Accurate estimation of CO_2 background level from near ground measurements at non-mixed environments

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Abstract

Atmospheric CO_2 background levels are sampled and processed according to the standards of the NOAA (National Oceanic and Atmospheric Administration) Earth System Research Laboratory mostly at marine environments to minimize the local influence of vegetation, ground or anthropogenic sources. Continental measurements usually show large diurnal and seasonal variations, which makes it difficult to estimate well mixed CO_2 levels.

Historical CO_2 measurements are usually derived from proxies, with ice cores being the favorite. Those done by chemical methods prior to 1960 are often rejected as being inadequate due too poor siting, timing or method. The CO_2 versus wind speed plot represents a simple but valuable tool for validating modern and historic continental data. It is shown that either a visual or a mathematical fit can give data that are close to the regional CO_2 background, even if the average local mixing ratio is much different.

Preliminary remarks

Many of the discussions concerning anthropogenic global warming center on the important role of atmospheric CO_2 as a greenhouse gas. Having good CO_2 measurement data at many regional locations is particularly important. When these locations do not fulfill the usual criteria for obtaining CO_2 background levels, a procedure to derive these levels with the help of other meteorological parameters will be useful. The same holds for the study or the validation of historical CO_2 measurements.

Daily pattern of CO_2 mixing ratios

The daily pattern of the CO_2 mixing ratio depends essentially on the presence and/or the strength of the near ground inversion layer. This layer (which exists mostly at night, during the morning hours or at late afternoon) prevents a thorough mixing up of the atmosphere and coincides usually with large CO_2 peaks (Massen, 2007). During the midday hours, solar heating is normally at a maximum and creates the strongest convective air movements. As a consequence, the atmospheric boundary layer is well mixed up, and CO_2 mixing ratios fall to their daily minimum. This minimum is seen as the most representative measure of the regional CO_2 background level.

The inversion periods are much shorter and less intense at the border of open sea or at smaller islands, where a quasi continuous breeze mixes up the boundary layer at most periods of the day. As a consequence, the daily CO_2 variation is much lower at these locations, considered as the most suitable for background CO_2 measurements.

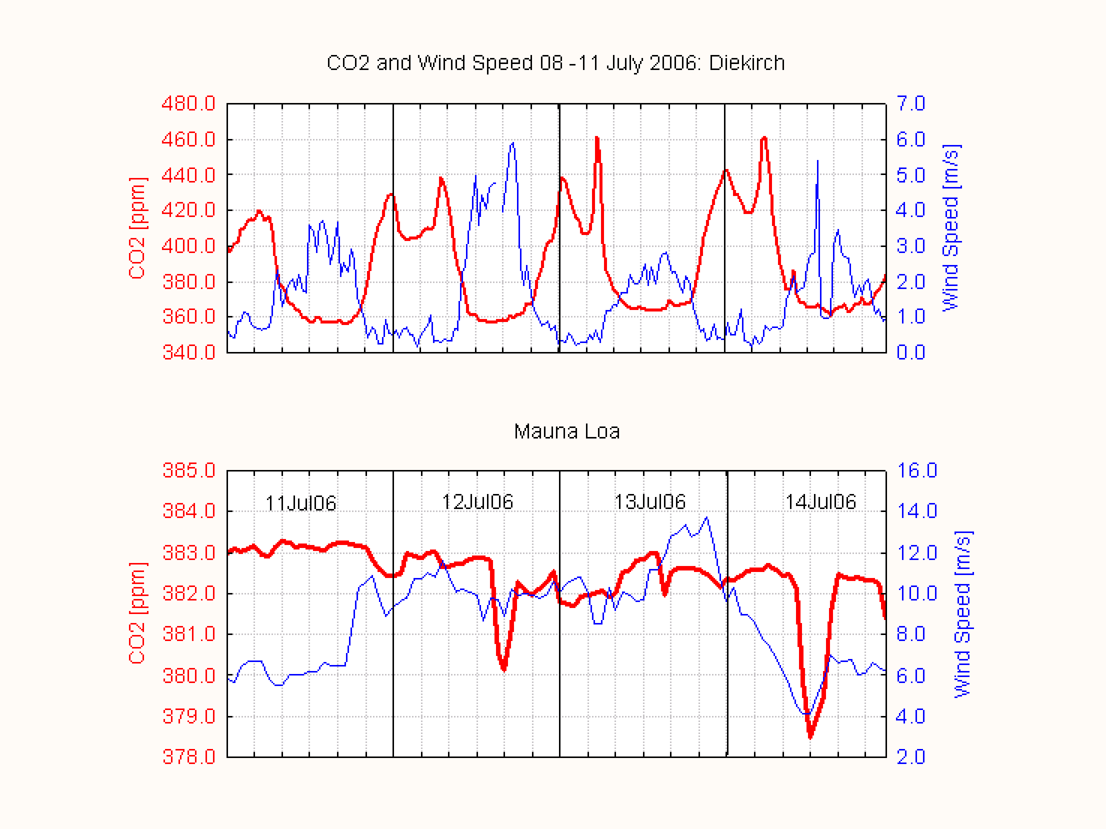


Fig.1 Daily pattern at Diekirch, Luxembourg and Mauna Loa for the 11-14 July 2006 period (Massen, 2007): very strong diurnal variations of up to 100 ppm exist at the semi-rural location of Diekirch, practically none (less than 4 ppm) at Mauna Loa (island of Hawaii). Note the different scales of the 2 plots!

Meanwhile vertical profiles of the atmospheric CO_2 concentration are available at many environments; they usually show different mixing ratios, with location having a much greater influence than altitude.

The North Hemisphere (NH) mean near ground mixing ratio shown in fig.2B differs by only 1.13 ppm from the background level above 4 km altitude. Extrapolation to ground level results in a 2.56 ppm difference. Large seasonal variations of the order of 30 ppm are typical at continental environments e.g. Surgut (SUR, Wetland, Siberia); at marine locations (e.g. Cape Grim Baseline Air Pollution Station, Bass Strait, Cape Grim, Australia) the variations around the local background level are small.

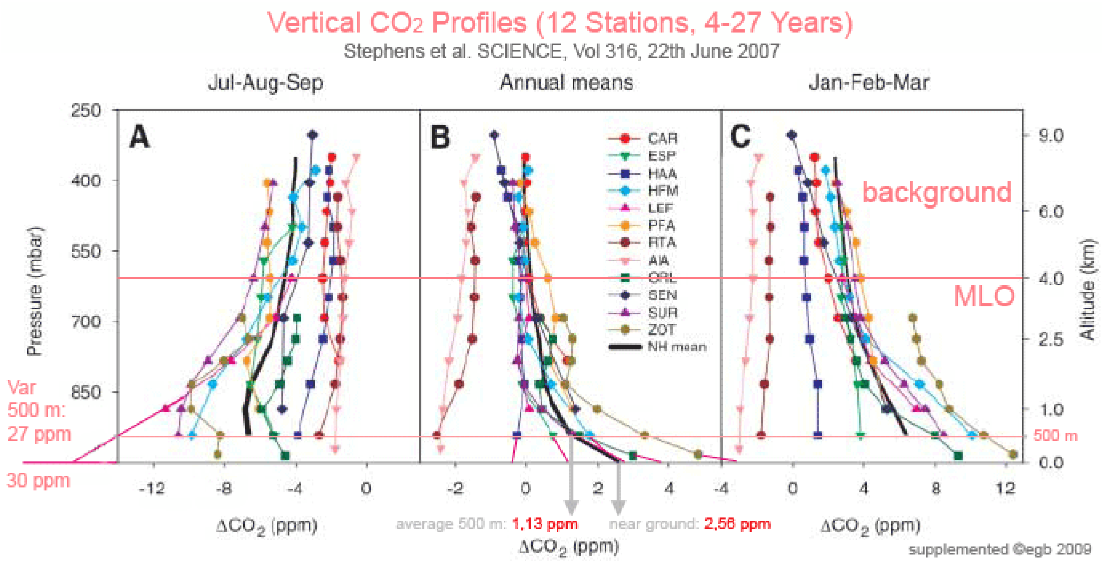


Fig.2 Vertical CO_2 profiles from 12 global stations derived from flask samples collected from aircraft during midday with records extending over periods from 4 to 27 years (Stephens, 2007). Additions to the original fig 1 of the paper by E-G. Beck. MLO = the Mauna Loa sampling station as a reference. B has been calculated by subtracting the MLO data. Stations were located from lat. 40.37 N, long. –104.30 E, to lat. 40.5 S, long. 144.30 E.

The problem of continental near-ground CO_2 measurements

CO_2 data sampled at continental environments near ground usually show large diurnal and seasonal variations which make it difficult to estimate the proper well mixed levels. Historical measurements prior to the high quality continuous recordings available since 1958 have been shown as being often very precise, done with great care by outstanding scientists. Many have been done in rural, semi-urban and marine environments (Beck, 2007). These measurements were usually spot measurements, made at different times of the day, and as such are difficult to evaluate: depending on the measurement routine, they may have a positive bias (for instance for measurements done during the morning hours) or show large variations. Nevertheless, there exist historical continuous sampling series done under fixed conditions over one or more seasons.

When meteorological parameters have been registered together with the CO_2 mixing ratios, there is a good chance to validate historical as well as modern continental data by using a CO_2 versus wind-speed plot.

The typical CO_2 versus wind-speed profiles

It is well known, that CO_2 pattern vary with latitude and time: mixing ratios and seasonal amplitude are lowest at the South Pole and highest at northern locations.

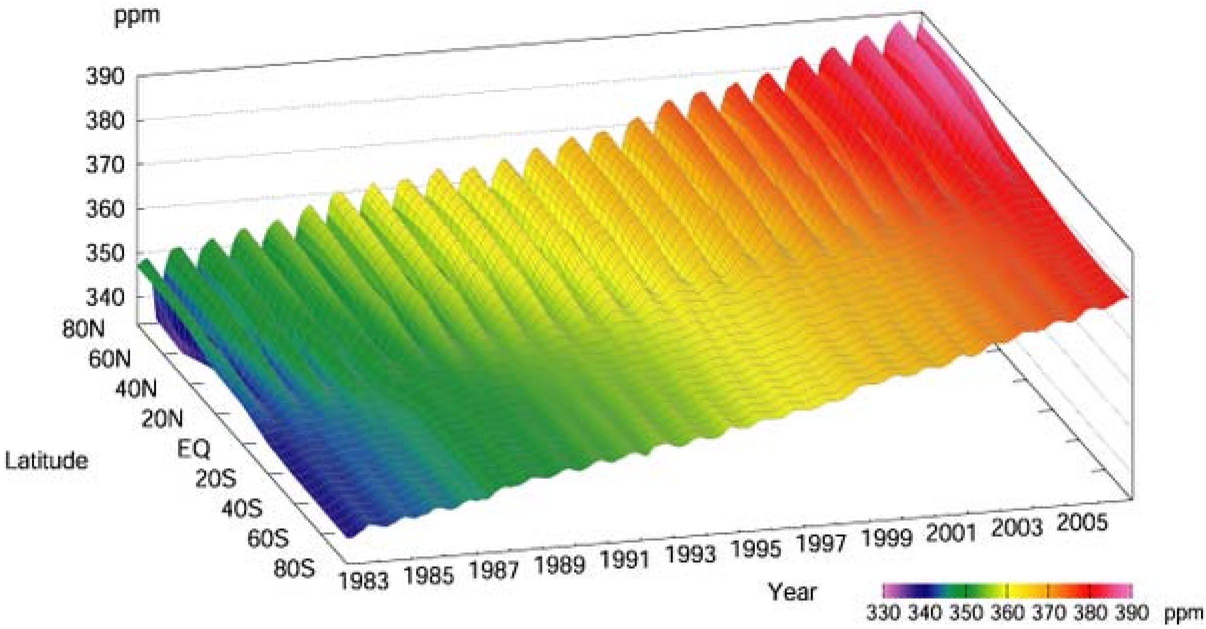


Fig.3 CO_2 pattern from South-pole to North-Pole (source: WDCGG, http://gaw.kishou.go.jp/wdcgg/)

If we plot CO_2 versus wind speed, a few typical patterns show up, as given in fig.4 for a group of selected stations ranging from North to South.

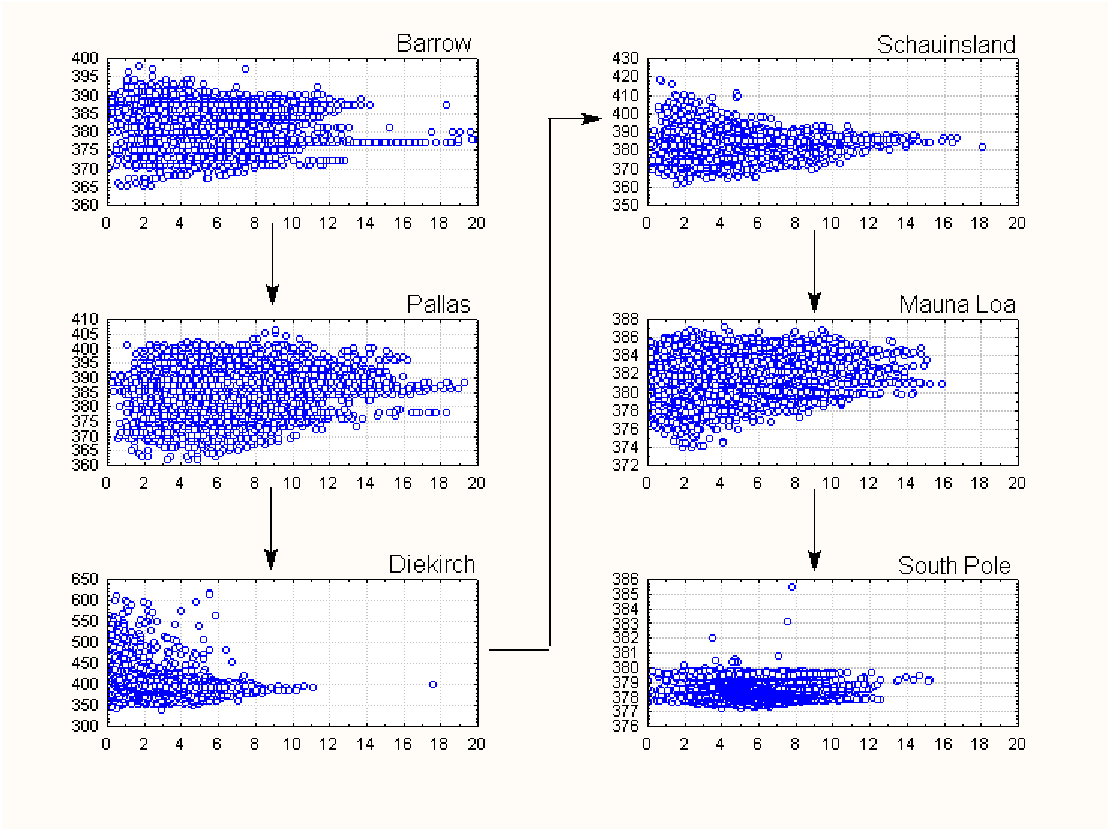


Fig.4 Typical CO_2 versus wind-speed pattern for selected stations from North Pole to South Pole (year 2006 data from NOAA, WDCGG and meteoLCD**)**

When CO_2 data have a strong seasonal amplitude, as is the case for Barrow (Alaska), Pallas (Finland) and Mauna Loa (Hawai), a typical "multi-fingered" figure appears:

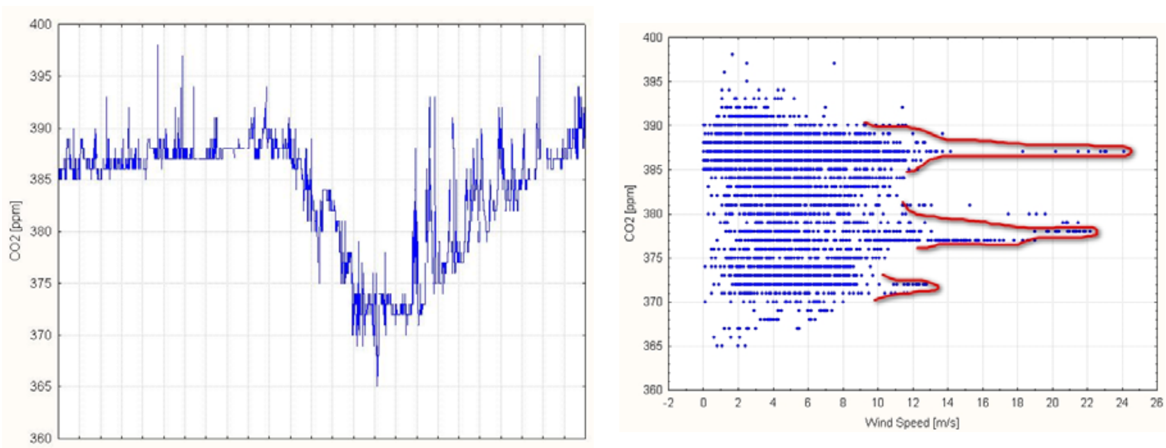


Fig.5 CO_2 data and “finger pattern” for Barrow, Alaska, 2006 (data source: NOAA)

In the Barrow example the top finger corresponds to the "mean" CO_2 mixing ratio during the first part of the year (January to May); the middle one to the two periods of either decreasing or rising values, and the lowest one to the bottom summer mixing ratio (here month of August). Simple inspection locates these finger-levels at about 387, 378 and 372 ppm. The average for the year 2006 is 383.6 ppm.

period	number of data points	calculated average CO_2 mixing ratio in ppm	approx. finger location
01 Jan. to 31 May 2006	3322	387	387
Jun, Jul, Sept-Dec 2006	3922	378	378
August 2006	713	372	372

What these "fingers" tell us is that most relevant data should be in the interval [372...387]; in the Barrow case, 60% of the data belong to that interval. A second important conclusion is that the overall regional global background mixing ratio should also be in the interval defined by the extreme fingers.

The same calculation for the Pallas data shows two fingers located at about 388 and 378 ppm; the yearly average is 384.5 ppm. The Pallas graph has only 2 fingers, because there is practically no longer period of low summer CO_2 levels. The top finger corresponds to the winter/spring background CO_2 levels, the lower to those of the 2 mid-year periods of falling or rising levels.

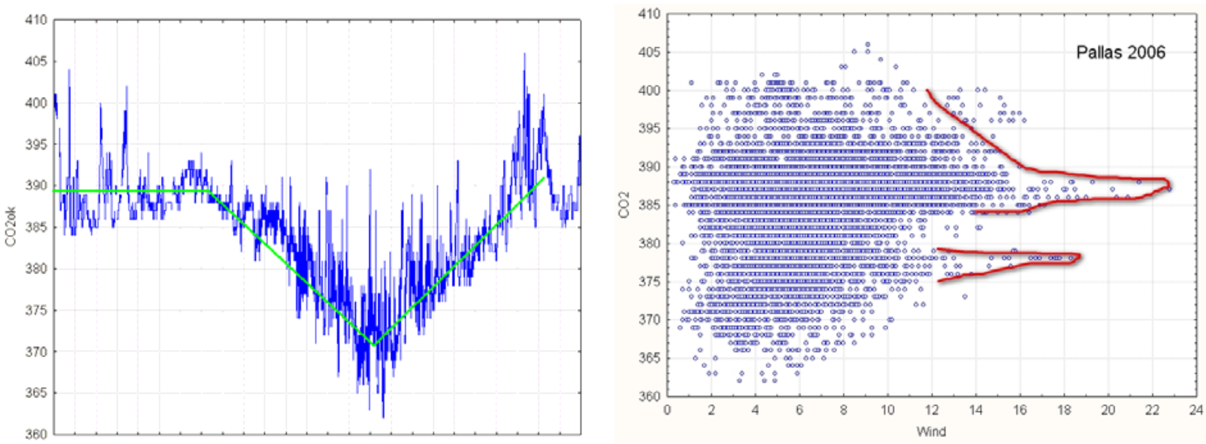


Fig.6 CO_2 and finger pattern for Pallas, Finland, 2006 (data: WDCGG)

Semi-rural, inland located stations like Diekirch (L) have a very different CO_2/wind-speed pattern: the absence of a strong seasonal swing gives a typical boomerang-shaped graph.

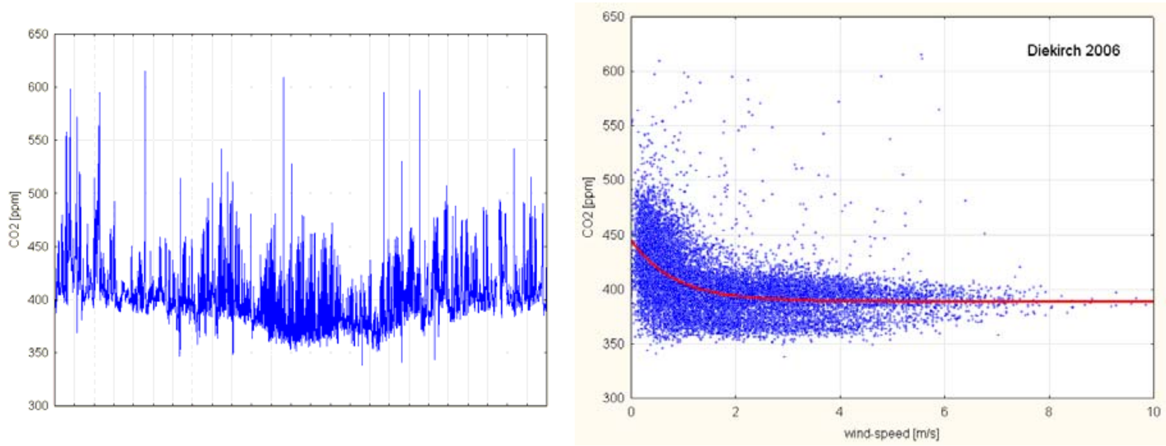


Fig.7 Year 2006 CO_2 levels and CO2 versus wind-speed pattern at Diekirch, Luxembourg.

This boomerang pattern is typical for inland stations, and shows up for instance at the Neuglobsow and Schauinsland stations, located in the North and in the Black Forest of Germany.

The pattern of the graph shows the magnitude of the regional background level; a primitive mathematical model allows calculation of the asymptotic mixing ratio that would be present if wind speed was infinite.

The authors found that a simple dilution formula like

$$CO_2 = a + b * e^{-c*windspeed} \quad \text{[eq.1]}$$

often is adequate. For the Diekirch data shown in fig.7 this model suggest

$$CO_2 = 389 + 56.1 * e^{-1.2*windspeed} \quad \text{[eq. 2]}$$

with an asymptotic value of 389 ppm (red curve in right plot of fig.7). R = 0.51 and the fit parameters are all significant at the 5% level (calculations done using the Statistica 7 package, Levenberg-Marquardt algorithm applied). The yearly average was 404.1 ppm, considerably higher than this asymptotic value.

The year 2006 Mauna Loa average was 381.7 ppm. If we assume a latitudinal gradient of 0.06 ppm/degree (as suggested by a prior unpublished study of one of the authors) this would correspond to 381.7 + 0.06*(50 -20) = 383.5 ppm for a sea-side station at the latitude of Diekirch. The NOAA CO_2 average for the whole globe is **382.5 ppm** for 2006.

It can be concluded that the "finger method" deviating by less than 7 ppm from the “official” global average gives an acceptable and very easy to implement validation tool.

Table 1 shows the 2006 results for all the above-mentioned stations, including Neuglodsow (D); all results are rounded to the nearest integer. Significant means statistically significant at the 5% level.

Table 1: Results of the wind-speed plot for selected stations

Station	Lat.	Environ-ment	Asymptotic CO_2 level(s)	Method	R	Signi-ficant?	2006 mean
Barrow	71	tundra/ ice	382	eq.1	0.14	yes	384
Pallas	68	forest	407 385	eq.1 eq.3	0.24 0.04	yes yes	385
Neu-glodsow	53	semi-rural	382 373	visual eq.1	 0.48	 yes	400
Diekirch	50	semi-rural	400 389	visual eq.1	 0.51	 yes	404
Schau-insland	48	rural	385 382	visual eq.1	 0.04	 yes	384
Mauna Loa	20	volcanic	382	eq.1	0.14	yes	382
South Pole	-90	ice	379	visual			379

We found on several occasions that a rational function like

$$CO_2 = a + \frac{b * windspeed}{c + windspeed} \quad \text{[eq. 3a]}$$

or

$$CO_2 = a + \frac{b + windspeed}{c + windspeed} \quad \text{[eq. 3b]}$$

can give a better fit (higher R); the asymptotic CO_2 levels are ***a+b*** (eq.3a) or ***a+1*** (eq.3b). One has to check the validity of the fitting equation from case to case.

Table 2 shows the differences between the asymptotic value given by the wind-speed model and the global background level for 7 locations (all results rounded to the nearest integer).

Table 2: Difference between asymptotic and global background

Station	Smallest difference to global background	Comment
Barrow	-1 ppm	eq. 1
Pallas	+8 ppm	avg. of eq.1 and eq.3 results

Neuglodsow	-1 ppm	visual inspection
Diekirch	+ 6 ppm	eq. 1
Schauinsland	-1 ppm	eq. 1
Mauna Loa	-1 ppm	eq. 1
South Pole	-4 ppm	visual inspection

The examples shown above represented the single year 2006 situation. It is quite interesting to note that applying the wind-speed method to multi-year data also can give a very close estimate of the mean global background CO_2 mixing ratio for this extended period. We will use the 17 year series from the Harvard Forest Station (Ameriflux project) to document this.

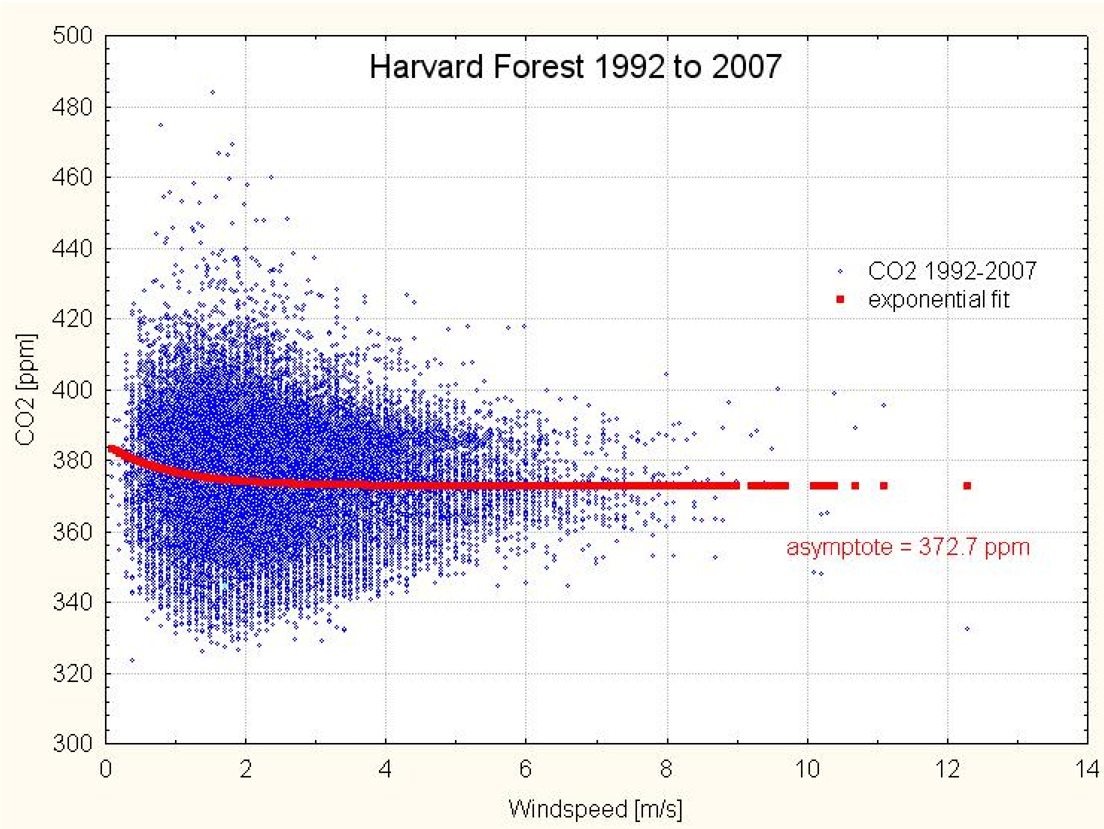


Fig.8 1992 - 2007 yearly averaged data from Harvard Forest, Ameriflux (data source: Bill Munger, Steven Wofsy): the asymptotic value of 372.7 ppm deduced by an exponential fit differs only by 1.2% from the mean global value at sea level (and only by 0.6% from the latitude adjusted mean Mauna Loa levels over the same 16 years period)

Let us make a first conclusion:

To validate CO_2 data the procedure to follow would be the following.

1. If the CO_2 versus wind-speed plot has visible unambiguous fingers, use these to obtain a first interval for the regional background level of the year. A single finger directly points to that level.

2. If the plot is boomerang shaped either detect the asymptotic level by simple inspection, or use one or two mathematical fits. Be sure that applying the fit gives a statistical significant result, with parameters having meaningful physical magnitudes and signs (for instance the parameter c in $e^{-c*windspeed}$ must be positive).

3. If there is neither a finger nor boomerang shape present, a mathematical fit by an exponential or rational function of CO_2 to wind-speed should be used with the usual caution.

Applying an average of visual inspection and/or mathematical fits should give a value that differs not more than about 10 ppm from the convential **global** background CO_2 level.

Validation of historical data

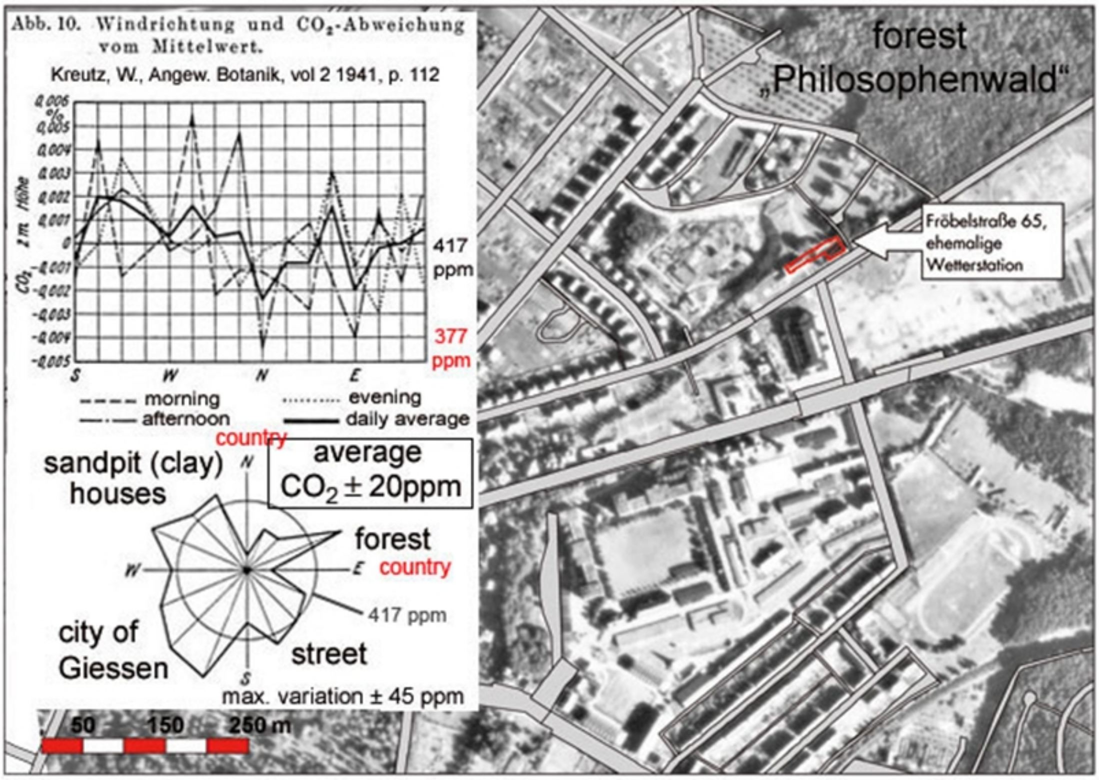
The accuracy of historic measurements is estimated at being least at 3% (Beck, 2007); this means that the insecurity interval of a result of for example 355 ppm is [344...366 ppm]. We will apply the preceding validation checks to 3 historical CO_2 measurement series made at Giessen (D), Liège (B) and Vienna (AU) during the 19th and 20th centuries.

The Giessen (Germany) measurements by W. Kreutz

CO_2 and weather data were measured by Wilhelm Kreutz in Giessen, Germany (latitude 50.5°) from the 31th August 1939 to the 31st May 1941 by a volumetric chemical method, a variant of the Pettenkofer method (Kreutz, 1941; Beck, 2007)**.** The instrument used was a commercially available Riedel RICO C gas analyzer with an accuracy of ~ 1.5 %.

Fig. 9 shows the analysis done by Kreutz in 1939 -1941 on the influence of wind-direction on CO_2 levels: the urban effect of the city of Giessen upwind in the SW direction from the measurement point is quite visible. North and East winds from the open rural regions correspond to the lowest afternoon CO_2 levels (~377 ppm).

Local influences Giessen weather station 1939-41



Source: City of Giessen, Agency for environment and nature, aereal view 1944, station adress: Fröbelstr. 65

Fig.9 Location of the Giessen weather station at the periphery of Giessen and the CO_2-wind analysis done by W. Kreutz. Data from Kreutz, 1941 cited in Beck, 2007. The legend “country” means “rural environment”.

The CO_2 versus wind-speed plot using data sampled at 2 m above ground until May 1940 has neither clear finger nor a boomerang shape, but the high wind speed data suggest a possible CO_2 range between 466 and 326 ppm, a range too large to be of much use. The mathematical fit by an exponential function (eq. 1) points to a regional background level of 393 ppm (R = 0.18, the asymptote and damping parameter being statistically significant). The IPCC (Intergovernmental Panel on Climate Change) consensus is that global CO_2 levels were about 310 ppm during that period. If we agree to the fact that the Giessen measurements were done with uttermost care and great precision, that higher wind speeds cause a more thorough mixing up and that as a consequence the asymptotic level detected will not be an artifact due to poor sampling time and sub-optimal siting, the 310 ppm global CO_2 level seems much lower than the regional background level at Giessen during 1939/1940.

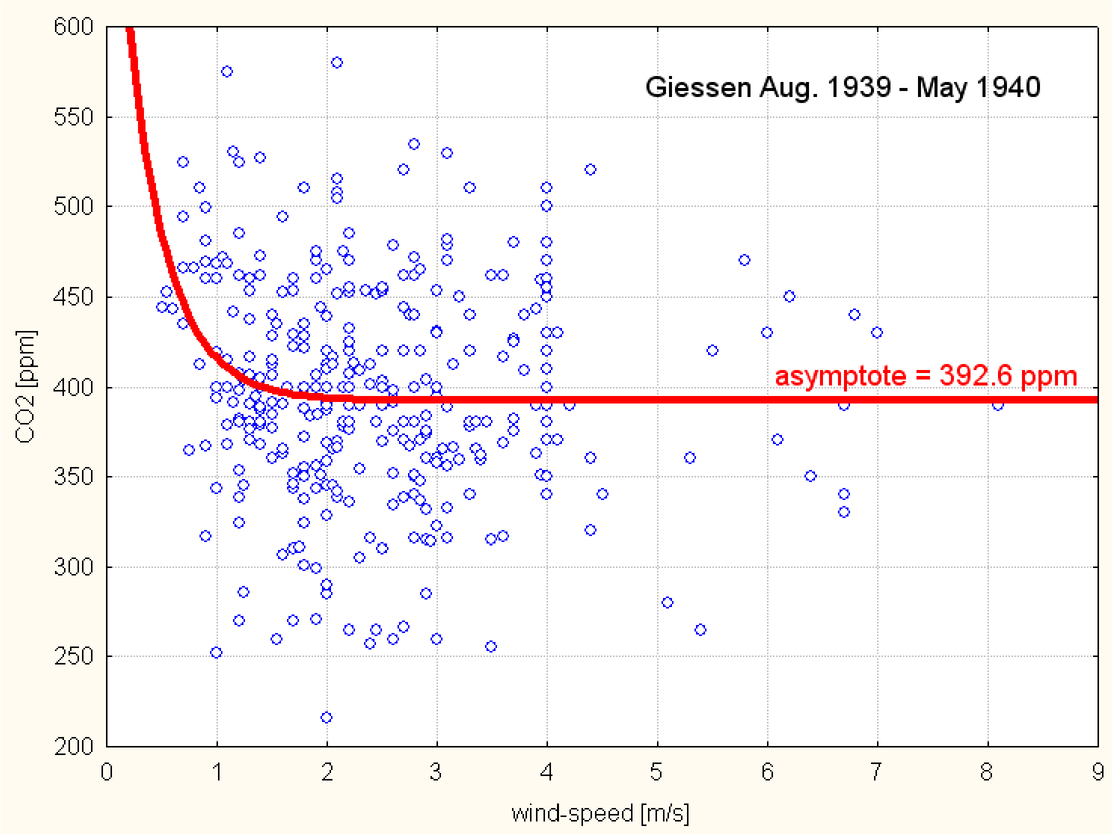


Fig.10 The CO_2 versus wind speed plot of the Giessen measurements by W. Kreutz (average = 398, stdev = 62)

The Liège (Belgium) measurements by W. Spring

Much older historical measurements by Spring and Roland were made during the 1883/84 period at Liège, Belgium (latitude 50.6°) (Spring, 1886). This series is characterized by a careful calibration of the Pettenkofer method and the used gas analyzer and by daily sampling conditions held constant. Sampling location was the laboratory of the chemical institute of the University of Liège with air sampled by a tube through the laboratory window at a height of 6 m. Despite the urban location the Spring measurements can be regarded as one of the most accurate 19th century measurement series of CO_2. Fig.11 shows the CO_2 versus wind-speed plot of these Spring data.

The asymptotic fit by an exponential function (eq. 1) has a poor goodness of fit (R=0.13), but the asymptote is still statistically significant. Similar to Giessen, the local background mixing ratio would be considerably higher than the global ice cores samples consensus value of about 280 ppm for the 1883/84 period.

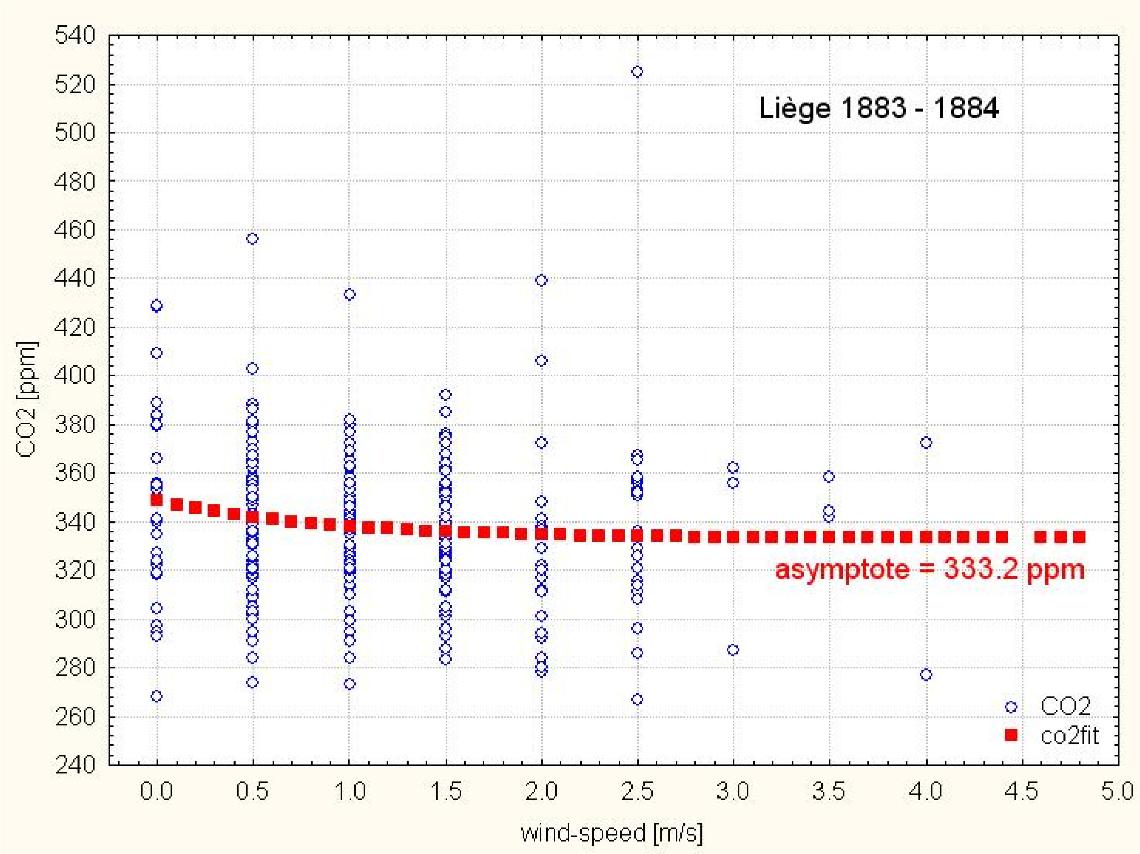


Fig.11 *The CO_2 versus wind-speed plot of the Liège measurements by W. Spring in 1883/84 (average = 338.9, stdev = 32.9)*

The Vienna (Austria) measurements by F. Steinhauser

There is no obvious pattern visible in this collection of the CO_2 measurements done by Ferdinand Steinhauser from May to August 1957 and from November 1957 to February 1958 at the Zentralanstalt für Meteorologie (located at a hill on the North/West boundary of Vienna, Austria, latitude 48.2° (Steinhauser, 1958). Sampling was once a day at a height of 25 m above ground. Usually the wind blew from a West/North direction, with the corresponding CO_2 levels lower than the average (as given by the WDCGG)**.** The absence of any finger or boomerang pattern leaves a mathematical fit as a last resort.

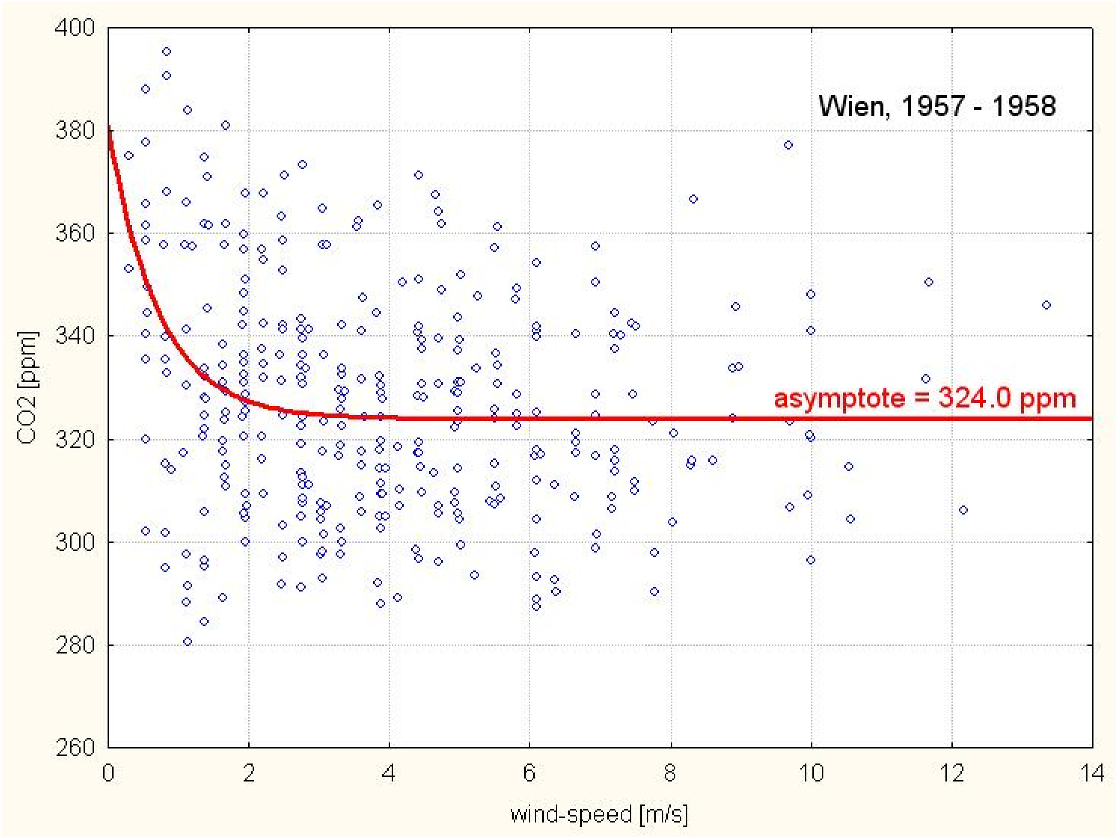


Fig.12 The CO_2 versus wind-speed plot of the measurements made by F. Steinhauser at Vienna in 1957/58 (average = 327.4, stdev = 22.7)

Here R = 0.29, the parameters of the exponential fit (eq.1) all are statistically significant and suggest a regional background level of 324 ppm, reasonably close to the extrapolated Mauna Loa level of 314 ppm for 1957; if we apply a latitudinal correction of 0.06*(50 - 20) = 2 the difference between the asymptotic Wien background and the latitude adjusted Mauna Loa levels is only 8 ppm**,** well below the 12-13 ppm criterion suggested in chapter 3. As a consequence the Steinhauser measurements should be considered as valid.

Conclusion

It has been shown that the CO_2 versus wind-speed plot can represent a valuable tool to estimate continental local background CO_2 levels despite of distorted mixing ratios or local influences. Applying the procedure to recent well known data gives results that are relatively close to the yearly average of the observational data at Mauna Loa and suggest a maximum difference of about 10 ppm with the global CO_2 background as given by NOAA (National Oceanic and Atmospheric Administration).

A validation check has been made for 3 historical CO_2 series. The overall impression is one of continental European historic regional CO_2 background levels significantly higher than the commonly assumed global ice-core proxy levels.

The CO_2 versus wind-speed plot seems to be a good first level validation tool for historical data. With the required caveats it could deliver a reasonable approximation of past regional and possibly past global CO_2 background levels.

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