Tellus
SERIES B CHEMICAL AND PHYSICAL METEOROLOGY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2010), 62B, 417–426

TELLUS

Climate variability as reflected in a regional atmospheric CO_2 record

By L. HASZPRA[1]* and Z. BARCZA[2], [1]*Hungarian Meteorological Service, H-1675 Budapest, P.O. Box 39, Hungary*; [2]*Department of Meteorology, Eötvös Loránd University, H-1117 Budapest, Pázmány Péter sétány 1/A, Hungary*

(Manuscript received 20 November 2009; in final form 26 August 2010)

ABSTRACT

This paper analyses a 15-year long atmospheric CO_2 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 CO_2 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 CO_2 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 CO_2 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 (CO_2) emitted by anthropogenic activity (IPCC, 2007, and references therein). CO_2 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 CO_2 absorbed by the vegetation (if other conditions are also provided) mitigating the anthropogenic climate forcing. However, warming also stimulates the respiration causing CO_2 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 CO_2 exchange, which is reflected in the atmospheric CO_2 concentration. Bacastow et al. (1985), Keeling et al. (1996) and Myneni et al. (1997) reported an increase in the annual amplitude of the atmospheric CO_2 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 CO_2 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 CO_2 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 CO_2 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

*Corresponding author.
e-mail: haszpra.l@met.hu
DOI: 10.1111/j.1600-0889.2010.00505.x

budget the CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 data series, we demonstrate the usefulness of the combination of tall tower CO_2 mixing ratio and CO_2 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 CO_2 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 CO_2 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 CO_2/H_2O 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 km^2) or the whole country (93 030 km^2) (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 SF_6 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 CO_2 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 CO_2 exchange is going on. These CO_2 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 CO_2 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 CO_2 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 CO_2 sink and the quickening vertical mixing starts to dilute the CO_2 enriched, shallow nighttime boundary layer (Denning et al., 1996; Larson and Volkmer, 2008).

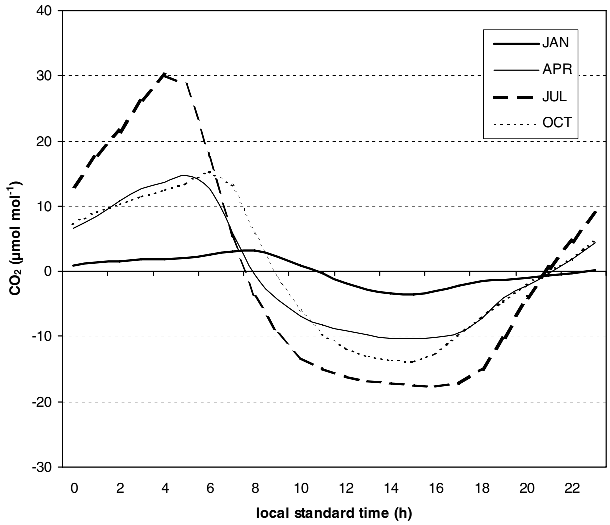

Fig. 1. Average (1994–2008) diurnal variation of carbon dioxide mixing ratio relative to the daily mean at Hegyhátsál, at 10 m above the ground, in different seasons.

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 CO_2 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 μmol mol^{-1} 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 CO_2 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 CO_2 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 CO_2 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 ± 15 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

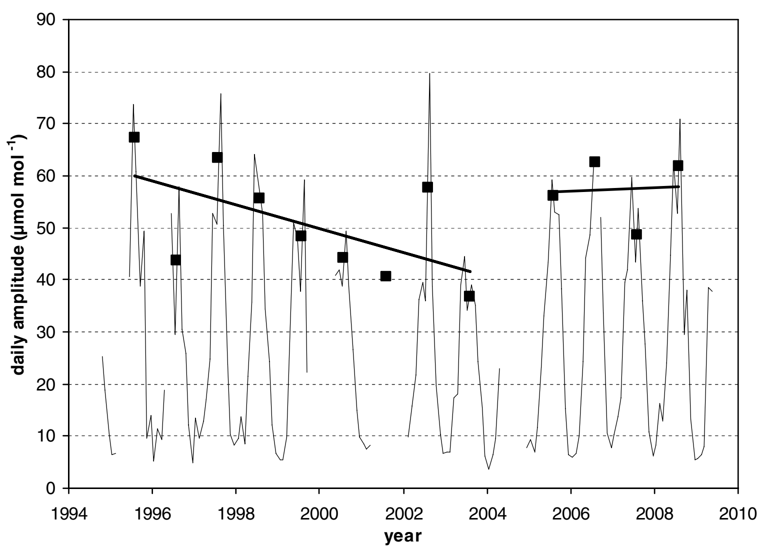

Fig. 2. Temporal variation in the monthly mean daily mixing ratio amplitude observed at 10 m above the ground at Hegyhátsál. Straight lines indicate the characteristic tendencies in the July–August mean daily mixing ratio amplitudes (plotted as black squares).

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 μmol mol^{-1} when the PBL height is 120 m, it is still about 10 μmol 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

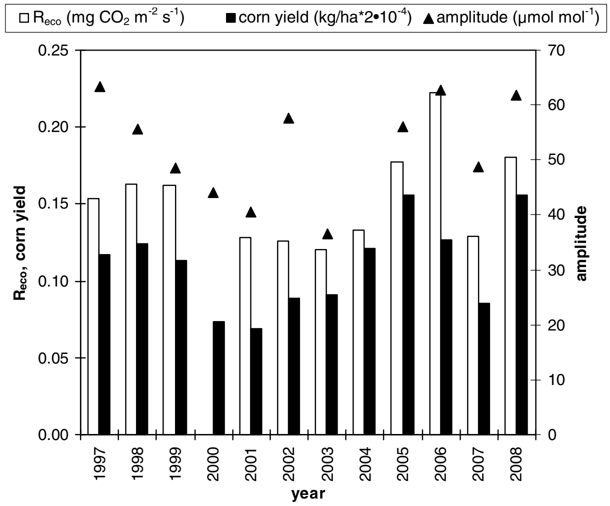

Fig. 3. Co-varying behavior of mean nighttime (0–4 h LST) ecosystem respiration (R_{eco}) and the mean daily amplitude of CO_2 mixing ratio in July–August, as well as the corn yield in the region of Hegyhátsál (Vas County). Corn yield data are rescaled to be comparable with R_{eco}. X-axis starts at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

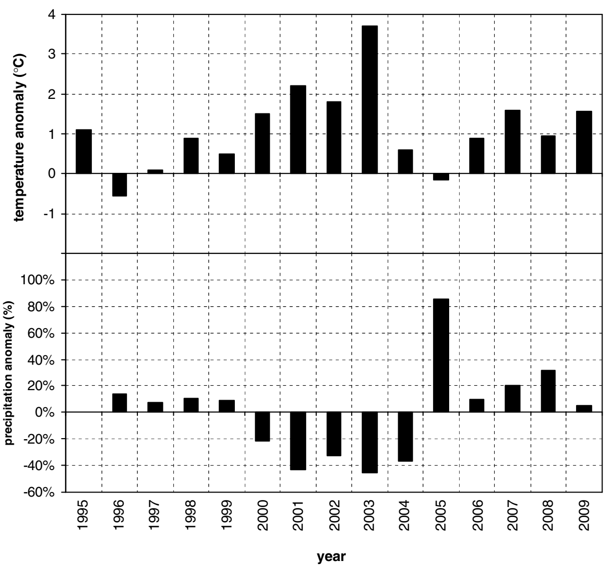

Fig. 4. July–August anomalies of air temperature and precipitation amount, relative to the 1961–1990 average, from a nearby meteorological observatory (Farkasfa, 46°55'N, 16°19'E, 312 m asl). (Precipitation anomaly in 1995 is 0.3%).

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 CO_2 mixing ratio. During the winter period NEE is positive, as ecosystems release more CO_2 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 CO_2 mixing ratio reaches its annual maximum in December–January (Fig. 5), well before the vegetation becomes a net CO_2 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 CO_2-depleted air masses from lower latitudes where growing season starts earlier. However, the seasonal cycle in atmospheric CO_2 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 CO_2-enriched boundary layer. This process overcompensates the contribution of the surface that is still a net CO_2 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.

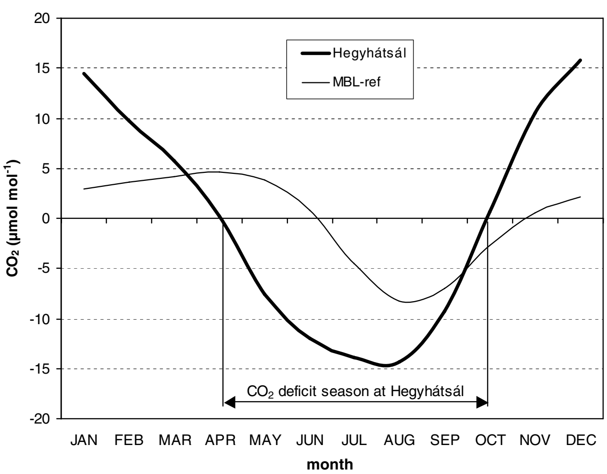

Fig. 5. Mean seasonal cycle of CO_2 mixing ratio at Hegyhátsál (10 m) and in the modelled marine boundary layer (GLOBALVIEW-CO2, 2009) corresponding to the geographical latitude of Hegyhátsál.

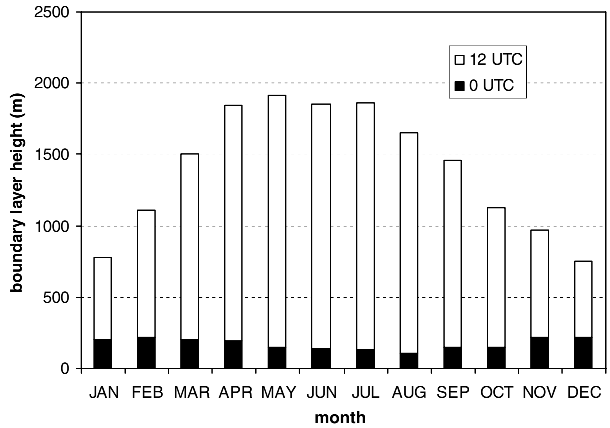

Fig. 6. Seasonal variation of the average daytime (13 h LST = 12 UTC) and nighttime (1 h LST = 0 UTC) heights of the planetary boundary layer at Hegyhátsál (1994–2008, data source ECMWF MARS database).

The effect of the changing vertical mixing on the CO_2 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 CO_2 mixing ratio here deviates from the usually expected one.

To demonstrate the overwhelming effect of the vertical mixing on the CO_2 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 CO_2 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 CO_2 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

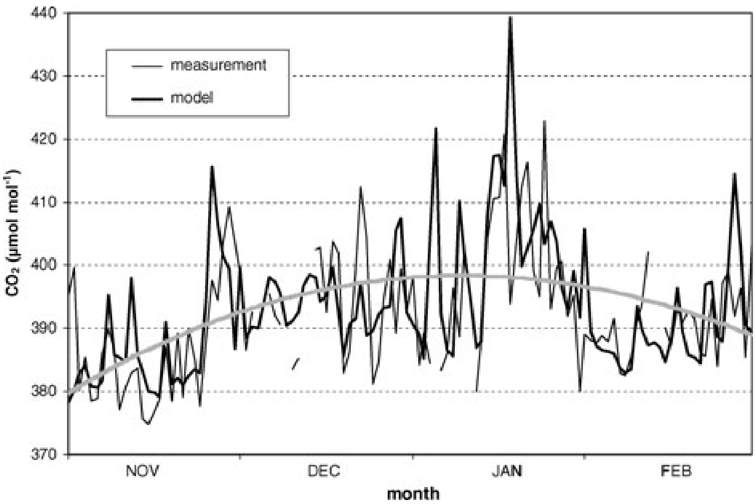

Fig. 7. Measured and simulated CO_2 mixing ratios for the period of November 2002–February 2003. The line fitted to the simulated values is a 3rd order polynomial.

temporal course of the mixing ratio. CO_2 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 CO_2 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 ± 9.55 μmol 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 CO_2 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 CO_2 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 Hegyhátsál, 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 CO_2 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 CO_2 deficit season (April). Temperature shows a statistically significant upward trend (level of confidence >95%) and the correlation between the timing of the beginning of the CO_2 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 CO_2 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 CO_2 deficit season make highly probable that the trend revealed in the start of the CO_2 deficit season indicates a real tendency.

In principle, warming could also prolong the growing season and move the autumn zero-crossing (the time when CO_2-deficit season turns into CO_2-sufficit 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%. CO_2 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 CO_2 uptake from the atmosphere by the vegetation and the enhancement of respiration, which increases the CO_2 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-

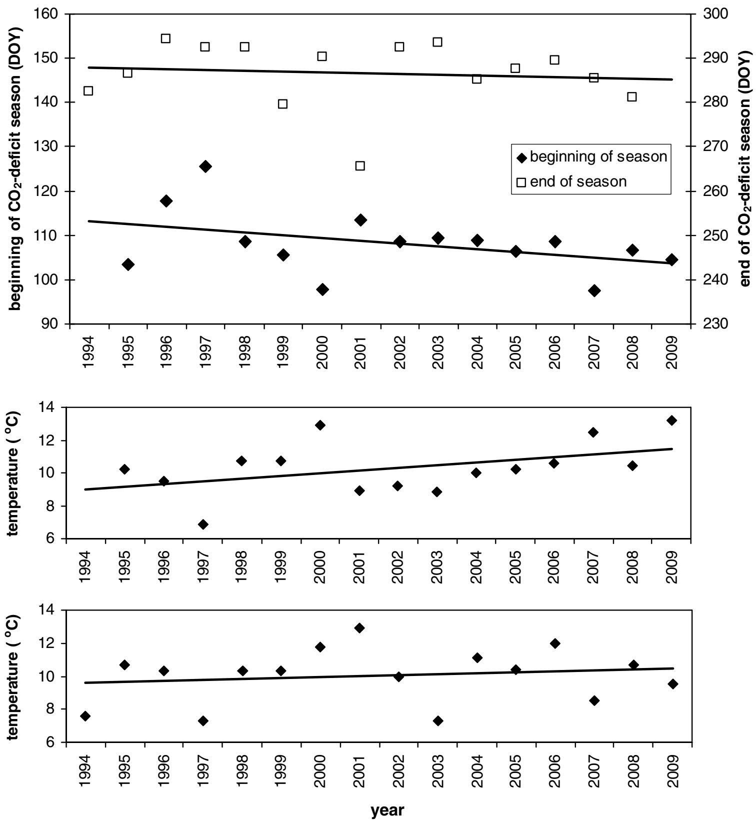

Fig. 8. Tendencies of the beginning and end of the CO_2 deficit season (upper panel) and that of the monthly mean temperatures in the relevant months (April – middle panel; October – bottom panel).

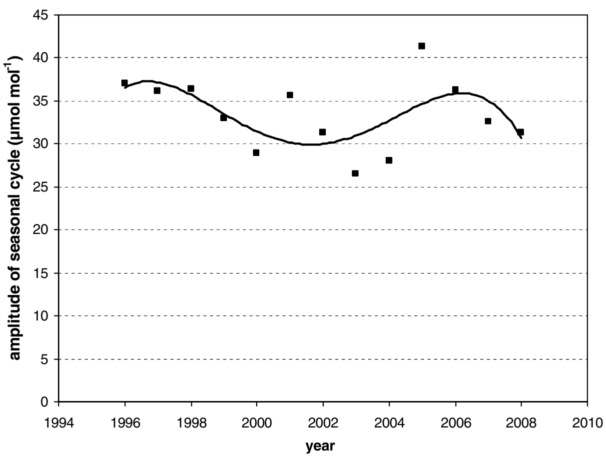

Fig. 9. Temporal variation in the amplitude of the seasonal cycle of CO_2 mixing ratio. The fitted line is a 4th order polynomial.

tensify respiration, while the prolonged growing season may increase carbon uptake. In the Hegyhátsál CO_2 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 CO_2 uptake capacity of the biosphere in the influence area of the station. The less intensive CO_2 uptake in the summer season decreased the annual amplitude of the atmospheric CO_2 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 CO_2 mixing ratio significantly exceeded that in the other seasons (Fig. 10, Table 1). While the mixing ratio grew by 2.66 μmol mol^{-1} yr^{-1} in summer during this period the overall growth rate was only 2.08 μmol mol^{-1} yr^{-1}. As it was mentioned before, these years were increasingly warm and dry, although the interannual variation was high. The high temperature

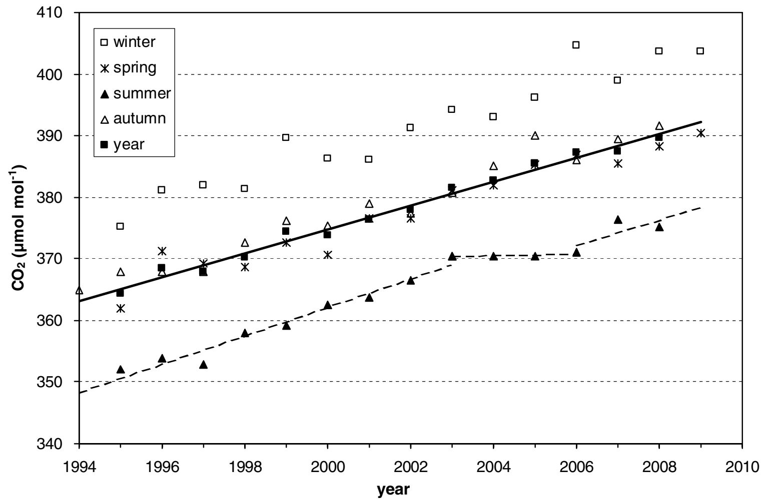

Fig. 10. Seasonal trends in the early afternoon (12–16 h LST) atmospheric CO_2 mixing ratio at 10 m elevation above the ground at Hegyhátsál. The lines are indicating linear trends (dashed line – summer [three separated periods], thick line – whole year).

Table 1. Seasonal growth rates (μmol mol^{-1} yr^{-1} ± standard error) of early afternoon (12–16 h LST) atmospheric CO_2 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 CO_2 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 CO_2 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 CO_2 mixing ratio record measured at a mid-continental, low-elevation, tall tower site located 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 CO_2 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 CO_2 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 CO_2 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 CO_2 and can provide modellers with important information on the underlying mechanisms.

7. Acknowledgment

During the years the monitoring program at Hegyhátsál was supported by the U.S.-Hungarian Scientific and Technological Joint Fund (J. F. no. 162 and 504), by the Hungarian Scientific Research Fund (OTKA T042941, CK77550), by the Hungarian Ministry of Economy and Transport (GVOP-3.2.1.-

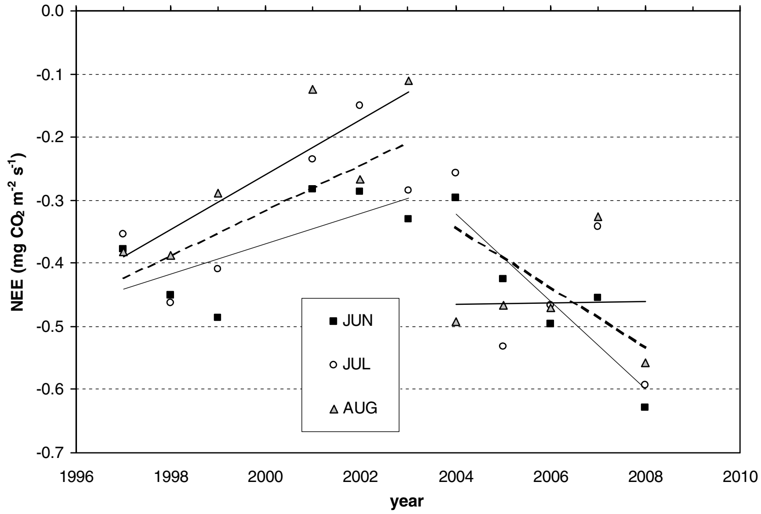

Fig. 11. Tendencies in the monthly mean NEE in summer at Hegyhátsál. The lines are only graphical representations of the tendencies (thin dashed line – June, thick dashed line – July, solid line – August).

2004-04-0107/3.0), by the INTERREG IIIB CADSES program (5D038), as well as by the 5th and 6th R&D Framework Programmes of the European Commission (AEROCARB—EVK2-CT-1999-00013, CHIOTTO—EVK2-CT-2002-00163, CarboEurope-IP — GOCE-CT-2003-505572, IMECC—RII3 026188). The authors thank Kirk Thoning, NOAA ESRL (U.S.A.), for the CCGCRV data analysis software used in this study for a part of the calculations. We are also grateful to Frederic Chevallier (LSCE, France) for his contribution.

References

Bacastow, R. B., Keeling, C. D. and Whorf, T. P. 1985. Seasonal amplitude increase in atmospheric CO_2 concentration at Mauna Loa, Hawaii, 1959–1982. *J. Geophys. Res.* **90**, 10529–10541.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D. and co-authors. 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bull. Am. Meteorol. Soc.* **82**, 2415–2434.

Banta, R. M., Mahrt, L., Vickers, D., Sun, J., Balsley, B. B. and co-authors. 2007. The very stable boundary layer on nights with weak low-level jets. *J. Atmos. Sci.* **64**, 3068–3090.

Barcza, Z., Kern, A., Haszpra, L. and Kljun, N. 2009. Spatial representativeness of tall tower eddy covariance measurements using remote sensing and footprint analysis. *Agric. For. Meteorol.* **149**, 795–807, doi:10.1016/j.agrformet.2008.10.021.

Beljaars, A., Jakob, C. and Morcrette, J.-J. 2001. New physics parameters in the MARS archive. *ECMWF Newsletter* **90**, 17–21.

Cadule, P., Bopp, L. and Friedlingstein, P. 2009. A revised estimate of the processes contributing to global warming due to climate-carbon feedback. *Geophys. Res. Lett.* **36**, L14705, doi:10.1029/2009GL038681.

Churkina, G., Brovkin, V., von Bloh, W., Trusilova, K., Jung, M. and Dentener, F. 2009. Synergy of rising nitrogen depositions and atmospheric CO_2 on land carbon uptake moderately offsets global warming. *Global Biogeochem. Cycles* **23**, GB4027, doi:10.1029/2008GB003291.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J. and co-authors. 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* **437**, 529–533, doi:10.1038/nature03972.

Davis, K. J., Bakwin, P. S., Yi, C., Berger, B. W., Zhao, C. and co-authors. 2003. The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. *Global Change Biol.* **9**, 1278–1293.

Denning, A. S., Randall, D. A., Collatz, G. J. and Sellers, P. J. 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part II.: simulated CO_2 concentrations. *Tellus* **48B**, 543–567.

EC-JRC/PBL (European Commission, Joint Research Centre/Netherlands Environmental Assessment Agency). 2009. Emission Database for Global Atmospheric Research (EDGAR), release version 4.0. Available at: http://edgar.jrc.ec.europa.eu. Accessed 20 October 2009.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W. and co-authors. 2006. Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. *J. Clim.* **19**, 3337–3353.

GLOBALVIEW-CO2. 2009. *Cooperative Atmospheric Data Integration Project – Carbon Dioxide*. CD-ROM, NOAA ESRL, Boulder, Colorado [Also available on Internet via anonymous FTP to ftp.cmdl.noaa.gov, Path: ccg/co2/GLOBALVIEW].

Gloor, M., Bakwin, P., Hurst, D., Lock, L., Draxler, R. and Tans, P. 2001. What is the concentration footprint of a tall tower? *J. Geophys. Res.* **106D**, 17831–17840.

Haszpra, L. 1999. On the representativeness of carbon dioxide measurements. *J. Geophys. Res.* **104D**, 26953–26960.

Haszpra, L., Barcza, Z., Bakwin, P. S., Berger, B. W., Davis, K. J. and Weidinger, T. 2001. Measuring system for the long-term monitoring of biosphere/atmosphere exchange of carbon dioxide. *J. Geophys. Res.* **106D**, 3057–3070.

Haszpra, L., Barcza, Z., Davis, K. J. and Tarczay, K. 2005. Long term tall tower carbon dioxide flux monitoring over an area of mixed vegetation. *Agric. For. Meteorol.* **132**, 58–77, doi:10.1016/j.agrformet.2005.07.002.

Haszpra, L., Barcza, Z., Hidy, D., Szilágyi, I., Dlugokencky, E. and co-authors. 2008. Trends and temporal variations of major greenhouse gases at a rural site in Central Europe. *Atmos. Environ.* **42**, 8707–8716, doi:10.1016/j.atmosenv.2008.09.012.

Higuchi, K., Murayama, S. and Taguchi, S. 2002. Quasi-decadal variation of the atmospheric CO2 seasonal cycle due to atmospheric circulation changes: 1979–1998. *Geophys. Res. Lett.* **29**, L1173, doi:10.1029/2001GL013751.

IPCC. 2007. Climate change 2007. The physical science basis. In: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis and co-authors). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keeling, C. D., Chin, J. F. S. and Whorf, T. P. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Nature* **382**, 146–149.

Larson, V. E. and Volkmer, H. 2008. An idealized model of the one-dimensional carbon dioxide rectifier effect. *Tellus* **60B**, 525–536, doi:10.1111/j.1600-0889.2008.00368.x.

Linderholm, H. W. 2006. Growing season changes in the last century. *Agric. For. Meteorol.* **137**, 1–14, doi:10.1016/j.agrformet.2006.03.006.

Linderholm, H. W., Walther, A. and Chen, D. 2008. Twentieth-century trends in the thermal growing season in the Greater Baltic Area. *Clim. Change* **87**, 405–419, doi:10.1007/s10584-007-9327-3.

Lintner, B. R., Buermann, W., Koven, C. D. and Fung, I. Y. 2006. Seasonal circulation and Mauna Loa CO_2 variability. *J. Geophys. Res.* **111D**, D13104.

Menzel, A. and Fabian, P. 1999. Growing season extended in Europe. *Nature* **397**, 659.

Miller, J. B. 2008. Carbon cycle: sources, sinks and seasons. *Nature* **451**, 26, doi:10.1038/451026a.

Murayama, S., Yamamoto, S., Saigusa, N., Kondo, H. and Takamura, C. 2005. Statistical analyses of inter-annual variations in the vertical profile of atmospheric CO_2 mixing ratio and carbon budget in a cool-temperate deciduous forest in Japan. *Agric. For. Meteorol.* **134**, 17–26, doi:10.1016/j.agrformet.2005.08.017.

Murayama, S., Higuchi, K. and Taguchi, S. 2007. Influence of atmospheric transport on the inter-annual variation of the CO_2 seasonal cycle downward zero-crossing. *Geophys. Res. Lett.* **34**, L04811, doi:10.1029/2006GL028389.

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. and Nemani, R. R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**, 698–702.

Oishi, R., Abe-Ouchi, A. Prentice, I. C. and Sitch, S. 2009. Vegetation dynamics and plant CO_2 responses as positive feedbacks in a greenhouse world. *Geophys. Res. Lett.* **36**, L11706, doi:10.1029/2009GL038217.

Piao, S., Friedlingstein, P., Ciais, P., Viovy, N. and Demarty, J. 2007. Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades. *Global Biogeochem. Cycles* **21**, GB3018, doi:10.1029/2006GB002888.

Piao, S., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M. and co-authors. 2008. Net carbon dioxide losses of northern ecosystems in response to autumn warming. *Nature* **451**, 49–52, doi: 10.1038/nature06444.

Raich, J. W. and Schlesinger, W. H. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus* 44B, 81–99.

Ramonet, M., Ciais, Ph., Aalto, T., Aulagnier, C., Chevallier, F. and co-authors. 2010. A recent build-up of atmospheric CO_2 over Europe. Part 1: observed signals and possible explanations. *Tellus* **62B**, 1–13, doi:10.1111/j.1600-0889.2009.00442.x.

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S. and co-authors. 2007. Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis. *Global Change Biol.* **13**, 634–651, doi:10.1111/j.1365-2486.2006.01224.x.

Reichstein, M. and Beer, C. 2008. Soil respiration across scales: the importance of a model-data integration framework for data interpretation. *J. Plant Nutr. Soil Sci.* **171**, 344–354, doi:10.1002/jpln.200700075.

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 CO_2 budget. *J. Geophys. Res.* **108**, D4619, doi:10.1029/2002JD003085.

Stull, R. B. 1988. *An Introduction to Boundary Layer Meteorology*. Kluwer Acad., Norwell, Mass.

Thum, T., Aalto, T., Laurila, T., Aurela, M., Hatakka, J. and co-authors. 2009. Spring initiation and autumn cessation of boreal coniferous forest CO_2 exchange assessed by meteorological and biological variables. *Tellus* **61B**, 701–717, doi:10.1111/j.1600-0889.2009.00441.x.

Tucker, C. J., Slayback, D. A., Pinzon, J. E., Los, S. O., Myneni, R. B. and Taylor, M. G. 2001. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. *Int. J. Biometeorol.* **45**, 184–190.

Varga-Haszonits, Z. 2004. Az éghajlati változékonyság és a természetes periódusok (Climatic variability and natural periods). *"AGRO-21" Füzetek* **37**, 23–32.

Vermeulen, A. (ed.) 2007. CHIOTTO Final report. ECN-E-07-052. Available at http://www.ecn.nl/docs/library/report/2007/e07052.pdf. Accessed on 20 October, 2009.

Xia, Y., Conen, A., Haszpra, L., Ferenczi, Z. and Zahorowski, W. 2010. Evidence for nearly complete decoupling of very stable nocturnal boundary layer. *Boundary-Layer Meteorol.* (submitted).

Zimov, S. A., Davidov, S. P., Zimova, G. M., Davidova, A. I., Chapin, F. S., III and co-authors. 1999. Contribution of disturbance to increasing seasonal amplitude of atmospheric CO_2. *Science* **284**, 1973–1976.