Atmospheric $\Delta^{14}$CO$_2$ trend in Western European background air from 2000 to 2012

By INGEBORG LEVIN*, BERND KROMER and SAMUEL HAMMER,
Institut für Umweltphysik, Heidelberg University, INF 229, 69120 Heidelberg, Germany

(Manuscript received 14 November 2012; in final form 2 February 2013)

**ABSTRACT**
Long-term measurements of atmospheric $\Delta^{14}$CO$_2$ from two monitoring stations, one in the European Alps (Jungfraujoch, Switzerland) and the other in the Black Forest (Schauinsland, Germany), are presented. Both records show a steady decrease, changing from about 6% per year at the beginning of the century to only 3% per year on average in the last 4 yr. A significant seasonal variation of $\Delta^{14}$CO$_2$ is observed at both sites with maxima during late summer and minima in late winter/early spring. While the $\Delta^{14}$C maxima are similar at Jungfraujoch and Schauinsland, the minima at Schauinsland are lower by up to 10%, due to a larger influence from $^{14}$C-free fossil fuel CO$_2$ emissions in the footprint of the Schauinsland station in winter. Summer mean $\Delta^{14}$C values at Schauinsland are considered best suited as input for studies of biospheric carbon cycling in mid-northern latitudes or for dating of organic material of the last half century.

**Keywords:** carbon dioxide, radiocarbon, clean air reference

1. **Introduction**
The bomb radiocarbon signal in atmospheric carbon dioxide (CO$_2$) has been used as transient tracer in numerous applications, for example, to: (1) study the dynamics and transport processes in the atmosphere, hydrosphere and biosphere (e.g. Czeplak and Junge, 1974; Oeschger et al., 1975; Maier-Reimer and Hasselmann, 1987; Dörr and Münich, 1986; Johnston, 1989; Trumbore, 2000; 2009); (2) constrain fluxes in the global carbon cycle (e.g. Siegenthaler et al., 1980; Randerson et al., 2002; Naegler, 2009; Naegler and Levin, 2009; Levin et al., 2010); and also (3) for dating of young organic material and in forensic studies (e.g. Wild et al., 2000; Spalding et al., 2005; Ubelaker et al., 2006). Common basis of these investigations are precise atmospheric $^{14}$CO$_2$ observations, which serve as an input or reference signal that is transferred into the carbon reservoir under investigation or that are used for dating at annual resolution. The radiocarbon measurement records available for Central European background stations, such as Vermunt, Austrian Alps; Schauinsland, Black Forest, Germany; and Jungfraujoch, Swiss Alps, covering the period from 1959 onwards (Levin and Kromer, 2004), have served as such a reference for applications in mid-latitudes of the Northern Hemisphere. Here, we present an extension of our measurements from the two stations Schauinsland and Jungfraujoch. These data are not only of importance for the above-mentioned applications, but Jungfraujoch measurements are also often used to define the European clean air reference when estimating regional fossil fuel CO$_2$ levels at polluted stations in Europe (e.g. Levin et al., 1980; Levin et al., 2003; Rakowski et al., 2004; Van Der Laan et al., 2010; Levin et al., 2011). In the following, we present and discuss the data covering the past decade (2000 to 2012). Earlier measurements are available in Levin and Kromer (2004), and in digital form under http://www.iup.uni-heidelberg.de/institut/forschung/groups/kk/Data_html. The new data presented here will be available at the same link.

2. **Sampling sites and methods**
The high-alpine monitoring station Jungfraujoch is located in the Swiss Alps (JFJ, Berner Oberland, 46°33’N, 7°59’E) at an elevation of 3450 m a.s.l. This high-elevation Global Atmosphere Watch (GAW) station is only occasionally influenced by regional CO$_2$ sources (e.g. Tucson et al., 2011), but for most of the time it samples air from the free troposphere over Europe
The Schauinsland observatory in the Black Forest, situated on a mountain ridge at an elevation of 1205 m a.s.l. (SIL, 47°55’N, 7°54’E), is located at the eastern border of the upper Rhine valley and normally samples free tropospheric air during night. During the day and particularly in summer, Schauinsland station is frequently influenced by boundary layer air and moderate pollution events from the industrialised and populated Rhine valley (Schmidt et al., 2003). At both stations, JFJ and SIL, 2-week integrated CO2 samples are collected by chemical absorption in carbonate-free concentrated sodium hydroxide solution (Levin et al., 1980). In the Heidelberg laboratory, CO2 is extracted from the basic solution with phosphoric acid; samples are then purified over activated charcoal and measured by conventional counting (Kromer and Münnich, 1992). All D14CO2 data presented here are reported as fractionation-corrected permil-deviations from Oxalic Acid standard activity corrected for decay (Stuiver and Polach, 1977); the measurement precision of individual samples is generally ±2σ (1 sigma).

3. Results

The long-term decrease of Δ14C in atmospheric CO2 observed since the 1960s has continued in the last decade, albeit at a decreasing rate of only about 3‰ per year in 2007–2011. This decreasing trend reduces the precision of bomb 14C dating compared to the preceding decades. The Δ14CO2 decline today is driven primarily by the ongoing input of 14C-free fossil fuel CO2 into the global atmosphere, as the atmospheric bomb 14C perturbation of the early 1960s has been almost fully equilibrated with surface ocean water and the terrestrial biosphere (Levin et al., 2010; Graven et al., 2012). Figure 1a shows individual Δ14C data measured on the Jungfraujoch samples. In most years we observe a seasonal variation with minimum Δ14C values in winter and spring and maxima in summer and autumn. The solid line in Fig. 1a is a fit curve calculated according to Nakazawa et al. (1997) through monthly mean Jungfraujoch data (Table 1). Levin et al. (2010) could show with the carbon cycle box model GRACE that this seasonality is mainly due to seasonal variations of the share of 14C-elevated stratospheric air in the northern hemispheric troposphere and to a seasonally changing amount of fossil fuel CO2 in the troposphere. At Schauinsland station (Fig. 1b), the seasonal variation of Δ14C is larger by more than a factor of two compared to Jungfraujoch data. This is due to the closer proximity of the Schauinsland site to the fossil fuel sources, for example, in the Rhine valley. However, the summer values at Schauinsland are very close to those observed at Jungfraujoch, indicating that in summer European fossil fuel CO2 emissions are smaller and diluted into a higher mixed layer depth than in winter (Levin et al., 2003).

When searching for the proper European 14CO2 reference curve for investigations linked to the terrestrial biosphere reservoir or for dating of recent organic material, the question is, which data set is most appropriate as input curve. Keeping in mind that photosynthesis by plants is mainly restricted to spring and summer months, and that generally the organic material to be dated has grown in rural areas and at lower elevation than Jungfraujoch, we suggest that only spring and summer months’ data from SIL may best be taken for reference in such applications. Mean Δ14C values for May to August have thus been calculated from monthly mean Schauinsland data and are also plotted in Fig. 1b, together with a 1σ standard deviation of the four monthly values. Our suggestion would be to use these numbers as input 14C/C ratios which are transferred into plant material. However, there may be
Table 1. Monthly mean $\Delta^{14}$CO$_2$ data from Jungfraujoch and Schauinsland as well as monthly values from the fitted curve through Jungfraujoch data. Last column gives spring and summer mean values (including 1 sigma standard deviations of the monthly averaged data).

| Decimal date | Month | Jungfraujoch $\Delta^{14}$C | JFJ fit curve $\Delta^{14}$C | Schauinsland $\Delta^{14}$C | May–Aug \%  |
|--------------|-------|----------------------------|-----------------------------|-----------------------------|------------|
| 2000.044     | 1     | 92.3                       | 91.31                       | 86.9                        |            |
| 2000.126     | 2     | 91.0                       | 90.03                       | 89.3                        |            |
| 2000.208     | 3     | 89.4                       | 89.15                       | 84.6                        |            |
| 2000.291     | 4     | 85.2                       | 88.74                       | 83.7                        |            |
| 2000.374     | 5     | 87.2                       | 88.73                       | 87.6                        |            |
| 2000.458     | 6     | 88.8                       | 88.96                       | 84.1                        | 86.5 ± 2.0 |
| 2000.541     | 7     | 90.6                       | 89.20                       | 85.9                        |            |
| 2000.626     | 8     | 92.3                       | 89.21                       | 88.5                        |            |
| 2000.709     | 9     | 88.6                       | 88.82                       | 85.9                        |            |
| 2000.792     | 10    | 86.5                       | 87.95                       | 85.3                        |            |
| 2000.876     | 11    | 84.8                       | 86.65                       | 87.5                        |            |
| 2000.959     | 12    | 84.7                       | 85.09                       | 85.4                        |            |
| 2001.044     | 1     | 84.6                       | 83.51                       | 79.5                        |            |
| 2001.125     | 2     | 80.9                       | 82.16                       | 73.4                        |            |
| 2001.206     | 3     | 80.6                       | 81.23                       | 80.1                        |            |
| 2001.289     | 4     | 77.3                       | 80.82                       | 74.7                        |            |
| 2001.374     | 5     | 81.0                       | 80.91                       | 79.4                        |            |
| 2001.458     | 6     | 82.1                       | 81.34                       | 80.8                        | 80.8 ± 1.6 |
| 2001.541     | 7     | 83.9                       | 81.89                       | 83.1                        |            |
| 2001.626     | 8     | 82.8                       | 82.30                       | 79.8                        |            |
| 2001.709     | 9     | 81.1                       | 82.38                       | 80.9                        |            |
| 2001.792     | 10    | 83.0                       | 82.02                       | 83.3                        |            |
| 2001.876     | 11    | 81.8                       | 81.22                       | 76.7                        |            |
| 2001.959     | 12    | 80.5                       | 80.12                       | 77.1                        |            |
| 2002.044     | 1     | 77.7                       | 78.93                       | 73.1                        |            |
| 2002.125     | 2     | 75.2                       | 77.88                       | 71.6                        |            |
| 2002.206     | 3     | 76.2                       | 77.15                       | 70.3                        |            |
| 2002.289     | 4     | 74.6                       | 76.85                       | 67.5                        |            |
| 2002.374     | 5     | 75.6                       | 76.96                       | 73.9                        |            |
| 2002.458     | 6     | 78.6                       | 77.33                       | 75.1                        | 74.8 ± 1.4 |
| 2002.541     | 7     | 79.1                       | 77.74                       | 76.7                        |            |
| 2002.626     | 8     | 80.9                       | 77.94                       | 73.5                        |            |
| 2002.709     | 9     | 79.3                       | 77.73                       | 74.5                        |            |
| 2002.792     | 10    | 76.2                       | 77.00                       | 70.5                        |            |
| 2002.876     | 11    | 74.5                       | 75.77                       | 67.3                        |            |
| 2002.959     | 12    | 68.3                       | 74.18                       | 67.9                        |            |
| 2003.044     | 1     | 70.6                       | 72.47                       | 66.0                        |            |
| 2003.125     | 2     | 69.8                       | 70.93                       | 62.0                        |            |
| 2003.206     | 3     | 70.2                       | 69.78                       | 62.3                        |            |
| 2003.289     | 4     | 66.6                       | 69.17                       | 65.8                        |            |
| 2003.374     | 5     | 70.4                       | 69.13                       | 67.3                        | 69.1 ± 1.4 |
| 2003.458     | 6     | 70.4                       | 69.54                       | 70.2                        |            |
| 2003.541     | 7     | 73.7                       | 70.16                       | 68.7                        |            |
| 2003.626     | 8     | 71.9                       | 70.74                       | 70.1                        |            |
| 2003.709     | 9     | 70.3                       | 70.99                       | 68.1                        |            |
| 2003.792     | 10    | 69.5                       | 70.75                       | 67.5                        |            |
| 2003.876     | 11    | 68.4                       | 69.95                       | 65.3                        |            |
| 2003.959     | 12    | 65.7                       | 68.67                       | 63.6                        |            |
| 2004.044     | 1     | 63.4                       | 67.10                       | 61.5                        |            |
| 2004.125     | 2     | 64.0                       | 65.48                       | 58.7                        |            |
| 2004.206     | 3     | 65.5                       | 64.10                       | 56.3                        |            |
| 2004.289     | 4     | 62.5                       | 63.13                       | 57.7                        |            |
| 2004.374     | 5     | 62.3                       | 62.69                       | 56.0                        |            |
Table 1 (Continued)

| Decimal date | Month | Jungfraujoch $\Delta^{14}$C [%$_{oo}$] | JFJ fit curve $\Delta^{14}$C [%$_{oo}$] | Schauinsland $\Delta^{14}$C [%$_{oo}$] | SIL summer May–Aug [%$_{oo}$] |
|--------------|------|-------------------------------------|-------------------------------------|--------------------------------------|------------------------------|
| 2004.458     | 6    | 64.3                                | 62.74                               | 63.4                                 | 61.5 ± 3.7                  |
| 2004.541     | 7    | 63.3                                | 63.13                               | 62.9                                 |                             |
| 2004.626     | 8    | 64.0                                | 63.66                               | 63.9                                 |                             |
| 2004.709     | 9    | 65.2                                | 64.10                               | 62.6                                 |                             |
| 2004.792     | 10   | 62.1                                | 64.05                               | 62.3                                 |                             |
| 2004.876     | 11   | 63.1                                | 63.47                               | 59.0                                 |                             |
| 2004.959     | 12   | 63.4                                | 62.62                               | 61.4                                 |                             |
| 2005.044     | 1    | 63.1                                | 61.69                               | 56.1                                 |                             |
| 2005.125     | 2    | 60.1                                | 60.86                               | 49.0                                 |                             |
| 2005.206     | 3    | 60.1                                | 60.28                               | 51.8                                 |                             |
| 2005.289     | 4    | 56.1                                | 60.03                               | 54.3                                 |                             |
| 2005.374     | 5    | 62.3                                | 60.09                               | 58.4                                 |                             |
| 2005.458     | 6    | 59.3                                | 60.36                               | 57.2                                 |                             |
| 2005.541     | 7    | 63.9                                | 60.66                               | 58.7                                 | 57.9 ± 0.8                 |
| 2005.626     | 8    | 60.1                                | 60.82                               | 57.1                                 |                             |
| 2005.709     | 9    | 60.8                                | 60.71                               | 54.6                                 |                             |
| 2005.792     | 10   | 59.3                                | 60.28                               | 53.6                                 |                             |
| 2005.876     | 11   | 60.0                                | 59.55                               | 54.8                                 |                             |
| 2005.959     | 12   | 57.2                                | 58.65                               | 50.8                                 |                             |
| 2006.044     | 1    | 58.0                                | 57.76                               | 51.1                                 |                             |
| 2006.125     | 2    | 58.0                                | 57.06                               | 46.9                                 |                             |
| 2006.206     | 3    | 55.4                                | 56.68                               | 48.4                                 |                             |
| 2006.289     | 4    | 54.8                                | 56.69                               | 53.6                                 |                             |
| 2006.374     | 5    | 56.4                                | 57.03                               | 55.3                                 |                             |
| 2006.458     | 6    | 59.2                                | 57.57                               | 55.2                                 |                             |
| 2006.541     | 7    | 59.1                                | 58.11                               | 58.8                                 | 57.0 ± 2.0                 |
| 2006.626     | 8    | 62.0                                | 58.43                               | 58.5                                 |                             |
| 2006.709     | 9    | 57.1                                | 58.38                               | 54.6                                 |                             |
| 2006.792     | 10   | 57.8                                | 57.88                               | 56.3                                 |                             |
| 2006.876     | 11   | 52.6                                | 56.95                               | 55.2                                 |                             |
| 2006.959     | 12   | 54.0                                | 55.71                               | 54.1                                 |                             |
| 2007.044     | 1    | 54.7                                | 54.37                               | 56.9                                 |                             |
| 2007.125     | 2    | 54.2                                | 53.14                               | 49.3                                 |                             |
| 2007.206     | 3    | 50.5                                | 52.21                               | 46.8                                 |                             |
| 2007.289     | 4    | 52.9                                | 51.70                               | 45.3                                 |                             |
| 2007.373     | 5    | 51.0                                | 51.62                               | 48.7                                 |                             |
| 2007.456     | 6    | 53.0                                | 51.88                               | 50.3                                 | 50.1 ± 1.0                 |
| 2007.540     | 7    | 53.2                                | 52.31                               | 50.7                                 |                             |
| 2007.625     | 8    | 52.8                                | 52.71                               | 50.7                                 |                             |
| 2007.708     | 9    | 52.9                                | 52.89                               | 53.3                                 |                             |
| 2007.792     | 10   | 49.6                                | 52.74                               | 45.0                                 |                             |
| 2007.875     | 11   | 49.7                                | 52.22                               | 46.1                                 |                             |
| 2007.959     | 12   | 52.4                                | 51.40                               | 46.1                                 |                             |
| 2008.044     | 1    | 51.3                                | 50.40                               | 45.4                                 |                             |
| 2008.125     | 2    | 51.9                                | 49.40                               | 44.4                                 |                             |
| 2008.206     | 3    | 49.3                                | 48.56                               | 43.7                                 |                             |
| 2008.289     | 4    | 46.2                                | 47.97                               | 43.5                                 |                             |
| 2008.374     | 5    | 42.5                                | 47.65                               | 44.2                                 |                             |
| 2008.458     | 6    | 46.0                                | 47.56                               | 45.6                                 |                             |
| 2008.540     | 7    | 49.1                                | 47.56                               | 50.0                                 | 47.1 ± 2.7                 |
| 2008.625     | 8    | 49.3                                | 47.50                               | 48.6                                 |                             |
| 2008.708     | 9    | 46.6                                | 47.26                               | 47.0                                 |                             |
| 2008.792     | 10   | 49.1                                | 46.77                               | 42.7                                 |                             |
| 2008.875     | 11   | 44.5                                | 46.06                               | 42.4                                 |                             |
other applications where different data selection may be appropriate. For this purpose, monthly mean Schauinsland values, respective values from the Jungfraujoch together with the monthly data from the Jungfraujoch fit curve are listed along with the SIL summer mean values in Table 1. The individual 2-week integrated data are available online under http://www.iup.uni-heidelberg.de/institut/forschung/groups/kk/Data_html.

| Decimal date | Month | Jungfraujoch | JFJ fit curve | Schauinsland | SIL summer |
|--------------|-------|--------------|---------------|--------------|------------|
|              |       | $\Delta^{14}C$ | $\Delta^{14}C$ | $\Delta^{14}C$ | May–Aug     |
| 2008.959     | 12    | 42.3         | 45.22         | 38.4         |            |
| 2009.044     | 1     | 45.0         | 44.43         | 39.4         |            |
| 2009.125     | 2     | 43.8         | 43.87         | 37.3         |            |
| 2009.206     | 3     | 45.3         | 43.70         | 37.6         |            |
| 2009.289     | 4     | 39.4         | 43.98         | 38.9         |            |
| 2009.374     | 5     | 46.3         | 44.71         | 43.6         |            |
| 2009.458     | 6     | 48.2         | 45.74         | 48.8         |            |
| 2009.540     | 7     | 49.5         | 46.85         | 46.8         | 46.7 ± 2.2 |
| 2009.625     | 8     | 49.8         | 47.80         | 47.6         |            |
| 2009.708     | 9     | 47.8         | 48.36         | 42.7         |            |
| 2009.792     | 10    | 47.3         | 48.38         | na           |            |
| 2009.875     | 11    | 44.7         | 47.80         | 39.0         |            |
| 2009.959     | 12    | 44.7         | 46.73         | 39.3         |            |
| 2010.044     | 1     | 45.1         | 45.33         | 32.3         |            |
| 2010.125     | 2     | 45.1         | 43.88         | 34.8         |            |
| 2010.206     | 3     | 38.8         | 42.61         | 37.4         |            |
| 2010.289     | 4     | 41.5         | 41.73         | 33.9         |            |
| 2010.374     | 5     | 42.2         | 41.36         | 38.0         |            |
| 2010.458     | 6     | 39.9         | 41.48         | 37.8         | 40.0 ± 2.7 |
| 2010.541     | 7     | 42.6         | 41.97         | 40.7         |            |
| 2010.626     | 8     | 44.5         | 42.63         | 43.5         |            |
| 2010.709     | 9     | 47.1         | 43.22         | 41.5         |            |
| 2010.792     | 10    | 41.4         | 43.47         | 42.2         |            |
| 2010.876     | 11    | 42.5         | 42.97         | 37.7         |            |
| 2010.959     | 12    | 41.1         | 42.13         | 33.6         |            |
| 2011.044     | 1     | 39.7         | 41.10         | 38.2         |            |
| 2011.125     | 2     | 40.5         | 40.08         | 32.0         |            |
| 2011.206     | 3     | 39.3         | 39.23         | 31.4         |            |
| 2011.289     | 4     | 39.5         | 38.69         | 35.8         |            |
| 2011.374     | 5     | 38.0         | 38.49         | 35.6         |            |
| 2011.458     | 6     |              |               | 39.4         |            |
| 2011.541     | 7     |              |               | 41.0         | 39.0 ± 2.4 |
| 2011.626     | 8     |              |               | 40.1         |            |
| 2011.709     | 9     |              |               | 37.8         |            |
| 2011.792     | 10    |              |               | 32.6         |            |
| 2011.876     | 11    |              |               | 33.4         |            |
| 2011.959     | 12    |              |               | 32.8         |            |
| 2012.044     | 1     |              |               | 32.8         |            |
| 2012.125     | 2     |              |               | 25.2         |            |
| 2012.206     | 3     |              |               | 33.7         |            |
| 2012.289     | 4     |              |               | 31.8         |            |
| 2012.374     | 5     |              |               | 28.7         |            |
| 2012.458     | 6     |              |               | 31.4         | 31.5 ± 2.0 |
| 2012.541     | 7     |              |               | 33.4         |            |
| 2012.626     | 8     |              |               | 32.3         |            |
| 2012.709     | 9     |              |               | 32.5         |            |
4. Summary and conclusions

Long-term integrated \(\Delta^{14}\)CO\(_2\) measurements have been continued at the high-alpine Jungfraujoch station in the Swiss Alps as well as at Schauinsland in the Black Forest, southern Germany. The almost exponential decrease of \(\Delta^{14}\)C since 1963 has continued with a current rate of ca. 3\% per year in the last 4 yr. We suggest using the Jungfraujoch fit curve as a clean air reference for estimates of the fossil fuel CO\(_2\) concentration at polluted European stations, while mean summer (May–August) data from Schauinsland may best represent atmospheric \(\Delta^{14}\)C transferred into the biospheric reservoir. It should be noted, that the mid latitude northern hemispheric reference values presented here may not be applicable for tropical and southern hemispheric studies, as the increasing fossil fuel CO\(_2\) emissions in northern mid-latitudes tend to increase the meridional gradient, so that respective background \(\Delta^{14}\)C data may be higher in latitudes further to the south by as much as 5\% (see Levin et al., 2010; Graven et al., 2012).

Continuation of our long-term measurements seems appropriate as these data sets are essential as input to study carbon cycle dynamics or for future dating purposes.

5. Acknowledgements

We wish to thank the technical personnel at Jungfraujoch and Schauinsland for their careful work collecting the numerous \(^{14}\)CO\(_2\) samples as well as the Jungfraujoch Foundation and the German Umweltbundesamt for logistic support at the stations. Sabine Kühr and Eva Gier took care of the \(^{14}\)CO\(_2\) sample preparation in the Heidelberg Radiocarbon laboratory. Financial support for these long-term \(^{14}\)CO\(_2\) measurements was provided by a number of agencies in Germany and Europe, namely the Heidelberg Academy of Sciences, the Ministry of Education and Science, Baden-Württemberg, Germany, the German Science Foundation, the German Minister of Science and Education (FKZ 01LK1102A), and the European Commission, Brussels, under the projects CarboEurope-IP (Project No. GOCE-CT-2003-50572) and ICOS Preparatory Phase (Project No. 211574).

References

Czeplak, G. and Junge, C. 1974. Studies of interhemispheric exchange in the troposphere by a diffusion model. Adv. Geophys. 18, 57–72.

Dörfl, H. and Münich, K. O. 1986. Annual variations of the \(^{14}\)C content of soil CO\(_2\). Radiocarbon 28(2A), 338–345.

Graven, H. D., Guilderson, T. P. and Keeling, R. F. 2012. Observations of radiocarbon in CO\(_2\) at La Jolla, California, USA 1992–2007. J. Geophys. Res. 117, D02302. DOI: 10.1029/2011JD016533.

Johnston, H. S. 1989. Evaluation of excess carbon-14 and strontium-90 data for suitability to test two-dimensional stratospheric models. J. Geophys. Res. 94, 18485–18493.

Kromer, B. and Münich, K. O. 1992. CO\(_2\) gas proportional counting in Radiocarbon dating – review and perspective. In: Radiocarbon after four decades (eds. R. E. Taylor, A. Long and R. S. Kra), Springer-Verlag, New York, pp. 184–197.

Levin, I., Hammer, S., Eichelmann, E. and Vogel, F. 2011. Verification of greenhouse gas emission reductions: the prospect of atmospheric monitoring in polluted areas. Philosophical Transactions A 369, 1906–1924.

Levin, I., Hammer, S., Kromer, B. and Meinhardt, F. 2008. Radiocarbon observations in atmospheric CO\(_2\): determining fossil fuel CO\(_2\) over Europe using Jungfraujoch observations as background. Sci. Total. Environ. 391, 211–216. DOI: 10.1016/j.scitotenv.2007.10.019.

Levin, I. and Kromer, B. 2004. The tropospheric \(^{14}\)CO\(_2\) level in mid-latitudes of the Northern Hemisphere (1959–2003). Radiocarbon 46(3), 1261–1272.

Levin, I., Kromer, B., Schmidt, M. and Sartorius, H. 2003. A novel approach for independent budgeting of fossil fuel CO\(_2\) over Europe by \(^{14}\)CO\(_2\) observations. Geophys. Res. Lett. 30(23), 2194. DOI: 10.1029/2003GL018477.

Levin, I., Münich, K. O. and Weiss, W. 1980. The effect of anthropogenic CO\(_2\) and \(^{14}\)C sources on the distribution of \(^{14}\)CO\(_2\) in the atmosphere. Radiocarbon 22, 379–391.

Levin, I., Naegler, T., Kromer, B., Diehl, M., Francey, R. J. and co-authors. 2010. Observations and modelling of the global distribution and long-term trend of atmospheric \(^{14}\)CO\(_2\). Tellus 62B, 26–46. DOI: 10.1111/j.1600-0889.2009.00446.x.

Maier-Hein, E. and Hasselmann, K. 1987. Transport and storage of CO\(_2\) in the ocean – an inorganic ocean-circulation carbon cycle model. Clim. Dyn. 2, 63–90.

Naegler, T. 2009. Reconciliation of excess \(^{14}\)C-based global CO\(_2\) piston velocity estimates. Tellus 61B, 372–384. DOI: 10.1111/j.1600-0889.2008.00408.x.

Naegler, T. and Levin, I. 2009. Biosphere-atmosphere gross carbon exchange flux and the \(^{14}\)C and \(^{14}\)CO\(_2\) disequilibria constrained by the biospheric excess radiocarbon inventory. J. Geophys. Res. 114, D17303. DOI: 10.1029/2008JD011116.

Nakazawa, T., Ishizawa, M., Higuchi, K. and Trivett, N. B. A. 1997. Two curve fitting methods applied to CO\(_2\) flask data. Environmetrics 8, 197–218.

Oeschger, H., Siegenthaler, U., Schotterer, U. and Gugelmann, A. 1975. A box diffusion model to study the carbon dioxide exchange in nature. Tellus 27(2), 168–192.

Randerson, J. T., Enting, I. G., Schuur, E. A. G., Caldeira, K. and Fung, I. Y. 2002. Seasonal and latitudinal variability of tropospheric \(^{14}\)CO\(_2\): post bomb contributions from fossil fuels, oceans, the stratosphere, and the terrestrial biosphere. Global Biogeochem. Cycles 16(4), 1112. DOI: 10.1029/2002GB001876.

Rakowski, A., Kuc, T., Nakamura, T. and Padzur, A. 2004. Radiocarbon concentration in the atmosphere and modern tree rings in the Kraków area, southern Poland. Radiocarbon 46(2), 911–916.

Schmidt, M., Graul, R., Sartorius, H. and Levin, I. 2003. The Schauinsland CO\(_2\) record: 30 years of continental observations.
and their implications for the variability of the European CO2 budget. J. Geophys. Res. 108(19), 4619. DOI: 10.1029/2002JD003085.

Siegenthaler, U., Heimann, M. and Oeschger, H. 1980. 14C variations caused by changes in the global carbon cycle. Radiocarbon 22, 177–191.

Spalding, K. L., Buchholz, B. A., Bergman, L.-E., Druid, H. and Frisén, J. 2005. Age written in teeth by nuclear tests. Nature 437, 333–334.

Stuiver, M. and Polach, H. 1977. Discussion: Reporting of 14C data. Radiocarbon 19, 355–363.

Trumbore, S. E. 2000. Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics. Ecol. Appl. 10(2), 399–411.

Trumbore, S. E. 2009. Radiocarbon and soil carbon dynamics. Annu. Rev. Earth Planet. Sci. 37, 47–66.

Tucson, B., Henne, S., Brunner, D., Steinbacher, M., Mohn, J. and co-authors. 2011. Continuous isotopic composition measurements of tropospheric CO2 at Jungfraujoch (3580 m asl), Switzerland: real-time observation of regional pollution events. Atmos. Chem. Phys. 11, 1685–1696.

Ubelaker, D. H., Buchholz, B. A. and Stewart, J. E. B. 2006. Analysis of artificial radiocarbon in different skeletal and dental tissue types to evaluate date of death. J. Forensic. Sci. 51, 484–488.

Van Der Laan, S., Karstens, U., Neubert, R. E. M., Van Der Laan-Luijkx, I. T. and Meijer, H. A. J. 2010. Observation-based estimates of fossil fuel-derived CO2 emissions in the Netherlands using Δ14C, CO and 222Radon. Tellus 62B(5), 389–402. DOI: 10.1111/j.1600-0889.2010.00493.x.

Wild, E. M., Arlamovsky, K. A., Golser, R., Kutschera, W., Priller, A. and co-authors. 2000. C-14 dating with the bomb peak: an application to forensic medicine. Nucl. Instrum. Methods Phys. Res. B 172, 944–950.