Upper air temperature trends above Switzerland 1959–2011

E. Brocard,1 P. Jeannet,1 M. Begert,2 G. Levrat,1 R. Philipona,1 G. Romanens,1 and S. C. Scherrer2

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[1] This study summarizes 53 years of radiosonde measurements at the MeteoSwiss Aerological Station of Payerne, Switzerland. The temperature time series is the result of a careful reassessment of the original data, mainly based on the internal station documentation. Comparisons with HadAT2 and RAOBCORE/RICH adjusted data sets document the high quality of our technical reevaluation. In the lower troposphere, we compare radiosonde measurement trends to independently homogenized surface trends measured at lowland and Alpine stations up to 3580 m. We find an average difference among trends below 0.03 K/decade (7–8%), showing consistency between upper air and surface temperature measurements. Upper air data show the 0°C isotherm to rise by about 70 m/decade on average over the whole period, which is consistent with the 60 m/decade trend found using surface measurements. A similar change has also been measured for the tropopause height, which rose by 54 m/decade over the last five decades. Analysis of the phase and amplitude of the diurnal temperature cycle shows a strongly decreasing amplitude with height from about 3 K at the surface to 0.2 K at 700 hPa. The diurnal cycle peaks at about 15 UTC at the surface and shifts to later hours with height, reaching almost midnight at 400 hPa. In the stratosphere, diurnal temperature again peaks at around 15 UTC, but with low amplitude. Annual temperature cycle amplitude is in the order of 15 K and fairly constant with height. The peak temperature, however, shifts from July–August in the troposphere to June–July in the stratosphere. Temperature trends in the troposphere exhibit a clear warming trend since the 1980s, which decreases with height and changes to a cooling trend in the stratosphere, with no trend or minor warming since the end of the 1990s. The warming in the troposphere is found to be larger during summer months, whereas the cooling in the stratosphere is larger during winter months.


1. Introduction

[2] Changes in surface temperatures is a topic that has become increasingly popular over the recent years and receives broad media coverage. However, temperature changes are not limited to the Earth surface, but are extending to the troposphere and the stratosphere. Changes occurring at the surface, in the troposphere, and in the stratosphere are three complementary components of climate change. Surface temperature changes in Switzerland have been discussed elsewhere [Philipona, 2012; Scherrer et al., 2012; Ceppi et al., 2010] and are not the main subject of this paper. Global and regional tropospheric temperature trends have been intensely debated as climate model and observation results were differing for a long time. An overview of the evolution of tropospheric temperature trends understanding is given in Thorne et al. [2011]. Stratospheric temperature changes have also been intensively studied during the last decades within international projects, such as the World Meteorological Organization’s (WMO) SPARC or NDAAC programs, particularly in relation to the thinning of the ozone layer [Randel et al., 2009; Forster et al., 2011]. A recent review by Seidel et al. [2011] provides a comprehensive analysis of the evolving understanding of global stratospheric temperature changes. Aside from the need for climate model improvements, the scientific community is constantly emphasizing the need for improving the homogeneity and quality of long-term upper air observations. As the global radiosonde network started upper air observations more than two decades prior to satellite measurements, it represents a unique source of information on the state of the atmosphere before the 1980s. Therefore, significant efforts have been put in the homogenization of historical radiosonde records on a global scale, which resulted in homogenized data sets such as HadAT2, RATPAC, RAOBCORE,
or RICH. These projects deal with the global radiosonde data sets exchanged within the WMO global telecommunication system (GTS) with limited vertical resolution (the so-called TEMP messages) [World Meteorological Organization (WMO), 1995] and treat parameters individually. Their strength lies in the comparison of 100 to 1000 individual series with global model re-analyses. However, there is also a need for reevaluating individual, long-term, high vertical resolution radiosonde series. As part of the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) [Seidel et al., 2009], the station of Payerne is committed to this task. Payerne radiosondes provide a detailed vertical trend profile in the whole troposphere and in the stratosphere up to approximately 30 km. However, the balloon burst altitude and measurement technique limit this analysis for the full time series in the 1960s to approximately 20 km (60 hPa). Continuous improvements allowed reaching 31 km (10 hPa) in the 1970s.

The aim of this paper is to present the Payerne radiosonde time series data (46.80°N, 6.95°E, 491 m above sea level, WMO code 06610) from 1959 to 2011. The data set used in this study is derived from a methodical reevaluation of the original data set, involving corrections to pressure, temperature, and humidity. The re-analysis is based primarily on the detailed historical station documentation.

It is noted that time periods used in this paper for trend calculations are chosen according to periods seen elsewhere in literature that seems relevant for this study [e.g., Forster, 2011].

The paper is structured as follows: In section 2, we present the reevaluation method used to generate the data set. In section 3, we compare five upper air temperature time series of the troposphere to surface stations at similar altitudes from 500 m to 3580 m. In section 4, we present diurnal and annual temperature cycles. In section 5, we show trends calculated for different altitude layers and time periods. Section 6 is devoted to a trend comparison with RAOBCORE, RICH, and HadAT2 data sets. In section 7, we present the evolution of the 0° isotherm height calculated from radiosonde data. We compare these results to surface data. In section 8, we show the evolution of the tropopause height. Finally, section 9 presents the conclusions and Appendix A the technical details of the reevaluation.

2. Reevaluation

A statistical homogenization of the upper air temperature series has been carried out in the past for the period 1959–1999 [Aschwanden et al., 1996; Häberli, 2006]. Details on the station history and the digitalization of historical protocols can be found there. Of primary importance in the Payerne station history was the move from a mechanical chronometric radiosonde to an electronic radiosonde on 1 April 1990 (see Table 1). The new radiosonde had a water hygrometer until 2010, then a GPS receiver. Its very small thermocouple thermometer underwent only minor hardware changes. However, conversion algorithms between raw and final values and solar radiation errors on temperature measurements were updated on several occasions. The mechanical radiosonde had aneroid capsules and a bimetallic spiral as thermometer. Both sensors stayed unmodified between October 1970 and March 1990. The first full computer processing was introduced step-by-step between 1966 and 1974. It underwent a major modification in May 1980. Between January 1962 and October 1970, the thermometer silver coating was not yet as well polished as it will be later on and consequently not as reflective for solar radiation, but a rotating radiation shield reduced this error. Prior to 1962, solar radiation protection was achieved with a large aluminium sheet around the radiosonde wicker basket. Numerous other improvements related to pressure sensor, radiosonde box, or calibration facilities, to name but a few, were introduced over the years (details are available in Appendix A1).

The technical reevaluation carried out for the present work required a comprehensive investigation of published literature, internal documentation, and computer archives in order to understand, reproduce, and homogenize, as far as possible, the historical steps of the data processing with a due account of the measurement techniques. The Payerne series has in the past been embedded within large international homogenization projects, e.g., RAOBCORE and RICH [Haimberger et al., 2008, 2012]. These projects rely on the low vertical resolution of the radiosonde records from the global WMO network (standard and significant levels internationally provided on GTS) and on a simplified station history helping to fix the break points. Here the reevaluation uses the full available vertical resolution of each digitally available Payerne profile using the full station history and results of radiosondes comparisons. We reprocess the past profiles using the latest knowledge on their technical specifications. In addition, we compare our time series with independent time series from other stations using a break analysis as a diagnostic tool. Where no new technical understanding emerges, mainly due to the lack of past technical documentation, we either introduce conservative approximate corrections or no correction at all. Our corrections require plausible technical explanations and do not solely rely on statistical break analyses.

The reevaluation rationale is as follows. We use recent technical and scientific advances to bring improvements to the historical data sets, provided they have been properly documented and related to the current records. This means working backward in time, stepwise, starting with the present time. Steps are defined and delimited by changes in radiosondes and operational procedures. We proceeded in the following order: (1) pressure correction, (2) temperature correction, (3) solar radiation temperature correction (daytime only), (4) temperature break analysis with external or internal series as working references, (5) humidity corrections, (6) geopotential altitude calculation (prior to GPS), and (7) overall consistency control.

Figures 1 and 2 illustrate the temperature corrections made to the Payerne radiosonde series for nighttime and daytime data, respectively. They show the difference between the corrected and the original time series. The original series approximately corresponds to the TEMP messages exchanged within WMO and deposited in the world radiosonde archives. Thin lines reproduce the monthly differences for each level between 925 and 10 hPa. Overlaid thick lines represent the result of the Kolmogorov-Zurbenko adaptive (KZA) low-pass filter [Zurbenko, 1986]. The KZA filter dynamically adjusts the length of the moving average according to the rate of change of the signal. The quantitative
<table>
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<tr>
<td><strong>Radiosonde</strong></td>
<td>CH III-IV (mechanic, in a wicker basket up to 1961)</td>
<td>CH Va (white plastic housing)</td>
<td>CH Vbc (Styrofoam housing)</td>
<td>SRS 400 (electronic)</td>
<td>SRS 400 (electronic)</td>
</tr>
<tr>
<td><strong>Pressure sensor</strong></td>
<td>Aneroid capsules (one pair)</td>
<td>Aneroid capsules (double pair, switch after 100 hPa level)</td>
<td>Larger bimetallic spiral with polished silver coating, no solar radiation protection</td>
<td>SRS 400 (electronic)</td>
<td>SRS 400 (electronic)</td>
</tr>
<tr>
<td><strong>Digital data set</strong></td>
<td>Standard levels plus km levels or characteristic levels since 1968</td>
<td>1974: 30 s intervals</td>
<td>30 s intervals (raw data set can be approximately restored, better since May 1980 than since July 1975)</td>
<td>3 s intervals (T)</td>
<td>3 s intervals (T)</td>
</tr>
<tr>
<td><strong>Processing</strong></td>
<td>Analog charts (calibration and sounding) 1966: first calculator</td>
<td>Move from chart processing to computer processing 1974: 30 s processing</td>
<td>Full computer- based processing</td>
<td>Fully new data processing</td>
<td>Fully new data processing</td>
</tr>
<tr>
<td><strong>Special corrections</strong></td>
<td>Editing of isolated outliers and correction of documented time limited temperature errors</td>
<td>Improved correction for the temperature dependence of the aneroids, day/night and period dependent</td>
<td>Editing of isolated outliers in raw data</td>
<td>Uniformizing thermocouple transfer functions</td>
<td>Uniformizing thermocouple transfer functions</td>
</tr>
<tr>
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<td>Improved correction for the temperature dependence of the aneroids, day/night and period dependent</td>
<td>Improved correction for the temperature dependence of the aneroids, day/night and period dependent</td>
<td>Improved correction for the temperature dependence of the aneroids, day/night and period dependent</td>
<td>Improved correction for the temperature dependence of the aneroids, day/night and period dependent</td>
</tr>
<tr>
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<td>Time lag correction</td>
<td>Time lag correction</td>
<td>Time lag correction</td>
<td>Time lag correction</td>
</tr>
<tr>
<td><strong>Geopotential altitude</strong></td>
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<td>Uniform calculation with reevaluated PTU values</td>
<td>Uniform calculation with reevaluated PTU values</td>
<td>Uniform calculation with reevaluated PTU values</td>
<td>Uniform calculation with reevaluated PTU values</td>
</tr>
</tbody>
</table>

*T stands for temperature, P for pressure, U for humidity.*
Figure 1. Time series of the monthly differences between corrected and uncorrected Payerne radiosonde temperatures at selected levels between 850 and 20 hPa (thin lines), with nighttime data (00 UTC) and KZA-filtered time series (thick lines). Cross symbols on the standard level lines depict breaks according to KZA. Numbers between the cross symbols give the averaged corrections (in K) between KZA breaks. The scales on the right of each standard level correspond to \(\pm 0.5\) K.

Figure 2. Same as Figure 1, but for daytime data (12 UTC, near-solar noon).

3. Comparison With Surface Observations

Switzerland has a dense network of meteorological stations covering its mountainous topography. Surface station measurements can reasonably be taken as working references in order to check the consistency of radiosonde measurements. We used homogenized temperature data [Begert et al., 2005] from single mountain stations or from sets of stations at similar altitude levels from 500 m to 3580 m and compared them to radiosonde measurements at similar altitudes in the atmosphere. A map showing the chosen surface stations is shown in Figure 3. Figure 4 shows the results of the comparison (first panel) between mountain station of...
Figure 3. Map of Switzerland showing surface stations used for the comparison with Payerne upper air data. Jungfraujoch (3580 m) and 650 hPa upper air data, (second panel) between mountain station of Saentis (2502 m) and 750 hPa upper air data, (third panel) between average of five alpine stations near the 2000 m level and 800 hPa upper air data, (fourth panel) between mountain station of Chaumont (1073 m) and 900 hPa upper air data, and (fifth panel) between average of 10 lowland stations on the Swiss plateau near the 500 m level and surface level in the radiosonde profile. The surface level value in the radiosonde profile is taken as the 2 m surface reference measurement at launch time (i.e., not from the homogenized climatological time series).

Table 2 quantifies the trends over the different periods shown in Figure 4. For the period 1959–2011, trends are similar and highly significant for all altitude levels, in the

Figure 4. Comparison between upper air and surface station temperatures. (left column) Single trend for the period 1959–2011. (right) Trends for three periods: 1959–1980, 1981–2000, and 2001–2011. Surface stations are shown in Figure 3. Y axis temperature range is constant at 5 K in the five panels. By convention, the surface value in the radiosonde profile is taken as the 2 m surface reference measurement at launch time.
order of +0.3 to +0.4 K/decade. Over the 53 years, upper air and surface data show similar trends with slightly larger trends at low altitude (e.g., at 900 hPa). The average difference in the five panels shown in Figure 4 for the period 1959 to 2011 is below 0.03 K/decade. When looking at shorter time periods, all levels show a slight, although not significant, cooling in the period 1959–1980 (negative trend), followed by a strong warming in the period 1981–2000 (positive trend), and then a fairly constant state in the period 2001–2011. In the last 10 year period, trend uncertainty increases due to both a smaller number of years and no clear trend signal. Based on these data, we estimate that the lower troposphere temperature has effectively increased by about 1.5 K in the last 50 years. This is slightly lower than the calculated linear trend of about 0.33 K/decade due to the more constant state in recent years and high values around year 1960.

4. Upper Air Data

4.1. Diurnal Cycle

[12] Measuring the diurnal temperature cycle in the troposphere and in the stratosphere would require sending radiosondes at a high-temporal resolution. Two profiles per day at 00 and 12 UTC might not capture the whole cycle, neither in phase nor in amplitude. Here we selected days when four radiosondes were launched, i.e., one flight every 6 h (0, 6, 12, and 18 UTC). The period covers the years 1993 to 2010, in order to have a consistent data set (electronic radiosonde SRS-400). We found 247 days with four soundings reaching 25 km, representing all seasons. For the fitting, we assume a sine-shaped cycle. Figure 5 shows the (left) phase and (right) amplitude of the resulting fitting for 15 standard levels from the surface to 20 hPa. The amplitude of the diurnal cycle (one half of the diurnal temperature change) is larger at the surface (nearly 3°C, mainly due to daytime surface heating) and decreases rapidly with height in the first couple of hundred meters of the troposphere. At 700 hPa, the amplitude is already in the order of 0.2°C. This amplitude stays at values below 0.2°C until 30 hPa. The diurnal change, which amounts to about 0.6 K near 20 hPa, is within the upper uncertainty margin of solar radiation corrections for modern high-quality radiosondes [Immler et al., 2010].
results differ to some extent. It is also noted that these results tentatively agree with Seidel et al. [2005], although the phase differences between day and night (12 and 00 UTC) are also shown. Near the surface and in the middle stratosphere day temperatures are higher than night temperatures, as previously seen in Figure 5. In the lower free troposphere (e.g., 850 hPa) and higher up, day and night temperatures are very similar. Assuming a sinusoidal daily cycle, this would happen when the twice-daily sounding at 00 and 12 UTC samples values shifted by $\pi/2$ (6 h) compared to the diurnal cycle maximum or minimum. The large annual cycle at all radiosounding levels suggests that seasonal trend analysis is relevant. It should provide valuable information in addition to annual trends.

5. Trends

5.1. Time Series

Over the course of the year, we observe large temperature variations at all levels of the troposphere and the stratosphere. Figure 6 shows a selection of four levels illustrating the annual temperature cycle. The amplitude of the cycle is rather homogeneous at all levels, in the order of 10 to 15°C. The peak, however, seems to shift from July–August near the surface to June–July in the middle stratosphere. Differences between day and night (12 and 00 UTC) are also shown. Near the surface and in the middle stratosphere day temperatures are higher than night temperatures, as previously seen in Figure 5. In the lower free troposphere (e.g., 850 hPa) and higher up, day and night temperatures are very similar. Assuming a sinusoidal daily cycle, this would happen when the twice-daily sounding at 00 and 12 UTC samples values shifted by $\pi/2$ (6 h) compared to the diurnal cycle maximum or minimum. The large annual cycle at all radiosounding levels suggests that seasonal trend analysis is relevant. It should provide valuable information in addition to annual trends.

### Table 3. Temperature Trends in Four Regions of the Atmosphere for Different Time Periods and Seasons

<table>
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<tbody>
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<td>Middle stratosphere&lt;br&gt;50–15 hPa</td>
<td>DJF</td>
<td>$-0.78 \pm 0.59$</td>
<td>$-0.68 \pm 1.13$</td>
<td>$+0.55 \pm 2.24$</td>
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<td></td>
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<td>Year</td>
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<tr>
<td>Lower stratosphere&lt;br&gt;150–60 hPa</td>
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<tr>
<td>Upper troposphere&lt;br&gt;500–250 hPa</td>
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*Trends given in Kelvin per decade ± 2 standard deviations. Figures in italics indicate significant trends.

*B: Middle stratosphere statistics are made from 1971.

Figure 6. Annual temperature cycle at four levels. For levels 30 and 20 hPa, a 50° offset is added for better visibility. Data from the period 1993–2010.
for the whole year (12 month average), and Figure 8 shows the results taking only warm months (April to September, left) and only cold months (October to March, right). The lowest layer (fourth panel) represents the lower troposphere. It is the average of nine pressure levels (925, 900, 850, 800, 750, 700, 650, 600, and 550). The second layer (third panel) represents the upper troposphere. It encompasses five levels (500, 450, 400, 300, and 250 hPa). The third layer (second panel) represents the upper stratosphere. It encompasses seven levels (150, 120, 100, 90, 80, 70, and 60 hPa). The uppermost layer (first panel) represents the middle stratosphere. It encompasses six levels (50, 40, 30, 25, 20, and 15 hPa). In this layer, trends are calculated as from 1971 instead of 1959. Prior to 1971, data are either missing or their quality is too low to qualify for trend studies. Level 200 hPa is left out since it is very close to the mean tropopause level (212 hPa in Payerne). We consider level 200 hPa as neither part of the upper troposphere nor of the lower stratosphere. [16] Yearly trends in the lower troposphere layer (Figure 7, fourth panel) are consistent with the trends seen with surface station temperatures (Figure 4), as expected. In the upper troposphere, the behavior is also qualitatively similar, with a decreasing temperature until the end of the 1970s, followed by a temperature increase until 2000, with a subsequent and fairly stable situation until 2011. In the stratosphere, we divided the time series into two subperiods: from 1959 (or 1971 in the middle stratosphere) to 1995 (turning point according to Forster [2011]) and from 1996 to 2011. Stratospheric cooling until 1995 is well observed, with cooling rates of –0.47 K/decade and –0.51 K/decade for the lower and middle stratosphere, respectively. In both the middle and the lower stratosphere, the year 1991 stands out as a warmer year compared to the previous and subsequent years, corresponding to the stratospheric warming reported after the Pinatubo eruption [Forster, 2011]. In the period 1996–2011, trends are less pronounced and the uncertainties are larger. This result suggests that stratospheric temperatures since 15 years have a larger year-to-year variability, but the stratospheric cooling trend came to a halt. [17] Seasonal trends have also been calculated (Table 3). The 3 month seasons generally show a large year-to-year variability, especially in winter. This is mainly due to the fixed season dates definition, not necessarily representing the variable synoptic weather pattern reality of a midlatitude station. For instance, winter, defined as December, January, and February, might in some years include a warm December and miss out a cold March. Consequently, we looked at 6 month seasonal trends (Figure 8), defining a warm season (April to September) and a cold season (October to March). [18] Comparing warm- and cold-season trends shows interesting results, although it is hard to draw conclusions since many trends are not significant (see Table 3 for details). In the troposphere, the temperature increase seen in the period 1981 to 2000 seems to carry on into the period 2001–2011 in the warm season, whereas it seems to reverse into a nonsignificant cooling trend in the cold season. This asymmetry could be related to other work, such as Cohen et al. [2012, and references therein]. In the stratosphere, the cooling trend observed prior to 1995 seems to carry on into the period 1995–2011 in the warm season, whereas it reverses into warming trend in the cold season. [19] If confirmed with future data, these results would suggest that since the last 10 to 15 years, warm and cold months have a different behavior, suggesting a larger annual temperature cycle in the troposphere and a smaller annual temperature cycle in the stratosphere. However, the yearly variability remains large. These results also seem to point at a decoupling of the troposphere and the stratosphere in terms of temperature trends. It is noted that the warm anomaly in the last years has an impact on the derived trends and that part of the effects seen here might be due to atmospheric expansion due to a higher tropospheric temperature.

5.2. Trend Profile

[20] Additionally to trends in thick layers, trend profiles with higher vertical resolution have been calculated. Trend profiles detail the overall trends at each altitude level for a given period. Figure 9 shows the trend profile at 30 pressure levels plus surface. The covered period is 1959–2011 from the surface to 60 hPa and 1971–2011 from 50 to 10 hPa. This difference in period does not produce any visible break between 60 and 50 hPa. This profile confirms the results of Figure 7 and Table 3. It indicates a consistency in the

Figure 7. Temperature trend in different layers of the atmosphere. (first panel) Six levels in the middle stratosphere from 50 to 15 hPa. (second panel) Seven levels in the lower stratosphere from 150 to 60 hPa. (third panel) Five levels in the upper troposphere from 500 to 250 hPa. (fourth panel) Nine levels in the lower troposphere from 925 to 550 hPa. Level 200 hPa is not used because it is too close to the mean tropopause level of 212 hPa. The Temperature scale is relative to the average 1961–1990.
lower and middle troposphere up to about 5–6 km, with values between +0.3 and +0.4 K/decade. Above this layer, the positive trend decreases toward zero. The trend changes sign from positive to negative near the 250 hPa level, which is slightly below the mean tropopause level of 212 hPa above Payerne. The temperature trend is negative throughout the stratosphere from approximately −0.2 K/decade in the lower stratosphere, up to −0.5 K/decade in the middle stratosphere. The trend is statistically significant in most of the troposphere and most of the stratosphere, except in the region around the tropopause. When looking at seasonal results, it appears that there are some differences from season to season (Figure 10), even if we acknowledge that trend differences between different seasons may be of rather low statistical significance. In the middle troposphere for instance, trends are close to zero in winter, whereas they are stronger than the annual mean in summer, reaching values of +0.4 to +0.5 K/decade. In the middle stratosphere as well, there are large seasonal differences between winter and summer. The winter trend is stronger with values reaching −0.8 K/decade (with a large uncertainty), whereas it is around −0.4 K/decade in summer. This result suggests that stratospheric cooling is stronger in winter than in summer. Conversely, tropospheric warming is stronger in summer than in winter. Autumn trends are closer to zero compared to other seasons and are hardly statistically significant. Spring results are similar to summer results although with less pronounced trends.

6. Trend Comparison With RAOB CORE, RICH, and HadAT2

[21] In this section, we compare our results with those of HadAT2 and RAOB CORE/RICH related to Payerne. We also consider the instrumental and statistical uncertainties in the trend estimates. Assuming that the trend model’s statistical errors are similar for all these data sets, we assume that the differences in their trends are mainly due to a combination of (a) instrumental errors, (b) quality of the corrections, and (c) sample size in the stratosphere.

[22] HadAT2 is the recommended version of the UK MetOffice gridded radiosonde temperature product. It provides adjusted monthly anomalies for individual radiosonde stations since 1958 on nine pressure levels between 850 and 30 hPa [Thorne et al., 2005]. RAOB CORE and RICH deliver monthly averages of adjusted temperatures on 15 standard pressure levels for the years 1958–2011. We use RAOB CORE version 1.5.1. The RICH adjustments are a mean of 32 realizations using neighboring station temperature anomalies for adjustment [Haimberger et al., 2012].
Figure 10. Seasonal trend profiles for the period 1959–2011. In the upper part of the profile (p \leq 50 hPa, dotted), the period is restricted to 1971–2011. DJF stands for December-January-February, MAM for March-April-May, JJA for June-July-August, and SON for September-October-November. The mean tropopause level over Payerne (dash-dotted gray) is shown for reference.

We first compare the RAOBCORE and RICH adjustments with the corresponding results of the present reevaluation. Most breakpoints agree within a few months, as they rely on the station history. Some of them are not explained by the station history and differ in the three analyses. Since 1990, a rather qualitatively fair agreement appears between the three corrections. RICH still introduces adjustments after 1998 whereas RAOBCORE does not. In the 1980s, RICH adjustments are close to our results for 12 UTC, but are larger in the stratosphere for 00 UTC. Main differences are found before 1980 for the 00 UTC ascents, where RICH produces large adjustments above 100 hPa and in the mid-troposphere. Our 00 UTC reevaluation has the smallest impact on the original series, assuming a negligible infrared error of our thermometer and being very conservative in correcting the 1960s data. On the contrary, RICH and RAOBCORE bring rather large nighttime adjustments in the troposphere, sometimes even larger than on daytime. The 00 UTC RAOBCORE and RICH adjustments induce long-term trends of 0.1 to 0.2 K/decade at some levels (not always the same for the two methods), whereas our reevaluation does not. The 12 UTC adjustments increase strongly with altitude. Large steps in the adjustments characterize the changes in radiosonde type and solar radiation correction. A long-term trend can be seen in almost all 12 UTC corrections.

Figure 11 illustrates the influence of reevaluation and adjustments on temperature trends. The trend model used is a simple linear regression applied to annual means. The vertical trend profiles between 925 and 10 hPa are compared for different series that are all 00–12 UTC averages. Figure 11 applies to years 1971–2011, as radiosondes were seldom reaching the middle stratosphere before 1970. The main results are as follows: (a) The original time series used in the present work and in the other projects do not lead to exactly the same trends; at 20 hPa, the difference is approximately 0.05 K/decade. (b) RICH trends in the upper troposphere and middle stratosphere strongly disagree with both RAOBCORE and our reevaluation. (c) RAOBCORE trends agree well with our reevaluation in the whole

Figure 11. Temperature trends in Payerne for the period 1971–2011 (average of 00–12 UTC) for the original and the present reevaluated series, as well as for the HadAT2 series (Payerne and 47.5°N) and for RAOBCORE/RICH original and adjusted series.
stratosphere. (d) Our reevaluation leads to the strongest trends in the lower and middle troposphere; they compare well with surface stations, as shown in section 3. (e) HadAT2 strongly disagrees with the other data sets in the troposphere. The agreement is slightly better at 30 hPa. HadAT2 zonal mean trend profile for 47.5°N matches well with RAOBCORE for Payerne. This comparison shows the importance of comparing the results for individual stations. Comparing an individual station with hemisphere trends does not allow assessing the used techniques. Comparing vertical trend profiles of the 00, 12, and 00–12 UTC over different periods provides insight into the internal consistency of the Payerne series. In the stratosphere up to 30 hPa, trend differences between 00 and 12 UTC remain small (<0.05 K/decade over the years 1971–2011, not shown). At 10 hPa, trends at 00 and 12 UTC strongly diverge (approximately 0.5 K/decade) and our reevaluation does not bring them closer together. As a matter of fact, one would expect that the long-term trends remain rather close between night and day. Unequal and reduced number of radiosondes reaching this level adds to the instrumental error. Both are responsible for a large total trend uncertainty at 10 hPa. It is difficult to evaluate how both error types cumulate with the statistical trend model uncertainty. However, the 00–12 UTC trend keeps a good vertical continuity with the lower levels. Its statistical trend model uncertainty is very large (see Figure 9) and should already partly account for the small and varying number of available measurements. Between 500 and 50 hPa, trend differences between night and day are negligible over the years 1971–2011 (0.02 K/decade). In the lower troposphere, the influence of change in launch time in 1981 is expected to influence the calculated trends at 00 and 12 UTC.

[25] The estimation of the true instrumental uncertainty is a difficult task, especially for the pioneer decades of radiosonde upper air measurements. Combining it with the statistical trend model error is an additional challenge. However, the internal comparison between the present reevaluation as well as with RAOBCORE, RICH, and HadAT2 allows for some interesting results: (a) Our trend results agree to be better than 0.05 K/decade between 500 and 30 hPa when comparing 00 and 12 UTC. (b) Our 00 and 12 UTC trends strongly diverge at 10 hPa. However, it is noted that the large statistical trend model error is coherent with this feature (c) Trends should not be calculated since 1959 in the middle stratosphere (Figure 9 is limited to 1971–2011 for p ≤ 50 hPa). (d) Our results agree well with RAOBCORE in the whole stratosphere. (e) RICH and HadAT2 trends produce somewhat different results, respectively, in the stratosphere and in the troposphere. As an overall general statement, we estimate the influence of instrumental uncertainty to ±0.05 K/decade for trends over more than 30 years, which should be added to the statistical trend uncertainty.

[26] One special instrumental uncertainty can be partly analyzed by comparisons between radiosonde and surface Alpine stations. In the present reevaluation, we assume that the thermal radiation error of the bimetallic thermometer used before 1990 is negligible and that the nighttime ascents need no such corrections. We only account for the thermometer response time that lowers measured temperatures in the troposphere (see Figure 1 or 2). The latest results of R. Philipona et al. (Solar and thermal radiation errors on upper air radiosonde temperature measurements, submitted to Journal of Atmospheric and Oceanic Technology, 2013) demonstrate that the thermal radiation errors on the very thin thermocouple produce a radiative cooling in the lower troposphere of 0.1 K. The previous bimetallic spiral was large. Although it had a well-polished silver coating, one can question if an error of a few or several tenths of degree should be expected. The analysis of the temperature differences between 700 (850) hPa and the homogenized Jungfraujoch (Säntis) series does not support a radiative cooling of several tenths of degree, but possibly of 0.2 K. More interesting is the comparison between the adjusted RAOBCORE and RICH series and the homogenized surface series. RAOBCORE and RICH series produce periods with temperatures noticeably diverging from those of the surface Alpine stations. It is not the case in the present reevaluation.

[27] The results of this section confirm the high quality of the Payerne radiosonde technical reevaluation. This
The 0°C isotherm height is written in each individual sounding report. Here we computed the average height for all soundings recorded each year. Additionally, we show 0°C isotherm height computed from the Swiss Network of Surface Stations [Güller, 1978].

The comparison with HadAT2 and RAOBCORE/RICH shows the high quality of the Payerne radiosonde technical reevaluation. The data sets are largely in agreement, with RAOBCORE 1.5.1 coming the closest to our results. The performance of our reevaluation is strongly supported in the troposphere where independent homogenized surface Alpine series exist. In the stratosphere, performance validation is much more difficult. Long-term trends in the middle stratosphere are characterized by a very large uncertainty and are hardly achievable before 1971. This is due to limitations in the radiosonde technique during the first decades of our study (instrumental errors and low balloon burst altitude). An instrumental uncertainty in the order of ±0.05 K/decade can possibly be added to the statistical long-term trend uncertainty.

8. Tropopause Height

Aside from trends in the vertical temperature profile, tropopause height has also been identified as a candidate for climate change detection [Sausen and Santer, 2003]. According to literature, tropopause height has been rising with time in extratropical regions in the last decades (see for instance Seidel and Randel [2006] for the period 1980–2004). Accordingly, tropopause pressure and tropopause temperature decrease. Thermal tropopause height above Payerne has been calculated according to WMO definition [WMO, 1992]. It is found to increase over the period 1959–2011, as illustrated by Figure 13. Tropopause height raised by +54 m/decade over the period 1959–2011, with a 95% confidence interval of 15 m/decade. The corresponding tropopause pressure trend is found to decrease by −1.6 ± 0.8 hPa/decade (2 standard deviations), and the temperature trend is −0.2 ± 0.2 K/decade.

During these 53 years, 0°C isotherm height rose on average by 366 m (radiosondes) and 316 m (surface stations).

9. Conclusions

This paper presents a summary of 53 years of radiosonde temperature measurements at the aerological station of Payerne, Switzerland. The data set used is the result of an extensive re-assessment of the original radiosonde data. This re-assessment takes into account all existing historical documentation on instruments and methods used in the past and applies corrections in light of the latest knowledge.

The comparison with HadAT2 and RAOBCORE/RICH shows the high quality of the Payerne radiosonde technical reevaluation. The data sets are largely in agreement, with RAOBCORE 1.5.1 coming the closest to our results. The performance of our reevaluation is strongly supported in the troposphere where independent homogenized surface Alpine series exist. In the stratosphere, performance validation is much more difficult. Long-term trends in the middle stratosphere are characterized by a very large uncertainty and are hardly achievable before 1971. This is due to limitations in the radiosonde technique during the first decades of our study (instrumental errors and low balloon burst altitude). An instrumental uncertainty in the order of ±0.05 K/decade can possibly be added to the statistical long-term trend uncertainty.

Radiosonde temperature measurements in the lower free troposphere have been compared to homogenized temperatures measured at surface stations around Payerne and in the Alps. Upper air and surface trends have been calculated at different heights, and similar results were found for different time periods. For the full period 1959 to 2011, the average difference of the trends calculated at five altitude levels is lower than 0.03 K/decade (about 7–8%), validating the quality of radiosonde measurements in the lower troposphere. Trends are slightly decreasing with altitude going from +0.39 K/decade at 500 m to +0.32 K/decade at 3580 m (650 hPa) over the full period. Hence, present temperature is about 1.5 K higher than 50 years ago in the lower troposphere.
A1. Temperature Reevaluation

Appendix A: Technical Details of the Reevaluation

which rose by 54 m/decade over the last five decades. The change has also been measured for the tropopause height, higher values and a trend of about 70 m/decade. A similar analysis of diurnal phase and amplitude shows that the diurnal cycle of upper air temperature is larger near the surface (nearly 3 K) and decreases sharply with height. It is already less than 0.4 K above 850 hPa. The maximum temperature is reached on average around 15 UTC near the surface, and later on higher up, suggesting energy transport through convective motions in the troposphere. In the stratosphere, the maximum is again rather around 15 UTC.

The annual temperature cycle shows a rather homogeneous amplitude of about 15 K at all altitudes. However, while in the troposphere, the amplitude peaks in July–August, the temperature peaks already in June–July in the stratosphere.

Temperature trends measured in the troposphere and the stratosphere over the investigated period are consistent with trends shown in the existing literature. A clear warming in the troposphere, which decreases with altitude, changes to a clear cooling in the stratosphere since the 1960s. The warming in the troposphere is more pronounced during summer, whereas the cooling in the stratosphere is larger during winter. During the strong tropospheric warming from 1981 to 2000, the stratosphere is cooling.

The present analysis shows that temperature changes in the troposphere and in the stratosphere are very different and often opposite. The fact that the diurnal and the annual temperature maxima are also not in phase between the troposphere and the stratosphere suggests that temperature changes in the troposphere and in the stratosphere are disconnected and driven by different physical phenomena.

Appendix A: Technical Details of the Reevaluation

Section 2 explains the overall method used in the present reevaluation. Here we provide technical details highlighting the fundamental difference with statistical adjustment methods developed in other projects. Table 1 provides an insight into the Payerne station history since the beginning of the present reevaluation in 1959. It also summarizes the different steps in the reevaluation.

A1. Temperature Reevaluation

The thermometer used in the electronic radiosonde SRS 400 (Meteolabor) since April 1990 underwent very few hardware modifications. However, results of the 2005 WMO radiosonde intercomparison in the tropics [Nash et al., 2006] triggered a new thermocouple calibration against a national standard. Furthermore, the 2010 WMO radiosonde intercomparison confirmed the too strong radiation correction scheme [Nash et al., 2011], which was put in operation in 1999 [Ruffieux and Joss, 2003]. Consequently, intensive measurements were organized at Payerne with multiple sondes (shaded and unshaded thermometers, pyranometers, pyrrhadiometers, etc.). A weaker radiation error was found for the so-called x-shaped thermometer: 1.2 K at 10 hPa instead of 1.8 K (Philipona et al., submitted manuscript, 2013). This error is 0.1 K at the surface and 0.5 K at 200 hPa. The raw data files allowed an up-to-date temperature reproprocessing involving all these new findings. Temperature in the 2 years without raw data has been corrected with a transfer function determined on the basis of radiosonde ascents in the second half of 1992 processed with the operational and the new data handling. Temperature differences in synchronized profiles have been fitted with a fourth-order polynomial as a function of temperature. This temperature correction is almost linear in temperature and amounts to ~0.5 K at ~65°C with 0.1 K standard deviation. It changes sign and becomes +0.1 K at 30°C. The reprocessed Payerne stratospheric series compares better with the surrounding stations (Stuttgart, Munich, Vienna) during these years than the original series, with a higher average in 1991 than in 1992 after the Pinatubo eruption. Indeed, the European midlatitudes did not undergo the large temperature increase following the Pinatubo eruption that the other latitudes underwent.

The new solar radiation correction leads to new results related to the mean temperature differences between the 12 and 00 UTC profiles. Previously, we admitted a zero difference in the stratosphere, neglecting not well-known— but small—factors such as tidal waves, ozone, etc. We used to adjust the stratospheric solar radiation correction to such a 0 K difference. Now we find a few tenths of a degree K difference at 20 hPa (see section 4) and assume that this difference shall be valid over the whole 1959–2011 period. The silver-coated metallic spiral of the Swiss sonde thermometer (thoroughly polished since 1971) had quite a different behavior from that of the thermocouple. It had a slow response time (4.5 s at 700 hPa, 28 s at 10 hPa according to Phillips et al. [1980]) whereas the thermocouple reacts within half a second at 10 hPa. It was subject to a strong heating from the direct solar radiation, but was having a small infrared emission. Therefore, it required a strong daytime correction, while the nighttime temperature error was considered small and not significant. Experimental studies at the beginning of 1980 led to a polynomial correction function depending on pressure, radiosonde ascent speed, Sun elevation, and cloud cover [Rieker and Joss, 1985]. The correction was as high as 5.2 K at 10 hPa. Although some residual errors have been found in the following years [Rieker, 1984], the data processing did not change until 1990. The present new correction applied retroactively to the Swiss time series of 1980–1989 amounts to nearly 7 K at 10 hPa. The detailed procedure starts by inverting the operational daytime temperature correction. This inversion can be reproduced with best accuracy in the 1980s and reasonably well in the 1970s. Next, the breaks in the 12–00 UTC temperature differences are analyzed with KZA filtering at standard pressure levels. Then, breaks at the change from the bimetallic thermometer to the thermocouple in April 1990 are brought to zero at all these levels. Note that the increase of this new solar radiation correction is consistent with the findings of Rieker [1984]. Following this first correction, breaks in previous years are analyzed, compared to entries in the station history, and iteratively corrected. In 1982, the launch time was changed from 0945 and 2145 UTC to 1100 and 2300 UTC, respectively. It explains a break in the lowest troposphere. Other small breaks appear during the 1980s although
station history does not provide a sound explanation. A minor change in the solar radiation correction between 1980 and 1989 is now defined in 1984. As solar radiation error is not the same during all seasons and depends in first approximation on the Sun elevation, a Sun elevation function is introduced. Due to the special geometry of the bimetallic spiral, this function is not the same as in the case of the thermocouple [Rieker and Joss, 1985; Ruffieux and Joss, 2003]. Through this method, the annual cycle of solar radiation correction is taken into account. This procedure goes further back iteratively in the previous years, with main periods defined by changes in radiosonde model, data handling, and calibration procedure: 1971–1979 with sonde model Va-b and automation of the radiosonde data handling, 1962–1970 with radiosonde model IV having a solar radiation shielding, and finally 1959–1961 with radiosonde model III and second generation calibration chamber.

A2. Pressure Reevaluation

[41] Pressure is the variable which vertically positions the other radiosonde measurements. Prior to GPS, it was directly measured and later calculated. Pressure errors may be noticeable for temperature trend analyses in atmospheric layers with large vertical gradients, i.e., in the troposphere, including the tropopause region, and in the middle stratosphere where the temperature increases with altitude. However, compared to temperature measurement errors, pressure errors have a smaller influence on trends. The pressure reevaluation presented below is embedded in the temperature reevaluation, so that temperature break analyses of the previous section take both of them into account. The water hypsometer used in the electronic radiosonde since April 1990 underwent small hardware upgrades in the first 2 years only, but its thermocouple calibration has been improved three times. The first two have been introduced in the operational processing (1993, 1999). In 2005, all thermocouples used on the radiosonde have been recalibrated down to −90°C at the National Metrology Office. Since all copper and constantan wires were always supplied from the same batch, and as the raw radiosonde data set is available since mid-1992, all profiles could be reprocessed with the newest and best calibration functions and the pre-flight hypsometer check could be repeated. It is worth mentioning that the high boiling temperature accuracy required is 0.01°C in order to achieve an accuracy of 0.05% (0.5 hPa at 1000 hPa) in pressure range 1000–10 hPa [Richner et al., 1996]. As previously explained, pressure measurements in the 2 years without raw data have been corrected with a transfer function. Maximum pressure correction amounts to −2.2 hPa near 500 hPa with a standard deviation of 1.3 hPa and to +0.05 ± 0.10 hPa at 20 hPa. The reprocessing of the pressure measurements of the mechanical radiosonde between 1959 and March 1990 is much more challenging, and the available technical documentation is sparse in the first decade (radiosonde with one pair of aneroid capsules). These aneroid capsules depicted a temperature dependency. They were calibrated in a facility reproducing a radiosonde ascent through a standard atmosphere (pressure and temperature). Their temperature coefficients and the difference between their temperature course during the calibration process and during the sounding are needed to be accurately known. Major difficulties arise here because the temperature coefficients should take into account the whole transducer system and because the aneroid temperature during flight is not equal to the air temperature. Initiated by the results of the ASOND-78 radiosonde intercomparison [Phillips et al., 1980], measurements related to these items have been performed during 1978–1980. A few complete radiosondes have been calibrated at different constant temperatures between +20°C and −60°C and aneroid temperature coefficients have been derived. They brought an improvement in the operational radiosonde pressure measurements since May 1980 [Richner and Phillips, 1982; Rieker and Joss, 1985]. However, a comparison campaign held in 1993 between the old and the new sonde confirmed systematic residual pressure errors, which had already appeared in the first comparisons between the old radiosonde and hypsometer prototypes (Häberli, unpublished report, 1996). The largest error was found in the lower troposphere (up to several hPa too low), it changed its sign near 220 hPa, and the pressure jump at the switch to the second pair of aneroids (approximately 95 hPa) was a few hPa. The pressure measurements above the 95 hPa level were constantly too low. The simplifications in the correction model adopted in 1980 could only partly explain these errors. In order to improve the correction, we studied the vertical profile of balloon ascent speed over the years 1974 (start of sounding’s time in digital files) to 2000. We found a clear peak near 100 hPa (with changes in different periods), as well as suspiciously high values at 10 hPa (up to 10 m/s on average in different periods). We adopted a rather conservative pressure correction scheme, with different modulations for the 00 and 12 UTC profiles and for the distinct periods between October 1970 and March 1990 (see Table 1). As the pressure switch from the first to the second pair of aneroid capsules was variable and is not documented in the digital files, we smoothed the pressure profile around 100 hPa after applying our correction scheme. We did not correct the pressure measurements before October 1970, as we found no appropriate document allowing for a well-founded choice. This would require digitalizing paper protocols in their 60 s resolution. At that time, the radiosonde had only one pair of aneroid capsules and was hardly reaching 70 hPa.

A3. Re-Integration and Final Processing

[42] Following all these corrections, including humidity (not discussed in this paper), individual profiles have been re-integrated in order to obtain uniform geopotential altitudes, respectively, re-calculate pressure for GPS radiosondes in 2011 as the solar radiation correction slightly changed temperature. Furthermore, temperature and geopotential altitude have been again interpolated at an extended number of standard pressure levels. Finally, monthly means have been calculated for these pressure levels, separately for the 00 and 12 UTC ascents, as well as for both day times. Final reevaluation results are given in Figures 1 and 2 in the form of averaged temperature differences between reevaluated and original series. Similar break analyses can be applied to temperature or geopotential altitude (e.g., 12–00 UTC differences), in order to assess the improvements brought by the reevaluation (not shown here).
ACKNOWLEDGMENTS. The authors contributed as follows: Pierre Jeannet made all historical investigations on the Payerne upper air measurements, homogenized the data records, and made the trend analysis. Michael Begert homogenized the surface measurements. Simon Scherrer analyzed the zero-degree isotherm. Gilbert Levrat and Gonzague Romanens provided the technical support. Emmanuel Brocard wrote the manuscript. Rolf Philipona directed this work and contributed to surface measurements and the writing. The authors would like to acknowledge the radiosounding group of the Payerne aerological station for launching radiosondes daily for more than 53 years. Source of HadAT2 is www.metoffice.gov.uk/hadobs group of the Payerne aerological station for launching radiosondes daily. Rolf Philipona directed this work and contributed to surface measurements analyzed the zero-degree isotherm. Gilbert Levrat and Gonzague Romanens Michael Begert homogenized the surface measurements. Simon Scherrer Jeannet made all historical investigations on the Payerne upper air measurements.

References


