Influence of CO_2 fluxes in a coupled mesoscale land surface and atmospheric model system

Markus Uebel and Andreas Bott

University of Bonn, Meteorological Institute, *email:* markus.uebel@uni-bonn.de

Meteorological Institute
University Bonn

TR32

universitätbonn

1) Motivation

For a precise numerical weather prediction an accurate simulation of the interaction of the land surface with the lower atmosphere plays a major role. Thus, we use the coupled model system "TerrSysMP" (Fig. 1) to calculate the exchange between the soil, the vegetation and the atmosphere. TerrSysMP consists of the numerical weather prediction model (NWP) ***COSMO*** that is coupled with the Community Land Model (***CLM***) via the external coupler *OASIS*.

Field measurements on the regional scale indicate distinct spatio-temporal heterogeneities in the distribution of atmospheric carbon dioxide (CO_2). This variability induces a direct response on the stomata of plants which regulate canopy transpiration – an important water vapor flux that controls moisture in the atmospheric boundary layer (ABL). For a consistent representation of the partitioning of sensible and latent heat fluxes, natural CO_2 fluxes – calculated in CLM – are used to update the atmospheric CO_2 concentration. These CO_2 fluxes consist of photosynthesis **A** as atmospheric sink as well as plant and soil respiration (**R_{plant}** and **R_{soil}**) as atmospheric source of CO_2 (Fig. 2). Additional to these natural fluxes anthropogenic emissions influence the patterns of atmospheric CO_2 and are included in the model system. With this treatment CO_2 is a prognostic variable in TerrSysMP and directly contributes to the calculation of canopy processes.

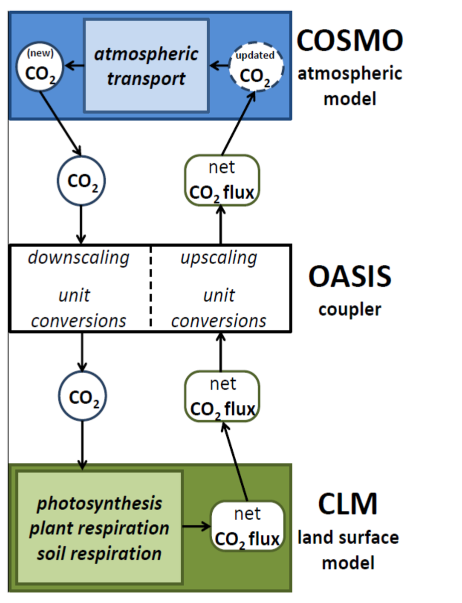


Fig. 1: Model system „TerrSysMP"

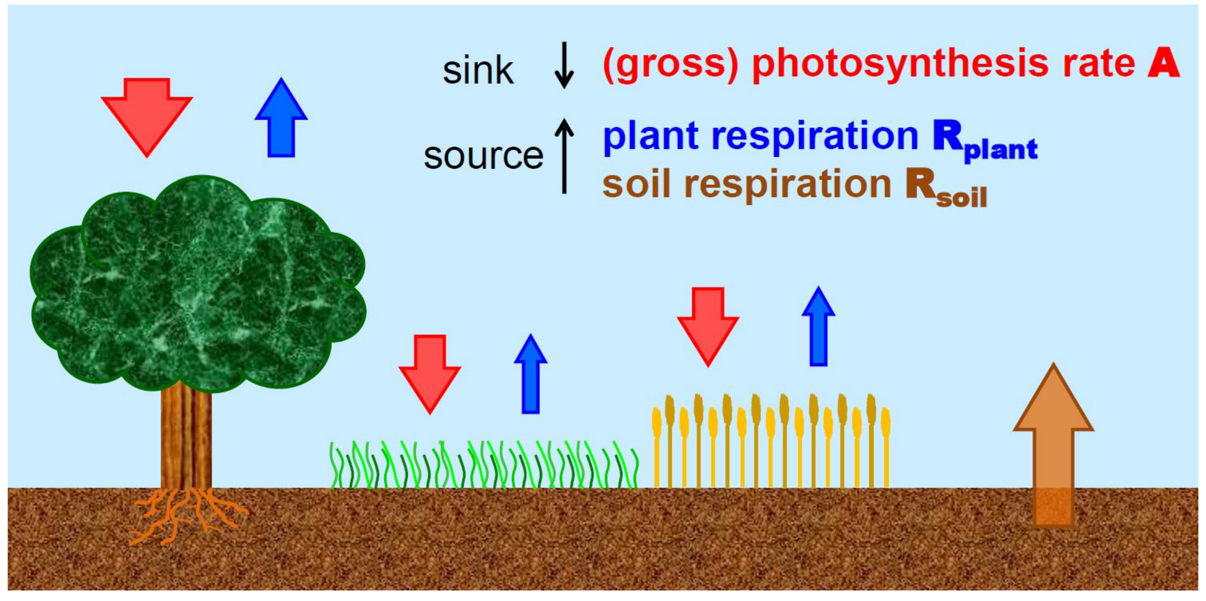
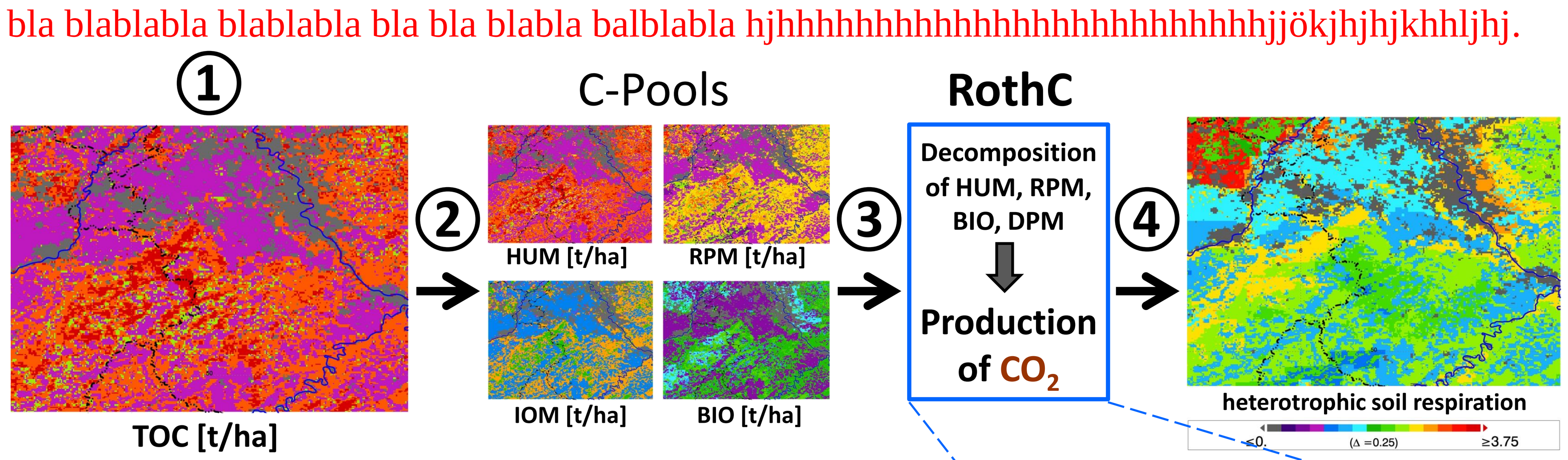


Fig. 2: Natural CO_2 fluxes between the land surface and the atmosphere

2) Soil respiration

<u>**Soil respiration**</u> **R_{soil}** consists of <u>heterotrophic</u> (microbial) and <u>autotrophic</u> (root/rhizosphere) respiration. For calculation of heterotrophic respiration we included the carbon turnover model **RothC-26.3** (Coleman and Jenkinson, 2008) in CLM. For autotrophic respiration … blablabla bla bla blablabla blablabla bla bla blabla balblabla hjhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhjjökjhjhjkhhljhj.



<u>Method:</u>

① Determination of **total organic carbon (TOC)** depending on plant type using measurements

② Splitting of TOC in **C-Pools** (humified organic matter [HUM], resistant plant material [RPM], microbial biomass [BIO], inert organic matter [IOM]) with <u>pedotransfer functions</u> (**PTFs**) (Weihermüller et al., 2013)

③ Calculation of **CO_2 production** with <u>RothC-26.3</u> using characteristic decomposition rates of each C-pool (Fig. 3)

④ **heterotrophic respiration** as sum of CO_2 production of every CLM soil level

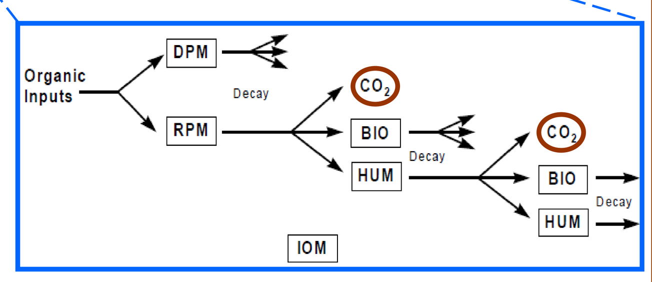


Fig. 3: Structure of the RothC-26.3 model

3) Canopy processes

The <u>**photosynthesis rate**</u> **A** and **transpiration TP** is controlled by the „stomatal resistance" r_{st} which describes the permeability of leaves (Fig. 4):

$$\frac{1}{r_{st}} = \frac{A}{c_s}\frac{e_s}{e_i^*}P_{atm} + b$$

e_i^* water vapor saturation pressure inside the leaf
b minimum stomatal conductance
V_{cmax} maximum rate of carboxylation

<u>**Plant respiration**</u> through leaves:

$$R_{plant} = 0.015 V_{cmax}$$

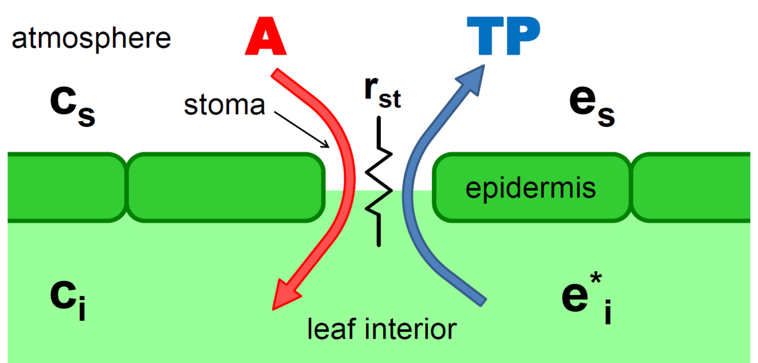


Fig. 4: Transpiration and CO_2 uptake through leaf stomata (leaf cross section)

Upscaling from leaf to canopy is performed in CLM with a canopy integration scheme using sunlit and shaded LAI.

<u>Coupling of CO2 fluxes:</u>

atmospheric pressure	$P_{atm}(lat,lon,t)$	**prognostic** (atmospheric forcing variables)
water vapor pressure at leaf surface	e_s (lat,lon,t)	
CO_2 partial pressure at leaf surface	c_s (lat,lon,t)	

Coupling of CO_2 fluxes → lower atmospheric CO_2 compared with constant CO_2 (see Fig. 7c)
→ **decrease** of **photosynthesis** → **decrease** of r_{st} (opening of stomata) → **increase** of **transpiration**

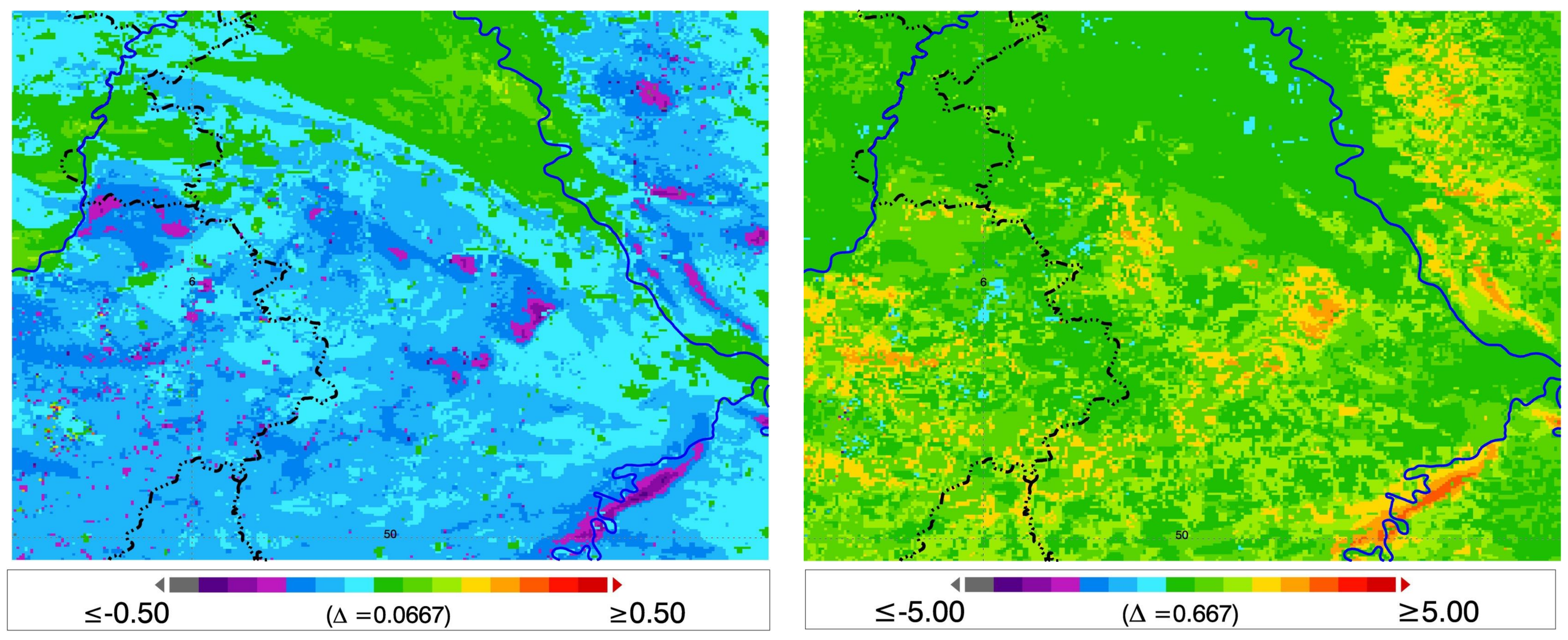


Fig. 5: Reaction of plant processes on variable atmospheric CO_2: difference of photosynthesis [μmol(CO_2)m^{-2}s^{-1}] **(a)** and transpiration [Wm^{-2}] **(b)** between constant CO_2 [*reference*] and prognostic CO_2 [*coupling*]: 08.05.2008, 09 UTC [see box "Case Study" in 4)]

4) CO_2 in the atmosphere

Atmospheric processes are simulated with the non-hydrostatic NWP model **COSMO** of the German Meteorological Service (DWD). We perform <u>mesoscale weather predictions</u> (grid resolution: **1 km**) for western Germany (area: **150×150 km**). The boundary values are provided by a nesting of TerrSysMP (grid resolution: 2,8 km) over Central and Western Europe.

Budget equation:

$$\underbrace{\frac{\partial(q_{CO_2})}{\partial t}}_{\text{local tendency}} + \underbrace{\boldsymbol{v}\cdot\nabla(q_{CO_2})}_{\text{advection}} = \underbrace{S^{CO_2}}_{\text{source sink}} + \underbrace{M^{CO_2}}_{\text{subgrid scale processes}}$$

- inclusion of a <u>**passive**</u> **tracer** in COSMO needed for the atmospheric transport of CO_2
- S^{CO_2} consists of natural sources/sinks (A, R_{plant}, R_{soil}) and <u>anthropogenic emissions</u>
- coupling with CLM → atmospheric CO_2 becomes <u>**active**</u> (e.g. modified atmospheric moisture with variable CO_2)

➢ Anthropogenic emissions:

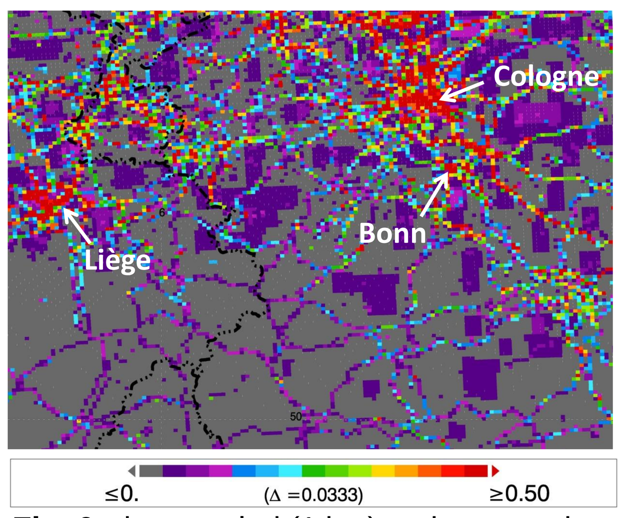
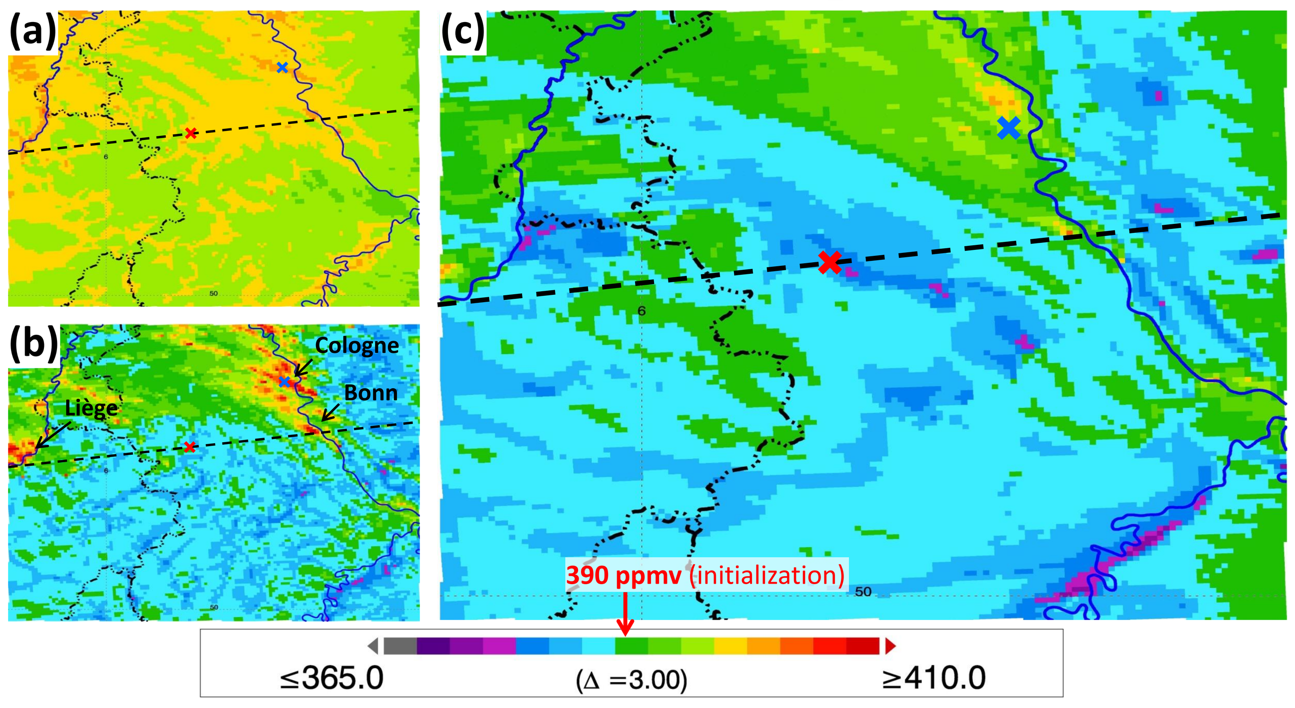


Fig. 6: downscaled (1 km) anthropogenic CO_2 emission (sum of all snap codes) [mg m^{-2} s^{-1}]: 08.05.2008, 17 UTC

- use of **CO_2 emission** data classified in <u>10 snap codes</u> (yearly emissions) provided by the TNO, Netherlands
- **downscaling** of the data (14 km resolution) to a 1 km grid with geographical information on the responsible source of emitted CO_2 (e.g. motorway network, industry, urban areas)
- calculation of <u>**hourly**</u> **emissions** for each snap code depending on month, weekday and hour of the day (e.g. more domestic heating during winter, rush-hour, …)
- inclusion of **hourly emissions** (Fig. 6) as **CO_2 source** in the COSMO model

➢ Simulation of atmospheric CO_2 with TerrSysMP:



Case Study: 08.05.2008

- fair weather conditions, cloud free
- initialisation with **390 ppmv** in all COSMO levels
- <u>reference:</u> constant CO_2 ($S^{CO_2} = 0$)
- <u>coupling:</u> coupling of **A**, **R_{plant}**, **R_{soil}**, hourly anthropogenic emissions → CO_2 **prognostic**

Fig. 7: CO_2 concentration [ppmv] in COSMO (surface layer): **(a)** 04 UTC, **(b)** 06:30 UTC, **(c)** 09 UTC (*dashed*: line of cross section, *red/blue cross*: land/urban vertical profile)

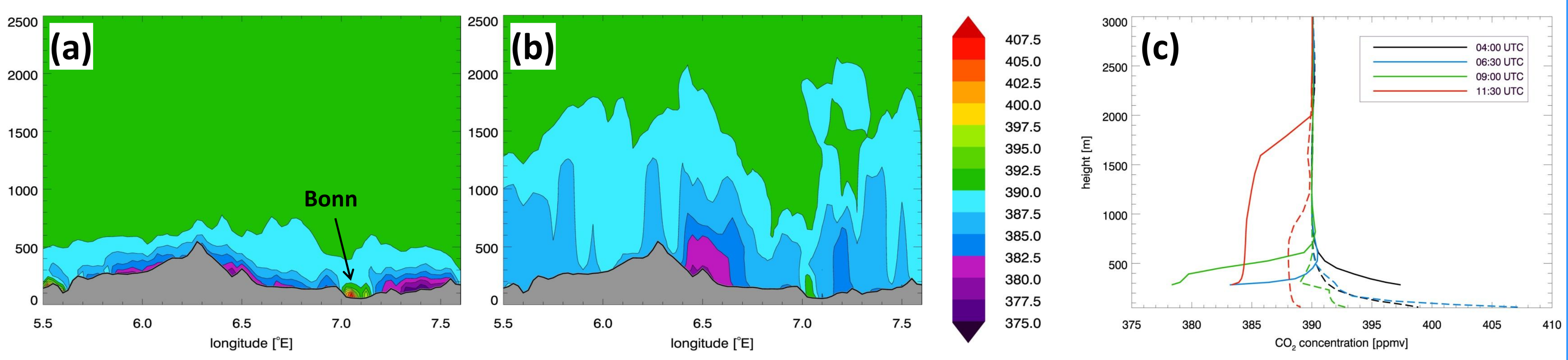


Fig. 8: (a,b) vertical cross section of CO_2 [ppmv] in COSMO (07:30 UTC, 10:00 UTC), **(c)** vertical CO_2 profiles [ppmv] at different times on a land (*continuous, red cross*) and urban grid point (*dashed, blue cross*)

- heterotrophic **soil respiration** <u>during night</u> → **increase** of near-surface CO_2 (Fig. 7a, 8c)
- **photosynthesis** <u>after sunrise</u> → strong **decrease** of CO_2 in vegetated areas (Fig. 7b, 8a,c) <u>rush-hour</u> (**CO_2 emissions**) in the morning → strong **increase** of CO_2 in urban areas (Fig. 7b, 8a,c)
- **rising of the ABL** <u>durning the morning</u> → turbulent mixing of decreased CO_2 to higher atmospheric levels (Fig. 8b,c); smoothing due to **advective transport** with the wind (Fig. 7c)

→ *<u>horizontal variability of CO_2:</u> result of plant type depending net CO_2 flux and atmospheric transport*

5) Summary and Outlook

The coupling of the net CO_2 flux (**A**, **R_{plant}**, **R_{soil}**) with the COSMO model and anthropogenic emissions simulate <u>heterogeneity</u> in the near-surface atmospheric CO_2 concentration. Turbulent mixing generates <u>diurnal variations</u> in the vertical distribution of CO_2 in the ABL and together with advective transport the measured CO_2 patterns can be simulated using TerrSysMP. This variability has a direct effect on the stomatal resistance and, thus, results in <u>modified photosynthesis</u> and <u>transpiration</u> rates.

<u>Outlook:</u>

- **Sensitivity studies** with TerrSysMP under different <u>weather situations</u> and in different <u>seasons</u> to analyze the atmospheric vaiabilty of CO_2 and its influence on plant processes
- Investigation of the influence of modified heat and moisture fluxes on moisture content in the ABL
- **Validation** of model results with a measured <u>vertical CO_2 profile</u> at a tower (120m) and with <u>horizontally</u> distributed EC stations at different land use formes

<u>Conclusion:</u>

Atmospheric CO_2 variability caused by natural CO_2 fluxes at the surface and anthropogenic emissions is an important controlling factor – also on temporal scales of weather predictions!

Acknowledgments:

The authors thank the German Meteorological Service (DWD) for providing the COSMO model and the analysis data needed for driving the model. We gratefully acknowledge financial support from SFB/TR32 "Patterns in Soil-Vegetation-Atmosphere Systems: Monitoring, Modelling and Data Assimilation" funded by the Deutsche Forschungsgemeinschaft (DFG). www.tr32.de

Literature:

Baldauf, M. et al. (2011). "Operational convective-scale numerical weather prediction with the COSMO model: Description and sensitivities". In: *Mon. Wea. Rev., 139, pp. 3887-3905*

Coleman, K. and D. Jenkinson (2008). "RothC-26.3. A model for the turnover of carbon in soil. Technical Report, IACR-Rothamsted, Harpenden URL: http://www.rothamsted.ac.uk/aen/carbon/mod26_3_win.pdf

Weihermueller et al. (2013). "Simple pedotransfer functions to initialize reactive carbon pools of the RothC model". In: *European Journal of Soil Science*

Shrestha, P. et al. (2014). „Development of a Scale-Consistent Soil-Vegetation-Atmosphere Modeling System Using COSMO, CLM and ParFlow" (submitted)