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SNOWCARBO

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List of abbreviations

ECHAM5	European Centre Hamburg Model, a general circulation model
EO	Earth observation
GCM	General circulation model
FMI	Finnish Meteorological Institute
JSBACH	Jena Scheme for Biosphere-Atmosphere coupling in Hamburg, a model describing biosphere-atmosphere interaction
JSBACH-SA	A standalone version of JSBACH
LSS	Land surface scheme, a model accounting for atmosphere-surface interactions in the framework of earth system models, typically with detailed description of vegetation processes such as protosynthesis
MPI-M	Max Planck Institute for Meteorology, Hamburg, Germany
NEE	Net ecosystem exchange of CO2
RCM	Regional climate model

REMO RCM of MPI-M

SYKE Finnish Environment Institute

1 Introduction

In Snowcarbo a regional climate model (RCM) REMO (Regional MOdel) with a land surface scheme (LSS) JSBACH are used for estimating present day carbon dioxide (CO2) balance of Northern areas. The goal of the project is to improve the model predictions facilitating a variety of earth observation (EO) and *in situ* data in constraining and calibrating the models. The core region for which the most extensive set of model simulations and evaluations of model performance will be carried out covers Scandinavia and Baltic countries. However, as the available EO data covers northern Eurasia in whole, the ultimate aim of the project is to provide insight into the quality of the CO2 balance predictions of the Northern Hemisphere. The climate and earth ecosystem models of Max Planck Institute for Meteorology (MPI-M) are used for climate and CO2 exchange simulations in this project. JSBACH model was developed from a vegetation model BETHY into a LSS of general circulation model (GCM) ECHAM. REMO in its present form lacks a LSS capable of simulating CO2 cycle. Thus JSBACH will be used for predicting the terrestrial CO2 exchange with REMO. For simulation for this project REMO and JSBACH will be coupled offline so that REMO feeds JSBACH with climatic driving data but does not receive any feedback from JSBACH. However, in a consequent REMO simulation JSBACH CO2 flux rates together with information on anthropogenic and ocean CO2 source strengths are utilized to produce the CO2 concentration fields. In this documentation the modeling framework and the applied coupling schemes will be described. Furthermore, the sequence of model runs together with facilitation of the EO data and the approach for the evaluation of the results will be discussed. Especially, all the revisions in the modeling framework since the 1st Progress Report on Methodology will be scrutinized.

2 Models

The COSMOS model family climate models developed at MPI-M are used to simulate past present and future climates over wide range of spatial resolution. Their applications include weather forecasting, analyzing the climate system and projecting climate change. Physical core of these models is Navier-Stokes equation on a rotating sphere with consideration of the relevant energy sources, such as radiation or latent heat, by means of inclusion of appropriate thermodynamic terms. These equations are derived for suitable temporal and spatial resolution using boundary and initial conditions representative for the actual research problem. A regional model REMO (Majewski,1991; Jacob 2001) and a biosphere model JSBACH (Raddatz et al. 2007) are used in this work. As JSBACH is originally a LSS of the general circulation model ECHAM (Roeckner et al. 2003) and because ECHAM can be in further applications used as a boundary data for our modeling framework, it will be briefly introduced in the following in addition to REMO and JSBACH.

2.1 ECHAM

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ECHAM has its origin in global forecast model developed at European Centre for Medium-Range Weather Forecasts (ECMWF). The model has been further modified for climate research. ECHAM is a comprehensive GCM of the atmosphere and together with the LSS JSBACH the coupled system describes terrestrial surface-atmosphere interactions including CO2 cycle. For present day simulations ECHAM is typically driven with sea surface temperature (SST) and does not consequently predict actual weather conditions but rather the prevailing climate. For climate predictions the modeling framework can further be coupled with a model describing general circulation of the oceans. Such a fully coupled comprehensive system is called an earth system model. ECHAM requires as input atmospheric concentration of greenhouse gases and areal fields of orography and land cover type that further determines the surface parameters such as surface albedo, leaf area index and vegetation ratio. When JSBACH is used as LSS of ECHAM, the above listed surface parameter fields are handled within JSBACH.

2.2 REMO

REMO is a RCM that derives from the operational weather forecast model of the German weather service (DWD), thus it has been thoroughly evaluated for its capability to predict the synoptic scale meteorological phenomena. It can be driven in climate mode and in forecast mode which differ in their boundary data requirements and to some degree in their ability to reproduce actual weather conditions. The description and application of these modes in this project are given in Chapter 7. As the model does not presently consider ecosystem processes implicitly, the LSS JSBACH is used to simulate CO2 exchange in the present work.

Surface characteristics which are constant in time are orography, surface roughness length, land-sea mask and soil field capacity. Monthly varying parameters are surface background albedo, vegetation fraction and leaf area index (LAI). REMO uses a fractional surface coverage *i.e.* each grid box can contain a land, a water and a sea ice fraction. The large scale forcing fields are atmospheric variables and surface variables such as surface temperature, soil temperatures, soil wetness and snow depth. The first mentioned surface characteristics as well as the boundary and forcing variables are provided for the model as gridded parameter fields.

The above mentioned surface parameter values are allocated according to the surface cover class that gives areal information about the prominent vegetation type or, in the absence of vegetation, other characterization of land surface cover, such as desert or city, or a characterization of water surface, such as lake or ocean. In standard model versions the surface cover data is adopted from a global 1km resolution land cover dataset by Hagemann et al. (1999, 2002) that is classified according to Olson (1994a, 1994b) dataset constructed by the U.S. Geological Survey (1997, 2002). This is essentially the same data that ECHAM uses for its surface maps. The land cover classes are unambiguously related to following parameters: background surface albedo, fractional vegetation cover, leaf area index (LAI), forest ratio, roughness length, and soil water holding capacity.

2.3 JSBACH

The role of a LSS is to 1) provide the lower boundary condition to the atmosphere for the vertical diffusion scheme (turbulent exchange of heat, moisture, momentum and passive tracers); 2) radiation scheme (short-wave, long-wave radiation fluxes) and 3) hydrological cycle (moisture flux) such that the surface energy and water balance are closed. The model treats the water cycle of vegetated areas by considering the physiological response of vegetation to the climatic variables. This requires taking into account the resistance for water vapor exchange due to functioning of water pathways within the plants. The most crucial control of water vapor exchange between the vegetation and the atmosphere – stomatal functioning – constrains the CO2 exchange as well. Thus a LSS, such as JSBACH, that simulates water and energy balances with a high degree of sophistication, is readily able to produce reliable CO2 exchange by vegetation. Additionally, in order to produce a reliable net ecosystem exchange (NEE) the allocation of carbon into various pools in soil and vegetation and the decomposition of these storages are described.

Vegetation has been divided into plant function type (PFT) classes who each has its own set of parameters. These parameters include *e.g.* PTF specific biochemical parameters, such as maximum carboxylation and electron transport rates and physical parameters such as albedos in visible and near infrared bands. In JSBACH the fractions of the four most prominent land cover types are given in each grid cell. This so called 'tile approach' is necessary in global scale as the grid cells are large and various PFTs play a role through highly nonlinear processes that cannot be fully represented by parameter aggregation.

3 Boundary and initial data

3.1 Land cover data

Both ECHAM and REMO use land surface parameter (LSP) dataset (Hagemann et.al., 1999, Hagemann 2002) based on Olson ecosystem classification (Olson 1994a; 1994b) as land cover map. Its spatial resolution is about 1 km and it consists of about 100 classes to whom a set of surface parameters is related. These parameters are background surface albedo α_s, surface roughness length due to vegetation $z_{0,veg}$, fractional vegetation cover c_v and leaf area index LAI for the growing (g) and dormancy season (d), forest ratio c_f, plant-available soil water holding capacity W_{ava}, and volumetric wilting point f_{pwp}.
The parameters allocated to each land cover class are further aggregated into surface boundary maps. The method of areal synthesis depends on the nature of the respective parameter. For instance a simple areal weighing cannot be applied to parameters that function through unlinear processes, such as aerodynamic roughness length that controls surface wind shear (see Hagemann et.al., 1999).
Aggregation of certain parameters is revised in Hagemann (2002). In the Nordic areas the standard aggregation of two parameters is modified to account for region specific vegetation and soil features. These two parameters are soil field capacity and fractional vegetation which is related to forest ratio. Soil field capacity is typically high in wide areas of forested wetlands in Finnish and Swedish Lapland, where the land cover is boreal coniferous forest whose allocated soil field capacity is 0.21 that is too low for the soils. Thus the value is overwritten with a constant value of 0.71 according to the distribution of class 15 of the FAO/Unesco soil type dataset (Hagemann 2002).
Vegetation cover and forest ratio of the Olson class Conifer Boreal Forest of Northern Europe are over-written with values 0.91 and 0.80, respectively, instead of their default values 0.52 and 0.46 (Hagemann 2002).

JSBACH can use the same land cover data as REMO but the handling of surface parameters deviate for some parts. Certain parameter fields, such as geopotential height or forest fraction, can be adopted as such from the aggregates produced for REMO. However, utilization of certain other parameters exploits the 'tile approach' (see previous chapter). In addition to providing the model with parameter fields as boundary data, the model is provided with a table of parameter values related to PFTs. These parameters are used in run-time according to the input parameter field that includes the PFT tiles. Thus no parameter aggregation is needed but the predicted variables are first computed for each tile separately and the results are consequently aggregated according to the tile fractions.

3.2 Coupling between a LSS and a climate model

Vertical diffusion is the process accounting for the matter and energy exchange between the atmosphere and the surface. The interaction between the climate model and a LSS can be either *implicit* or *explicit*. In an *implicit* coupling scheme, present values of climatic variables that control the surface processes are used, and the LSS is called in the vertical diffusion scheme. An *explicit* coupling approach uses the old values of the controlling climatic variables, and the LSS can be called anywhere in the GCM. Because vertical transfer coefficients are calculated in the LSS the surface energy balance stability is improved. The coupling between ECHAM5 and JSBACH is implicit.
In REMO the standard LSS is coupled implicitly as well but the LSS does not account for biophysical processes such as photosynthesis or decomposition of carbon in the soils. Thus, in order to estimate CO2 balance a standalone version of JSBACH is forced with climate variables produced by REMO. This is called an *offline run* where neither implicit nor explicit coupling between JSBACH and REMO takes place. Consequently, to evaluate the consistency between the models, it is necessary to estimate the differences in prediction of variables related to surface processes by both models. These variables include for instance sensible heat flux and components of water balance such as surface evaporation and snow depth.

3.3 Boundary and initial data use

Typically climate models have to be provided with various gridded data that serve as boundary and initial data fields for model runs. Especially a regional model requires an extensive set of driving data as it has to be frequently constrained from the domain boundaries. Boundary and initial data for climate models consist of 2D surface fields and 3D meteorological fields. The form and contents of 2D surface parameter fields that REMO and JSBACH require were described above. Additionally, when REMO is driven in a mode capable of carrying tracers (See Chapter 7 for description of the modeling framework) within the domain, the model has to be constrained with the boundary and initial fields of the tracer – in this study CO2. The sources of 2D and 3D meteorological and tracer flux and concentration data are given in the "*In situ* data document" (31/12/2009) of Snowcarbo project. In order to predict atmospheric radiative forcing due to absorbers, yearly series of green house gas (GHG) background concentrations are given to the climate model.

4 RCM specific features

4.1 Running modes

REMO can be run in *climate* and *forecast modes*. In the *climate mode* the model is constrained once in ignition of the simulation with initial 3D meteorological and tracer fields and after that it is only forced from domain boundaries while the climate and tracer concentrations within the domain are estimated by the model. In the *forecast mode* the model is continuously forced with the boundary data with typically daily ignition and a spin up of couple of hours. Because the spin up period is rejected, the daily runs overlap for a duration of the spin up. A run in *forecast mode* follows closer to the boundary data than a run in *climate mode*. Thus, as Snowcarbo aims at simulating actual climate, the *forecast mode* is used for production runs. However, for evaluation of model performance, a *climate mode* run is performed as well.

4.2 Restart

The forecast mode run is realized through a series of so called restarts. In such a restart every variable is initialized with the observed or modeled data fields and no history from the previous time-step is preserved. This procedure is also known as a cold start as opposed to a warm start where the modeled system has been spun up to an equilibrium. Consequently, this approach provides us with an easy way to force the climate model with gridded data from other work packages of this project. A restart can also use a model specific restart file as a starting point. The latter is a warm start providing that the restart file has been stored from a run that has reached an equilibrium.

4.3 Nesting

Because the gridded boundary and initial data fields for a RCMs have to be typically interpolated from observations or global model simulations, their quality is dependent on difference in resolutions between the regional and the global domain. In order to avoid effects due to distorted boundary data, the RCM runs are often performed in two steps: first the period of interest is simulated for a larger regional domain of intermediate resolution with a subsequent run in the smaller fine resolution domain of interest. This is called nesting. Nesting is not applied in the simulations for Snowcarbo. However, for further development of the modeling framework the quality of the model results will be evaluated also form this aspect.

5 Preprocessing of surface and climate data

All the data that REMO and JSBACH use have to be preprocessed from various data sources and data forms into the form applicable by the models. The project personnel possess the preprocessors for creating the REMO surface boundary maps (Fig 1) while the REMO climate data has been produced in MPI. Due to the tile approach applied in JSBACH the preprocessing differs from that of REMO's. However, as many of the parameters of the two models are equal their consistency has to be taken care of.

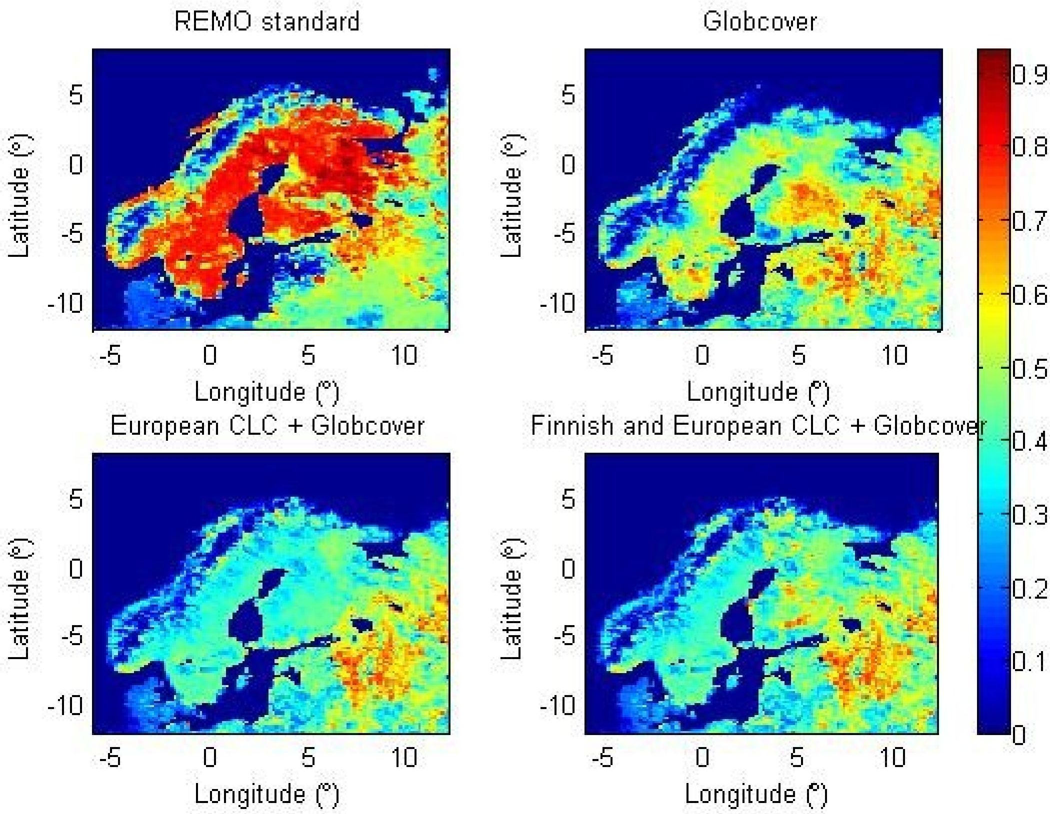

Figure 1. Forest fraction used as boundary data for the Scandinavian domain of the REMO model. Shown are the forest fraction attained by using the default land cover data together with those based on the revised land cover maps. In the final results of this project the National Corine land cover based boundary data is used for Finland, European Corine for the rest of Europe and Globcover for the Western parts of Russia (see lower left figure).

Pre-existing JSBACH surface boundary fields are for global context and in this project a pre-processor for creating the corresponding fields for the regional domain have been received from MPI-M.

6 Model implementation

REMO is written mostly in FORTRAN 77, and JSBACH model is mostly coded in Fortran 90. Both models are being actively developed at MPI-M. They extensively utilize the Message Passing Interface parallel programming infrastructure, and are hence able to utilize the power of modern parallelized supercomputers well.

The REMO and JSBACH models are run on a Cray-XT5m at the Finnish Meteorological Institute. Running the REMO climate model requires lots of computing resources – both in terms of CPU power and disk space. Due to scalability limitations of the code and the limited grid size, the model is run with 120 processor elements. Running one year's simulations and postprocessing the results takes approximately two days, producing over 500 gigabytes of data. The data comes out initially in “IEG” file format (“Max Planck Institute internal file format"), and it is then automatically post-processed to the more widely used NetCDF file format. After this, the JSBACH model reads these NetCDF files as input.

The standalone JSBACH model is quite lightweight as there is no interaction between the grid points, and running it requires no significant computing resources. The data for one year can be generated in less than one hour, and the JSBACH model produces the data directly in NetCDF format. Not all of REMO's output data is needed as input to JSBACH, and the amount of data that JSBACH standalone products is significantly more manageable than that which comes out of REMO.

7 Sequence of Snowcarbo model runs

In this project the sequence of model runs consists of three steps (see Figure 2): First REMO is run in forecast mode with daily restarts in order to produce climate data of relatively high spatial and time resolutions; Second JSBACH is run with the REMO derived climate data; Third REMO is run in a version that is able to carry tracers (henceforth a "REMO tracer run"). From the meteorological point of view the last run is essentially similar to the first REMO run – is uses the same boundary and initial data and is run in forecast model, and thus it produces the same values of climatic variables as the first runs. However, the REMO tracer runs additional boundary data is needed. The third run utilises CO2 flux estimates from JSBACH run. Additionally, in order to produce 3D CO2 fields it requires information on anthropogenic CO2 emissions as well as emissions from land fires and CO2 exchange by the seas and oceans. Furthermore the background 3D CO2 fields have to be added to the contribution from the sinks and sources within the regional domain.

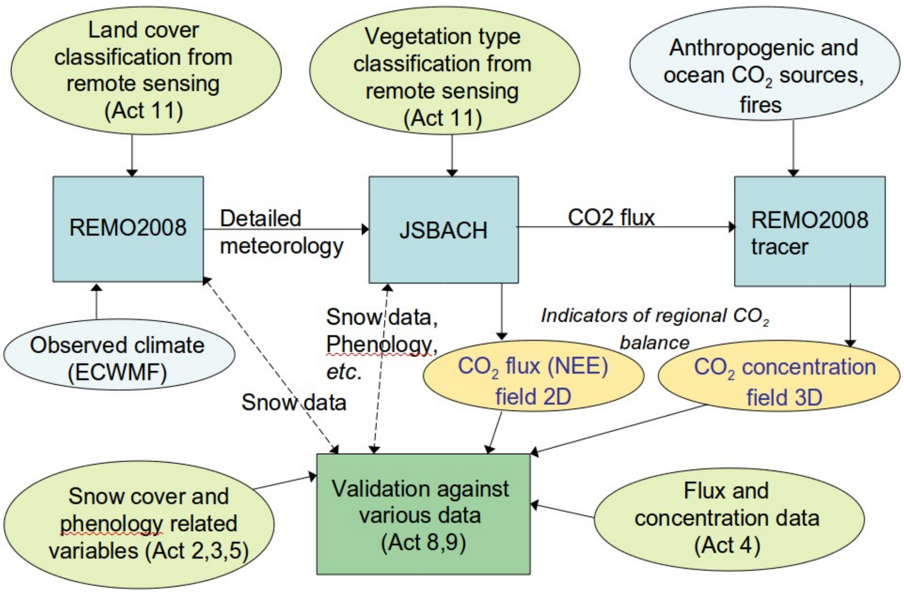

Figure 2. Schematic figure showing the central modeling steps (blue boxes) together with various data sources

8 Model evaluation

While the principle product of the modeling framework is the estimated CO2 balance, a few other predicted variables can be assessed against the wide observation data set available for the project. Assessment of the variables that can be considered as by-products, from the CO2 balance point of view, is important in order to find out the strengths and weaknesses of the overall modeling framework.

The predicted variables that will be evaluated include the central climatic variables such as temperature and precipitation together with closely related snow cover. In general the variables related to the surface energy balance reveal fundamental features of model performance. In addition to comparison with the observation data, the differences in the predictions of both models have to be explored. In evaluation the areas of good and bad performance are first visually recognized and differences in driving variables are further explored. In order to evaluate the influence of improved land cover data sets both REMO and JSBACH predictions with different surface data will be compared. All in all, the model evaluation consists of model intra-comparison (that is, comparison among runs with different boundary and initial data), model inter-comparison (that is, comparison of products of two different models) and comparison to the observations. In the following the intended evaluations of some central variables are discussed with outline of the methods.

Because at northern areas snow-cover plays a crucial role in controlling the CO2 exchange rates due to its effects on air and soil temperatures and on the soil water content, the snow cover extent and snow depth predicted by both models will be compared to the observations (see WP2). In models the snow depth is given in terms of water content and thus conversion factors have to be used to translate that into relevant units. In the applied offline coupling of REMO and JSBACH, both models predict snow-cover independently. Thus, an inter-comparison of their predictions has to be carried out.

Regionally the performance of the vegetation model can be evaluated against phenological data, such as NDVI from satellites (Work package 3 of Snowcarbo, WP3) or in situ data set for phenology (WP5). In the case of for instance bud burst or NDVI there is no identical variable predicted by the model but variables closely related, such as LAI (leaf area index) or GPP (gross primary production) will be used instead. Some variables, such as soil moisture, are both among the in situ phenological data and predicted by the model. In such a case, however, it is crucial to make sure that the definitions of the two variables match. Often, due to deviations in specifications, the phase of the data series rather than their absolute magnitudes of the variables should be observed.

Finally the direct evaluation of the CO2 exchange measures – fluxes and concentrations – will be carried out against *in situ* data (WP4). In this case there is one to one correspondence between the definitions of the measured variables and their modeled counterparts. However, there are certain conditions which have to be fulfilled (WP8). Especially flux signal is of so local nature that its representativeness for the model results has to be carefully considered and the most suitable grid cell for comparison has to be selected before evaluation of model performance against flux data. Concentration data (see WP4 documentation on the nature of this data) represents a large area horizontally but the most representative vertical model level has to be determined. In both cases the complications due to special meteorological situations have to be carefully considered.

In addition to the CO2 flux data, from the eddy covariance (EC) sites there is local data available on the counterparts of surface energy balance who can be separately evaluated against the model. Furthermore these non-CO2 flux variables can be utilized in finding the grid cell of best representativeness.

9 Simulation settings

In order for the final production run to produce the most reliable estimates of CO2 balance, the sequence of the run has to be designed with care. This will include evaluation of the models against various data, estimation of the errors, recognition of the reasons for faulty predictions and finding the ways to reduce the problems. In the following the intended runs are listed with a brief explanation on the purpose of the run and a approach to evaluate the attained results.

REMO model is run for the pre-existing climate data series, i.e. for years 2001-2009, in climate and forecast modes. The results by both modes are checked for any distortion due to relatively dense model grid and the need of double nesting (see Chapter 5) is estimated accordingly. Even though the forecast mode with daily ignitions from the observed data is the climate modeling approach chosen for the production runs of this project, the comparison with climate mode runs is expected to provide insight in strengths and weaknesses of both approaches.

REMO model is run with three different land use data – the original Olson data set, GlobCover and Corine (CLC)+GlobCover land cover classifications from WP11. The differences in energy balance partitioning due to different surface parameter maps will be assessed – this is considered as model intra-comparison, because both the model and the driving meteorological data are identical for these runs. Unfortunately a decisive selection of the most suitable land cover data is handicapped because of a lack of reference data that would cover the whole domain. Eddy covariance flux and energy balance data from Finnish flux sites (WP4) is the most appropriate reference as variables identical to the modeled ones are measured at these sites. However, due to the local nature of the data the it does not serve as regional reference. Thus, further modeling steps will be carried for both newly implemented land cover classifications.

JSBACH runs subsequent to the REMO simulations will be carried out with a version of the stand alone JSBACH that uses hourly mean weather data forcing. An important preparation for JSBACH simulations is creation of suitable land cover maps that are consistent with the respective data set from REMO runs. An essential simulation step is accumulation of model's vegetation and soil carbon storages. This necessitates repeating the climate data record for couple of years in a sufficiently long continuous series so that even the most slowly varying carbon storages in the ecosystems are stabilized. A storage is stable when its value in the end of each cycle is equal to the value in the beginning. Within each cycle the storage varies according to the climatic variations among the data record. However, no stable storage shows a trend between consequent cycles.
The actual production runs will be made with the stabilized carbon storages. Point-wise evaluation of the produced 2D maps of CO2 fluxes will be carried out against the data from several flux sites located in the domain. Because of the relatively small source area of the CO2 flux measurements (typically tens of hectares) and because the flux sites are typically located in a monoculture forest stand, the measurement data is only suitable for comparison of selected simulation results. Very importantly, the PFTs of reference and simulation results have to match and thus only the relevant PFT tiles have to be picked from simulated balances.

In addition to regional simulations, for certain sites JSBACH is run with locally measured meteorological data. In that case the comparison to the flux measurements at the respective site are more straightforward as the PFT distribution of the simulations can be adjusted to match with that of the site. Moreover, the climate forcing is the actual weather that occurred at the site during the time of the flux measurements.

The final step of each complete model sequence is the second REMO run in a mode that transport the CO2 tracers producing concentration field due to surface sources within the domain. The results of this modeling step are consequently compared with CO2 concentration data obtained from Pallas GAW station (see *In situ* data documents). Even though this variable is expected to be the most uncertain the phase of the yearly cycle will provide a reference for timing of ecosystem functioning.

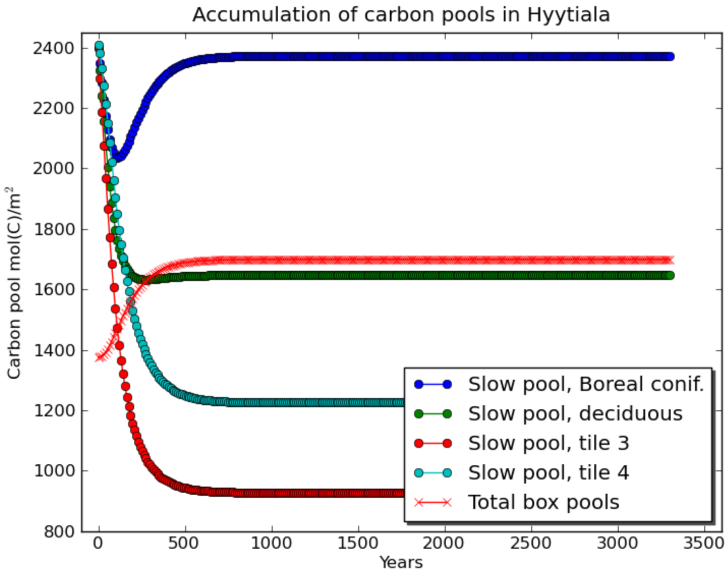

Figure 3. The accumulation of slow carbon storages of the four tiles introduced in the boundary data at Southern Finnish site (Hyytiälä). All the vegetation tiles are shown even though the fraction of tiles 3 and 4 is zero and thus they do not contribute to the total. The records for individual tiles are given per canopy area whereas the total is given per land area.

10 Illustration of the expected results

In the following, first, in order to illustrate temporal variation of CO2 exchange between Boreal ecosystems and the atmosphere, the local NEE simulations at two Scots pine forests in Finland are shown. Before a production run, ecosystem carbon storages were accumulated by repeating the present day data series requisite number of times to gain a time series of 1000 years or more. According to similar accumulation runs, at both a Southern Finnish (Figure 3) and a Northern Finnish (Figure 4) site, an accumulation of 1000 years with the present climate is enough for stabilization of the carbon storages. In Figures 5 and 6 and shown the daily NEEs of the data series driving with meteorological data of the past years after the proper 'spin-up' for stabilization of the ecosystem carbon storages.
Figures 7a and 7b show the regional daily NEE rates of two days – one from the beginning of the growing season (end of May) and one from the peak of the growing season (mid July). For the final representation of the results the time average will be set to month and eight bordering grid cells will be abandoned from each edge of the domain.

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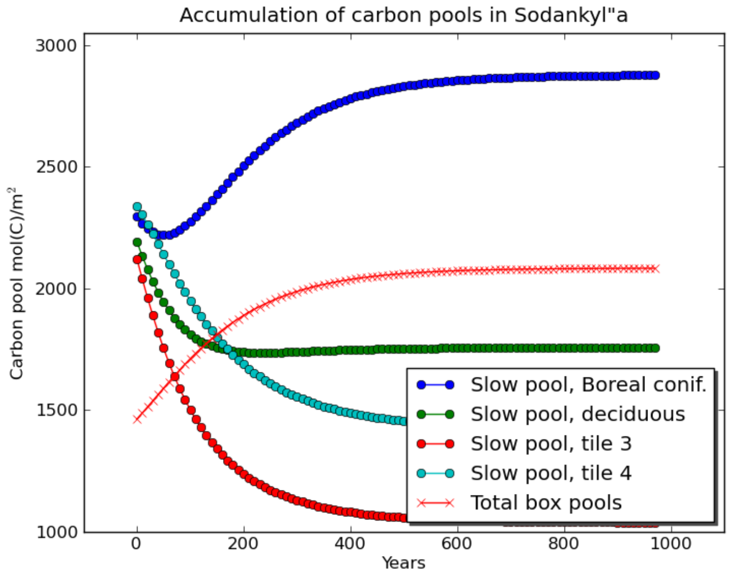


Figure 4. The accumulation of slow carbon storages of the four tiles introduced in the boundary data at Northern Finnish site (Sodankylä). All the vegetation tiles are shown even though the fraction of tiles 3 and 4 is zero and thus they do not contribute to the total. The records for individual tiles are given per canopy area whereas the total is given per land area.

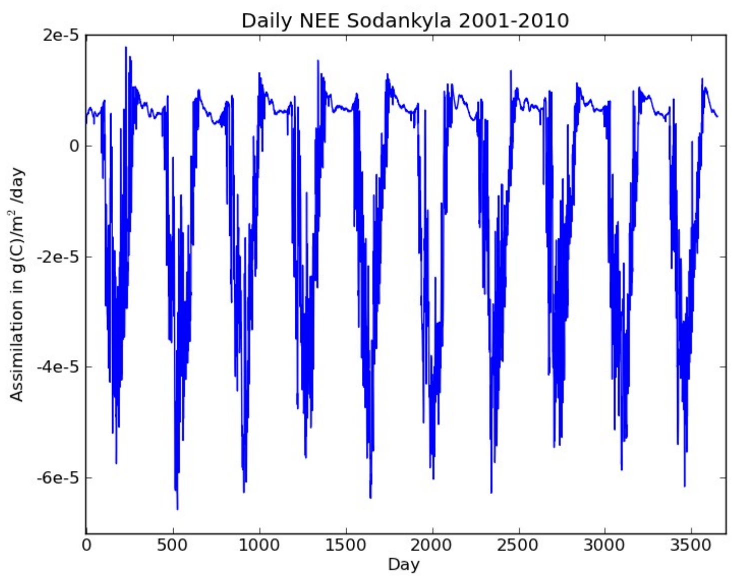


Figure 5. Daily average NEE in Sodankylä site in Northern Finland (67°21' N, 26°38' E, 179 m above the sea level) from 2001 to 2010. The sign in the figure is according to convention used for NEE: assimilation of CO2 is negative and emission is positive.

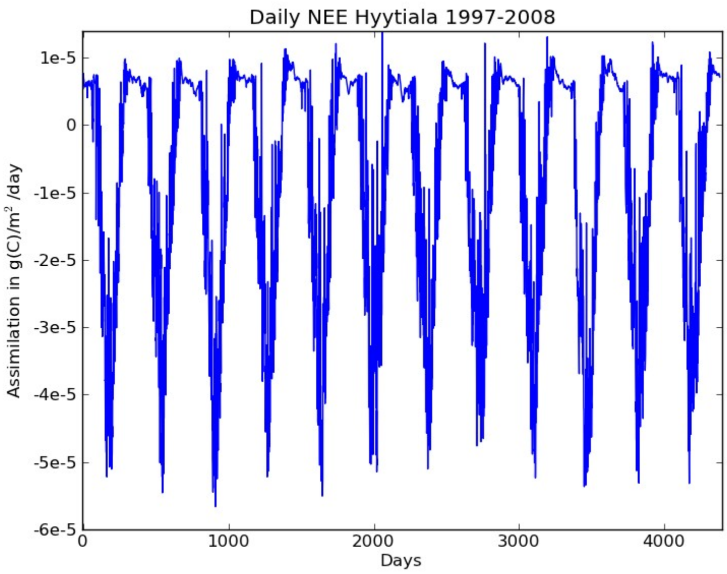
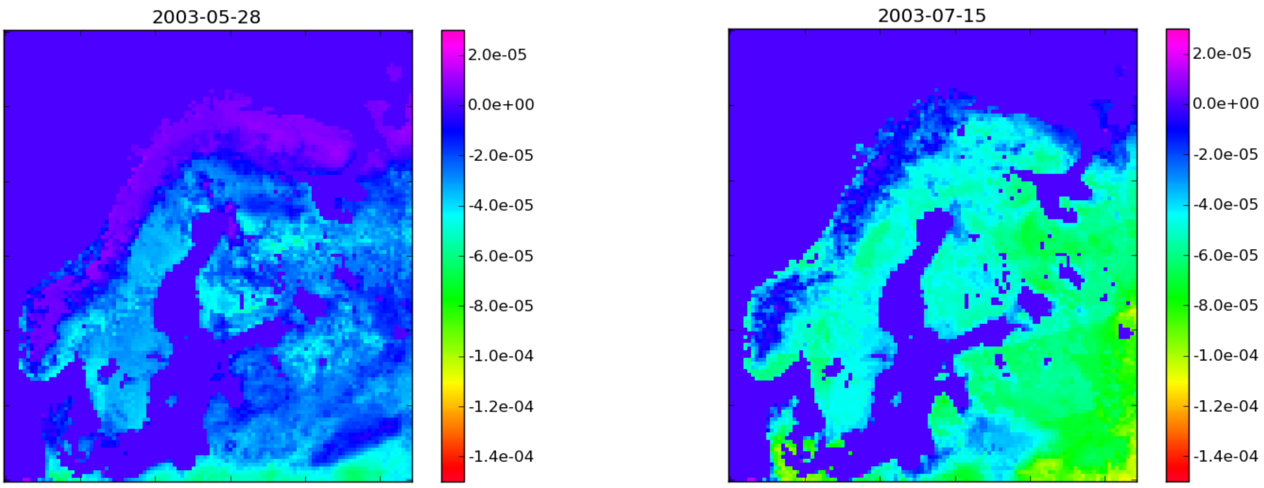


Figure 6. Daily average NEE in Hyytiälä site in Southern Finland (61°31' N, 24°17' E, 181 m above the sea level) from 1997 to 2008. The sign in the figure as in the Figure 1.



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