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D1.3: Present day simulation with each ESM using common protocol. Evaluation and, where possible, constraint of new components using available observations

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1. Introduction

The aim of COMBINE has been to implement new processes in ESMs and to quantify the impact of these on feedbacks and projections. In stream-I the COMBINE ESMs performed and delivered a subset of the CMIP5 simulations. The stream-II simulations form a repeat of these experiments with the newly developed components in the project ESMs. The rationale for repeating the experiments is therefore to measure the impact of the new processes on the existing projections and feedback analyses.

Evaluation of the new component is a prerequisite before future projections and feedback analysis. The aim of this deliverable is to evaluate COMBINE ESMs developments that occurred in WP1 “Carbon and Nitrogen cycle”.

Table 1.3.1 lists the developments initially anticipated by each modelling group.

Table 1.3.1 ESMs developed to incorporate new components (Y=yes, N=no)

Partner	*Land use*	*Nitrogen cycle*	*Permafrost*	*Wetlands*	*Fire*
HadGEM	Y	Land+Ocean	Y	Y	Y
IPSL-ESM	Y	Land+Ocean	Y	Y	Y
COSMOS	Y	Land+Ocean	N	N	N
EC-EARTH	Y	N	Y	Y	N
CNRM-CM	Y	N	N	N	N
NOCLIM	Y	Ocean	N	N	N

Within COMBINE, three modelling groups, METO (HadGEM model), MPG (previously named COSMOS, now MPI-ESM model) and CNRS (IPSL-ESM model) expected to have a full nitrogen cycle for the stream-II experiments, UiB proposed to have a marine nitrogen cycle with continental inputs, while KNMI (EC-EARTH model), and CNRM (CNRM-CM) did not promise any development on the nitrogen cycle.

In terms of methane modelling, METO and CNRS proposed to have CH_4 emissions from wetlands, permafrost and fire, while KNMI proposed developments on CH_4 emissions from wetlands.

In retrospect, the anticipated developments above were quite possibly over-ambitious for most groups. In particular, development of the land nitrogen cycle and the CH_4 wetland emissions suffers delays for all COMBINE modelling groups.

The implementation of the Nitrogen cycle in ESM is far from trivial. Up to now, only one of the CMIP5 ESMs has an interactive carbon cycle. CLM4CN, the NCAR land surface model includes a nitrogen cycle and is coupled to the NCAR ESM (CESM-BGC) as well as to NORESM (presented here, previously named NOCLIM). In terms of performances, these two models are generally below the average in terms of land carbon cycle fluxes and pools (Anav et al., 2013).

We briefly describe the main model developments related to WP1 for each group here with a justification for departure from the initial objectives when needed.

2. Current state of development.

<u>METO / HadGEM2-ES</u>

Within COMBINE, METO expected to have land-use change, a nitrogen cycle and methane emissions for the stream-II experiments. Here we present developments and evaluation of these components.

Land-use

As previously presented (e.g. D7.4) land-use emissions were incorporated into our CMIP5 simulations (COMBINE stream-I) and as such have not been included as “new” components in stream-II. Instead, in stream-II we will present results without land-use in order to quantify the impact of the scheme.

In terms of evaluation, there are little data available to directly measure “land use emissions” and in fact there is no single clear definition of the term (see, e.g. Pongratz et al. 2013). Using 2 simulations to quantify the effects on land-carbon storage and comparing with the commonly cited dataset of Houghton (2008) we can see that HadGEM2-ES simulates consistent magnitude of emissions (see D7.4 figure METO.1).

Nitrogen Cycle

Both the vegetation nitrogen model FUN (Fisher et al., 2010) and soil nitrogen model ECOSSE have been coupled to the land-surface model JULES (the land-surface model in HadGEM2-ES) and are being tested offline. FUN simulates the passive uptake of soil nitrogen through transpiration, as well as through active uptake, retranslocation and fixation by bacteria. ECOSSE simulates the inter-conversion of organic and inorganic forms of nitrogen and carbon, as well as the flux of nitrogen between ammonium and nitrate by nitrification and denitrification.

Methane

Methane has significant natural emissions from wetlands and fire, and in the future potentially from thawing of permafrost. All of these processes were intended to be coupled in HadGEM2-ES in COMBINE. Significant progress has been made on all three, but we are not yet able to fully couple them in our stream-II simulations (see D7.6 for details). It is also not possible to find evaluation data for direct global methane emissions by each single process, but here we show evaluation of some of the components that are required to enable these processes to be simulated with any confidence. Specifically, for wetland emissions we show simulated wetland extent compared with an observationally derived dataset and wetland emissions compared with other similar models. For permafrost emissions we show simulated present day permafrost extent and the ability of the model to recreate observed changes in active layer thickness.

MPG / MPI-ESM

Nitrogen Cycle

The new components that have been implemented in MPI-ESM as part of COMBINE WP1 are terrestrial N dynamics and the coupling between terrestrial and oceanic N dynamics via prognostic atmospheric N_2O concentrations.

Interactive N_2O has been implemented into MPI-ESM with the aim to quantify feedbacks between climate, N_2O emissions and C dynamics. Terrestrial N dynamics were added to the land component JSBACH of MPI-ESM to improve the reliability of estimates for future C sequestration potential. Oceanic N dynamics were already implemented in the CMIP5 experiments.

N availability constrains the C sequestration potential of the terrestrial biosphere. The amount of N that is available for plant uptake depends on input and output fluxes of N such as N released during mineralization, N deposition, fertilization, leaching, and gaseous emissions. The N status of plants correlates with their photosynthetic parameters for maximum carboxylation rate that can be directly measured for particular plants. By using those measured parameters in JSBACH, today's situation concerning N availability and N status of plants is implicitly represented. Under increasing atmospheric CO_2 concentrations, photosynthetic activity will increase beyond the N limits implied by currently observed photosynthetic parameters. The newly implemented N dynamics in MPI-ESM account only for this future limitation due to increased demand for N arising under enhanced atmospheric CO_2. Accordingly, by the very nature of the modeling concept, in JSBACH today's carbon cycle as represented in the historical CMIP5 simulations (1850-2005) remains unaltered.

Interactive N_2O, which is the other new N component in MPI-ESM, was implemented by coupling land and ocean N_2O emissions from JSBACH and MPIOM/HAMOCC to the ECHAM6 model via the OASIS coupler. N_2O emissions from land are a function of N inputs into the mineral soil N pool. These involve inputs by application of N fertilizer, N deposition, or N released during decomposition. Ocean N_2O exchange is calculated based on the concentration of N_2O in uppermost level of the ocean and the transfer coefficient for N_2O, which are transferred from MPIOM/HAMOCC to ECHAM by the OASIS coupler. The exchange rates between sea water and atmosphere are determined in ECHAM considering wind velocity and are communicated to the ocean via OASIS. Transport of N_2O in the atmosphere, as well as radiative forcing, are calculated in the respective sub-models in ECHAM. N_2O is inert in the troposphere and only decayed in the stratosphere by photolysis and reaction with exited O atoms. Stratospheric decay rates of N_2O are not simulated explicitly as ECHAM6 in MPI-ESM does not include atmospheric chemistry, but were provided from MOZART/ECHAM simulations by Martin Schultz and colleagues from the Forschungszentrum Jülich. MOZART is an atmospheric chemistry model coupled to ECHAM and was developed in close cooperation with the MPI for Meteorology in Hamburg. Stratospheric decay rates of N_2O were provided from a run with 90 atmospheric levels for the year 2008 and inter-annual variations are neglected. As soon as MOZART simulations for the IPCC RCP scenarios are available, changing stratospheric decay rates can be used in the new N_2O-setup.

Dynamic vegetation has already been used in the CMIP5 runs, however, a model setup with dynamic vegetation in combination with N dynamics is a new accomplishment. To this end, land C and N pools have to be re-initialized as compared to the COMBINE stream I CMIP5 simulations.

UiB / NorESM1

Nitrogen Cycle

The Norwegian Earth System Model NorESM as used for CMIP5/COMBINE stream I simulations is described and evaluated by Bentsen et al. (2013), and an evaluation of the carbon cycle component has been published by Tjiputra et al. (2013). For COMBINE stream II simulations, the riverine input of nutrients (nitrogen, phosphorus, silica), micronutrients (dissolved iron), and carbon to the ocean has been implemented to improve model skills on the continental shelves and to improve the representation of the global nitrogen (but also phosphorous, silica and iron) cycle. For the land carbon cycle NorESM uses the Community Land Model Version 4 (CLM 4.0), which also couples the nitrogen and carbon cycles. It turns out that the CLM nitrogen limitation dramatically alters the reaction of the land biosphere to enhanced atmospheric CO_2 and climate change. UiB therefore carried out an additional sensitivity experiment where the nitrogen limitation in CLM has been switched off.

The NEWS2 data base (Mayorga et al. 2010; Seitzinger et al. 2010; Beussen et al. 2009) containing discharge data for about 6000 river basins with global coverage (excluding Antarctica) has been adopted for the HAMOCC module of NorESM. NEWS2 provides data for inorganic and organic nitrogen, phosphorus and carbon in both, dissolved and particulate forms. Since the ocean carbon cycle module of NorESM (the HAMOCC model) is based on a Redfield ratio formulation, any excess relative to the Redfield ratio in any of the organic constituents is added to the respective dissolved inorganic forms. A 900-year spin-up had been performed for CMIP5 in order to attain a near steady state of the ocean and land carbon cycle. The last 200 years of this spin-up have been repeated for COMBINE stream II with the NEWS2 based river input switched on. Further, the run over the historical time period followed by the RCP8.5 scenario run have then been repeated with the new developments switched on. Also, the 1pctCO_2, esmFdbk1, and esmFixClim1 runs as well as the abrupt 4x CO_2 experiment have been repeated to assess the impact of the new developments on feedbacks (see Deliverable D7.6).

CNRM / CNRM-CM

Carbon Cycle

In COMBINE, CNRM has developed two versions including carbon cycle component. The first version is based on the CNRM-CM5-2 which only includes the ocean biogeochemistry component (PISCES, (Aumont and Bopp, 2006)). With this version, two streams of simulations have been performed. Each of them corresponds to the 1% CO_2 coupled and uncoupled (1pctco2 and esmFixClim1 in CMIP5 framework) plus a preindustrial control simulation (piControl in CMIP5 framework).

The difference between these two streams relies on the fact that biophysical feedbacks (Lengaigne et al., 2009) are taken into account only for one of them (referenced in the r1i1p5 on the CMIP5 database).

These two streams allow assessing change in climate sensitivity (transient TCR or at equilibrium ECR) due to biophysical feedback in the ocean. For CNRM-CM5-2, change in TCR related to ocean biogeochemistry amounts to ~7%.

The second version of carbon cycle model developed in the COMBINE framework includes both ocean and land carbon cycle component. This model is called CNRM-ESM1. It differs substantially from CNRM-CM5-2 since it benefits from the most recent version of the atmospheric component ARPEGE (6.0.4) and the land surface component (SURFEX7.2). In CNRM-ESM1, the carbon cycle component are PISCES for the ocean (as CNRM-CM5-2) and ISBA-CC (Gibelin et al., 2008) for the land. With this model version two simulations has been performed: a preindustrial control (400 years) and an historical from 1850 to 2005 following the CMIP5 framework.

KNMI / EC-EARTH

Methane

Two activities were brought to completion. First, a new lower boundary condition for methane for the atmospheric Chemistry Transport model TM5 were constructed by making use of a new version of the vegetation module LPJ-WhyMe, in which methane emissions from wetlands were implemented following Wania et al (2010).

A new computationa method was recently incorporated in the 2013 benchmark version of TM5. Methane emissions (instead of prescribed methane concentrations) are used in combination with chemistry (defining the methane loss) with a nudging term in the lower background troposhere to e.g. NOAA zonal monthly means to account for year-to-year gaps in our understanding of the methane budget, resulting from either uncertainties in the simulated methane loss or from the assumed natural methane emissions (mostly LPJ process-based, following Spahni et al., 2011) or from the anthropogenic inventories including e.g. biomass burning CH_4 emissions. The new nudging for methane procedure assured a correct year-to-year varation in the atmospheric growth rate in combination with 3-D spatial variability in the CH_4 concentrations

TM5 calculations were used to generate high and low air pollution scenarios (including methane) consistent with the RCP2.6 and RCP6.0 emission scenarios used in the CMIP5 model experiment (Chuwah et al, 2013). These alternative air pollution scenarios were not considered in the original RCPs (which were based on rather optimistic air pollution policies) but may have a clear effect on regional and global climate and air quality conditions. Air pollution control measures could significantly reduce the warming by tropospheric ozone and black carbon and the cooling by sulphate by 2020, and in the longer term contribute to enhanced warming by methane. On a global scale these effects tend to cancel out (see Fig KNMI.1). A coupling of these scenarios to the climate model EC-Earth was delayed due to technical constraints and is underway.

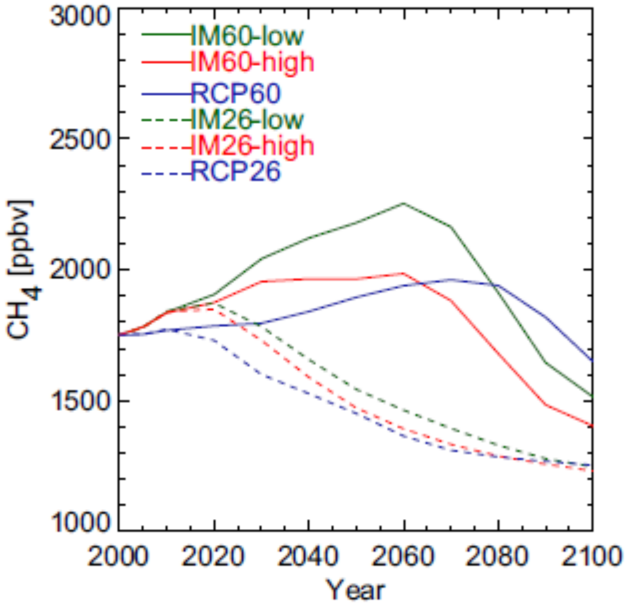


Figure KNMI.1. Time series of methane concentrations according to alternative air pollution scenarios. Solid lines represent RCP6.0, while dashed lines correspond to RCP2.6.

A second activity involved the inclusion of a wetland-methane module in another LPJ version (LPJ-Guess) (McGuire et al, 2012). In a thorough analysis of the high latitude carbon balance (CO_2 and CH_4) a comparison between regional observations and various process-based models (including LPJ-Guess) were made, focusing on the fluxes between 1990 and 2006. For CH_4 it was concluded that the arctic source increased of methane was on average 19 Tg/yr, but the uncertainty is large. Observational analyses lead to an estimate of 11 Tg/yr, while the model-based estimated were more than twice as large (26 Tg/yr). The observations showed a much stronger increase during the 1990-2006 period than the model estimates, but uncertainties remain to be large.

CNRS / IPSL-ESM

Land

ORCHIDEE (ORganizing Carbon and Hydrology In Dynamic EcosystEms) is a land-surface model, component of the IPSL Earth System Model (ESM), that simulates the energy and water cycles of soil and vegetation, the terrestrial carbon cycle, and the vegetation composition and distribution (Krinner et al, 2005). The IPSL ESM has been used to study the long-term response of the climate system to natural an anthropogenic forcing as part of the 5th Phase of the Coupled Model Intercomparison project (CMIP5, Taylor et al. 2011). ORCHIDEE can also be used in stand-alone mode, especially for developing new model features and analysing their impacts before an eventual merging with the version, which runs in the IPSL ESM. Hence, at a given time, there are several versions of ORCHIDEE, the “trunk”, the one which is included in the ESM, and the “branches” with new developments. The trunk itself can undergo changes (such as parallelising the code and changes some parameters which are crucial for the exchanges with the atmosphere) so that it runs smoothly within the ESM. As a result, the “branches” are based on a version of ORCHIDEE, which at the time of the initial developments was the most up to date version but, as the trunk version is modified specifically for the ESM, gradually become older than the trunk version. In the end, we have the new processes in the “old” version, in which the developments and improvements that are brought into the main (trunk) version of ORCHIDEE have not been implemented.

In Deliverable D1.2, IPSL had already indicated that the various processes (fire, N-cycle, wetlands/methane…) had all followed separate developments lines, under the responsibility of different groups and that as a result, many different versions of ORCHIDEE, each integrating a given process, existed. Meanwhile, the trunk version also evolved, not so much in its scientific content but mainly in its formulation (code parallelisation), so that the IPSL ESM as a whole could be run efficiently on dedicated super computers for the CMIP5 exercise. As a result, merging all these developments into one main version became a tremendous task that we were not able to achieve within the timeframe of the project. The case of the Nitrogen cycle is developed below. Therefore the initial objective of running the newly developed processes altogether in an offline and in a coupled simulation could not be met. Furthermore, based on the current state of development of the new processes, the objective of running both offline and coupled simulations for each new process was still a challenge. The IPSL therefore planned on focusing its efforts to i) better quantify the importance of each process on the fate of the land carbon sink, ii) to prioritize the inclusion of each process depending on its relative impact and iii) analyse the dependencies between processes. For each of these processes we initially planed to use a specific model, resulting from the integration of the process in the up-to-date version of ORCHIDEE. However, technical difficulties (such a code parallelisation) as well as scientific complications (linked to the merge of different versions) also led us to revise the objectives and to work with the individual branches.

The integration of the nitrogen cycle in the CMIP5 version,proved to be extremely challenging, much more than the integration of the fire module. Indeed, the code of the nitrogen cycle proved to be highly sensitive to parameters having changed between the two versions of ORCHIDEE. Also, the inclusion of the nitrogen cycle had strong implications and required modifications in other processes (e.g., photosynthesis, carbon allocation in plants, ...). Therefore, rather than performing the planned simulations with a model for which the level of confidence was not sufficient, it was decided to work with the “old” version of ORCHIDEE which integrates the nitrogen cycle, but with the objective to better apprehend the challenges of the Nitrogen-Carbon coupling. In the context of the fires study, the work led to the successful inclusion of the fire module in the up to date ORCHIDEE version. In this case, we focused on improving the parameterization of the model by doing an intensive evaluation. We could only perform simulations where the model is forced offline with climate fields coming from observations but time was lacking to run offline simulations forced by climate fields simulated by the IPSL model or on-line simulations.

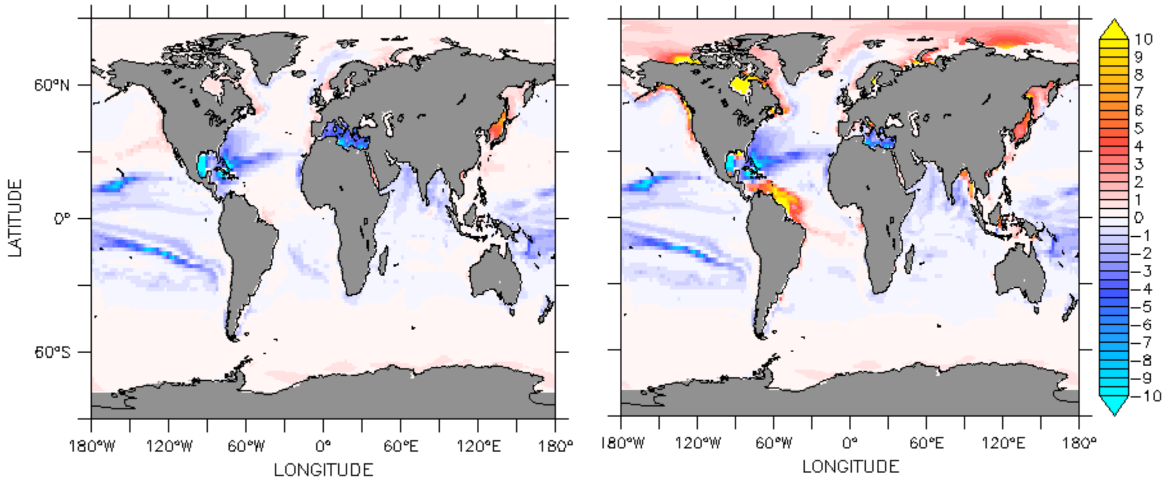
Several important studies were thus performed to better quantify the importance of each process for the land carbon cycle. The findings of these studies led to valuable improvements of each process and will help us to plan a new coherent model development strategy. These studies, although not fulfilling the initial goal of the COMBINE project, will ensure a more rigorous quantification of the impact of nitrogen, fires, forest management on the fate of the land carbon cycle in the next Phase of the Coupled Model Intercomparison project.

Ocean: Sensitivity analysis of atmospheric N deposition and river N supply in PISCES

Despite the fact that O-CN's developments were taking much more time than anticipated, we started to prepare for analyses of the nitrogen cycle in the fully coupled system by analysing the sensitivity of the ocean biogeochemistry to nitrogen sources, i.e. atmospheric deposition and river supply. Both these processes are of particular interest among the external mechanisms of N supply into the ocean. Atmospheric nitrogen deposition contributes with 68 Tg N yr^{-1}, while river N discharge provides 80 Tg N yr^{-1} [Duce et al., 2008, Gruber and Galloway, 2008]. Together, their contribution is in the same order of magnitude of that from N2-fixation alone, which is the largest input source of N with up to 134 Tg N yr^{-1} (Luo et al., 2012).

PISCES uses the model output of the INCA model (Hauglustaine et al., 2004) for atmospheric nitrogen deposition, deploying NOx and organic N compounds along large plumes associated with dense populated and industrialised areas. The river discharge of DIN, DIP, DIC is provided by the Global Erosion Model (GEM) from Ludwig et al., 1996. We test the sensitivity of PISCES model to the contribution of these two sources. Two experiments are designed for this purpose. Upon a standard (hereinafter STD) PISCES 150-year simulation using pre-industrial forcing files from NEMO ocean general circulation model, we built two separate runs. One simulation is run without atmospheric nitrogen deposition (hereinafter NDEP) and another one without the N supply from the rivers (hereinafter NRIV). We compare both runs with the standard fully-loaded run to analyse the effect of atmospheric and river inputs on the export of organic matter to depth at the 100m deep boundary.

Changes in export of organic matter are subtle without atmospheric nitrogen deposition. There is only a 4% decrease on coastal areas, from 0.24 to 0.23 Tg N yr^{-1}, leaving the global estimate almost constant on 7.7 Tg N yr^{-1}. Changes due to the effect of river discharge are more pronounced on coastal regions, with up to a 14% change on export focused mostly in the close proximity to the estuaries of large rivers. The results are summarised in Tables IPSL.1 and 2, and Figure IPSL.1.



(a) *(b)*

*Figure IPSL.1. Changes in export of organic matter at 100m (in g C m^{-2}) in **(a)** STD - NDEP simulations and **(b)** STD - NRIV simulations after 150 years.*

	STD	NDEP	Δ(%)
Coastal	0.24	0.23	-4.2
Open Ocean	7.4	7.3	-1.3
Global	7.7	7.6	-1.3

Table IPSL.1. Export of organic matter to depth (in Pg C yr^{-1}) for STD and NDEP simulations and change in % for Coastal, Open Ocean and Global estimates.

	STD	NRIV	Δ(%)
Coastal	0.24	0.21	-14.4
Open Ocean	7.4	7.3	-1.3
Global	7.7	7.5	-1.9

Table IPSL.2. Export of organic matter to depth (in Pg C yr^{-1}) for STD and NDEP simulations and change in % for Coastal, Open Ocean and Global estimates.

3. Evaluation

<u>METO / HadGEM2-ES</u>

Nitrogen Cycle

In addition to previous evaluation examples (e.g. see D1.2, figure 1.3) JULES-FUN-ECOSSE has been compared for its response to environmental changes such as increasing CO_2 with other models. Although no direct observational evaluation is possible for this idealized experiment, the JULES N-cycle behaves in a way consistent with other models and with our understanding of the nitrogen cycle. Under an elevated CO_2 level for example, vegetation carbon and soil nitrogen increase (Figure METO.1), but vegetation carbon is limited in its increase if there is not enough Nitrogen to sustain the additional growth.

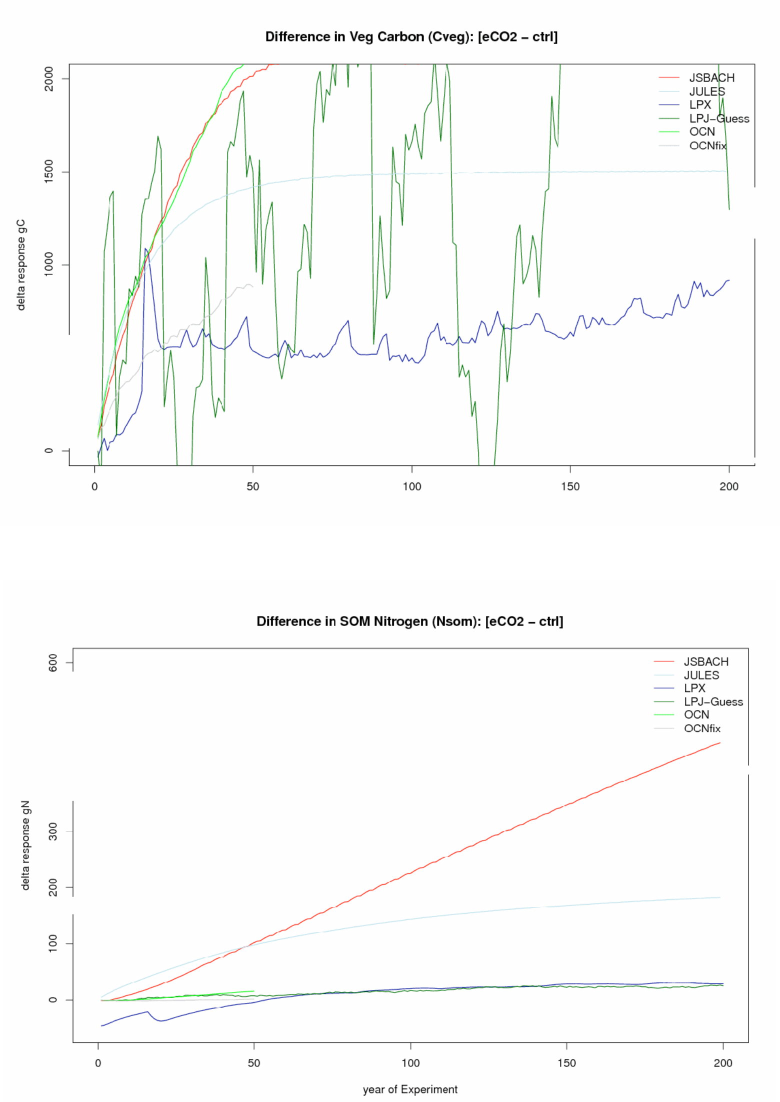


Figure METO.1. JULES simulated changes in vegetation carbon (top) and soil nitrogen (bottom) in an idealised experiment where atmospheric CO_2 is doubled.

Methane

Wetland methane

Wetland extent is not well observed, but datasets exist such as the GIEMS dataset (Prigent et al. 2007). Offline simulations with JULES show broad agreement in regions where wetlands are observed in high latitudes but also show a tendency to overestimate wetland extent (Figure METO.2). This is especially true in the tropics where seasonal inundation is a major cause of wetlands and the areal extent of this process is not well known. As a result, the HadGEM2-ES scheme simulates 62% of global wetlands to be in the tropics compared with just 57% in Prigent et al. (2007)

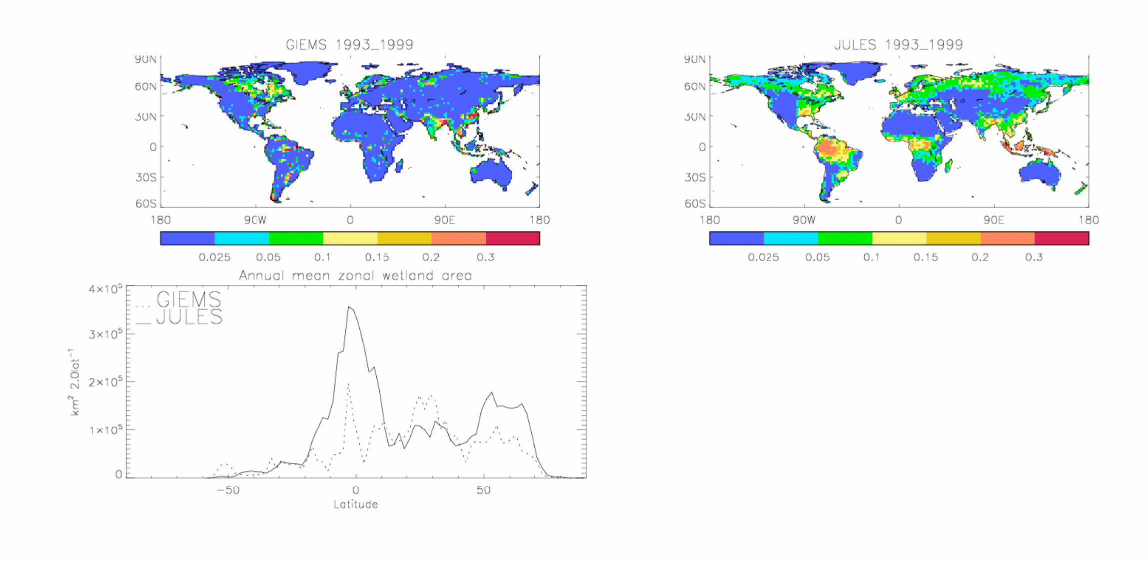


Figure METO.2. GIEMS observationally derived wetland map compared with JULES/ HadGEM2-ES simulated extent.

Melton et al. (2013) performed an intercomparison of many wetland methane models and concluded "… simulated wetland extents are also difficult to evaluate due to extensive disagreements between wetland mapping and remotely sensed inundation datasets." However, we are able to compare our own simulated results with those from other models. Figure METO.3 shows the distribution of our simulated methane fluxes from wetlands, tuned to give a global emission of 180 $TgCH_4$, and compared with the WETCHIMP models in Melton et al. (2013 – their figure 5). JULES is very similar to the WETCHIMP multi-model mean, with a peak of around 20 $TgCH_4$ just south of the equator and a secondary peak of about 5 $TgCH_4$ between 50-60^{o}N. The HadGEM2-ES scheme simulates 72% of methane emissions from the tropics. This can be compared with 64% estimated from the atmospheric inversion study of Bousquet et al. (2011).

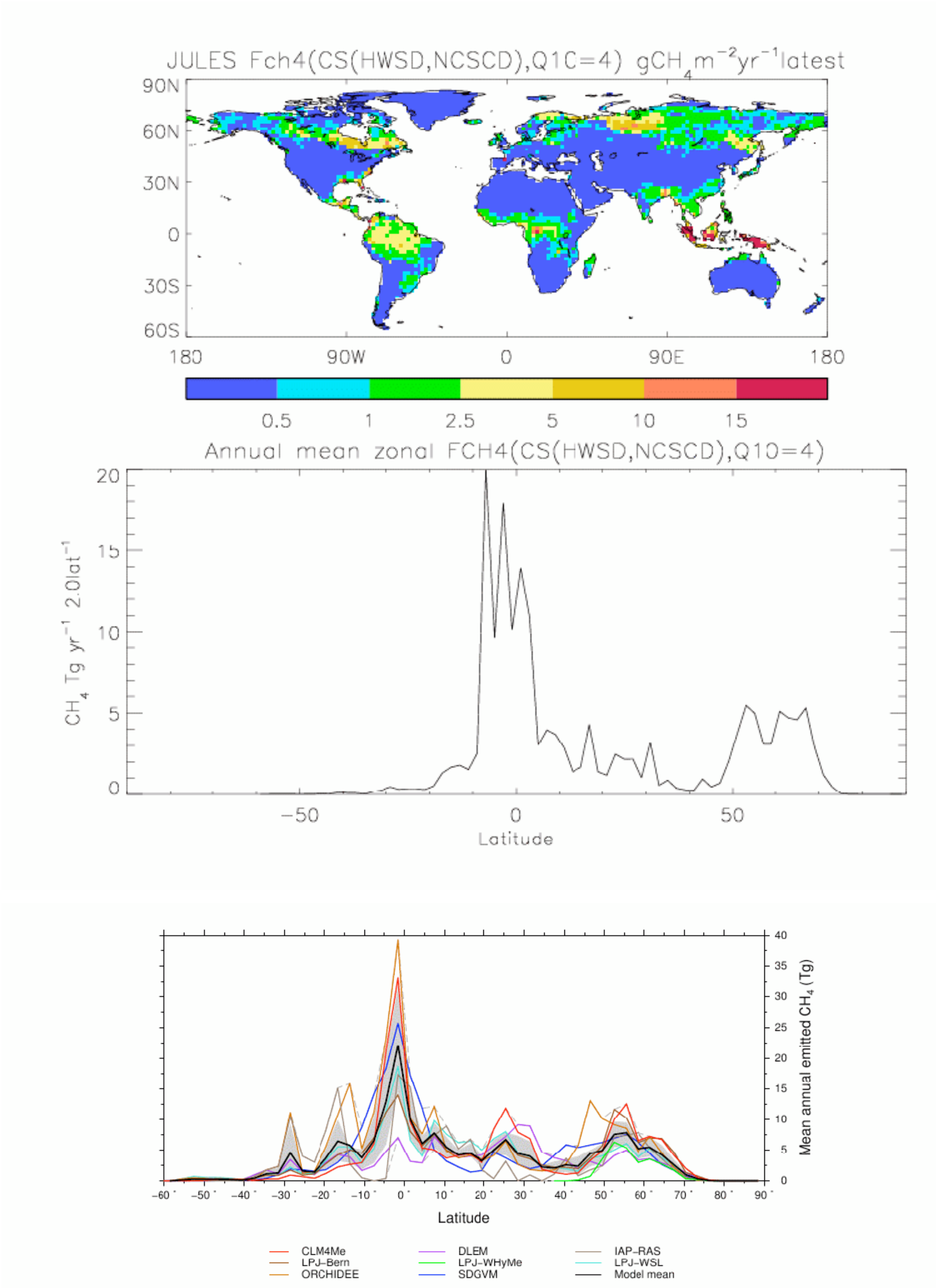


Fig. 5. Zonally summed mean annual CH_4 emissions for 1993–2004. The grey shading denotes the limits of the 25th and 75th percentile of the model distribution. Grey dashed lines are the 5th and 95th percentile limits. The CH_4 emissions are summed across 3° bins.

Figure METO.3. JULES/HadGEM2-ES simulated wetland methane emissions (Tg CH_4 yr^{-1}) compared with multi-model output from the WETCHIMP inter-comparison (Bottom panel reproduced from Melton et al., 2013, their figure 5).

Permafrost methane and CO_2

Permafrost extent is poorly modelled in most GCMs (Koven et al 2013). HadGEM2-ES was no exception, simulating too great a permafrost extent under present day climate in CMIP5/stream-I simulations. This was mainly due to a simplistic snow scheme which allowed too great a thermal coupling between atmospheric temperature and soil temperature, leading to a significant cold bias (and hence overestimate of permafrost) during winter.

A new snow scheme has now been tested in JULES and will be run in HadGEM2-ES. The new scheme is much improved in terms of permafrost extent and soil temperature (Figure METO.4). As a result, JULES is able to reproduce well site-level observations of changing active layer thickness over the 20th century (figure METO.5). Canadian and Russian soil temperature data is also available and has been used to evaluate and improve the model (Burke et al. 2013). Work is also in progress to add a moss layer to improve the surface thermodynamics. In conclusion, the HadGEM2-ES land-surface scheme is now much better able to reproduce the observed permafrost physical environment, its processes and its observed changes. This enables greater confidence in projections of thawed and released CH_4 and CO_2 as used as additional forcings in the HadGEM2-ES stream-II simulations presented in D7.6.

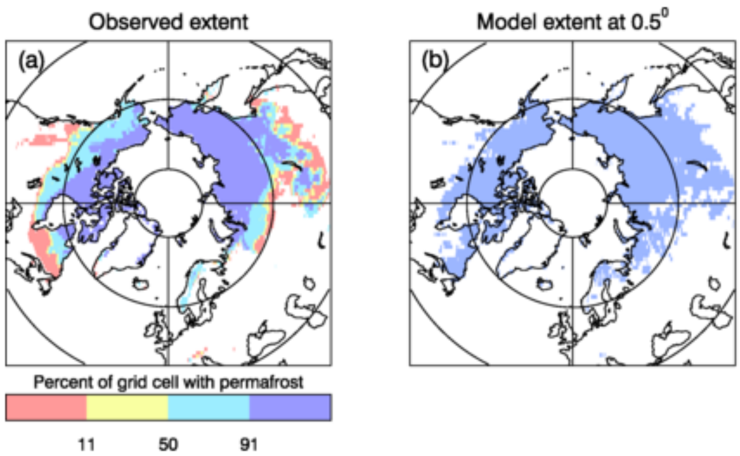


Figure METO.4. JULES/HadGEM2-ES simulated permafrost extent compared with observations.

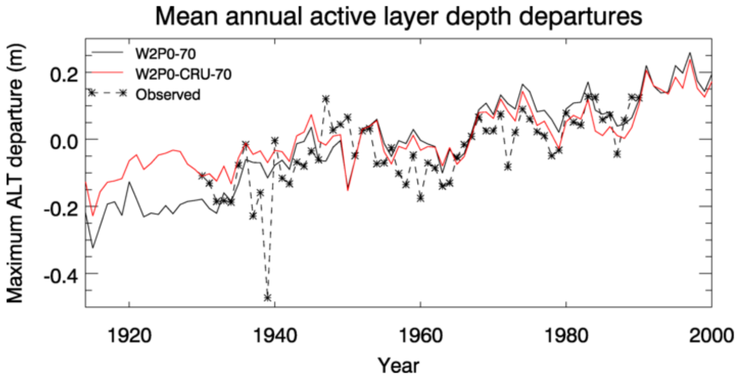


Figure METO.5. Change in mean annual active layer departures for the region of Russia between 60 and 70°N and 115-165°E. Observations are taken from Frauenfeld et al. (2004).

Fire

Work has not progressed far enough in COMBINE to incorporate methane emissions from fire, but here we present development of fire indices within the JULES land surface model (courtesy Richard Gilham and Ruth Lewis, Met Office). Several indices of fire activity are being trialled with a view to use in both NWP and climate applications – namely the Canadian fire weather index, the Nesterov fire index and the McArthur forest fire danger index – see figure METO.6. Although the indices can differ significantly on day-to-day and site-to-site level, they tend to agree in their large scale behaviour which is relevant to climate studies.

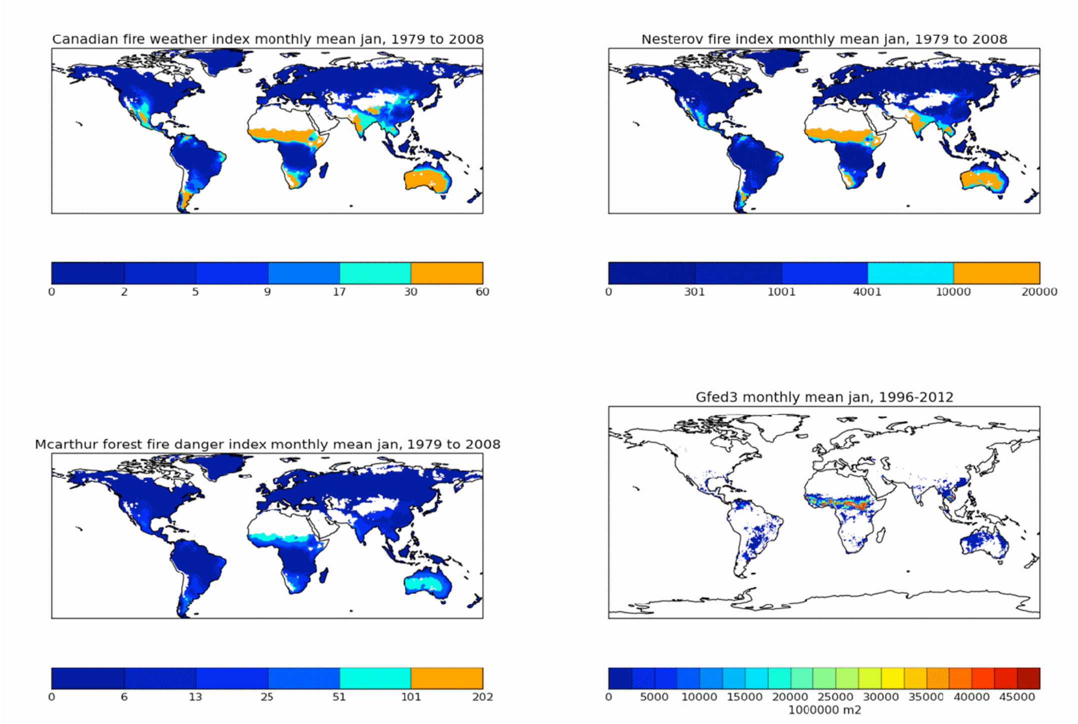


Figure METO.6. Simulated fire indices from JULES for January compared with monthly mean burned are product from GFED3 (Giglio et al., 2010).

The Nesterov index has been adopted by the more complex SPITFIRE fire model (Thonicke et al., 2010), and several other models either already exist or are under development. No decision has yet been taken as to which fire model(s) will be available in HadGEM2 or future METO climate models

MPG / MPI-ESM

Nitrogen

Usually C pools in JSBACH are initialized by running the offline model for at least 5000 years. For this runs, forcing data from coupled simulations are used. For the initialization of land C with dynamic vegetation and N dynamics active, this approach was adapted as well. When using the offline generated C and N pools in coupled mode the simulation aborts due to inconsistencies in the land cover distributions. This issue is independent of the newly implemented N dynamics and could not be solved within an adequate time frame. Another obstacle emerging is that by using the same climate forcing repeatedly, trends in the dynamic vegetation can be intensified unrealistically for some grid boxes, as long term variations are not represented in the repeated climate forcing. For those reasons, in a first attempt to stabilize the model, N dynamics and dynamic vegetation were switched on simultaneously in coupled mode. In order to save computation time, also interactive CO_2 and interactive N_2O were active in those runs. As land C was not in equilibrium from the beginning, expected trends in both atmospheric CO_2 and N_2O led to high atmospheric concentrations which were restored to the pre-industrial values every couple of simulated years. In addition, stratospheric decay rates of N_2O were adapted in order to match pre-industrial atmospheric N_2O concentration.

To enable a preliminary study of the new N components, a historical run was carried out in a setup with interactive N_2O, but without dynamic vegetation, to allow in particular for a first evaluation of atmospheric N_2O concentrations being simulated by MPI-ESM. From this simulation, global mean atmospheric N_2O concentrations in the troposphere were compared to literature values, see Figure MPG.2. Especially at the beginning of the historical run, simulated atmospheric N_2O concentrations are overestimated by MPI-ESM when compared to ice-core measurements from Machida et al. (1995), while the observation based increase in the early and middle 20^{th} century is less pronounced in the MPI-ESM simulations. The control run “ful_ctrl”, where terrestrial N dynamics, dynamic vegetation, interactive N_2O and interactive CO_2 were activated, already shows an improvement in N_2O concentrations. The time series plotted in Figure MPG.1 corresponds to the time period 1850-1940 as used in the feedback study (see D7.6) and was shifted by 100 years to avoid confusions, as the control run is representing pre-industrial conditions and not the historical time period.

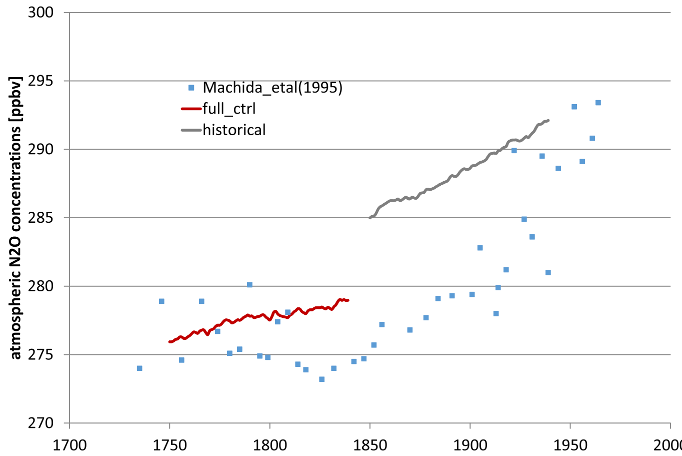


Figure MPG.1. Simulated atmospheric N_2O concentrations compared to measurements

Next, the vertical profile of simulated global mean N_2O concentrations is compared to observations by Kuttippurath et al. (2010), Figure MPG.2. The simulated atmospheric N_2O concentrations in the troposphere as well as in the upper atmospheric levels are in a similar range as observed, which indicates that atmospheric transport processes in ECHAM6 as well as the stratospheric decay rates of N_2O are reasonably realistic in the historical MPI-ESM simulation. However, note that the observations were carried out in the years 2002/2003, while the simulated vertical profile is from the year 1990, i.e. N_2O concentrations might look slightly different in later simulation years.

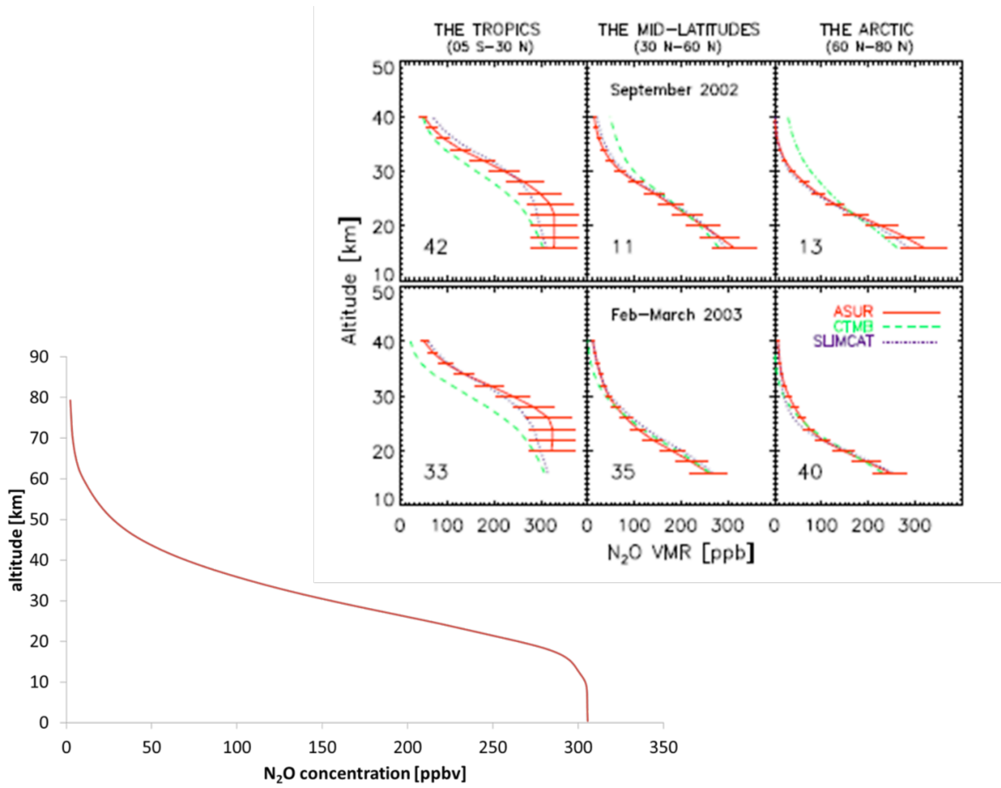


Figure MPG.2 Simulated vertical profile of global mean atmospheric N_2O concentrations (lower left) and observations at various latitude ranges (upper right) by Kuttippurath et al. (2010)

In Figure MPG.3, total global emissions of N_2O are compared with estimates from Syakila and Kroeze (2011). Simulated total global N_2O emissions underestimate the values by Syakila and Kroeze (2011) especially from the 1960s onwards. This hints to a potential underestimation of global land N_2O emissions as simulated ocean emissions of 4 Tg N_2O-N year^{-1} agree with the generally assumed natural oceanic source strength. As the observed increase in N_2O emissions is mostly evoked by increased availability of reactive N due to enhanced fertilizer application and increasing N deposition, the submodel for N_2O release due to external N inputs needs to be evaluated more thoroughly in MPI-ESM. As land C and N pools are currently initialized for dynamic vegetation and N dynamics, a more detailed evaluation of land N_2O emissions with observations will be carried out with a second historical run including dynamic vegetation in the near future.

As atmospheric concentrations of N_2O seem to be overestimated, but total global N_2O emissions underestimated by MPI-ESM simulations, the initialization of atmospheric N_2O concentrations is another aspect that needs to be tested and if necessary adjusted to ice-core observations.

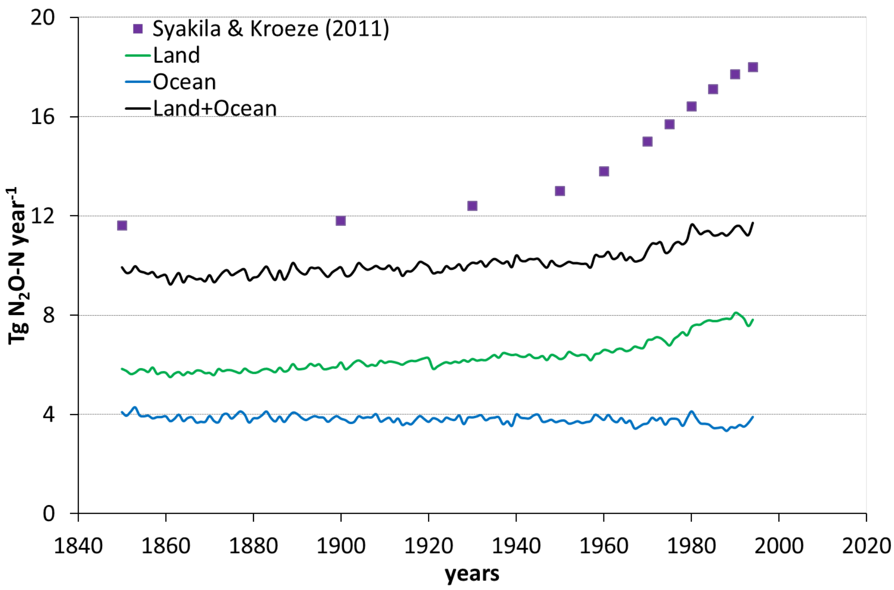


Figure MPG.3 Simulated global N_2O emissions compared to literature estimates

UiB / NorESM

Nitrogen

The riverine supply of carbon and nutrients into the world oceans balances the loss to the sediments, and the implementation of these processes into NorESM is supposed to improve the modelled mass balance. The total dissolved inorganic phosphate, nitrate, and silicate contained in the water column of the world ocean is displayed in Figure NorESM.1 for the historical run with and without the NEWS2 riverine input. The decreasing trend seen for all three constituents is reduced with the new scheme switched on, and for dissolved silica the negative trend is turned into an increase over time. We note that the sediment is not entirely spun up after 900 years and the 200 years spin-up run with the riverine supply switched on is probably too short to attain a balanced equilibrium state. Also, the differences between nitrate as well as phosphate and silica indicate that further tuning of the scheme is necessary. The impact of the new scheme on surface nitrate distribution and primary production in the NorESM historical simulation is illustrated in Figure NorESM.2. A large increase of surface nitrate is observed in the Arctic Ocean while the effect is mostly limited to the vicinity of large river mouth elsewhere. A slightly enhanced nitrate concentration is also observed in the Pacific subtropical gyres. Not surprisingly, primary production is only increased in regions where the biological activity is not limited by light, for example in large parts of the northern Indian Ocean. There are also found remote effects of the riverine nutrient supply: E.g., the primary production is clearly increased in the North Atlantic, which is due to increased advection of nutrients from low latitude rivers.

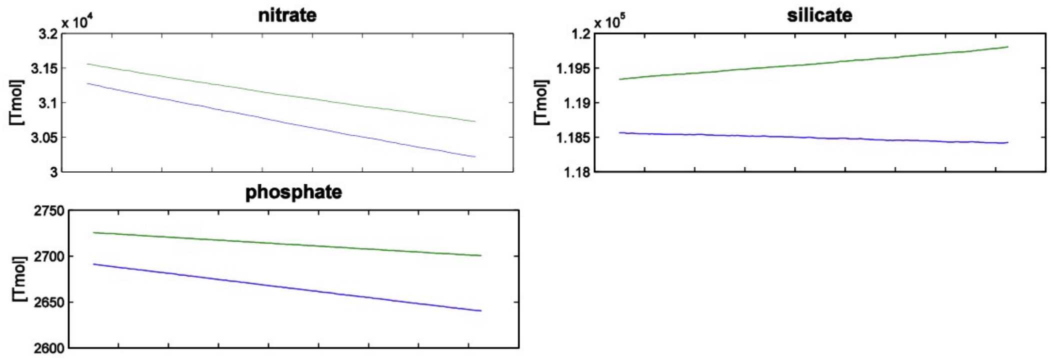


Figure NorESM.1. Total inorganic dissolved nitrate, silicate , and phosphate concentration for the stream I (blue lines) and stream II (green lines) historical simulations.

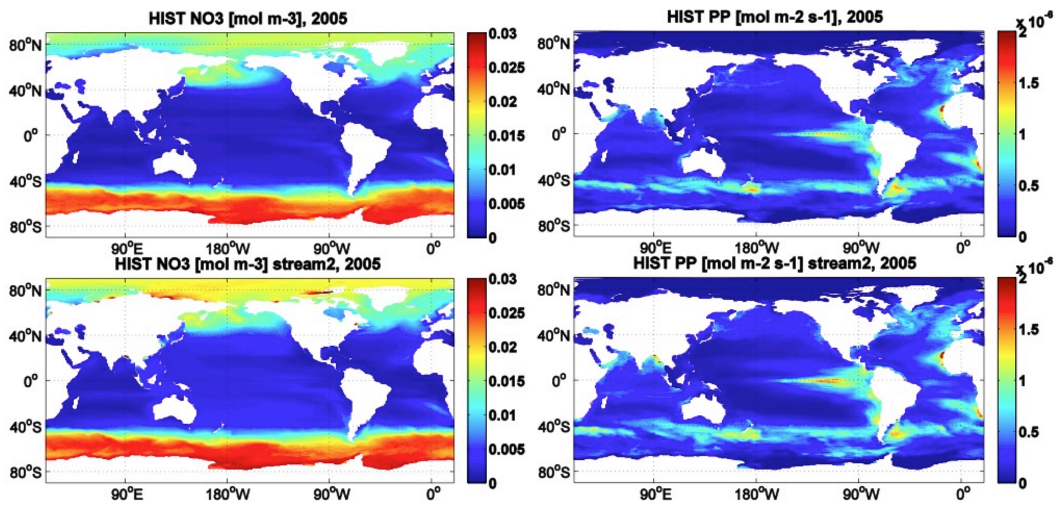


Figure NorESM.2. Surface Nitrate concentration (mol m^{-3}, left) and primary production (mol C m^{-2} s^{-1}, right) for the stream I historical simulation (top row) compared to the stream II results for year 2005 (bottom row).

CNRM / CNRM-CM

A basic evaluation of the land carbon cycle component has been performed for air-sea CO_2 exchange (Figure CNRM.1), leaf area index (LAI, Figure CNRM.2) and gross primary productivity (GPP, Figure CNRM.3). Comparison to recent database shows a rather good agreement in these 3 quantities. In addition, CNRM-ESM1 results compares well to other state-of-the-art earth system models results, acknowledging that there are large uncertainties in carbon fluxes among models (Figure CNRM.2 and CNRM.3).

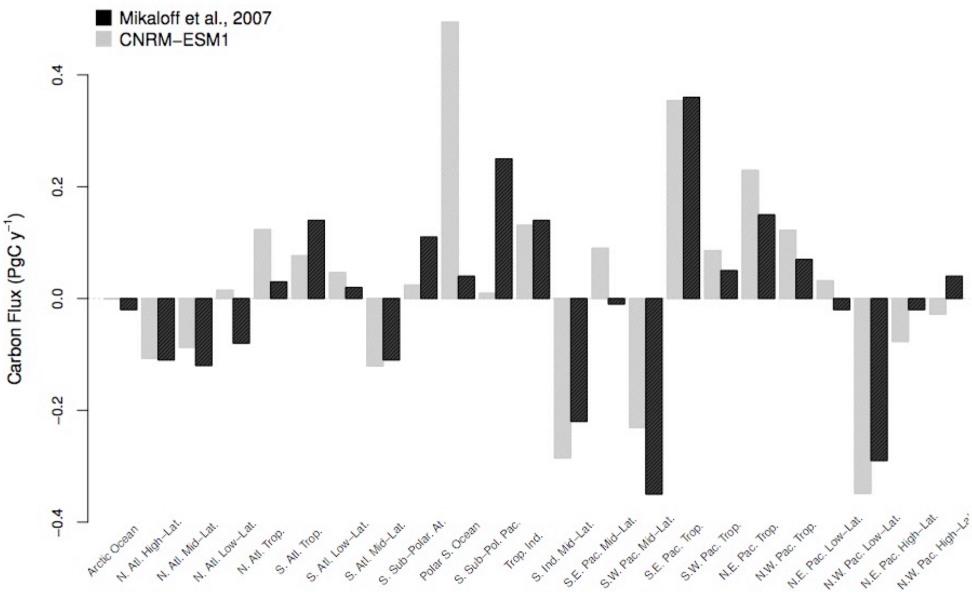


Figure CNRM.1. Comparison of net sea-air CO_2 exchange as simulated by the CNRM ESM with the observation based estimated from Milakoff et al., (2007).

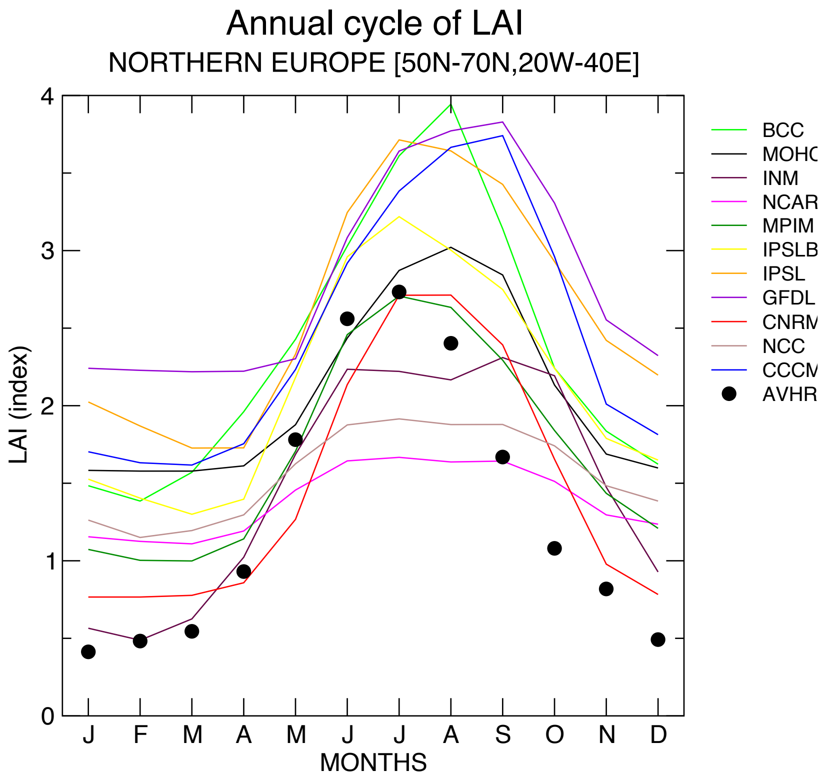


Figure CNRM.2. Comparison of seasonal climatological LAI as simulated by the CNRM ESM with the AVHRR derived LAI as well as with other CMIP5 ESMs.

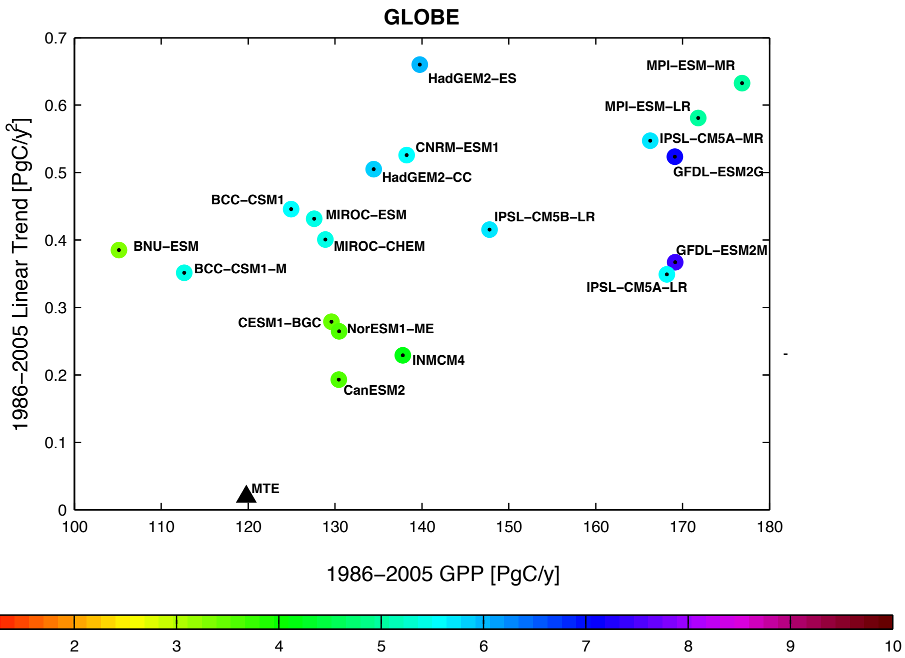


Figure CNRM.3. Comparison of mean, trends and variability of GPP as simulated by the CNRM ESM with the MTE derived estimate of GPP as well as with other CMIP5 ESMs.

CNRS / IPSL-ESM

1) Analysis of the impact of the Nitrogen cycle on the functioning of land ecosystems

An important task was to merge the O-CN version developed by Zaehle and Friend (2010) to the trunk version or ORCHIDEE. First, an update of O-CN was indispensable regarding to the development done in the trunk version compared to the version used to start the O-CN development. This task revealed some inconsistencies between both codes. For instance, the photosynthesis scheme used by O-CN is based on Friend and Kang (2005). This scheme needs a particular description of the solar radiation that was modified in the new drivers used to run the trunk version of ORCHIDEE. This modification resulted in a very low growth primary production and in particular the cropland presented a too low growth primary production to grow. Moreover, the dynamic vegetation modules were modified between the trunk version of ORCHIDEE and the ORCHIDEE version used to develop O-CN. In particular, the calculations of the plant establishment were rewritten to limit plant growth in unfavourable situations. To put it simply, when plant growth was too low, the plants were considered as non-viable and were killed in ORCHIDEE. However, the important feedbacks between nitrogen release from the soil, the primary production and the soil organic matter accumulation induced very low primary production rates in O-CN during the first years of simulations. These low rates were interpreted as non-viable by the vegetation dynamic modules and plants were killed. A huge amount of work was needed to detect all the inconsistencies between O-CN and the trunk version of ORCHIDEE and this work has been partially delayed given that other component such as forest management appeared to be as crucial (see section 1.2)

1.1) Nitrogen cycle impact on plant Leaf Area Index and soil carbon content

Based on the O-CN version developed by Zaehle and Friend (2010), we analyzed historical simulations to better understand how an explicit representation of the nitrogen dynamics may impact the functioning of land ecosystems. Using a satellite leaf area index (LAI) product based on the normalized difference vegetation index of global inventory monitoring and modelling studies dataset, we estimate the long-term trend of the LAI and we compare it with the results from the terrestrial biosphere models, either with (O–CN) or without (O–C) a dynamic nitrogen cycle coupled to the carbon–water-energy cycles. In this study (Guenet et al., 2013a) we observed that both versions largely overestimated the long-term trend of LAI over the period 1982-2002 (Figure IPSL.1).

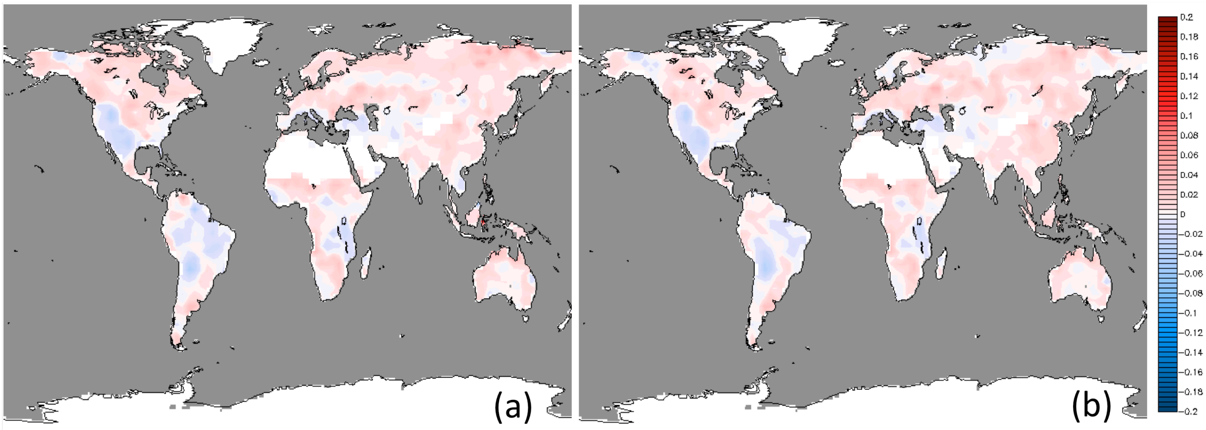


Figure IPSL.1._Differences between the slope of the long-term trend of LAI for O–C and GIMMS (a), and for O–CN and GIMMS (b). Unit: (m2/m2)/yr

At global scale, on the period 1982-2002, we estimated that the version without an explicit representation of the nitrogen dynamics (O-C) overestimated the long-term trend by 225% whereas the version with explicit representation of the N dynamic (O-CN), the long-term trend was overestimated by 185%. One of the explanations is an underestimation of the effect of the Pinatubo eruption on primary production in both versions of the model. However, when the period of influence on climate of the Pinatubo eruption was excluded from the period analyzed, both versions of the model still overestimated the long-term trends except for the temperate ecosystems before the Pinatubo eruption. We therefore conclude that some limiting mechanisms were missing in the model. In particular the release of mineral nitrogen from soil organic matter mineralization was probably largely overestimated. Since carbon and nitrogen dynamic are coupled in soils (Moorhead and Sinsabaugh, 2006), an overestimation of the nitrogen release suggests that the carbon emissions from the soils to the atmosphere are probably largely overestimated. It was therefore crucial to better represent the mechanisms of soil organic mineralization in the model before launch any simulations in a fully coupled mode.

Once this analysis was made we looked for data adapted to evaluate the capacity of O-CN to reproduce the soil organic matter dynamics. We used the data presented by Bellamy et al. (2005). In this paper, the authors showed that the soil organic carbon stocks over England and Wales decreased substantially during the period 1978-2003 (-4.44 Tg yr^{-1}). We ran simulations over England and Wales for the 20th Century using O-CN but also the version of ORCHIDEE used for the AR5 exercise and a new version taking into account the effect of the fresh carbon input (litter, roots exudates) on the soil organic carbon mineralization. This new version is called ORCHIDEE-PRIM. In this study (Guenet et al., 2013b), we assumed that an increase of nitrogen deposition may have reduced the allocation of carbon to the roots inducing a decrease of the C inputs into the soil and *in fine* a decrease of the soil organic carbon stock. However, we showed that the only version able to reproduce a decrease of the soil organic carbon stock over England and Wales as observed by Bellamy et al., (2005) was the ORCHIDEE-PRIM version (Figure IPSL.2) but the decrease was still underestimated even with this version.

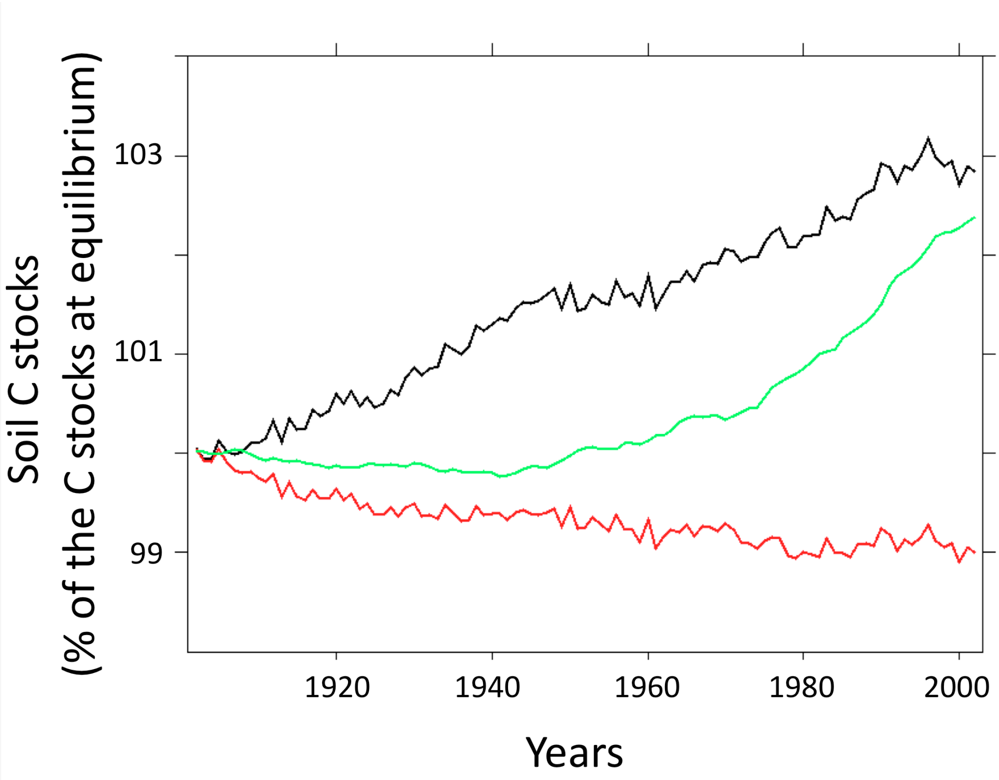


Figure IPSL.2. C stock evolution over the 20th century normalized by the C stock at equilibrium (annual values) for ORCHIDEE (black), ORCHIDEE-PRIM (red) and for O-CN (green). At equilibrium, soil C stocks corresponded to 13.9 kg.m^{-2}, 16.1 kg.m^{-2}, and 5.1 kg.m^{-2} for ORCHIDEE, ORCHIDEE-PRIM and O-CN respectively.

From these two studies, we concluded that the soil organic carbon dynamics was quite badly represented in O-CN inducing very strong uncertainties on the land surface carbon emissions. The soil organic carbon pool being three times more important than the carbon stored in vegetation, we considered that a particular effort had to be done to better represent the soil organic carbon dynamic in O-CN. Moreover, we considered as non-sense to perform simulation in a fully couple mode with a model that was not able to reproduce the dynamic of the most important organic carbon pool of the terrestrial ecosystems. Finally, the net ecosystem exchange of O-CN was not that bad compared to data (Zaehle et al., 2010). Regarding to the incapacity of the O-CN model to represent the carbon emissions from soil, it suggests that the good net ecosystem exchange predict by the model is due to bias compensation. The role of soil in the net ecosystem exchange is expected to change under climate changes (Jastrow et al., 2005), thus we believe that perform simulations in a couple mode for future prediction with a model presenting important bias compensation in the net ecosystem exchange was an exercise with a very limited scientific interest and we therefore invest a lot of time and energy to improve the description of the soil organic matter dynamic. Unfortunately, we were unable to finish this task before the end of the COMBINE project.

1.2) Nitrogen cycle and forest biomass

Using the O-CN version we have further evaluated the simulated above ground biomass and Net Primary Production (NPP) at specific forest sites where some measurements exists (over 200 sites, Luyssaert et al. (2007)). The location of the sites, displayed on Figure IPSL.3, mainly corresponds to temperate northern ecosystems. These simulations have been performed by Benjamin Poulter and the results are still under investigation.

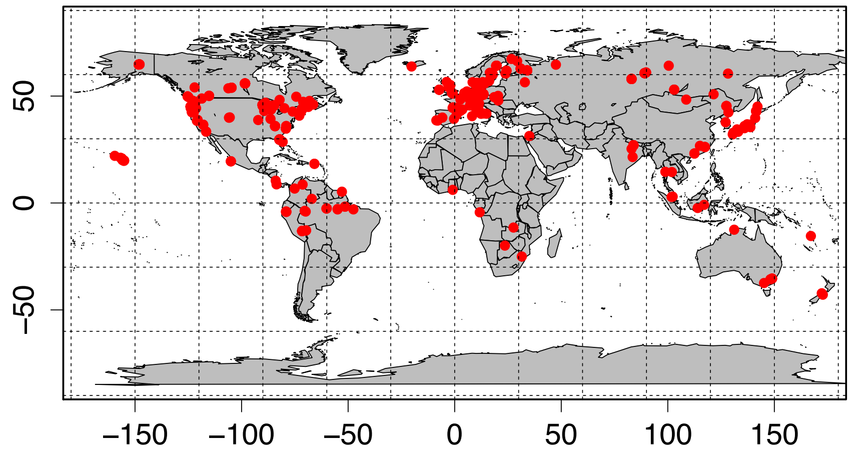


Figure IPSL.3. Site location of the database used to compare the output of OCN model.

Simulations:

The meteorological forcing corresponds to a combination of CRU data and NCEP model output and span the period 1901 to 2010 ("CRU-NCEP forcing"). First the model carbon pools are brought to equilibrium using a spin-up phase for 3000 years recycling the meteorological forcing. Then a transient simulation was performed from pre-industrial time (1860) to 2000, using observed atmospheric CO2 concentration. Note that for the period 1860 to 1901 the climate from 1901 to 1910 was used and recycled. Several configurations of the model were run:

- The O-C version without the nitrogen cycle in which the forest is grown to equilibrium.
- The O-CN version with the nitrogen cycle in which the forest is grown to equilibrium.
- The same O-CN version but where the forest is clearcut so that at the end of the simulation the forest age corresponds to that of the site.

Results:

At each site, the simulated NPP and above-ground biomass have been compared to the observations. Figure IPSL.4 shows the results of the model/data evaluation for both Biomass (upper panel) and NPP (lower panel) and for the three different model configurations. Overall, the NPP simulated by O-C is relatively stable across sites, with a mean value of 800 gC/m2, while the observations indicate large site-to-site variations, with NPP values ranging from 100 up to 1500 gC/m2. With the O-CN version, that couples C and N cycles together, the modelled NPP is in much better agreement with the observations. Note, however, that from a statistical point of view the R2 values associated to the regressions are not significant and close to 0.1. Adding the clearcut to the O-CN version does not improve the fit to the data, for NPP. For the Above-ground Biomass (AgB), the results slightly differ to those obtained for NPP. The O-C version fails to simulate correctly the site-to-site variations (top left panel), with a range of variation of AgB smaller than observed. Adding the nitrogen cycle with the O-CN version slightly improves the fit to the data (top middle panel). Finally adding the clearcut so that the simulated forest age match the age of the forest also further improves the correlations with the observation, although only slightly (upper right panel). Overall, the O-CN version accounting for the clearcut effect produce slightly better agreements, even if the site-to-site modelled variations are lower than those observed.

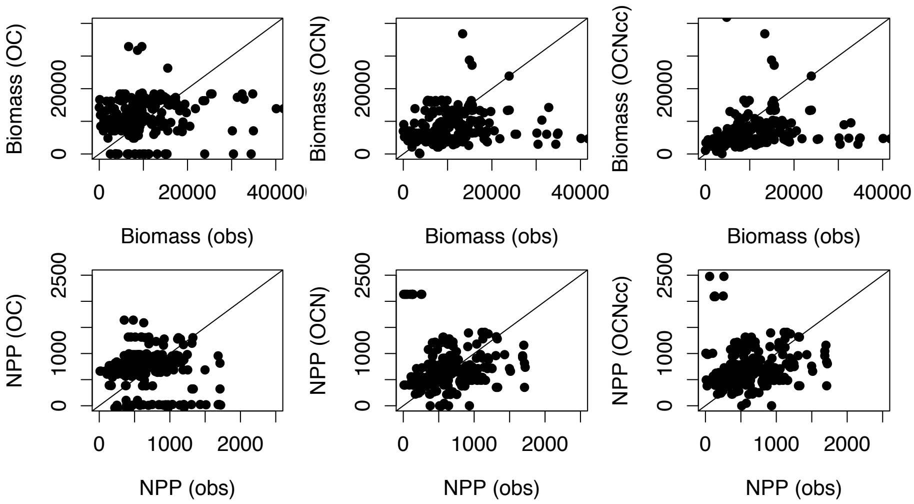


*Figure IPSL.4. Model/data comparison for the Aboveground Biomass (upper panels) and the NPP (lower panels) for O-C configuration (left panels), O-CN without clearcut (middle panels) and o-CN with clearcut (right panels)***.**

Figure IPSL.5 shows the time evolution of the aboveground NPP and biomass simulated with O-C, O-CN and O-CN with the clearcut effect at three sites and how the model estimates compare with the observations of carbon biomass (red point). Note that the blue curve in the figure indicates the nitrogen content in the AgB. At site A (top panel), the simulated Carbon stored in the biomass matches well the observation, only when the clearcut effect is added to the O-CN version, while the simulated biomass overestimates the observation, when using the two other versions of ORCHIDEE. However, there are sites such as site B, where the fit to the observation is mainly due to the use of the nitrogen cycle (O-CN version), the addition of the clearcut effect changing little. There are also sites for which both the C-N coupling and the clearcut effects are needed to improve the model fit to the observed biomass (site C, figure IPSL.3).

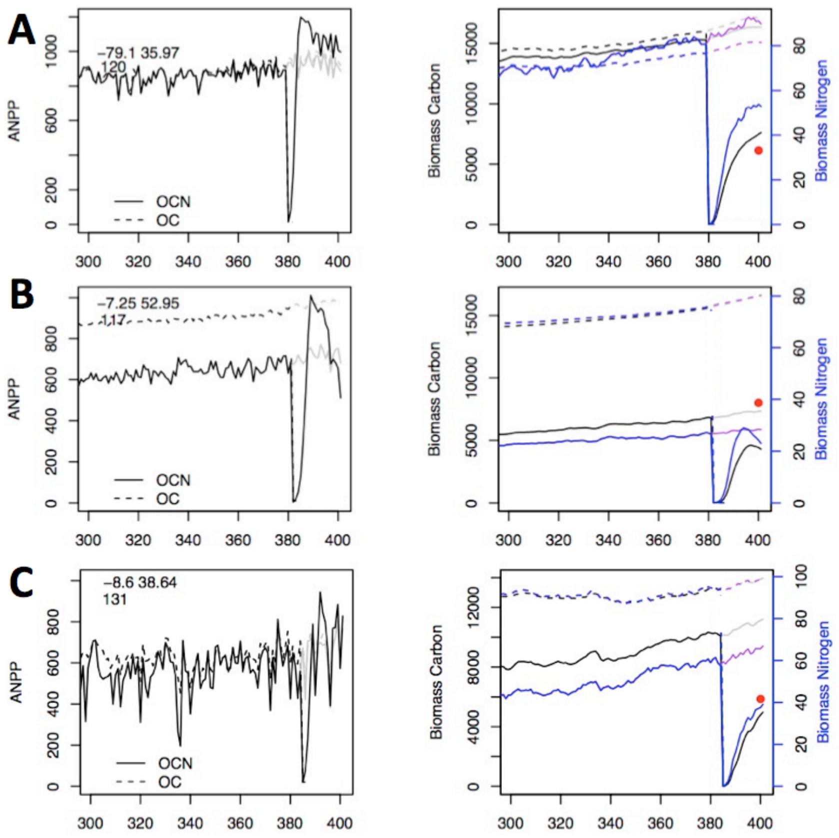


Figure IPSL.5. Time evolution of the Above NPP (left panels) in gC/m2 and Aboveground Biomass (right panels) in gC/m2 simulated by O-C, O-CN and O-CN with the clearcut effect, for three different sites. Dash line is for O-C and plain lines for O-CN. The Blue lines represent the Nitrogen content while the black line represents the carbon content. Biomass carbon observations are in red.

Overall and as expected, these results indicate that for young forests (< 30 years) there is a crucial need to account for the age effect and that without such effect the forest AgB tends to be overestimated by the model. This appears to affect the model's behaviour for a large part of the investigated sites (see results of Figure IPSL.4). On the other hand, accounting for the nitrogen cycle has a direct impact on old forests and by reducing the AgB, the nitrogen availability is a key driver to explain the observed variation of forest biomass content. From this study, we thus concluded that both nitrogen cycle and forest age structure should be accounted for in earth system models in order to make future prediction of the land carbon balance. Accounting for forest age implies that the model is able to deal with forest management at least for the extra-tropical ecosystems, where management is a key driver of stand age dynamic (Bellassen et al., 2011). Therefore, we believe that the nitrogen cycle needs to be implemented together with a recent development of ORCHIDEE, that accounts for forest management and the existence of several diameter/age classes in a stand (Bellassen et al., 2010).

2) Fire and ecosystem functioning

Fires have multiple biophysical and biogeochemical consequences, and they also control atmospheric chemistry through emissions of ozone precursors. By killing some plant types and concurrently promoting other types, fires play an important role in shaping ecosystem function and structure. In turn, fire induced ecosystem change may have an influence on the surface energy budget, and thus on boundary layer climate, via altered albedo and vegetation sensible, latent heat fluxes as well as roughness change. Thus mechanistic inclusion of fire processes and emissions is needed in earth system models, in order to investigate the role of fire in past, current and future biophysical and biogeochemical processes.

For the reasons described above, the novel prognostic fire module of SPITFIRE has been integrated into ORCHIDEE. Model optimization and historical transient simulations have been done in order to quantify the role of fire carbon emissions in the terrestrial carbon balance.

ORCHIDEE-SPITFIRE is able to generally reproduce the global spatial pattern and magnitude of burned area as reported by GFED3.1 data (Figure IPSL.6). Savannah vegetation fires in Africa and Australia are well captured by the model. However, simulated burned fraction is overestimated in boreal tundra, western and central US and middle latitude region of Eurasia. The overestimation is mainly on the magnitude of 0.1-1%. Fire burning fraction in southern African savannah region is especially underestimated by the model by on average ~60% during the fire season (June to October).

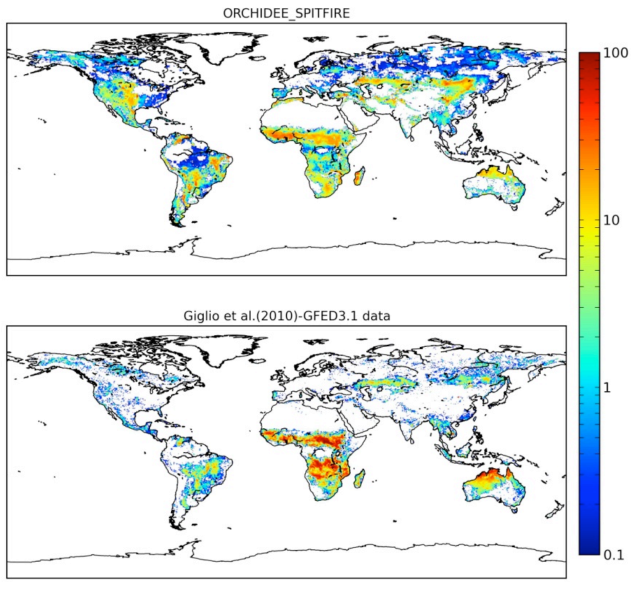


Figure IPSL.6. Mean annual fire burned fraction (in percentage) over 1997-2009 as simulated by ORCHIDEE-SPITFIRE and reported by GFED3.1 dataset.

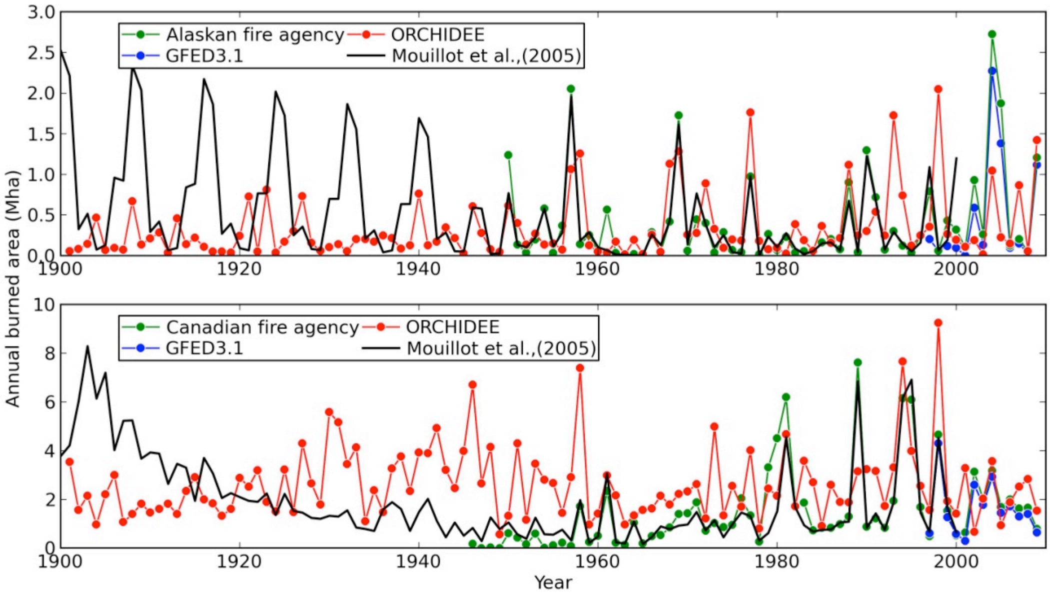


Figure IPSL.7. Simulated and observed fire burned area in Canada and Alaska for 1900-2009

Figure IPSL.7 shows the simulated burned area for the period of 1900-2009 in comparison with the observational datasets. The model could capture well the variation of fire burned area as reported by the fire management agencies.

3) Conclusion: a new model development strategy

Following the above analysis we thus decided that the initial objective proposed in the DoW of COMBINE, i.e. to "simply" include a previously developed nitrogen cycle, was not optimal and that several other processes would need to be included as well in the ORCHIDEE model. This would ensure a proper assessment of the impact of nitrogen limitation on plant productivity and on the fate of the land carbon sink at the horizon 2100. We have thus decided to implement successively the following steps:

1. First, we implemented a forest management module (previously developed) including a new carbon allocation scheme that fulfils specific allometric relations for each Plant Functional Types. This step is completed and the model is under evaluation.

2. Second, we decided to include the SPITFIRE module, working on the coupling with the management module and the ability of the model to simulate age/diameter classes. Fires indeed affect differently young and old trees. This step is under completion

3. Finally, we will include the nitrogen cycle and its impact on the plant productivity as well as the allocation of carbon in the different reservoirs accounting for the different forest age classes simulated by the model. This step only started.

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