40 and ECMWF operational analyses; (b) vertical plot of the mean temperature bias and rms values for 30230. (c) The equivalent vertical information for station 04018 (Keflavik: 63.97°N, 22.60°W). Data are for 0000 and 1200 UTC for the period December 2000–February 2001.](image2)
both sets of analysis data. The mean vertical errors (Fig. 2b) are also very similar (the biases are discussed in more detail in section 5). In general the spread in the error pattern is smaller with the higher-resolution operational analyses; this is more marked when the spread is large, as in the case of station 04018 (Fig. 2c) for this period. The differences between the results give an indication of the sensitivity to interpolation errors and differences in the assimilation systems. In view of the reasonable agreement in the results, we believe that the simulated data have merit in evaluating mean drift errors, particularly in data-rich areas; in data-sparse areas, the results need to be treated more cautiously.

To investigate the impact of the drift error on climate averages the simulated data are stratified by season (winter: December–February; spring: March–May; summer: June–August; autumn: September–November) and geographical region: Northern Hemisphere extratropics (NH), the Tropics (TR), here defined as extending from 20°S to 20°N, and the Southern Hemisphere extratropics (SH).

5. Drift error—Climate averages: Sample stations

a. Data-rich regions

Figure 3 shows the mean temperature drift error at the 50-hPa level, stratified by season, for sample stations for the temporally offset type II data. For the Icelandic station 04018 (Fig. 3a) there is a marked negative bias in the winter data, when the atmospheric flow is most active, with smaller biases in the other seasons. The pattern for the Greenland station 04360 (Angmagssalik)—located about 700 km west of 04018—is very similar (Fig. 3b) with mean winter biases of around $-0.25$ K for both stations, suggesting that the bias is a genuine regional feature. In both cases there is some evidence of a small negative trend in the bias: a linear least squares fit of the 04018 data shows a decrease of around $0.08$ K over the whole period, significant (two-tailed t test) at $p = 0.001$. For station 30230 (Kirensk, Russia) the bias is positive (Fig. 3c) with a mean value of around $0.40$ K. Note that for station 08495 (North Front, Gibraltar) the mean drift errors are very small (Fig. 3d), reflecting the weaker wind flow regime in this area compared with stations in the higher latitudes. For type I data the mean drift errors are in all cases slightly larger (not shown). The drift errors for 04018, 04360, and 30230 are the largest in this subset of CARDS stations.

Figure 4 shows the geographical distribution of the endpoints of the simulated radiosonde trajectories at 50 hPa for station 04018; data are for the winter periods 1960–79 (Fig. 4a) and 1980–99 (Fig. 4b). Note that in

![Figure 3](https://example.com/fig3.png)

**Fig. 3.** Mean seasonal temperature drift errors at 50 hPa for type II data for (a) station 04018 (Keflavik: 63.97°N, 22.60°W), (b) station 04360 (Angmagssalik: 65.60°N, 37.63°W), (c) station 30230 (Kirensk: 57.77°N, 108.07°E), and (d) station 08495 (North Front: 36.15°N, 5.35°W). Data are for 0000 and 1200 UTC for the period 1960–2002 stratified by season (winter: December–February; spring: March–May; summer: June–August; autumn: September–November).
both cases there is a slight northerly bias; the trajectories move to colder regions, in agreement with the cold bias in Fig. 3a. There are small differences between the two 20-yr periods that could be due to genuine change in the mean flow pattern or simply errors in the ERA-40 analyses. A comparison between the mean winter ERA-40 temperatures at 50 hPa in the vicinity of station 04018 shows that the mean north–south temperature gradient (of the order of 0.5 K per 100 km) increased by about 10% between the two periods; this could explain the negative trend in the temperature bias. However, the mean winds have also changed between the two periods (at 150 hPa, e.g., the mean wind speed has increased by ~15% in the later period). Plots for other stations show similar results. For station 30230, the displacement has a slight southerly bias with the trajectories at 50 hPa moving into warmer regions, in agreement with Fig. 3c.

Figure 5a shows the vertical profile of the mean winter bias and root-mean-square (rms) error for 04018 for type I and type II data. For both sets of data the bias is of the order of −0.1 K around 100 hPa, increasing to around −0.3 K at 10 hPa. The type II drift error has a much larger rms error in the lower atmosphere but is approximately the same, or slightly lower than, the type I rms error above 100 hPa when the measurements are temporally closer to the reference data. Note that the type II data show a small (<0.05 K) positive bias in the lower levels but have a slightly smaller bias and rms error above 100 hPa. The extreme drift errors are
smaller in the type II data (not shown). Figure 5b shows the same plot for station 30230 data. The maximum (positive) bias occurs around 30 hPa. Again, the type II data produce slightly reduced bias and rms error statistics above 100 hPa, but both types show small negative biases below 300 hPa.

It is difficult to find independent evidence for the temperature biases suggested by the simulated observations. Modern NWP analysis systems provide feedback on the differences between the observed radiosonde data and a background NWP field; averaged over time these differences are often used to identify systematic errors in the observations. However, instrumentation and model errors may mask the relatively small errors attributable to radiosonde drift, particularly in the stratosphere. For example, mean differences (observed minus background) for station 04018 for the period December 2004 to February 2005 from the ECMWF operational forecast system show a positive temperature bias of around 1 K at 50 hPa.

b. Data-sparse regions

Time series plots of the temperature bias at 30 hPa for two Antarctic stations are shown in Fig. 6. Station 89542 (Molodezhnaya) shows a rise of about 1 K in the autumn bias (type I) from 1987 to 2001 (Fig. 6a), but the trend is much reduced in the type II data (Fig. 6b) and the seasonal biases are also significantly reduced. However, the quality of the stratospheric analyses over Antarctica is problematical and the changes in the mid-1980s may be related to the introduction of the Special Sensor Microwave Imager (SSM/I) satellite data in the assimilation system around 1987. Results for station 89564 (Mawson; Figs. 6c,d) are similar to those for station 89542.

6. Drift error—Climate averages: Global impact

Figure 7 shows the vertical pattern of the bias and rms of the drift error for the combined stations in the NH. In general, the biases are very small and less than 0.05 K throughout the ascent. Note that the sign of the bias is positive for the temporally offset type II data up to about 300 hPa and that the corresponding rms errors are larger relative to the type I data. Above about 150 hPa, the rms errors are generally smaller for type II data, particularly in summer. For the SH (Fig. 8) and the TR (not shown) the patterns are very similar to those in the NH apart from a seasonal dependence in the magnitude of the rms error; the stratospheric temperature errors are a little larger but less than 0.1 K.

Time series of the mean temperature bias and standard deviation at 50 hPa for the NH, TR, and SH are shown in Figs. 9, 10, and 11, respectively. There are no
significant trends in the time series and the mean biases remain below 0.1 K (typically below 0.05 K in the NH). The largest spread in individual years occurs around 1976 in the NH and coincides with small jumps in the mean bias. This is also reflected in some, but not all, station data. In the TR and SH the spread is also rather large in the 1970s. It could be related to changes in observational usage in the reanalysis system.

7. Drift error: Wind and humidity

In general, the drift errors follow a similar pattern to those for temperature; occasionally, the errors are large relative to instrument error, particularly in regions with a strong upper airflow, but the mean errors are much smaller. As an example, Fig. 12 shows the mean and rms error in the vertical for the vector wind differences and relative humidity for winter months for station 04018. Compared with type I data the wind errors for type II data are larger up to about 150 hPa; at 300 hPa the extreme rms (vector wind) errors are 8.5 and 11.5 m s⁻¹ for type I and type II data, respectively. The stratospheric wind error shows a strong seasonal bias (not shown).

The humidity error is difficult to evaluate above 400 hPa due to the lack of moisture in the atmosphere but in the lower troposphere mean errors associated with radiosonde drift are generally less than 1% for type I
and type II data with a spread of around 3%. These estimates are lower than the typical instrument error and are therefore unrealistic; they probably reflect the smoothing of local horizontal gradients in the humidity fields by the reanalysis.

8. Summary and concluding remarks

Simulated radiosonde observations have been used to evaluate the impact of ignoring the spatial and temporal spread of data inherent in radiosonde observations. Simulations were generated for the period 1960–2002 for 87 stations from the CARDS archive using ERA-40 data to derive ascent profiles that mimic actual ascents and also reflect local practices (e.g., when the launch is temporally offset from a reference time). Supporting evidence for the validity of the method has been provided by using ECMWF operational analyses for a winter season.

The results for temperature show that the mean drift error is largest in the stratosphere (30–50 hPa) and seasonally influenced, particularly for stations located where the upper-airflow is strong and the horizontal displacement of the radiosonde is large. Stations 04018 (Iceland), 04360 (Greenland), and 30230 (Russian Federation) show well-marked winter biases of the order of a few tenths of a degree, but for other stations in the CARDS subset the biases are generally much smaller. Any trends in the bias, such as those in the Greenland and Iceland stations, are related to trends in the re-

![Fig. 8. Same as in Fig. 7, but in the SH.](image-url)
Fig. 9. Time series of the mean and standard deviation of the temperature drift error (type I data) for (top left) spring, (top right) summer, (bottom left) autumn, and (bottom right) winter in the NH (CARDS subset list).

Fig. 10. Same as in Fig. 9, but for the TR.
analysis data (changing temperature, changing temperature gradients, or changes in the mean flow). Even if the reanalysis trends are genuine, the complexity of the problem does not allow for a clear interpretation of the trends in the drift error. For isolated stations (e.g., in Antarctica) there is further evidence of data trends in the stratospheric temperatures, but the quality of the simulated observations is questionable in such a data-sparse area.

The impact of the temporal adjustment of the data is generally to reduce the drift bias and rms errors in the stratosphere, but the rms error is increased in the troposphere.

Combining data into geographical regions, the maximum mean temperature bias in the stratosphere is less than 0.05 K for the NH. In the SH and TR the biases are a little larger but less than 0.1 K. There is no evidence of trends in the regional data.

For wind and humidity the patterns are similar to those for temperature, and the mean errors are generally small (less than 1% for relative humidity, and typically 1–1.7 m s⁻¹ for the wind, for station 04018, e.g.). However, the estimates of the humidity error are probably heavily influenced by the smoothing of local horizontal gradients in the humidity fields by the reanalysis.

While the mean errors associated with radiosonde drift may be small, individual errors may be large and of significance for NWP applications and for the tuning of satellite data. These issues are not addressed here.

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APPENDIX

Generation of Simulated Observations

The simulated observations were derived using the ERA-40 analyzed model level velocities, temperatures
and specific humidities, and the surface pressure. For wind components, temperature, and surface pressure, the full spectral fields with a triangular truncation at wavenumber 159, at the 60 hybrid model levels, were used directly in the trajectory calculations to reduce interpolations errors. Fields were interpolated linearly in time and linearly in log pressure in the vertical using a simple predictor–corrector scheme to derive the trajectory arrival points at each time step. For specific humidity, the quasi-regular Gaussian grid fields of the ERA-40 data were interpolated linearly in space and time to derive the moisture data for the ascent.

For each station the three-dimensional trajectory of an air particle, launched from the surface, under the influence of the horizontal winds and a constant vertical velocity of $5 \, \text{m} \, \text{s}^{-1}$, was calculated using a 30-s time step. Each ascent was terminated when the trajectory extended beyond 10 hPa. The output data were postprocessed to derive data at standard pressure levels by vertically interpolating the wind components and temperature linearly in log pressure, and the specific humidity linearly in pressure.

For the assessment of the quality of the simulated data, ECMWF operational analyses for the 3-month period December 2000 to February 2001 were also used to generate simulated ascents. The processing method was identical to that used with ERA-40 data. The operational products are based on a more advanced four-dimensional variational data assimilation system (4DVAR) compared with the three-dimensional version (3DVAR) used for ERA-40. They also have a higher spatial resolution compared with ERA-40 products; the spectral fields have a triangular truncation at wavenumber 511, with 60 hybrid model levels. For both sets of analyses the observational datasets are similar but not necessarily identical due to time constraints in retrieving near–real time data with the operational products.

Compared with actual radiosonde ascents the simulated data suffer from deficiencies discussed in section 3. In other respects, the simulated data are not strictly representative of actual observations. For example, the rate of rise of the balloon, while typically $5 \, \text{m} \, \text{s}^{-1}$, is only approximately constant and varies with height; it is also influenced by the encountered weather conditions and will be slower in heavy precipitation. It is also assumed that the balloon follows the ambient air velocity without any drag effects. For long flight times these are serious issues that will degrade accuracy (Dvorkin et al. 2001), but in these experiments the flight time is typically under 2 h and we do not consider the errors to be significant when only the differences between simulations are being used to calculate seasonal averages.

REFERENCES


