Tellus (2002), 54B, 834–849
Printed in UK. All rights reserved

TELLUS
ISSN 0280–6509

Summertime Siberian CO_2 simulations with the regional transport model MATCH: a feasibility study of carbon uptake calculations from EUROSIB data

By ERIK KJELLSTRÖM[1]*, KIM HOLMÉN[1], KRISTINA ENEROTH[1] and MAGNUZ ENGARDT[2],
[1]*Department of Meteorology, Stockholm University, S-10691 Stockholm, Sweden;* [2]*Swedish Meteorological and Hydrological Institute, S-60176 Norrköping, Sweden*

(Manuscript received 5 June 2001; in final form 4 March 2002)

ABSTRACT

Biogenic surface fluxes of CO_2 over Europe and Siberia are implemented in the regional tracer transport model MATCH. A systematic comparison between simulated and observed CO_2 fluxes and mixing ratios is performed for two observational sites in Russia taking into account both surface observations and vertical profiles of meteorological parameters and CO_2 in the lowest 3 km from the summer months in 1998. We find that the model is able to represent meteorological parameters as temperature, humidity and planetary boundary layer height consistent with measurements. Further, it is found that the simulated surface CO_2 fluxes capture a large part of the observed variability on a diurnal time scale. On a synoptic time scale the agreement between observations and simulation is poorer which leads to a disagreement between time series of observed and simulated CO_2 mixing ratios. However, the model is able to realistically simulate the vertical gradient in CO_2 in the lowest few kilometres. The vertical variability is studied by means of trajectory analysis together with results from the MATCH model. This analysis clearly illustrates some problems in deducing CO_2 fluxes from CO_2 mixing ratios measured in single vertical profiles. Studies of the regional variability of CO_2 in the model domain show that there exists no ideal vertical level for detecting the terrestrial signal of CO_2 in the free troposphere. The strongest terrestrial signal is found in the boundary layer above the lowest few hundred metres. Nevertheless, this terrestrial signal is small, and during the simulated period it is not possible to detect relative variations in the surface fluxes smaller than 20%. We conclude that a regional flux cannot be determined from single ground stations or a few vertical profiles, mainly due to synoptic scale variability in transport and in CO_2 surface fluxes.

1. Introduction

The atmospheric content of the biologically active greenhouse gas carbon dioxide (CO_2) experiences variations on time-scales from seconds on the local level to hundreds of thousands of years and longer (Raynaud et al., 1993). On top of these natural variations man has perturbed the concentrations during at least the past 200 yr both through emissions from industrial processes and through flux perturbations induced by land-use changes (Ciais et al., 2000). The atmospheric concentrations are controlled by a balance of sources and sinks that are heterogeneously distributed on the surface with large temporal variations (daily as well as seasonal). Extensive investigations of the global carbon cycle have been made in pursuit of an understanding of how the atmospheric balance is achieved. The global scale balance, although fairly well constrained, remains uncertain in its finer elements (Falkowski et al., 2000). In order to refine our knowledge further, and also understand how different areas will respond to perturbations of land cover or climate, regional carbon cycle budgets are required.

*Corresponding author.
e-mail: erik@misu.su.se

Determination of a regional CO_2 budget requires either continuous flux measurements or a careful inventory monitoring or both. An inventory monitoring can either be in the surface reservoirs exchanging with the atmosphere or for the atmosphere itself or ideally both independently. For atmospheric CO_2 both the natural fluxes and the background inventory are large, and detecting changes in the fluxes or the inventories are inherently difficult problems.

CO_2 exchange fluxes can be determined locally with closed compartments or by eddy correlation techniques. Under certain circumstances a concentration gradient (horizontally or vertically) can be converted into a CO_2 flux also over larger scales. Inventory calculations can be made inside boxes, in other natural compartments (if the planetary boundary layer remains constant in depth for an extended period the concentration change within the layer can be converted to a net flux) or for the atmosphere as a whole. A problem when studying regional fluxes is that there is a tremendous scale gap between the local flux measurement and the global atmospheric CO_2 budget that must be bridged.

Regional atmospheric CO_2 inventory estimates require a detailed time-resolved three-dimensional mapping of CO_2, which can only be achieved with a formidable number of measurements. CO_2 is a long-lived gas, which is an asset when interpreting concentration fields in that there are no internal sources or sinks in the atmosphere but a difficulty in that vertical and horizontal transport on all time scales must always be considered. The present study explores whether a limited number of measurements combined with other (mainly meteorological) information suffice to make regional CO_2 budget calculations. In particular we study how flux signals propagate into the atmosphere from regional sources in a limited area transport and diffusion model (MATCH), and utilise the simulated tracer fields to discuss how representative are the EUROSIB local measurements and sparse vertical profiles.

2. Model and data description

For the current study we use the “off-line”, three-dimensional, Eulerian transport model MATCH (Multiple-scale Atmospheric Transport and Chemistry modelling system), which has been developed at the Swedish Meteorological and Hydrological Institute. A complete description of the boundary layer parameterisations and the advection scheme is given in Robertson et al. (1996; 1999). Driving meteorological fields for the present simulations are taken as the first guess from the European Centre for Medium range Weather Forecasts (ECMWF), available every 6 h. The data are interpolated to the rotated grid that is used as the MATCH domain and then linearly interpolated in time to 1-h resolution. In the following MATCH is used for simulating three months, June–August 1998. The horizontal resolution in this study is $1^\circ \times 1^\circ$. The vertical resolution is the same as in the input meteorological fields i.e. 31 levels unequally distributed from the surface to 10 hPa. Robertson et al. (1996; 1999) discuss the problem of interpolating the meteorological data prior to usage in an off-line model. They show that by adopting the adjustment procedure of Heimann and Keeling (1989) and an integrated flux scheme for the horizontal and vertical advection, MATCH produces realistic vertical profiles of ^{222}Rn in the lower troposphere and mass conservative model simulations. Langner et al. (1998) use data from a deliberate tracer release experiment (ETEX), as well as the Chernobyl accident, to demonstrate the ability of MATCH to simulate the dispersion, advection, and deposition of a tracer in MATCH. Based on the pre-study of Engardt and Holmén (1996), Engardt and Holmén (1999) and Brandefelt and Holmén (2001) use MATCH to simulate transport of CO_2 into the Arctic. By comparing with measurements collected in the high Arctic they show that the model, driven by meteorological data from ECMWF, performs well in terms of simulating synoptic variations in the near-surface CO_2 measured at Ny-Ålesund (79°N, 12°E) brought about by the CO_2 sources located in distant Siberia and Europe.

Terrestrial surface CO_2 fluxes are taken from the TURC model (Lafont et al., 2002). These fluxes are derived on a daily basis using satellite information on the normalised difference vegetation index (NDVI) together with meteorological information on temperature, humidity and radiation from ECMWF. TURC has a $1^\circ \times 1^\circ$ resolution and the data are interpolated into the rotated MATCH grid. The surface fluxes from TURC are given in three parts: gross primary production, and autotrophic and heterotrophic respiration. In MATCH, a diurnal cycle is applied for the net primary production (i.e. gross primary production minus autotrophic respiration). The terrestrial uptake of CO_2 by net primary production from TURC is distributed throughout the day in proportion to the sine of the local solar elevation angle during the daylight hours in each grid box. No uptake is assumed to occur during the night. The heterotrophic respiration (hereafter referred to as respiration) is assumed to occur at constant rate throughout the 24-h period.

For the lateral boundaries of MATCH we use CO_2 mixing ratios taken from the global tracer transport model TM3 (Chevillard et al., 2002). TM3 was run with the same emission scenario and for the same time period as described above. The TM3 data, which are originally on a $5^\circ \times 3.75^\circ$ grid with 19 vertical levels, are linearly interpolated to the $1^\circ \times 1^\circ$ grid and 31 levels used here. The lateral boundaries are updated with fields from TM3 every 6 h during the simulations. TM3 provides anomalies, i.e. fluctuations around zero. In MATCH we add 360 μmol mol^{-1} to these anomalies. This means that the absolute numbers presented below are to some degree fictitious. Further, we emphasize that TM3, TURC, and MATCH all use the same data from ECMWF. This provides us with a consistent description of the meteorology between the different models used in the present study. Finally it should be noted that we do not include other fluxes, such as the exchange of CO_2 between oceans and atmosphere or the anthropogenic CO_2 emissions. By CO_2, we refer in the following to the terrestrial signal of CO_2.

3. Results and discussion

3.1. Meteorology

Observed meteorology at the EUROSIB measurement stations Zotino (60.5°N, 89.4°E) and Fyodorovskoye (56.5°N, 33°E) (Kurbatova et al., 2002; Tchebokova et al., 2002; Milyukova et al., 2002) is compared to the meteorological data that were used to drive the transport model. Figure 1 shows a comparison between observed and calculated specific humidity at Zotino. The degree of correlation between observations and the ECMWF data is about 0.75. An even better agreement (correlation coefficient almost 0.9) is found for temperature (not shown), but the ECMWF data underestimates the amplitude of the diurnal cycle at the observational site. Further, the agreement between ECMWF and observational data is very good for pressure, with a correlation coefficient of about 0.99. Precipitation is more problematic. The degree of correlation is quite low (about 0.5). One reason for this low degree of correlation is the model resolution. In the real atmosphere precipitation, especially convective, occur on small horizontal scales that are not resolved in a $1^\circ \times 1^\circ$ grid. Since the precipitation is strongly coupled to vertical movements in the atmosphere this low degree of correlation indicates

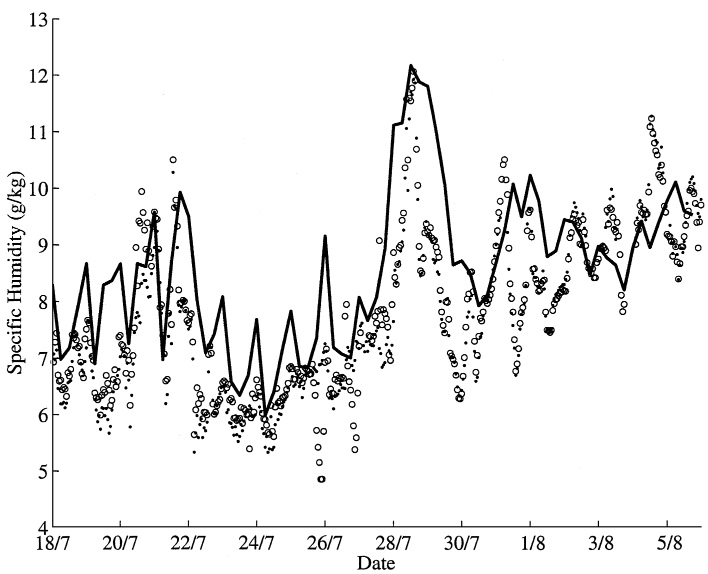

Fig. 1. Specific humidity at Zotino (60.5°N, 89.4°E) during the period 00.00 UTC 18 July until 00.00 UTC 6 August 1998. The full line is data from ECMWF interpolated to the rotated $1^\circ \times 1^\circ$ grid used by MATCH. Data are from the lowest model level, about 30 m above the ground. Observed data from the forest (dotted) and the bog (circles) are also shown (Tchebokova et al., 2002; Kurbatova et al., 2002).

that there might be problems with the vertical transport of tracers in association with frontal systems, and especially during convective episodes. Further, it should be noted that the degree of correlation between ECMWF and observed meteorology is not identical in the forest and on the bog, especially for temperature. This difference between the local measuring sites on a very small horizontal scale gives some idea of the local variability that is not captured by a relatively coarse grid-box model like MATCH. The corresponding time series and correlations for Fyodorovskoye (not shown) shows similar behaviour as for Zotino, although even worse agreement for precipitation (the correlation coefficient is less than 0.3).

Observed vertical profiles of temperature and humidity at Zotino (Lloyd et al., 2002) and Fyodorovskoye (Ramonet et al., 2002) are also compared to the input meteorological data. It is found that the model captures the gross features of temperature and humidity in the lowest 3 km. Boundary layer height is an important feature that has to be correctly simulated in a dispersion model. Table 1 shows planetary boundary layer (PBL) height from the observed profiles together with the values calculated by MATCH. Only 20 observations are too few to draw any strong conclusions about model behaviour, but there are some features that can be seen in the data. First, there is a general agreement between model and observation for convective cases (i.e. well mixed daytime boundary layers with only very small vertical gradients in potential temperature). In those situations the error is less than 35% in all cases. On the other hand, for stable boundary layers, the agreement between observed and simulated mixing height is less good, with both over- and underestimations of sometimes as much as a factor three. This poor agreement may partly be attributed to the uncertainties in determining the boundary layer height in stable cases (Seibert et al., 2000), especially since no wind information is available from the observed vertical profiles.

Table 1. *Vertical extent of the PBL at Zotino and Fyodorovskoye in July and August 1998*[a]

Date	Time UTC (LT)	Observed	Simulated
Zotino			
9/7	11 (19)	1700	1350
22/7	06 (14)	1500	1800
23/7	06 (14)	1800	1770
23/7	12 (20)	2600	2230
23/7	23 (07 24/7)	200	620
24/7	07 (15)	1800	1760
24/7	12 (20)	2100	1760
7/8	06 (14)	1400	1370
19/8	07 (15)	1700	1760
Fyodorovskoye			
24/7	06 (09)	610	360
24/7	12 (15)	1950	640
28/7	06 (09)	1030	630
28/7	09 (12)	2060	1000
28/7	15 (18)	1450	1370
29/7	06 (09)	530	980
29/7	09 (12)	1300	1180
29/7	15 (18)	1160	1390
30/7	06 (09)	1580	640
30/7	15 (18)	1520	980
31/7	09 (12)	1060	1230

[a]The observed heights are taken from the vertical soundings of potential temperature, relative humidity and CO_2 (Lloyd et al., 2002; Ramonet et al., 2002), simulated heights are calculated by MATCH (Robertson et al., 1999). Unit: m.

3.2. *Surface CO_2 fluxes*

There is a large regional variability of the surface fluxes due to different biota, local time and meteorological conditions; see Figs. 2a and 2b (surface fluxes at 00.00 and 12.00 UTC 24 July 1998). The respiration during night is seen at 00.00 UTC, with emission taking place in most of the area west of 90°E where night conditions prevail. At 12.00 UTC there is instead uptake in the entire region except in the easternmost part where the sun is below the horizon. Further, there are some patches with respiration being dominant also in daytime (e.g. a region in the middle of Scandinavia, which was covered by an extensive cloud cover connected to a low). On this particular day the incoming radiation in this area was too low to generate a net uptake in the TURC model.

Time series of surface CO_2 fluxes and mixing ratios are available from eddy flux measurements for both Zotino and Fyodorovskoye for large parts of summer 1998 (Styles et al. 2002; Arneth et al., 2002; Milyukova et al., 2002). These measurements are made on masts at two locations at both sites; one in a forest and another on a bog. We compare the diurnal cycle of the simulated surface fluxes to that of the observed surface fluxes at Zotino and Fyodorovskoye. Figure 3 shows a time series from Zotino (similar results to those presented in Fig. 3 are also found during other parts of the summer and also at the Fyodorovskoye station). Note that the two time series for CO_2 fluxes from the bog and forest sites are in some respects very different even though the locations are

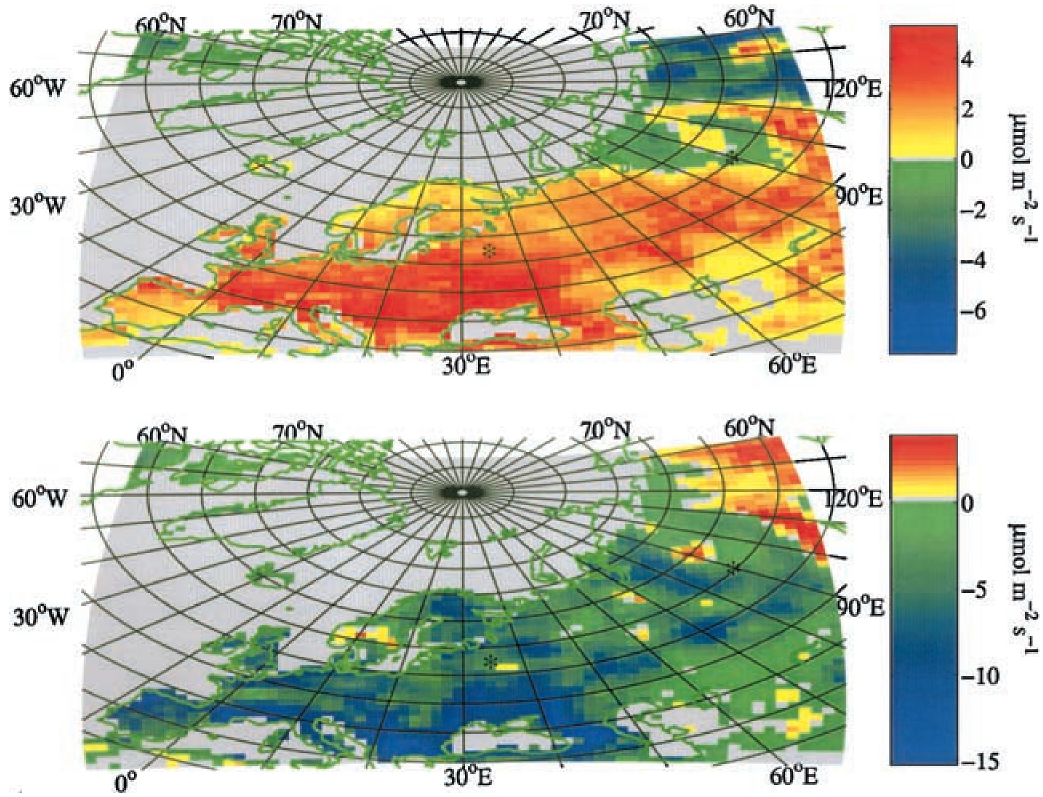

Fig. 2. Net flux of CO_2 on 24 July as calculated by the TURC model with the addition of the diurnal cycle described in the text. Conditions are shown at 00.00 UTC (upper panel) and 12.00 UTC (lower panel). Stars denote the location of the EUROSIB stations Zotino and Fyodorovskoye. Positive values indicate a CO_2 flux to the atmosphere. Unit: μmol m^{-2} s^{-1}.

close (i.e. less than 2 km) to each other. These local differences are not resolved in MATCH, which instead use TURC fluxes that are integrated over entire gridboxes. Thus it is not expected that we should resolve all the small-scale features seen in the observations.

The diurnally averaged data show poor agreement with observations. Correlation coefficients are 0.4 or less (Fig. 3, lower panel). The addition of a diurnal cycle improves the degree of correlation, since we add information. We have tested two different kinds of diurnal cycles: one as described in section two, and another with constant uptake during day and constant respiration throughout the full diurnal cycle. It is found that the variation of the uptake with solar elevation angle gives the best agreement with observations, and in the following only this case will be discussed. The daily-mean gross fluxes from the TURC model together with our simple parameterisation of diurnal variability catches a large part of the variability, see Fig. 3 (upper panel). Correlation coefficients for the whole summer 1998 are around 0.7 for three-hourly data.

A higher degree of correlation between observed and simulated fluxes could be achieved if either the TURC data or the formulation of the diurnal cycle is improved. Most meteorological parameters that have been used to drive the TURC model are consistent with measurements at Fyodorovskoye and Zotino (Lafont et al., 2002). Nevertheless, including meteorological data with a higher temporal resolution would improve the degree of correlation, since the present diurnal variability does not take into account diurnal variability in the solar radiation due to clouds. A test with meteorological data at a temporal resolution of half an hour calculated in the REMO model (Chevillard et al., 2002) gives a higher degree of correlation between modelled and observed surface fluxes (S. Lafont, personal communication). Other improvements in surface flux data

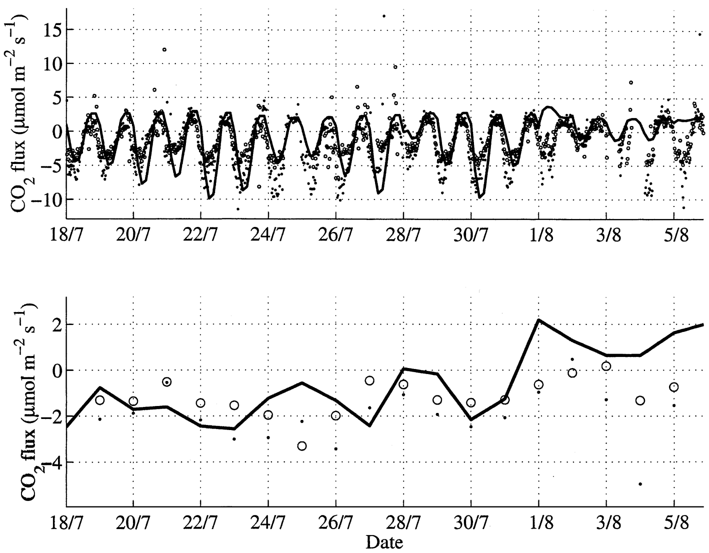

Fig. 3. Surface flux of CO_2 at Zotino (60.5°N, 89.4°E) during the period 00.00 UTC 18 July until 00.00 UTC 6 August 1998. The full line shows the calculated fluxes, dotted lines are observed data from the forest and circles data from the bog (Styles et al., 2002; Arneth et al., 2002). The upper panel shows instantaneous data every 3 h; the lower panel shows diurnally averaged values.

can be made if the TURC model formulation itself is improved (Lafont et al., 2002).

3.3. *Distribution of CO_2 over Europe and Siberia*

Figure 4 shows the calculated horizontal distribution of CO_2 in the lower troposphere at 12.00 UTC 24 July 1998. The pattern reveals large regional differences in mixing ratio. The influence of meteorology can clearly be seen in some regions. For instance, on this particular day a frontal zone was stretching through southern Scandinavia, across the Baltic and then towards the Southwest through central Europe to Spain. On the western side of this frontal zone the marine airmass is not depleted in CO_2, with calculated mixing ratios close to 360 μmol mol^{-1}. On the eastern side of the frontal zone the air is depleted in CO_2 due to ascent of air that is influenced by uptake close to the ground. A similar influence, with depleted air being lifted in connection to the lows and frontal zones, can be found along the frontal zone extending eastwards both in Europe and Siberia (Fig. 4). These kinds of anomalies are produced in MATCH in connection with cyclone activities and can be followed for several days at different altitudes during the entire life cycle of the cyclones. Similarly, anomalies in the middle and upper troposphere can be created by periods of intense convective activity, particularly when a larger area is weakly stratified and a large number of convective cells develop. After the cyclones have terminated or the convection has subsided the anomalies remain and will of course be advected, elongated and deformed as air masses travel. For long-lived species like CO_2 the anomalies will only loose their identity by mixing with adjacent air masses. The lifetime of an anomalous feature depends on altitude and meteorology. If the simulated anomalies are similar to those found in the real atmosphere it is clear that an observed feature in a particular vertical profile can have numerous origins. Therefore, quantifying the surface flux based on kinks and bends in a single profile is not a viable approach.

Monthly averages for July reveal a pronounced longitudinal gradient in CO_2 at all model levels in the lower troposphere (Table 2). This east–west gradient, as well as the vertical gradient at these observational locations, reflects the influence of the surface fluxes on atmospheric concentrations. The longer the air spends over the continent the more CO_2 is taken up by the vegetation. At the lowermost levels a gradient of almost 10 μmol mol^{-1} from Ireland to central Siberia is present in the monthly mean data. At higher levels the gradient is decreasing, and in the middle troposphere it is smaller than 2 μmol mol^{-1}. In terms of

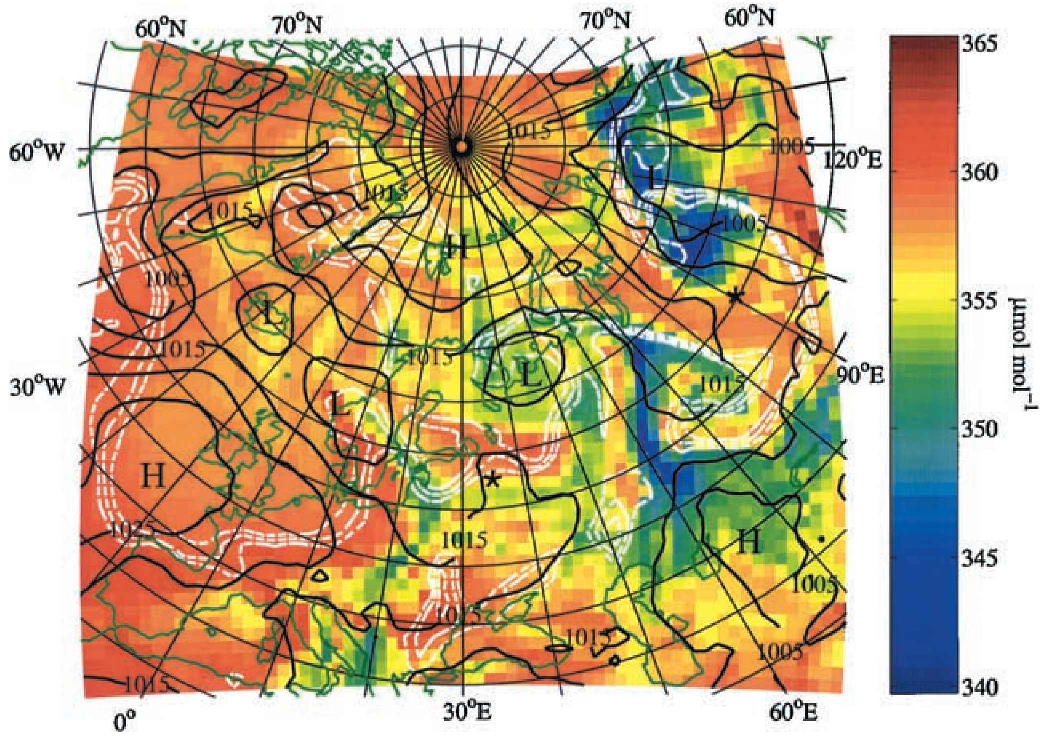

Fig. 4. Instantaneous CO_2 mixing ratios (given in μmol mol^{-1}) at 12.00 UTC 24 July 1998 as calculated by MATCH in model level eight corresponding to approximately 770 hPa. Also shown is the surface pressure (hPa) reduced to mean sea level (full black lines) and a selection of equivalent potential temperatures (312, 315, and 318 K) at model level eight (dashed white lines). Stars denote the location of the EUROSIB stations Zotino and Fyodorovskoye.

vertical gradients these are largest over Siberia with, on average, more than 10 μmol mol^{-1} between the surface and the middle troposphere at Zotino. Over west Europe, the monthly average vertical gradient is weak between these levels. Table 2 also shows standard deviations from the average monthly CO_2 mixing ratios. It is clearly seen that the variability increases when going from the west to the east and from high levels towards the ground. Given the model resolution, variability on small spatial scales (i.e. of the order of less than 100 km in the horizontal and a few hundreds of metres in the vertical) is not simulated. Therefore the

Table 2. *Simulated monthly average mixing ratio and standard deviation of CO_2 (μmol mol^{-1}) at five locations on an east west transect over Europe and Siberia*[a]

Level (hPa)	Mace Head (53°N, 10°W)		Schauinsland (48°N, 8°E)		Fyodorovskoye (56°N, 33°E)		Syktyvkar (62°N, 53°E)		Zotino (60°N, 90°E)	
460	359.3	0.4	359.5	0.3	358.4	1.4	358.2	1.3	357.6	1.5
680	359.0	0.7	359.0	1.0	357.3	1.6	357.1	1.9	356.1	2.1
770	358.7	1.2	358.6	1.6	356.4	2.1	356.1	2.5	355.0	2.6
940	358.1	1.8	355.6	3.9	353.2	4.0	351.9	3.1	348.4	3.2
1010	358.1	1.7	358.2	6.2	354.3	4.7	353.3	4.6	349.5	4.7

[a]Data are 3-hourly covering July 1998 ($N = 248$). Pressure levels starting at the ground correspond to model levels 1, 4, 8, 10 and 15.

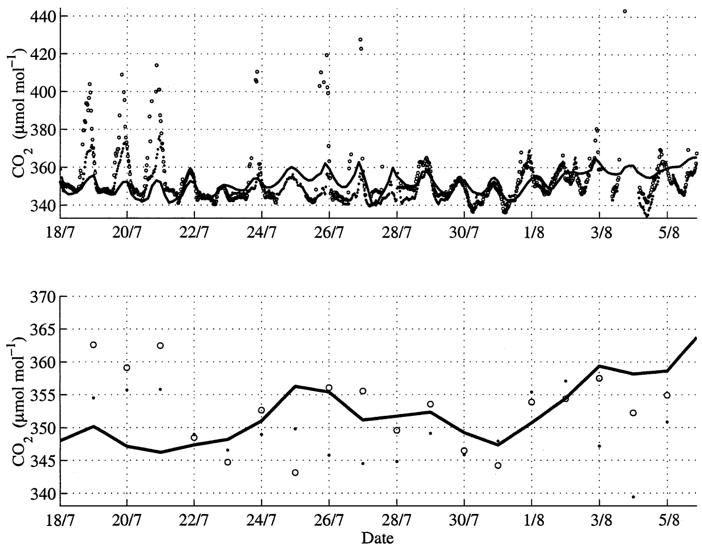

Fig. 5. Surface mixing ratios of CO_2 at Zotino (60.5°N, 89.4°E) during the period 00.00 UTC 18 July until 00.00 UTC 6 August 1998. The full line shows the calculated mixing ratios at the lowest model level, dotted lines are observed data from the forest and circles observed data from the bog (Styles et al., 2002; Arneth et al., 2002). The upper panel shows the full diurnal cycle, the lower panel shows diurnally averaged mixing ratios.

simulated variability represents a low estimate of the natural variability of CO_2.

3.4. CO_2 time-series

We compare model results to observations from the eddy flux measurements at Zotino and Fyodorovskoye (Styles et al., 2002; Arneth et al., 2002; Milyukova et al., 2002). It is found that the model often underestimates the diurnal cycle at the observational sites (Fig. 5). As can be seen in Fig. 5, a correlation between observations and model results at Zotino is nonexistent when studying diurnal averages (lower panel). Also, when looking at the whole summer the low degree of correlation between observation and model is prominent. Taking into account also the diurnal cycle (upper panel) leads to a somewhat higher degree of correlation (with a correlation coefficient of about 0.5). However, at the bog the correlation is very poor (correlation coefficient of about 0.3), since the model fails to catch the sometimes very high (up to 500 μmol mol^{-1}) mixing ratios during the night. The poor correlation between model and observations is a result of problems with the surface fluxes and the simulated meteorology. In particular, the amplitude of the diurnal cycle of the surface fluxes is sometimes underestimated (e.g. 24–26 July at Zotino), which leads to an underestimated diurnal cycle in the mixing ratios (cf. Figs. 3 and 5). On other occasions (e.g. 19–21 and 23 July), the diurnal cycle of the surface fluxes is captured in the model, but still the mixing ratios are not in agreement with the observations. At 23.00 UTC 23 July, the shallow PBL was not successfully simulated in MATCH (Table 1). An over-prediction of PBL height during night and early morning when there is an emission into the atmosphere leads to an under prediction of the nightly mixing ratios and hence the diurnal cycle. A part of the underestimated diurnal cycle could also be due to the fact that we compare the lowest model layer, which is about 60 m thick, to a measurement just above the canopy in the forest or on the bog. Also, it cannot be ruled out that the long-range transport of oceanic and man-made anomalies contribute to some of the observed CO_2 fluctuations. However, the influence from man-made emissions of CO_2 during summer is small at Zotino according to preliminary MATCH simulations.

3.5. CO_2 vertical profiles

The impact of synoptic disturbances on the CO_2 simulations is clearly seen in Fig. 6, which shows a

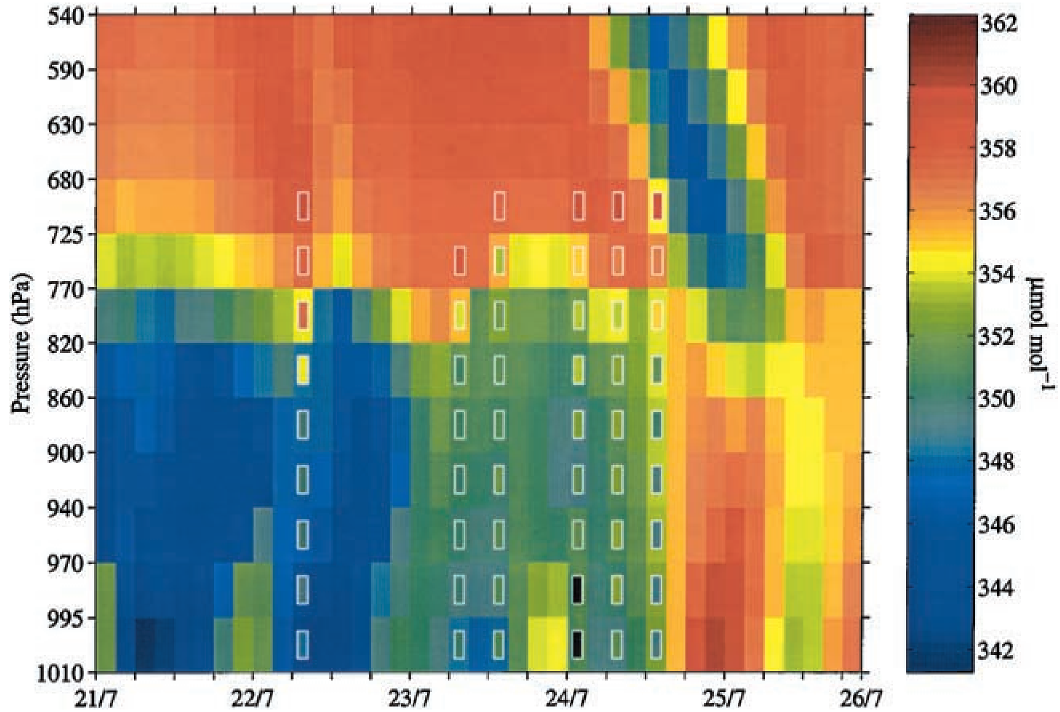

Fig. 6. Simulated time-series of vertical profiles of CO_2 at Zotino (60.5°N, 89.4°E) during the period 00.00 UTC 21 July until 00.00 UTC 26 July 1998. Observed profiles (Lloyd et al., 2002) averaged in vertical bins corresponding to the model grid are included in white frames using the same colour scale (black denotes higher mixing ratios than on the colour scale). Unit: μmol mol^{-1}.

time series of simulated vertical profiles at Zotino. At the lowermost levels the highest mixing ratios are found during the night and morning (note that local time at Zotino is UTC plus 8 h) when CO_2 has been emitted through respiration during night. In daytime, CO_2 mixing ratios drop when there is net uptake. Apart from the diurnal variability there is also large day-to-day variability present in Fig. 6, with a stronger uptake at the first days than at the end of the period. This day-to-day variability is generated by the TURC fluxes, which for this gridbox become smaller from 22 July to 25 July (Fig. 3).

There are also interesting features to be studied aloft, especially, the event first seen in the free troposphere on 24 July, working its way down through the atmosphere on 25 July. This anomaly is created far from Zotino when air from the Arctic basin and northern Siberia become depleted of CO_2 when approaching Zotino during the previous days (Fig. 7). The depletion can be studied in more detail in Fig. 8, which shows results from a three-dimensional trajectory model (McGrath, 1989) using the same meteorological fields as utilised by MATCH. The trajectory in the figure has an arrival height corresponding to approximately 4 km (600 hPa). Also shown in the figure are MATCH results from the gridboxes closest to the trajectory on its way to Zotino. From the figure it is seen that the air arriving at 600 hPa becomes depleted of CO_2 several days before arriving at Zotino. The air arriving at 950 hPa, on the other hand, becomes depleted of CO_2 when it is in contact with the surface, i.e. within the PBL, during the last 2 d before arriving Zotino (Fig. 9). This way of looking into the anomalies at Zotino tells us that the idealised model of a "regional footprint" is indeed not working when looking at tracers with a lifetime of more than a few hours. For instance, the "footprint" of the air arriving at 950 hPa would be confined to the boundary layers on 23 and 24 July when the air is depleted of CO_2. For the air arriving at 600 hPa the "footprint" will be areas that were passed by the air during daytime on 20, 21 and 22 July, i.e. more than 2 d prior to arrival or more than

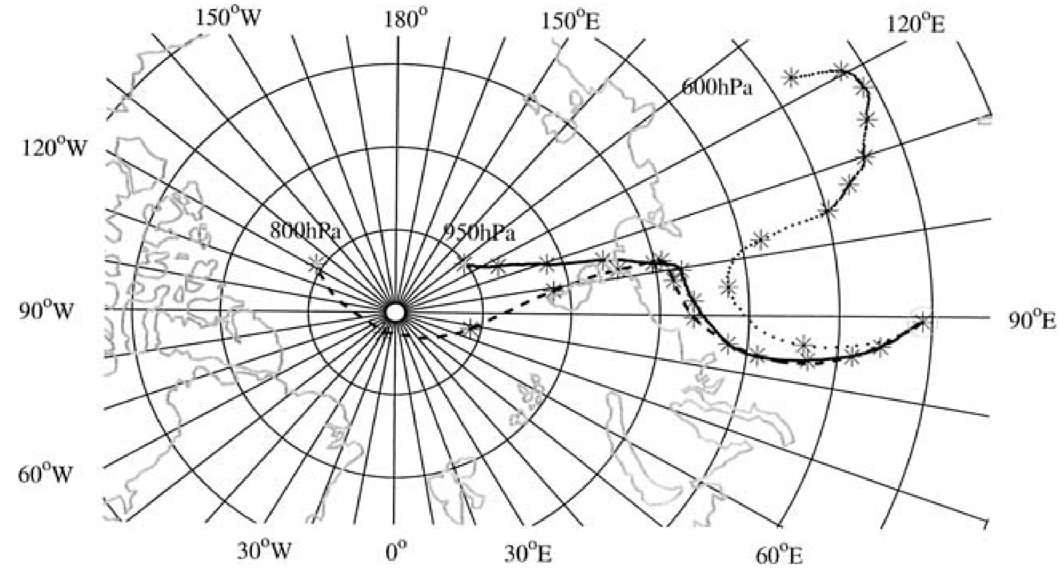

Fig. 7. Three-dimensional 5-d back trajectories arriving at different pressure levels at Zotino (60.5°N, 89.4°E) at 12.00 UTC 24 July 1998. Stars denote positions of trajectories every 12 h.

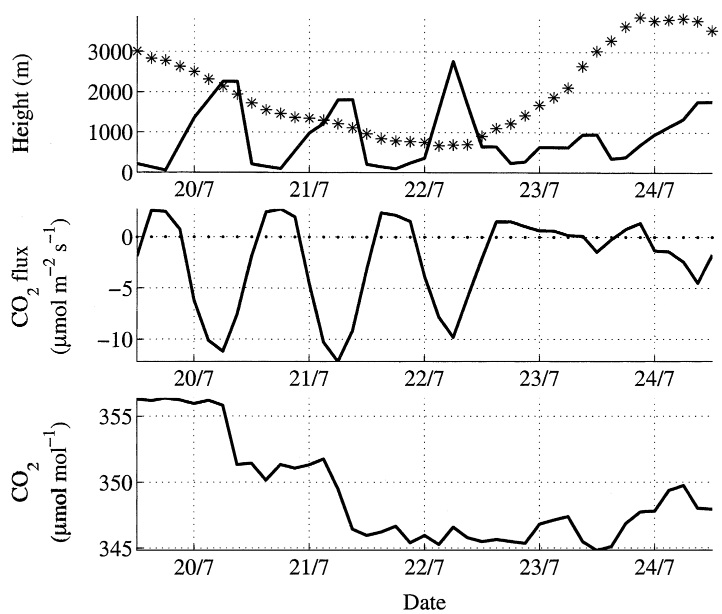

Fig. 8. The upper panel shows vertical path of the trajectory arriving at 600 hPa above Zotino (60.5°N, 89.4°E) at 12.00 UTC 24 July 1998 ($*$) and the boundary layer height as calculated by MATCH for the gridboxes closest to the path of the trajectory (full line). The middle panel shows the surface flux of CO_2 in the gridboxes closest to the trajectory (unit: μmol m^{-2} s^{-1}). The lower panel shows CO_2 mixing ratios calculated by MATCH in the gridboxes closest to the trajectory vertically interpolated to the height of the trajectory (unit: μmol mol^{-1}).

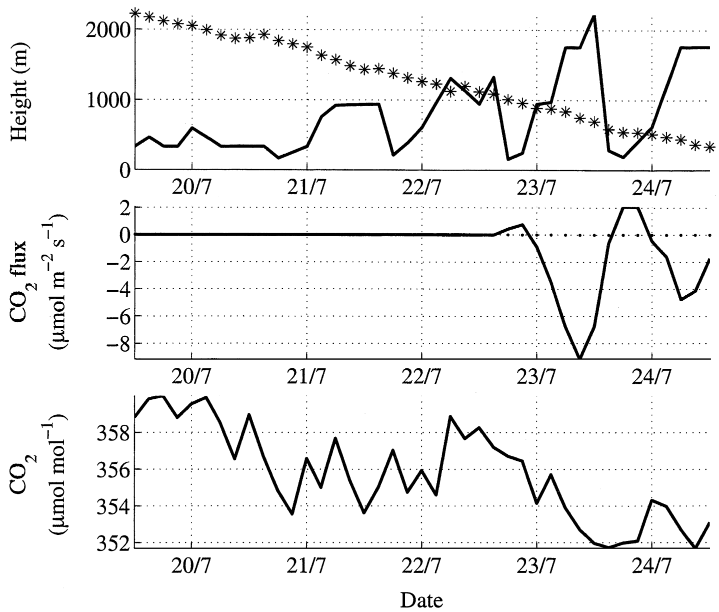

Fig. 9. As Fig. 8, but for the trajectory arriving at 950 hPa.

1000 km away from the observational site. Finally, it should be noted that this method of studying air mass history using trajectories is connected with uncertainties, since the trajectories are uncertain, especially when they have been in contact with the PBL (Stohl, 1998).

The period 22–24 July was studied at Zotino during an intense campaign by sampling from aircraft (Lloyd et al., 2002). In all there are six vertical profiles during these days (Fig. 6). During this period the model is able to simulate the local PBL height in a realistic way (Table 1). Also the simulated surface fluxes at Zotino are close to the observations during this period (Fig. 3). Taken together this good agreement between model and observed meteorology and fluxes leads to an overall good agreement also between observed and simulated CO_2 mixing ratios close to Zotino (Figs. 5 and 6). It is clearly seen in Fig. 6 that the model captures the main features, i.e. the depletion of CO_2 in the PBL and the higher mixing ratios aloft. The morning of 24 July is an exception. At this time, the model overestimates the boundary layer height (Table 1) and the respiration is too low, resulting in underestimated CO_2 mixing ratios. Apart from this kind of discrepancy there is still a high degree of variability in the observations that is not captured in the model (Fig. 10). Further, it should be mentioned that even though there was a large effort in collecting profiles at a rather high intensity the anomaly discussed in the previous paragraph is almost absent in the observational data. There is an indication of a local reduction in CO_2 at the highest altitude during the last flight prior to the event (Fig. 10). This example illustrates that if these kinds of anomalies on the regional scale are to be detected with representative data the sampling frequency of vertical profiles must be at least once a day.

The shape of a vertical profile simulated by MATCH depends on the underlying assumptions in the model, both regarding meteorology and fluxes. We have performed several sensitivity runs to check model performance. It is found that the highest sensitivity is found for surface fluxes of CO_2; doubling the fluxes leads to significantly different vertical profiles. A 100% change in fluxes at all locations during the whole period is not realistic, but a 20% change could be motivated taking uncertainties in the TURC model and our inferred diurnal variation into account. Such a 20% change in emissions will in this particular case lead to changes in PBL CO_2 mixing ratios of about 1–2 μmol mol^{-1}. Similar differences were found for runs in which we changed the degree of mixing within the boundary layer by a factor two. The relative difference in response to changes in surface fluxes and meteorological parameterisations implies that our results are much more sensitive to CO_2 surface fluxes than to the boundary-layer parameterisation.

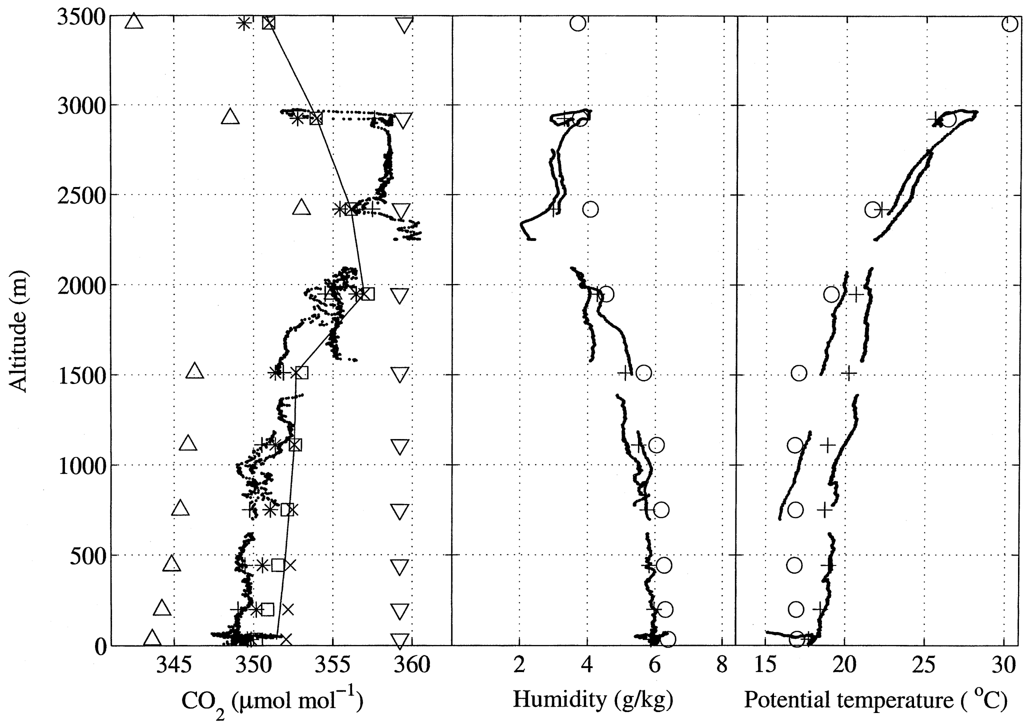

Fig. 10. Vertical profiles of CO_2 (μmol mol^{-1}), specific humidity (g kg^{-1}) and potential temperature (°C) at Zotino (60.5°N, 89.4°E) at 12.00 UTC 24 July 1998: (●) Observations (Lloyd et al., 2002); (+) averages of the observations in layers corresponding to the model levels; (○) ECMWF data for humidity and temperature. CO_2 profiles are from simulations with (—) the reference case, (∇) no internal sources, (△) terrestrial surface fluxes increased by 100%, (∗) surface fluxes increased by 20%, (□) the degree of mixing in the PBL reduced to 50% and (×) the degree of mixing in the PBL increased with 100%.

A difference in mixing ratio of 1–2 μmol mol^{-1} is large in comparison to instrument accuracy and precision. It is, however, a deviation that is too small for quantitative conclusions in a model of this resolution. A much larger uncertainty than the instrumental errors emanate from sample representativity and model resolution questions. From the variability in the measured profiles we see variations of order 1 μmol mol^{-1} within the "well mixed" boundary layer. Whether this is due to incorrect diagnosis of the depth of the boundary layer or if it is real internal variability has no implication for this discussion: the current model resolution requires larger deviations for firm conclusions.

3.6. Detecting signals in CO_2

The terrestrial CO_2 signal from the surface fluxes in the model domain is calculated as the difference between a run with the terrestrial sources and sinks included compared to a run with no internal sources and sinks of CO_2 (i.e. only the lateral boundaries from TM3 are used). In this run, without internal sources and sinks, the simulated variability at Zotino and Fyodorovskoye is very low. Day-to-day variations at these two stations are less than 1 μmol mol^{-1} during the entire simulation. Also, the vertical profiles show very small vertical gradients in the lowest few kilometres (Fig. 10). The externally generated signal is small also at higher altitudes. In the mid- and upper troposphere, variability is larger than in the PBL, but still the anomalies are only of the order 1–2 μmol mol^{-1}. This experiment tells us that the large variability seen in the reference case is to a great extent a result of the surface fluxes within the model domain.

The variability of CO_2, exemplified by the standard deviation from the monthly average in Table 2, is compared to the terrestrial signal defined above. We calculate a signal-to-noise ratio (SNR) as the ratio of the monthly average terrestrial signal defined above and

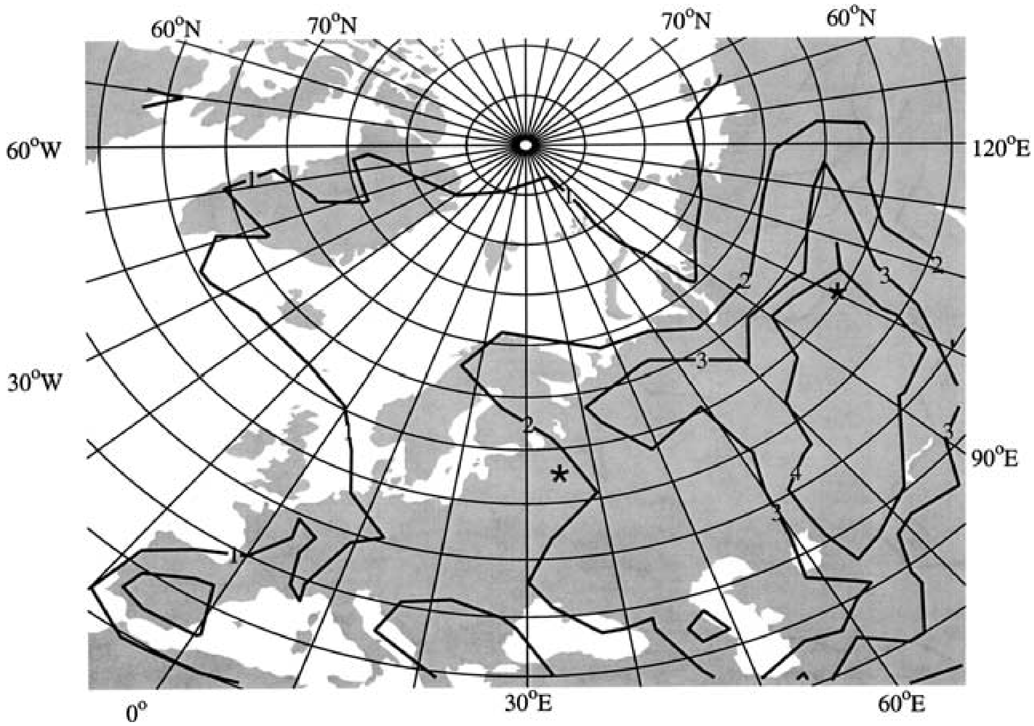

Fig. 11. Signal-to-noise ratio (SNR) at model level five (approximately 900 hPa) for July 1998. The SNR is calculated as the difference between the reference simulation including terrestrial sources/sinks and a simulation without, divided by the standard deviation of the run including the terrestrial sources/sinks. Stars denote the location of the EUROSIB stations Zotino and Fyodorovskoye. Isolines are 1, 2, 3, and 4.

the standard deviation from the monthly average in the reference run. The SNR is highest at levels close to 900 hPa. At these levels the high-frequency noise due to the diurnal variation of CO_2 close to the ground is filtered out, and at the same time the terrestrial signal is strong. A similar vertical pattern with a small diurnal variability a few hundred metres above the surface was also found by Bakwin et al. (1998) from measuring CO_2 at two high (more than 400 m) towers in the USA. The simulated vertical structure of the SNR implies that the terrestrial signal should be searched for in the PBL, excluding the lowest few hundred metres, rather than in the free troposphere. However, there is a problem with this interpretation: the model does not capture all the variability that is present in the real atmosphere. For example, the resolution (horizontal, vertical, and temporal) is too coarse to resolve small-scale phenomena. The inherent variability in the real atmosphere will lead to a smaller chance of finding a high SNR in the planetary boundary layer than that indicated by the present study.

Further, there are geographical and temporal differences in the SNR. This is illustrated in Fig. 11, which shows this ratio for July 1998 at model level 5 (corresponding to 900 hPa), the level that shows the highest SNR in the simulations. It is clearly seen that the SNR is highest in a region east of 60°E and south of 60°N. During this particular month the terrestrial signal should be easy to detect in this area since the SNR is four or even more. The pattern of the SNR is highly dependent on surface fluxes and meteorology. Similar fields from August 1998 show a completely different pattern (Fig. 12). First of all the signal is much weaker, depending on the smaller surface fluxes during August. Further, the pattern for August is much patchier, with relatively large SNRs in several different areas including the Arctic.

In the previous paragraphs detection of the entire terrestrial signal generated by internal sources and sinks is discussed. A more difficult problem is to detect changes in the terrestrial signal (e.g. interannual variability in surface fluxes). Therefore we perform a

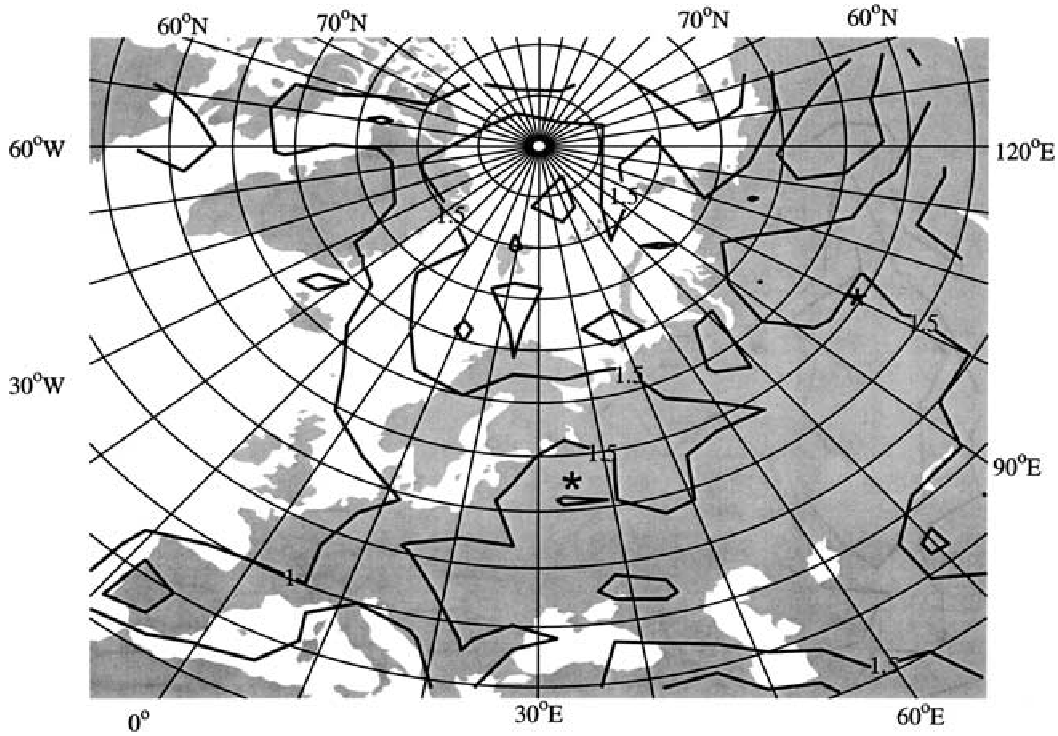

Fig. 12. As Fig. 11, but for August 1998. Isolines are 1, 1.5, and 2.

sensitivity test in which all the surface fluxes were increased by 20% in the entire domain during the whole simulation. This increase leads to a larger signal but also to a larger noise. If we now want to detect the signal generated by this 20% increase in the fluxes we can compare results from the reference case with results from this sensitivity run in a similar way to that shown in Figs. 11 and 12. The pattern of SNR (now defined as the ratio of the 20% increase in the terrestrial signal to the standard deviation) is the same but the values reduce to one fifth of the values in Figs. 11 and 12. Therefore, this change will be difficult to detect on a monthly basis. The highest SNRs are of the order of one. In August the signal would not be detectable, since the SNR is everywhere lower than one.

4. Conclusions

We have shown that the regional transport model MATCH, given appropriate boundary conditions, is able to simulate CO_2 and meteorological conditions over Europe and Siberia for a summer period in 1998. In particular, we find that the modelled temperature and humidity are consistent with the measurements at Fyodorovskoye and Zotino. Also simulated planetary boundary layer height is in reasonable agreement with observations. Exceptions are during some stable conditions, when MATCH either over- or underestimates the planetary boundary layer height by as much as a factor three. We find that the diurnal amplitude of the lowest model layer CO_2 mixing ratio is sometimes small compared to the ground-based observations. This too small simulated amplitude is attributed either to a too small diurnal variability in the modelled surface fluxes, or, during some occasions with a stable planetary boundary layer, to an unrealistic representation of boundary layer height. Other possible reasons can be a mismatch between the lowest model layer and the observation level, a too rapid model mixing between the lowest model levels, or unresolved features of the real atmosphere.

We have used MATCH to investigate temporal and spatial variability of CO_2 and have shown that synoptic events (fronts) transport pulses of air into upper layers that have complicating characteristics that render interpretation of single CO_2 profiles unwieldy. These pulses, which consist of different volumes of air with different geographic origins, show CO_2 mixing ratios that differ by event. Also, we point out that the times the volumes spend in contact with the surface also differ with event as well as the surface fluxes during these contact episodes. The observed vertical profiles of CO_2 contain features showing that the model results presented above have relevance in the real atmosphere. Our study of these pulses shows that there is no ideal level of sampling for the "regional footprint". Vertical profiles are therefore required frequently and at a high spatial resolution. The temporal and spatial scales are governed by meteorological variability as well as CO_2 flux heterogeneity, and will vary between regions and seasons. Judging from synoptic scale meteorology these temporal and spatial scales appear to be a few days or shorter and a few hundred kilometres or less.

It is shown that the modelled CO_2 variability in the lowest model layers is controlled by internal processes (e.g. surface fluxes), with little influence from the boundaries of the model region. Also, we show that the modelled vertical profiles are only weakly sensitive to changes in the parameterisation of the boundary layer vertical mixing (1 μmol mol^{-1}in the bottom layer for 100% perturbations, which is small compared to the measured variability). Finally, it is shown that the difference between modelled and measured vertical profiles of CO_2 is not significantly altered by 20% alterations of the modelled surface fluxes. It is illustrated that such an alteration in surface fluxes will give signals that differ geographically and temporally. The ability to detect such a signal on a monthly basis is low in the entire model domain, since the simulated internal variability in MATCH is large. The low degree of detectability is most pronounced in the free troposphere, where the signal is weak and the variability is high.

5. Acknowledgements

This work is part of the EUROSIB project, and we are grateful to collaborators who have provided data: in particular, Martin Heimann for boundary data from the TM3 model, and Sebastien Lafont for surface fluxes from the TURC model, and Michel Ramonet and Jon Lloyd, who provided vertical profiles from Fyodorovskoye and Zotino respectively. Ray McGrath at the Irish Meteorological Service is acknowledged for practical help and permission to use the software needed to calculate the trajectories. ECMWF is acknowledged for providing the meteorological data through the MARS facility.

REFERENCES

Arneth, A., Kurbatova, J., Kolle, O., Shibistova, O., Lloyd, J., Vygodskaya, N.N. and Schulze, E.-D. 2002. Comparative ecosystem–atmosphere exchange of energy and mass in a European Russian and central Siberian bog. II. Interseasonal and interannual variability of CO_2 fluxes. *Tellus* **54B**, this issue.

Bakwin, P., Tans, P., Hurst, D. and Zhao, C. 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus* **50B**, 401–415.

Brandefelt, J. and Holmén, K. 2001. Anthropogenic and biogenic winter sources of Arctic CO_2 – a model study. *Tellus* **53B**, 10–21.

Chevillard, A., Karstens, U., Ciais, P., Lafont, S. and Heimann, M. 2002. Simulation of atmospheric CO_2 over Europe and Siberia using the regional scale model REMO. *Tellus* **54B**, this issue.

Ciais, P., Cramer, W., Jarvis, P., Khesgi, H., Nobre, C., Semenov, S. and Steffen, W. 2000. Global Perspective. In: *Land use, land-use change, and forestry* (eds. R. Watson, I. Noble, B. Bolin, N. Ravindranath, D. Verardo and D. Dokken). Integovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Engardt, M. and Holmén, K. 1996. Towards deducing regional sources and sinks from atmospheric CO_2 measurements at Spitsbergen. *Phys. Chem. Earth* **21**, 523–528.

Engardt, M. and Holmén, K. 1999. Model simulations of anthropogenic CO_2-transport to an Arctic monitoring station during winter. *Tellus* **51B**, 194–209.

Falkowski, P., Scholes, R.J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., Mackenzie, F. T., Moore, B. III, Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetack, V. and Steffen W. 2000. The global carbon cycle: A test of our knowledge of earth as a system. *Science* **290**, 291–296.

Heimann, M. and Keeling, C. D. 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds: 2. Model description and simulated tracer experiments. In: *Aspects of climate variability in the Pacific and the western Americas* (ed. D. H. Peterson). American Geophysical Union, Washington, DC, 237–275.

Kurbatova, J., Arneth, A., Vygodskaya, N. N., Kolle, O., Varlagin, A. B., Milyukova, I. M., Tchebakova, M. M., Schulze, E.-D. and Lloyd, J. 2002. Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. I. Interseasonal and interannual variability of energy and latent heat fluxes during the snow-free period. *Tellus* **54B**, this issue.

Lafont, S., Kergoat, L., Dedieu, G., Chevillard, A., Karstens, U. and Kolle, O. 2002. Spatial and temporal variability of land CO_2 fluxes estimated with remote sensing and reanalysis data over western Eurasia. *Tellus* **54B**, this issue.

Langner, J., Robertson, L., Persson, C. and Ullerstig, A. 1998. Validation of the operational emergency response model at the Swedish meteorological and hydrological institute using data from ETEX and the Chernobyl accident. *Atmos. Environ*. **32**, 4325–4333.

Lloyd, J., Langenfelds, R., Francey, R. J., Gloor, M., Tchebakova, N., Zolotukhine, D., Brand, W., Werner, R., Jordan, A., Allison, C., Zrazhewske, V., Shibistova, O. and and Schulze, E.-D. 2002. A first trace gas climatology above Zotino, central Siberia. *Tellus* **54B**, this issue.

McGrath, R. 1989. Trajectory models and their use in the Irish Meteorological Service. Irish Meteorological Service, Glasnevin Hill, Dublin, International Memorandum No. 112/89, 12 pp.

Milyukova, I., Kolle, O., Varlagin, A., Vygodskaya, N., Schulze, E.-D. and Lloyd, J. 2002. Carbon balance of a southern taiga spruce stand in european Russia. *Tellus* **54B**, this issue.

Ramonet, M., Ciais, P., Nepomniachii, I., Sidorov, K., Neubert, R., Picard, D., Kazan, V., Biraud, S., Kolle, O., Schulze, E.-D. and Lloyd, J. 2002. Diurnal variability of trace gases above the Fyodorovskoye site, derived from intense airborne campaigns. *Tellus* **54B**, this issue.

Raynaud, D., Jouzel, J., Barnola, J. M., Chappellaz, J., Delmas, R. J. and Lorius, C. 1993. The ice record of greenhouse gases. *Science* **259**, 926–934.

Robertson, L., Langner, J. and Engardt, M. 1996. *MATCH – Meso-scale Atmospheric Transport and Chemistry modelling system. Basic transport model description and control experiments with* ^{222}Rn. Swedish Meteorological and Hydrological Institute, RMK No. 70, 37 pp.

Robertson, L., Langner, J. and Engardt, M. 1999. An Eulerian limited-area atmospheric transport model. *J. Appl. Meteorol*. **38**, 190–210.

Seibert, P., Beyrich, F., Gryning, S.-E, Joffre, S., Rasmussen, A. and Tercier, P. 2000. Review and intercomparison of operational methods for the determination of the mixing height. *Atmos. Environ*. **34**, 1001–1027.

Stohl, A. 1998. Computation, accuracy and applications of trajectories – a review and bibliography. *Atmos. Environ*. **32**, 947–966.

Styles, J., Raupach, M., Farquhar, G., Kolle, O., Lawton, K., Brand, W., Werner, R., Jordan, A., Schulze, E.-D., Shibistova, O. and Lloyd, J. 2002. Soil and canopy CO_2, $^{13}CO_2$, H_2O and sensible heat flux partitions in a forest canopy inferred from concentration measurements. *Tellus* **54B**, this issue.

Tchebokova, N., Kolle, O., Zolotoukhine, D., Arneth, A., Styles, J., Vygodskaya, N. N., Schulze, E.-D., Shibistova, O. and Lloyd, J. 2002. Interannual and seasonal variations of energy and water fluxes above a Siberian pine forest. *Tellus* **54B**, this issue.