

Climate variability as reflected in a regional atmospheric CO₂ record

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ABSTRACT

This paper analyses a 15-year long atmospheric CO₂ mixing ratio record measured at a mid-continental, low-elevation station (Hegyhátsál, Hungary) to reveal the effect of regional climate variability. While the long-term trend and the temporal fluctuation of the growth rate of CO₂ mixing ratio follow the global tendencies to a large extent, the shorter-term variations show special features. We present the distorted seasonal cycle caused by the seasonality in the atmospheric vertical mixing and the tendentious change in its shape, which can be attributed to the gradual warming and to the resulted prolongation of the growing season. The decreasing summer diurnal amplitude and the decreasing seasonal amplitude in the mixing ratio, furthermore the higher than average summer CO₂ mixing ratio growth rate in the first period of the measurements (1994–2003) with generally rising temperature and decreasing precipitation are explained as the consequence of the reduced activity of the biosphere in the influence area of the station and that of the reduced biomass under environmental conditions getting increasingly unfavourable. The explanation is supported by the co-located tall tower surface–atmosphere CO₂ exchange measurements and by the crop yield statistics of the dominantly agricultural region around the station.

1. Introduction

Terrestrial biosphere is an important actor of the global carbon budget. While it might be in quasi steady state in the past, the inverse models of the global carbon cycle indicate that in the past few decades it has been increasingly absorbing the extra carbon dioxide (CO₂) emitted by anthropogenic activity (IPCC, 2007, and references therein). CO₂ is the most important greenhouse gas in the atmosphere the quantity of which is modified directly by humankind. It may be the most influencing factor of the recent, human induced global climate change (IPCC, 2007). There is a strong feedback between the biosphere and the climate. Warming may increase the length of the growing season and so the amount of CO₂ absorbed by the vegetation (if other conditions are also provided) mitigating the anthropogenic climate forcing. However, warming also stimulates the respiration causing CO₂ release to the atmosphere and accelerating the climate change. Balance between these two major processes and its future change, may be an important issue in climate change mitigation (Friedlingstein et al., 2006; Cadule et al., 2009; Churkina et al., 2009; Oishi et al., 2009). In addition to temperature, we

must not forget about other climate factors like precipitation and soil moisture status, which also influence the activity of the biosphere.

Any change in the condition of the biosphere influences its CO₂ exchange, which is reflected in the atmospheric CO₂ concentration. Bacastow et al. (1985), Keeling et al. (1996) and Myneni et al. (1997) reported an increase in the annual amplitude of the atmospheric CO₂ mixing ratio in the 1980s and 1990s presumably caused by the prolonged growing season. In spite of the increasing growing season length proved by independent studies (see e.g. Linderholm, 2006, and references therein) Schmidt et al. (2003) and Lintner et al. (2006) did not detect increasing annual amplitude in their atmospheric CO₂ measurements. Higuchi et al. (2002) and Murayama et al. (2005, 2007) showed that interannual and quasi-decadal changes in the circulation pattern might also influence the regional CO₂ concentration. Response of an ecosystem to the environmental changes also depends on its age and type (Zimov et al., 1999).

Several climate, satellite and phenological studies prove the changes in the length and timing of the growing season (see e.g. Linderholm, 2006, and references therein), but these observations cannot predict the CO₂ budget of the biosphere because of the counteracting processes (enhanced photosynthesis/respiration) as discussed by Piao et al. (2008). To evaluate the behaviour of the biosphere relevant to the atmospheric carbon

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budget the CO₂ mixing ratio and its temporal variation should be monitored directly (see e.g. Miller, 2008).

In our phenomenological study one of the longest tall tower CO₂ data records is analysed. In addition to the evaluation of the seasonal cycle performed already at several sites in the past (see above), we also studied the changes in the diurnal cycle of the atmospheric CO₂ mixing ratio, which had been mostly missed before. Although, we could not separate objectively the contribution of the different factors to the observed changes, the data presented may be used in future, more extended studies. The data analysis can reveal regional climate features reflected in the CO₂ record, like the behaviour of the nighttime boundary layer, which should be handled in the fine resolution 3-D carbon budget models to avoid distortion.

In addition to the analysis of a CO₂ data series, we demonstrate the usefulness of the combination of tall tower CO₂ mixing ratio and CO₂ surface–atmosphere exchange measurements (Haszpra et al., 2001) initiated on European scale by the CHIOTTO project (2002–2006, <http://www.chiotto.org>, Vermeulen, 2007).

2. Monitoring site

The monitoring station from where data are used in this study is a tall tower site located in a fairly flat region, in rural environment (Hegyhátsál, western Hungary, 46°57'N, 16°39'E, 248 m asl), which provides high spatial representativeness to the measurements. The terrain does not modify the large-scale atmospheric conditions, thus no special microclimate can form around the station. Here CO₂ mixing ratio has been continuously monitored at four elevations (10 m, 48 m, 82 m and 115 m above the ground) since September 1994, using a non-dispersive infrared gas analyser (1994–2007: Li-Cor Model LI-6251, from 2007: Li-Cor Model LI-7000; Haszpra et al., 2001). Quality of the measurements is assured by the use of NOAA (National Oceanic and Atmospheric Administration, USA) certified standards and by the comparison with co-located NOAA flask air sampling (NOAA co-operative air sampling network code: HUN—<http://www.esrl.noaa.gov/gmd/ccgg/flask.html>).

Since 1997 direct surface–atmosphere CO₂ exchange measurements using eddy covariance (EC) technique have also been available at 82 m above the ground (Haszpra et al., 2005). The EC system consists of a Li-Cor Model LI-6262 fast response NDIR CO₂/H₂O analyser and a GILL R3–50 ultrasonic anemometer. The footprint of this high-elevation EC measurement extends to a few kilometers (Barcza et al., 2009), while the much larger influence area of the mixing ratio measurements can be estimated using for example the method of Gloor et al. (2001).

The monitoring site is surrounded by agricultural fields (mostly crops and fodder of annually changing types), pastures and forest patches. The distribution of vegetation types (53% agricultural region, 35% forest, 6% pastures, 6% other [transitional woodland-scrublands, settlements, etc.]) within 10 km of the tower is not much different from the average for the

surrounding Western Hungarian Landscape Unit (7300 km²) or the whole country (93 030 km²) (Barcza et al., 2009). The soil type in the region of the tower is 'Lessivated brown forest soil' (Alfisol, according to the USDA system). Human habitations within 10 km of the tower are only small villages (100–400 inhabitants). The nearest village is Hegyhátsál (170 inhabitants) about 1 km to the northwest. There is no notable industrial activity in this dominantly agricultural region. Local roads have mostly low levels of traffic. The site can be considered as rural in the highly industrialized, densely populated Central Europe, as it was shown by SF₆ measurements (Haszpra et al., 2008). A detailed description of the site and instrumentation can be found in Haszpra et al. (2001, 2005) or at the website of the station (<http://nimbus.elte.hu/hhs/>).

The climate of the region is temperate continental. The long-term (1961–1990) mean annual temperature is 8.9°C and the mean annual precipitation amount is 759 mm.

In this study, primarily CO₂ mixing ratio data from 10 m elevation above the ground are used. This level is always inside the planetary boundary layer (PBL) where the biosphere/atmosphere CO₂ exchange is going on. These CO₂ mixing ratio data are publicly available at the World Meteorological Organization World Data Centre for Greenhouse Gases (<http://gaw.kishou.go.jp/wdcgg/>), while the biosphere/atmosphere CO₂ exchange data can be obtained from the CarboEurope database (<http://www.carboeurope.org/>) or from the authors.

3. Changes in the diurnal variation

Hegyhátsál is a mid-continental, low elevation site in the temperate zone surrounded by vegetation. Photosynthesis/respiration generates a seasonally changing diurnal cycle and a seasonal cycle in the atmospheric CO₂ mixing ratio. The average diurnal cycle (1994–2008) is presented in Fig. 1 for the different seasons. As the concentration field is fairly isotropic around the monitoring site and the characteristic wind speed is rather low due to the geographical conditions (Haszpra, 1999) no data selection other than removing the technically false data was applied in the calculations. The maximum daily amplitude (defined as the difference between the maximum and the minimum in the average diurnal cycle) can be observed in August (56 μmol mol⁻¹ on the average), while the minimum forms in December–January (7 μmol mol⁻¹ on the average). The diurnal variation is dominated by both the photosynthesis/respiration cycle and the diurnal cycle in the intensity of the atmospheric vertical mixing (assuming that anthropogenic emission does not modulate the daily variation substantially). Therefore, the daily maximum can be observed shortly after sunrise, before the vegetation-soil system becomes a net CO₂ sink and the quickening vertical mixing starts to dilute the CO₂ enriched, shallow nighttime boundary layer (Denning et al., 1996; Larson and Volkmer, 2008).

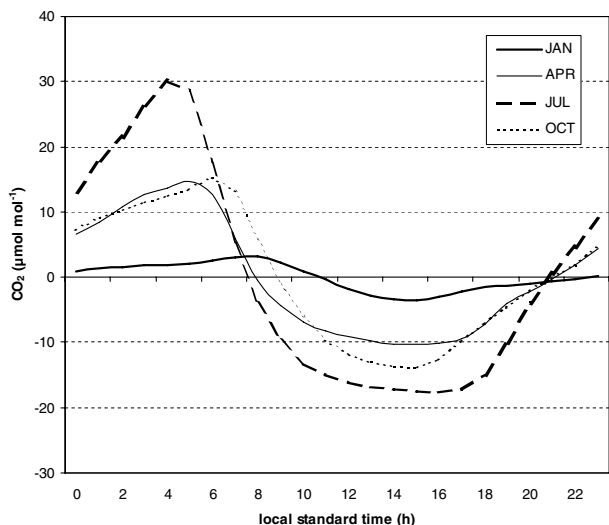


Fig. 1. Average (1994–2008) diurnal variation of carbon dioxide mixing ratio relative to the daily mean at Hegyhátsál, at 10 m above the ground, in different seasons.

Figure 2 shows the temporal variation in the monthly mean daily amplitude where the daily amplitudes are calculated as the difference of the daily maximum and minimum hourly CO₂ mixing ratio. While the wintertime amplitude hardly changes, the summer mean daily amplitudes vary from year to year. There was an almost decade-long period from the beginning of the measurements to the early 2000s when the summer mean daily amplitudes tended to decrease statistically significantly at a confidence level >95% (1995–2003: $2.3 \mu\text{mol mol}^{-1} \text{yr}^{-1}$). Then, from 2003 onward, it returned to the original level in two years.

The diurnal amplitude may be determined by the temporally changing anthropogenic emission, the natural surface–atmosphere exchange, as well as the horizontal and vertical mixing of the atmosphere. After the dramatic decrease in

anthropogenic CO₂ emission in Eastern Central Europe in the early 1990s (a consequence of the collapse and restructuring of the economy) no further significant change in the fossil fuel emission happened in the influence area of the monitoring station (see EDGAR (EC-JRC/PBL, 2009) for high-resolution emission data and UNFCCC (<http://unfccc.int/>) for the total emissions of Hungary and the neighbouring countries).

During summer days the convective boundary layer may grow above 2000 m in this geographical region. Any realistic change in the surface–atmosphere CO₂ exchange or in the vertical mixing can cause only small concentration change in this big air volume. The daily amplitude is then essentially governed by the nighttime conditions when relatively small absolute changes in the emission or in the mixing height may result in significant change in the CO₂ mixing ratio of the shallow boundary layer.

We used modelled boundary layer height data that are available from the MARS archive of the European Centre for Medium-Range Weather Forecasts (ECMWF; Beljaars et al., 2001). For this study PBL height data were retrieved on the reduced Gaussian grid of the ECMWF operative deterministic model and the data from the nearest grid point was used. The nearest grid point was 8–13 km away from the monitoring site depending on the year as a consequence of the development at ECMWF. We have checked the spatial homogeneity of the PBL height around the station and found no difference from the neighbouring four grid points (average deviation is $0.15 \pm 15 \text{ m}$, $r = 0.997$). Simulated PBL height data are only available in 3-h time steps from the short-range forecasts started at 00 UTC and 12 UTC. Both our unpublished study and Ramonet et al. (2010) concluded that in the region of the monitoring site there was no significant change in the height of the summer nighttime boundary layer during the period studied.

Vertical mixing of trace constituents emitted at the surface is rather limited during summer nights characterized by strong

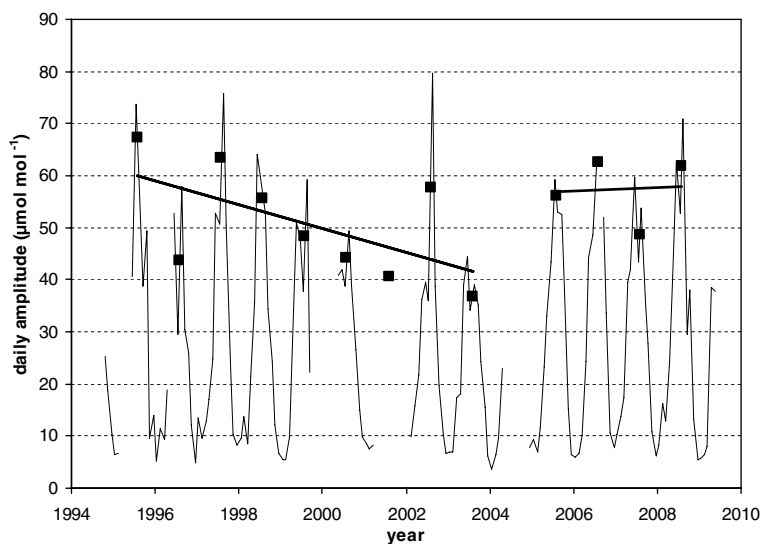


Fig. 2. Temporal variation in the monthly mean daily mixing ratio amplitude observed at 10 m above the ground at Hegyhátsál. Straight lines indicate the characteristic tendencies in the July–August mean daily mixing ratio amplitudes (plotted as black squares).

stable stratification, thus they dominantly accumulate in the lower few 10 m. The vertical mixing ratio gradient close to the ground hardly depends on the PBL height if it is higher than 100–120 m. While the average mixing ratio difference between the highest and the lowest monitoring levels is about $20 \mu\text{mol mol}^{-1}$ when the PBL height is 120 m, it is still about $10 \mu\text{mol mol}^{-1}$ if the PBL is as deep as 600 m. The nighttime boundary layer is hardly homogeneous unlike the daytime convective boundary layer. Decoupling of its upper part from the lower part is rather typical (Banta et al., 2007; Xia et al., 2010). In such a case, the surface processes can influence only the lower part of the nighttime PBL and any change in the height of the PBL does not modify much the accumulation of trace constituents emitted from the surface as long as the decoupling persists. This phenomenon explains why any reasonable change in the boundary layer height cannot be the primary cause of the observed variation in the daily amplitude. The relative independency of the CO_2 mixing ratio measured at 10 m above the ground during the nights from the height of the PBL is also indicated by the low correlation coefficient (-0.07) between them (July–August, 4 h UTC).

For the characterization of the CO_2 release at the surface we used our own net ecosystem exchange (NEE) measurements carried out at 82 m height above the ground on the tower at Hegyhátsál (Haszpra et al., 2005). Unlike the traditional, short EC towers monitoring only a specific ecosystem in their small footprint area (e.g. FLUXNET network—Baldocchi et al., 2001) the few tall tower EC systems can provide integrated signals from a much larger area covered by different ecological systems. The NEE data may be considered valid on an even larger area provided that the region has the same climate, soil condition and vegetation cover as the direct footprint of the measurements. Thus the results of the tall tower EC system are comparable with the mixing ratio measurements even if the footprint difference is large.

Figure 3 shows the relation between the mean nighttime (0–4 h local standard time [LST]) ecosystem CO_2 release and the mean daily amplitude for July–August. The correlation coefficient of 0.67 (statistically significant at $p < 0.05$) between the two variables indicates a relatively strong relation though the influence area of the mixing ratio measurements is larger than that of the NEE measurements (Gloor et al., 2001; Barcza et al., 2009). Importance of the soil respiration in the formation of the nighttime ground level CO_2 mixing ratio was also indicated by Murayama et al. (2005).

The period from the mid-1990s to the extremely hot and dry 2003 was getting gradually warmer accompanied with severe drought in the early 2000s (for July–August data used in this study see Fig. 4; for annual and growing season data see Haszpra et al., 2005). For a given ecosystem in a given status, nighttime temperature correlates with the ecosystem respiration (Raich and Schlesinger, 1992; Reichstein and Beer, 2008), although this relationship is modulated by other environmental

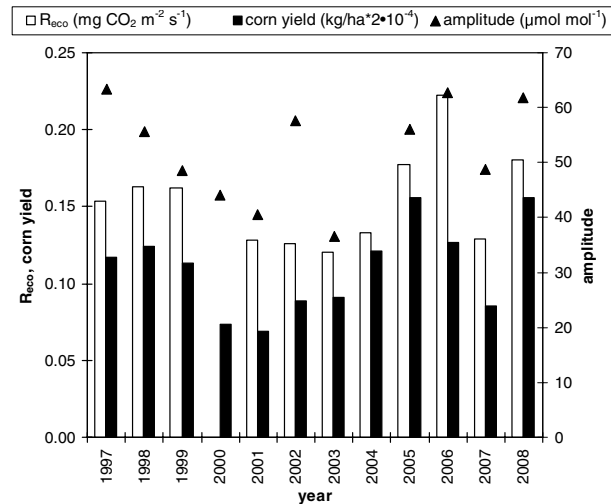


Fig. 3. Co-varying behavior of mean nighttime (0–4 h LST) ecosystem respiration (R_{eco}) and the mean daily amplitude of CO_2 mixing ratio in July–August, as well as the corn yield in the region of Hegyhátsál (Vas County). Corn yield data are rescaled to be comparable with R_{eco} . X-axis starts at 1997 because no R_{eco} data are available for the previous years. No R_{eco} measurements are available from 2000.

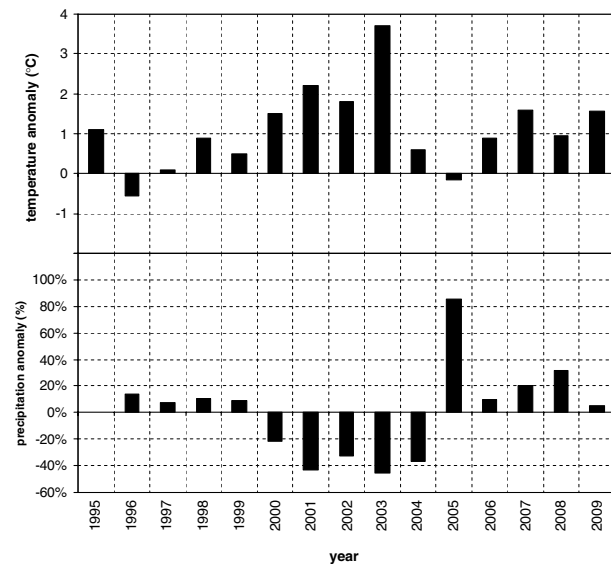


Fig. 4. July–August anomalies of air temperature and precipitation amount, relative to the 1961–1990 average, from a nearby meteorological observatory (Farkasfa, $46^{\circ}55' \text{N}$, $16^{\circ}19' \text{E}$, 312 m asl). (Precipitation anomaly in 1995 is 0.3%).

variables like soil water content, microbial activity and leaf area index (LAI). LAI is a proxy of the standing biomass and it may characterize the maintenance respiration. The unfavourable environmental conditions reduced the biomass in the region, which triggered a decrease in the total ecosystem respiration in spite of the temperature increase as it was also found by Ciais et al. (2005) and Reichstein et al. (2007) on European scale. The

assumed biomass reduction is supported by the yield data of summer crops as proxies for biomass and net primary production (<http://statinfo.ksh.hu/Statinfo/themeSelector.jsp?&lang=en>; Fig. 3). The correlation between the crop yield and the nighttime respiration is 0.72 in our case, which is statistically significant at $p < 0.01$.

4. Changes in the seasonal cycle

Life cycle of vegetation in the temperate and boreal zones generates an annual cycle in the atmospheric CO₂ mixing ratio. During the winter period NEE is positive, as ecosystems release more CO₂ than they absorb by photosynthesis. Atmospheric mixing ratio is expected to decrease when NEE becomes negative, typically in March–April, or even later at high latitudes (see e.g. <http://www.esrl.noaa.gov/gmd/ccgg/iadv/>). However, at Hegyhátsál the CO₂ mixing ratio reaches its annual maximum in December–January (Fig. 5), well before the vegetation becomes a net CO₂ sink [The seasonal cycle is calculated as the mean monthly averages of the detrended early afternoon (12–16 h LST) mixing ratio values]. A shorter phase-shift could be explained by long-range horizontal transport carrying CO₂-depleted air masses from lower latitudes where growing season starts earlier. However, the seasonal cycle in atmospheric CO₂ mixing ratio leads that of the regional NEE by approximately 12 weeks, which seems to be too long time to refer to any advection effect. The unusual seasonal cycle observed at Hegyhátsál can be explained by the regional feature of the vertical mixing of the atmosphere. From January, following the slowly increasing insolation after the winter solstice, the vertical mixing is quickly getting more vigorous (see Fig. 6) mixing more and more relatively clean free tropospheric air into the CO₂-enriched boundary layer. This process overcompensates the contribution of the sur-

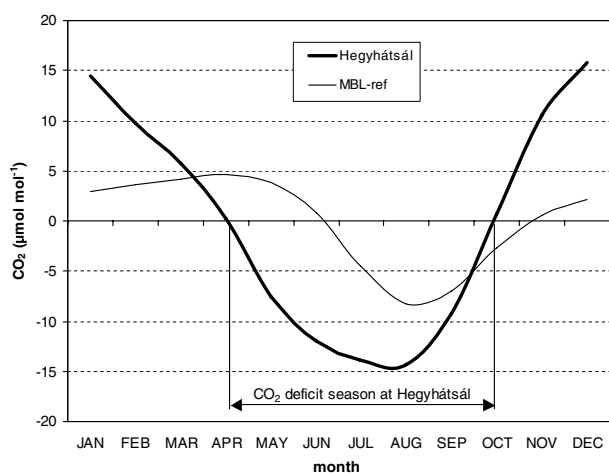


Fig. 5. Mean seasonal cycle of CO₂ mixing ratio at Hegyhátsál (10 m) and in the modelled marine boundary layer (GLOBALVIEW-CO₂, 2009) corresponding to the geographical latitude of Hegyhátsál.

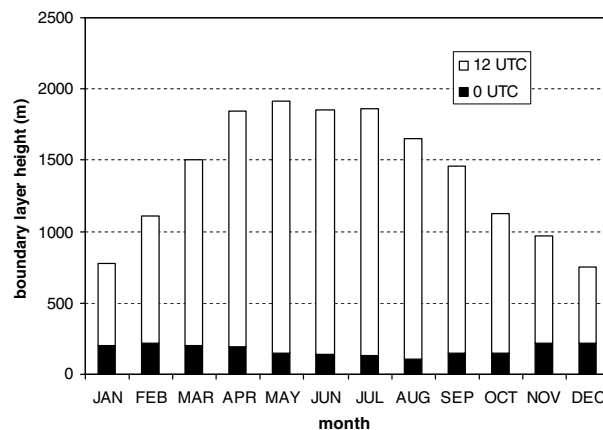


Fig. 6. Seasonal variation of the average daytime (13 h LST = 12 UTC) and nighttime (1 h LST = 0 UTC) heights of the planetary boundary layer at Hegyhátsál (1994–2008, data source ECMWF MARS database).

face that is still a net CO₂ source in that time of the year. A similar phase lag was observed by Davis et al. (2003) at the WLEF tall tower site in the continental U.S.A. (Wisconsin) but in that study it could not be determined whether the horizontal advection or the vertical mixing is the main contributing factor.

The effect of the changing vertical mixing on the CO₂ mixing ratio in the boundary layer sampled by the monitoring station can also be demonstrated by means of a very simple box model. This model, developed exclusively for this demonstration, is a box model with height following the height of the PBL. When it increases, air not influenced directly by the local surface processes (residual layer air or free tropospheric air—Stull, 1988) is incorporated into the box. This model is not intended to simulate the atmospheric processes entirely; it neglects important processes like advection and synoptic scale variations. Its only purpose is to give an impression to the reader why the seasonal cycle of CO₂ mixing ratio here deviates from the usually expected one.

To demonstrate the overwhelming effect of the vertical mixing on the CO₂ mixing ratio in the PBL only the period of November–February is simulated. Being in the dormant season of the vegetation, photosynthesis can be neglected and a constant 3.7 g CO₂ m⁻² day⁻¹ ecosystem respiration is supposed based on our multiyear measurements (Haszpra et al., 2005). Anthropogenic emission is set to 0.41–0.57 g CO₂ m⁻² day⁻¹ depending on the year (EC-JRC/PBL, 2009). To simulate the contribution of the residual layer of the atmosphere and that of the exchange between the PBL and the free troposphere a 40% : 60% mixture of boundary layer air and free tropospheric air is mixed into the box if its height is increasing. This ratio is adjusted to get the smallest offset from the real atmospheric mixing ratio. Its value systematically influences the bias between the simulated and the observed mixing ratio but does not modify the average

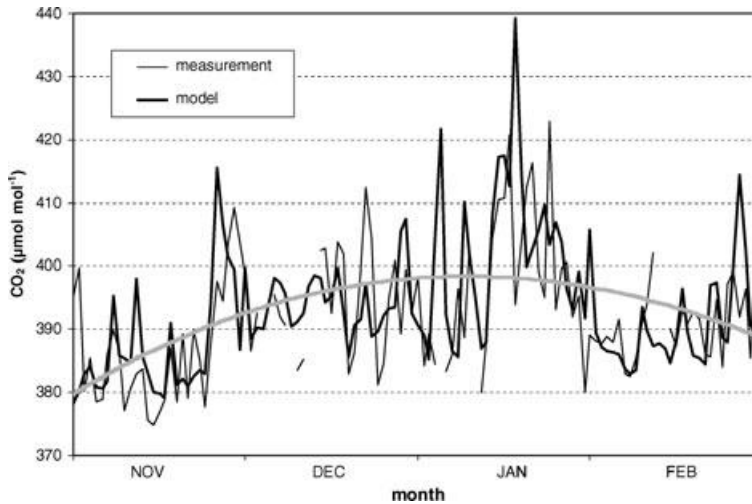


Fig. 7. Measured and simulated CO₂ mixing ratios for the period of November 2002–February 2003. The line fitted to the simulated values is a 3rd order polynomial.

temporal course of the mixing ratio. CO₂ mixing ratio in the free troposphere is considered identical with that in the marine boundary layer (GLOBALVIEW-CO₂, 2009) corresponding to the geographical position of the station. In Fig. 7 the resulting temporal variation of CO₂ mixing ratio is presented along with the measured values for 2002–2003. The average deviation of the measured values from the simulated ones is $-1.26 \pm 9.55 \mu\text{mol mol}^{-1}$ with a correlation coefficient of 0.56. In other simulation years (1997–2004) the correlation coefficients range 0.38–0.63 (statistically significant at $p < 0.01$). The relatively wide scatter of simulated values around the measured ones is certainly the consequence of the neglected advection and other important processes.

The seasonal cycle is not only unusual, but it also changes shape in time. The length of the CO₂ deficit season, when the mixing ratio is lower than the annual average (see Fig. 5), is increasing slowly. The beginning of the period is moving to earlier in the year, while its end hardly changes (Fig. 8). Assuming a linear trend, the beginning of the CO₂ deficit season has shifted almost 9 days earlier between 1995 and 2009. As the seasonal cycle is strongly influenced by that of the vertical mixing at Hegyhásál, the first idea might be to check this factor. However, based on the ECMWF PBL data, there is no tendency in the vertical mixing in spring. The earlier start of the CO₂ deficit season can be caused by the generally warming climate, by the earlier start of the growing season, as it has already been indicated by several international (e.g. Menzel and Fabian, 1999; Tucker et al., 2001; Linderholm, 2006; Piao et al., 2007; Thum et al., 2009) and Hungarian (e.g. Varga-Haszonits, 2004) research.

The primary environmental factor determining the start of the growing season at our geographical latitude is the temperature. The middle panel of Fig. 8 presents the temporal variation of the monthly mean temperature for the month of the beginning of the CO₂ deficit season (April). Temperature shows a statisti-

cally significant upward trend (level of confidence >95%) and the correlation between the timing of the beginning of the CO₂ deficit season and the monthly mean temperature is -0.85 (significant at $p < 0.01$). The level of confidence (93%) of the trend in the beginning of CO₂ deficit season based on the relatively short time series is a bit lower than that usually applied in the analyses of time series (95%). However, the parallel changes in the primary influencing factor (i.e. temperature) and its high correlation with the timing of the beginning of the CO₂ deficit season make highly probable that the trend revealed in the start of the CO₂ deficit season indicates a real tendency.

In principle, warming could also prolong the growing season and move the autumn zero-crossing (the time when CO₂-deficit season turns into CO₂-sufficient season) towards the end of the year. Both international (Linderholm, 2006; Linderholm et al., 2008) and Hungarian (e.g. Varga-Haszonits, 2004) studies showed that warming does not extend the growing season equally towards spring and autumn. The prolongation towards the end of the year is shorter. The bottom panel of Fig. 8 shows the tendency in the monthly mean temperature in the critical month of the year, that is, in October. Some warming might be seen in the series but its confidence level is only 65%. CO₂ exchange between the biosphere and the atmosphere in autumn is influenced by several factors including natural and anthropogenic ones. Temperature alone drives two counteracting processes, that is, the prolongation of the growing season, which may increase the CO₂ uptake from the atmosphere by the vegetation and the enhancement of respiration, which increases the CO₂ release from the biosphere to the atmosphere (Piao et al., 2008). Another contributing factor in this predominantly agricultural region may be the earlier harvest of summer crops, which prevents the biosphere to profit from the prolonged growing season.

In principle, warming may also increase the amplitude of the seasonal cycle as it was discussed by Keeling et al. (1996) and Zimov et al. (1999). The warmer winter temperature may in-

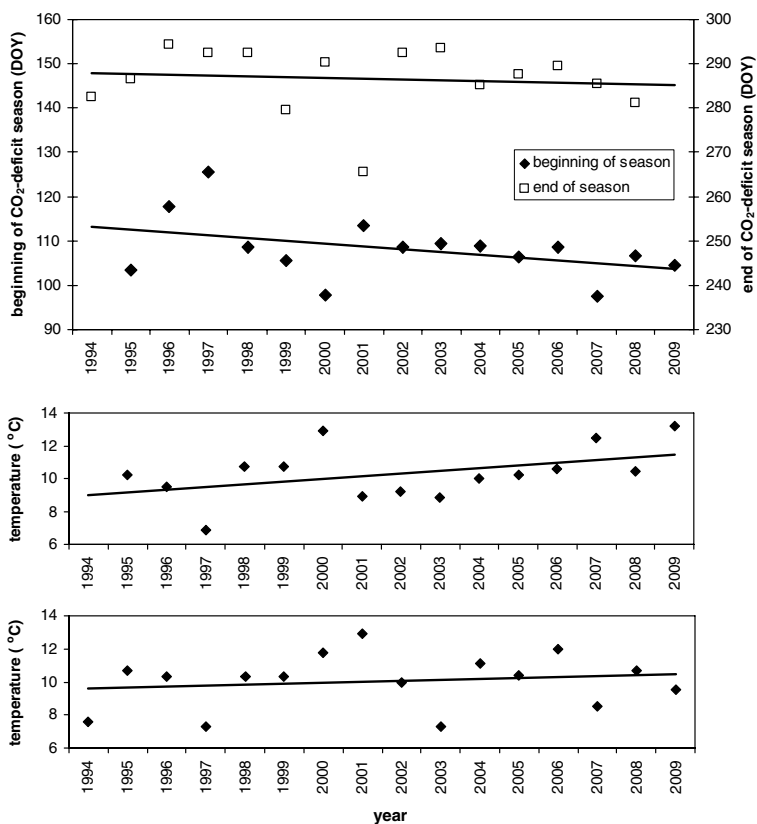


Fig. 8. Tendencies of the beginning and end of the CO₂ deficit season (upper panel) and that of the monthly mean temperatures in the relevant months (April – middle panel; October – bottom panel).

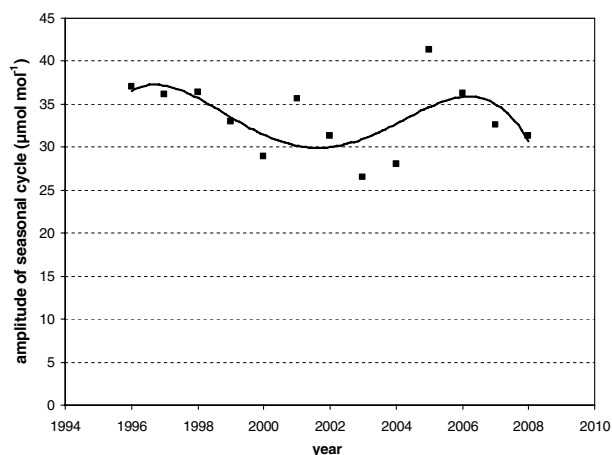


Fig. 9. Temporal variation in the amplitude of the seasonal cycle of CO₂ mixing ratio. The fitted line is a 4th order polynomial.

tensify respiration, while the prolonged growing season may increase carbon uptake. In the Hegyhátsál CO₂ record no obvious trend can be observed in the amplitude of the seasonal cycle. From the beginning of the measurements until 2003 the amplitude of the seasonal cycle decreased by about 20%, as estimated from the smoothed time series presented in Fig. 9, then it increased again. The most plausible reason might be the same

as in the case of the reduced diurnal amplitude: the increasingly unfavourable environmental conditions reduced the standing biomass and it reduced the CO₂ uptake capacity of the biosphere in the influence area of the station. The less intensive CO₂ uptake in the summer season decreased the annual amplitude of the atmospheric CO₂ mixing ratio. It is in accordance with the higher than average summer growth rate in the mixing ratio discussed in the next chapter.

5. Temporal variations in the long-term trend

As an earlier study (Haszpra et al., 2008) has already presented, the long-term trend and its fluctuation follow the global tendencies to a large extent despite of the unfavourable location of the station (middle of a highly populated, industrialized continent, surrounding active vegetation). However, if the long-term trend is decomposed by seasons, interesting tendencies become visible. During the period between the beginning of the measurements at Hegyhátsál (1994) and 2003, the summer growth rate of the CO₂ mixing ratio significantly exceeded that in the other seasons (Fig. 10, Table 1). While the mixing ratio grew by 2.66 $\mu\text{mol mol}^{-1} \text{yr}^{-1}$ in summer during this period the overall growth rate was only 2.08 $\mu\text{mol mol}^{-1} \text{yr}^{-1}$. As it was mentioned before, these years were increasingly warm and dry, although the interannual variation was high. The high temperature

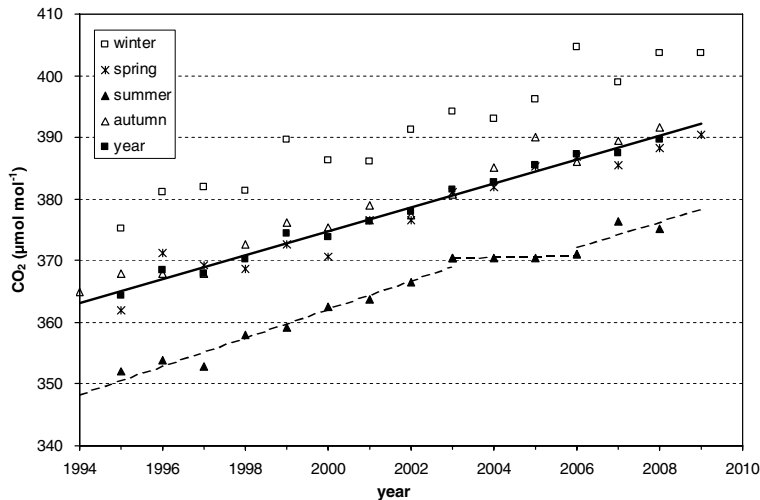


Fig. 10. Seasonal trends in the early afternoon (12–16 h LST) atmospheric CO₂ mixing ratio at 10 m elevation above the ground at Hegyhátsál. The lines are indicating linear trends (dashed line – summer [three separated periods], thick line – whole year).

Table 1. Seasonal growth rates ($\mu\text{mol mol}^{-1} \text{yr}^{-1} \pm$ standard error) of early afternoon (12–16 h LST) atmospheric CO₂ mixing ratio at 10 m above the ground at Hegyhátsál for the periods of 1994–2003 and 1994–2009.

	1994–2003	1994–2009
Spring	1.96 ± 0.35	1.86 ± 0.13
Summer	2.66 ± 0.19	1.94 ± 0.11
Autumn	1.81 ± 0.35	1.96 ± 0.13
Winter	1.89 ± 0.49	1.98 ± 0.15
Year	2.08 ± 0.20	1.95 ± 0.07

Note: Bold number emphasizes the extreme growth rate in summer between 1994 and 2003 discussed in the text.

and the lack of water could significantly reduce the development of biomass (as it was also referred in Chapter 3 and 4), which resulted in decreased net CO₂ uptake of the biosphere (Haszpra et al., 2005). From 2004 the climate has returned to normal, it has become relatively cooler and wetter in Eastern Central Europe. This has balanced the seasonal differences on the 15-year time scale (Table 1). It can be seen in Fig. 10 that the summer mixing ratios have hardly increased for 4 years after 2003.

The effect of the climate anomaly that lasted until 2003 is well presented by the biosphere-atmosphere CO₂ exchange measurements. We can see remarkably decreased net uptake in summer, especially in July and August (Fig. 11). From 2004 onward the situation has changed drastically, parallel with the changing regional weather pattern.

6. Summary

In this study, we looked at several characteristics of the shorter-term variations in the atmospheric CO₂ mixing ratio record measured at a mid-continent, low-elevation, tall tower site lo-

cated in rural environment. We could reveal special features like enhanced diurnal variation, strongly limited nighttime vertical mixing and the non-trivial shape of the seasonal cycle. These features may be characteristic only for certain stations and they should be taken into account in atmospheric modelling. The reduced diurnal and seasonal amplitudes and the seasonal differences in the longer-term trend equally show the joint effect of the warming climate and the developing drought in the first half of the measurements. While the long-term trend in the atmospheric CO₂ mixing ratio and its fluctuation measured locally follow the global tendencies to a large extent, the shorter-term variations reflect the regional climate fluctuations. In a more general approach, due to the complex interactions between the surface/biosphere and the atmosphere, watching the short-term variations in the atmospheric CO₂ mixing ratio records might call the attention to atmospheric/climatic changes in progress.

This study demonstrates the importance and usefulness of co-located, tall tower based CO₂ mixing ratio and NEE measurements as it was initiated by the CHIOTTO project (<http://www.chiotto.org/>; Vermeulen, 2007) and accepted by ICOS, the new pan-European integrated greenhouse gas observation network in preparation (<http://www.icos-infrastructure.eu/>). The joint use of measurements can highlight important physical processes helping us to better understand the synoptic variability of atmospheric CO₂ and can provide modellers with important information on the underlying mechanisms.

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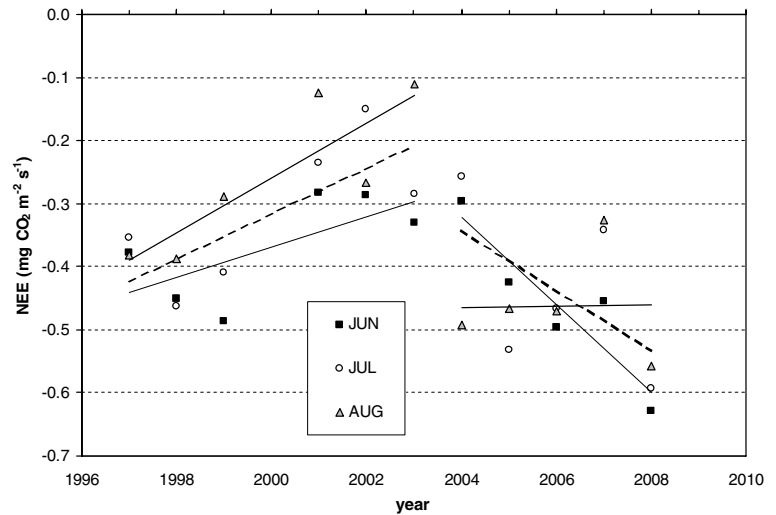


Fig. 11. Tendencies in the monthly mean NEE in summer at Hegyhásfal. The lines are only graphical representations of the tendencies (thin dashed line – June, thick dashed line – July, solid line – August).

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