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Project acronym: **COMBINE**

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Executive Summary

The European integrating project COMBINE brought together research groups to advance the capabilities of Earth system models (ESMs) for more accurate climate projections and climate prediction. COMBINE improved ESMs by including (1) key physical and biogeochemical processes, which were missing in predecessor models, but known to influence the variability of climate and the feedbacks determining climate change; and (2) analyses of the ocean and sea ice in prediction systems.

The overall carbon cycle feedback to climate change was confirmed to be positive. Models without nitrogen limitation simulate an excess uptake of carbon, which is not supportable by the available nitrogen. If nitrogen limitation is considered, then the overall carbon cycle feedback to climate change becomes more positive, and the allowable carbon emissions for a given CO_2 concentration pathway are smaller than if nitrogen limitation of the carbon cycle is neglected. Generally, however, it remains a challenge to properly include the fully coupled carbon/nitrogen cycle in models.

The Greenland ice sheet was found to shrink substantially for high CO_2 forcings, while the amount of melting still differs significantly among models, due to difficulties in parameterizing the albedo of snow on ice. Modeling the coupling to the Antarctica ice sheet in ESMs remains an open challenge. Improvements in the representation of the sea-ice have demonstrated a larger susceptibility of sea-ice associated with the coupling of atmosphere/ocean and sea-ice processes.

COMBINE developed and tested new ocean initialization techniques. Advancements in ocean re-analysis made also possible to diagnose the role of the ocean circulation for heat absorption variability, providing a plausible explanation for the recent hiatus in surface warming. Sea-ice assimilation and initialization techniques were developed and implemented for the first time in climate prediction systems.

Through COMBINE the European contribution to the projection experiments of the Coupled Model Intercomparison Project – phase 5 (CMIP5) was accomplished. CMIP5 is the latest set of climate projections and predictions, done in support to the Intergovernmental Panel on Climate Change (IPCC). In addition, the feedback analysis on radiative (aerosols), nitrogen & carbon, and cryospheric processes carried out on new COMBINE projections will contribute to the next cycle of CMIP.

European modeling groups lead by the COMBINE project were effective in advancing climate prediction by contributing to the first internationally coordinated set of decadal hindcacts and forecasts (under CMIP5). This set was and is currently investigated to assess its reliability and potentials, including decadal prediction of extreme events. Decadal forecasts showed that Atlantic sea surface temperatures appears to have considerable predictive capability up to ~10 years. Similarly, long-term predictability was found for near-surface air temperature over Northern Africa and the adjacent Mediterranean and Middle East. Improvements in climate variability resulted from the incorporation of the stratosphere.

Results from the COMBINE projection runs were used to assess impacts of climate change. These analysis confirmed significant consequences on hydrological extremes. Despite a global increase of water availability, in regions such as Central America, the Mediterranean and Northern Africa renewable water resources are assessed to diminish. Analyses showed that feedbacks could have a considerable impact on the strategy of climate policies and related costs, with mitigation costs varying by a factor of 8 depending on assumptions on climate sensitivity.

Project context and the main objectives

Over the last few decades the understanding of the circulation of the atmosphere and the ocean, of the role of biogeochemical processes and of the role of humankind in climate evolution has made great advances, based on observations, especially global remote sensing from satellite, laboratory work, theory and numerical modelling. Today, comprehensive models of the Earth system are our major tools for the investigation of climate dynamics and climate change, as they integrate the dynamical, physical and biogeochemical processes, which are known to be important for the past and future evolution of the climate.

Projection of the future evolution of the climate system heavily relay on such comprehensive models. Consequently, they provide the scientific bases for the development of policies that might mitigate climate change or adapt societies to inevitable anthropogenic driven changes of our environment. They are nowadays used to evaluate geo-engineering options proposed to counteract climate change.

In this context, a critical development and assessment of the capability of models used for climate projections is essential. The evaluation of the performance of climate models and, more recently, Earth system models (ESM) has been indeed constantly included in all Intergovernmental Panel on Climate Change (IPCC, from AR1 to AR5) assessments reports so far. In response to the challenge of evaluating models and internationally coordinating climate projection, the Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP) was first established in 1995. The life of the COMBINE project overlapped with the 5 phase of CMIP and the writing of the 5^{th} Assessment report of the IPCC.

The state-of-the-art scientific vision at the beginning of the COMBINE project was that climate projection could be improved in three main ways: refining the representation of the Earth system by including physical and biogeochemical processes and their coupling, increasing the numerical resolution of the global physical models, and increasing the size of the ensemble of simulations used for the projections. Early experimentations on near-term decadal prediction, evolved from seasonal forecast, also already took place prior to COMBINE.

The strategy taken by the project was to focus on the first of the three approaches described above, and aim to improve the comprehensive global models by representing the Earth system more realistically, in its processes, coupling and dynamics. The critical physical and biogeochemical processes addressed by the project were carbon and nitrogen cycle; aerosols coupled with clouds and chemistry; stratospheric dynamics and increased resolution; ice sheets, sea ice and permafrost for the cryosphere (“new components”). Another very actual aspect of climate science, that the COMBINE project took over, was to pioneer decadal prediction, by developing new analysis of the ocean circulations, explore for the first time the feasibility of sea-ice analysis and participating to the first internationally coordinated set of decadal hindcasts and prediction numerical experiments, coordinated under CMIP5. In addition, to reach its aim of a critically assessed model development, COMBINE carried out further small sets of specifically designed numerical experiments.

The concept of the project was based on a specific experimental design to quantify effects of new components for Earth system modelling and the protocols of the Coupled Model intercomparison Project phase 5 (CMIP5) for the definition of the simulations, and the use of an ensemble of seven European ESMs to assess inter-model uncertainty.

The specific objectives of the COMBINE project were as follows:

1. To improve Earth system models by incorporating additional processes and representing more Earth system parameters. The processes selected for this project represent: carbon and nitrogen -cycle; aerosols coupled with clouds and chemistry; stratospheric dynamics and increased resolution, and ice sheets, sea ice and permafrost for the cryosphere.
2. To improve initialisation and error correction schemes for decadal climate predictions;
3. To use the Earth system models for decadal climate prediction and climate projection experiments following the protocols of the Coupled Model Intercomparison Project for IPCC AR5 simulations.
4. To understand and quantify how single or combined new process components influence different climate feedbacks and the magnitude of projected climate change in the 21st century;
5. To understand how the initialisation by itself or initialisation combined with improved process components or improved resolution can reduce the uncertainty in decadal climate prediction.
6. To analyze projected climate change in three different climate regions: the Arctic, the Eastern Mediterranean and the Amazon basin; where different feedbacks are important. To analyse effects of selected new components in each region. To test if high spatial resolution has significant influence on strength of feedbacks.
7. Quantify the impacts in two sectors: water availability and agriculture, globally and within the regions, and analyze the effect of selected new components on these impacts.
8. Use Earth system models to find CO2 emissions that are compatible with representative concentration scenarios specified for IPCC AR5 climate projections, and use an integrated assessment model to revise the scenarios accordingly.
9. Contribute to IPCC AR5 by relevant research and by disseminating climate prediction and projection data to IPCC data archives.

At the start of the project the consortium had available climate and impact models, as used to contribute to the 4th Assessment Report of IPCC. The CMIP5 protocol for climate projections and climate predictions was published, though important data sets needed for CMIP5 were not yet available to the community. Prototypes of component models covering the physical and biogeochemical processes addressed in the project in some cases were also available to the consortium, although the knowledge and experience in the coupling between the component models and the ESMs were generally not available.

The project has been largely successful in pushing the state-of-the-art development and coupling of the physical and biogeochemical processes addressed. Substantial knowledge has also been produced on the understanding and quantification of the role of the new processes in determining climate feedbacks and the magnitude of projected climate change.

However, some non-critical delay in the project work was reported during the first 2 years of the projects. A major reason for this delay was the fact that convergence, within the international climate research community, in delineating and constructing the CMIP5 radiative forcing data was reached only toward the end of 2009 (and in some cases beginning of 2010). This situation was exploited for further advancing the status of the ESMs (i.e., the inclusion of a well-resolved stratosphere in the model versions used for CMIP5 benefitted from this delay), but it also delayed the actual running of the simulations. In some cases it also diverted resourced away from the development work on the incorporation of the new components in the project ESMs. This partial competition of resources (preparing and running CMIP5 experiments with respect to further advancing the ESMs), together with the fact that scientific difficulties became clear only during the course of the coupling of new components (notably examples: fully coupled nitrogen and carbon cycle; Antarctica ice-sheet) added further delay. In retrospect, the anticipated developments were quite possibly over-ambitious for most groups. Nevertheless, if not fully coupled, the new components have largely been implemented and evaluated in offline mode individually, and alternative strategies have been used to assess their role in determining their feedbacks and climate change. For the assessment of the climate change impacts, the regional studies and the assessment of mitigation costs, the delay of the CMIP5 simulations, which constituted the stream-1 simulation set, and consequently of the stream-2 simulations, meant that the primary focus of that work was put on the CMIP5 simulations, for which a larger set of simulations could be used.

The project has been fully successful in achieving a large scale European participation to IPCC AR5 in many ways: by using Earth system models for decadal climate prediction and climate projection experiments following the protocols of CMIP5; by improving initialisation (both ocean and sea-ice) and error correction schemes for decadal climate predictions; and by analyzing projected climate change both globally and locally to assess impacts on water availability and agriculture. The project contribution to IPCC A5 has been achieved quite comprehensively also through publications and direct input, as several COMBINE partners were active as lead or contributing authors.

Main scientific & Technical results

The COMBINE project was organised in 8 work packages (WP). New model components were developed in WP1 to WP4. WP5 provided initial data for climate predictions and investigated different assimilation methods. WP6 and WP7 made climate predictions and projections, respectively, using the experimental design of the Coupled Model Intercomparison Project phase 5 (CMIP5). Two streams of simulations were conducted in WP6 and WP7. The stream-1 simulations used the Earth system models (ESMs) ready early in the project, while the stream-2 simulations made use of the modified ESMs, including the new developments resulting from WP1 to WP5. Simulations from both streams were compared to assess the effect of the new developments on prediction skill (WP6) and feedback parameters (WP7). WP8 assessed impacts of the simulated climate change, e.g. on water availability, and downscale climate change into three selected regions for a more detailed analysis. Main results from these 8 work packages are reported in the following.

Carbon and nitrogen cycle (WP1)

The project was successful in pushing the state-of-the-art of coupled climate-carbon / nitrogen modelling capabilities and diagnose and quantify the additional CO_2 that would remain in the atmosphere if all models had interactive nitrogen cycles. It was possible to diagnose offline the magnitude of the nitrogen requirement to enable the land carbon uptake as projected by the CMIP5 multi-model ensemble. Invariably, all non-nitrogen CMIP5 models simulate an excess uptake of carbon which is not supportable by the available nitrogen, even accounting for biological fixation, liberated nitrogen from soil mineralisation and anthropogenic deposition.

Representations of carbon and nitrogen cycles and related relevant processes were included in six project ESMs (CNRM-ESM, EC-EARTH, HadGEM, IPSL-ESM, MPI-ESM, and NorESM1). Depending on available resources within the project, the developments in each ESM focused on one or more aspects of the carbon and nitrogen cycles.

Scientific and technical developments lead to a fully coupled carbon and nitrogen (C+N) component, including the simulation of N_20 emission, atmospheric transport and related radiative forcing in one ESM (MPI-ESM). The simulations performed with MPI-ESM show some promising results in terms of being able to represent interactions between climate and N_2O emissions. One project ESM (NorESM) had a coupled C+N cycle, based on the CLM4 land-surface model. Two further project models developed C+N coupling in their offline land surface models, ORCHIDEE-CN and JULES-FUN-ECOSSE. These offline land surface models were both tested and are currently being evaluated before being coupled interactively to their respective ESM.

Thawing of permafrost, changes in wetland extent and emissions, and fire are all capable of changing future biogenic methane emissions. Several project models (IPSL, HadGEM2-ES and EC-EARTH) enabled their land-surface to simulate changes in wetland methane emissions. Sensitivities include:

- Warmer temperatures increase wetland emissions per unit area of wetland, but may decrease the total extent
- Changes in precipitation may increase or decrease wetland extent
- Direct physiological response to higher CO_2 increases wetland ecosystem productivity and stimulates greater CH_4 emission

COMBINE models in conjunction with the independent WETCHIMP study (Melton et al. 2012) contributed to the IPCC Assessment Report 5 conclusion that future increases in wetland methane emissions were likely.

No project model interactively included CH_4 emission from permafrost thaw, though offline analysis quantified this and its inherent uncertainty (Burke et al. 2013). It was found that in the near term (few decades) CH_4 release from permafrost thaw would contribute more to additional warming than CO_2 from permafrost, but on longer timescales (by 2100) warming due to permafrost CO_2 was dominant.

Fire schemes were implemented in the land surface models of two project ESM (IPSL-ESM and HadGEM2-ES) , but not yet interactively. No results on changes in CH_4 emissions are available.

Most project ESMs already had land-use carbon emissions and biophysical effects included and analysis within COMBINE contributed to quantify the dual biophysical and biogeochemical effects simultaneously (Brovkin et al. 2013).

In terms of evaluation, much new data were collected, new metrics derived and trialed (Anav et al. 2013) and community activity initiated. However, still it remains a challenge to evaluate carbon/nitrogen cycle models in a way, which may constrain their future behavior. In an attempt to understand driving processes of the observed behavior, the evaluation of multiple models, including the COMBINE ESMs and their offline land surface models was expanded to assess multiple drivers of carbon fluxes. This is a first step towards establishing robust performance metrics for ESMs, based on understanding of the driving processes of the observed behavior and ultimately set constrains on their projections. As an example, Figure 1 show results from an ongoing analysis making use of the modeling capabilities developed during COMBINE. The models in the calculation shown in Figure 1 are:

- NorESM1-ME and its land surface CLM4CN. (The CESM1-BGC model also uses this land-surface scheme and is shown for comparison)
- HadGEM2-ES and its land surface scheme JULES
- IPSL-CM5-MR and its land surface scheme ORCHIDEE

Figure 1 shows that by decomposing the response of the annual gross primary production (a measure of photosynthesis and the flux of carbon from the atmosphere to the plants, positive implies uptake by the vegetation, so high numbers mean more uptake) between 3 key drivers (temperature, precipitation and radiation) we can begin to see different controls under different regimes - for example the response to precipitation may differ between hot and cold regions, or the response to temperature may differ between moist and arid regions. Observational uncertainty is accounted for by using 3 reference datasets. No direct observations at a global scale are available, so we explore 3 fundamentally different ways of estimating the fluxes: the MTE (Jung et al, 2011) dataset based on neural-network analysis linking site level data to environmental drivers; MODIS (Mao et al., 2012) uses a process-based model to retrieve flux estimates from satellite radiance observations; CARBONES (www.carbones.eu) is a process-based land surface model optimized using data assimilation techniques and a range of observational datasets. Finally, by running the models coupled and driven by observed meteorology we can see the impact of model errors in the driving climate versus model errors in the response of the carbon cycle.

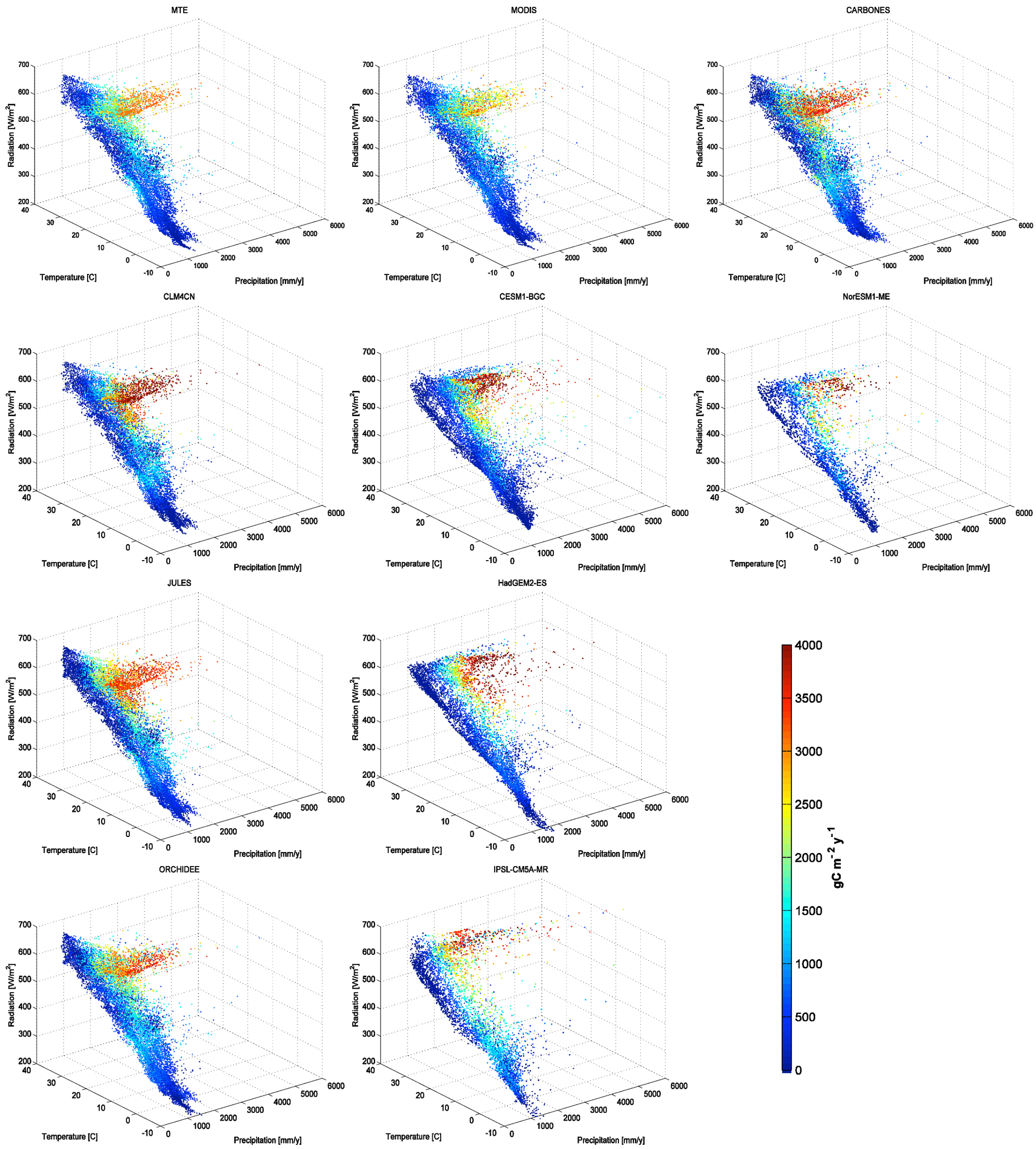

***Figure 1:** Annual global gross primary production [gC/m^2/yr] simulated by Earth system models in climate space represented by mean annual temperature (°C, left horizontal axis), precipitation (mm/yr, right horizontal axis), and radiation (W/m^2, vertical axis). Each data point represents one grid cell. 1st row left to right: MTE, MODIS, CARBONES; 2nd row: CLM4CN, CESM1-BGC and NorESM-ME; 3rd row: JULES and HadGEM2-ES; 4th row: ORCHIDEE and IPSL-CM5-MR.*

Aerosol, clouds and chemistry (WP2)

As part of the development of the MPI-ESM, a stochastic cloud-radiation treatment in ECHAM5 (a version of the atmospheric component of MPI-ESM) enabled to replace the so-called cloud overlap assumptions from the atmospheric model code with a more physically based modeling (Räisänen and Järvinen 2010). The new model showed a generally small impact for the mean present climate, but marked differences in response to increased atmospheric CO_2. The approach was extended in ECHAM5 coupled with the aerosol model HAM (ECHAM5-HAM) to also include aerosol cloud activation, thus contributing towards improved modeling of both aerosol-cloud and cloud-radiation interactions.

Further developments of ECHAM5-HAM included an improved description of the sub-grid scale aerosol-cloud interactions. This description of aerosol processing advanced the modeling of aerosol-cloud interaction by accounting for the nucleation and impaction scavenging of aerosol particles, and introducing the addition of dissolved material on existing insoluble particles inside cloud droplets during the evaporation stage. These processes increase the size, reduce the number, and change the chemical composition of aerosol particles and hence have an influence on subsequent cloud and ice nucleation events. As a result, newly formed aerosol particles tend to be larger and more hygroscopic and thus more apt as cloud condensation nuclei than in the previous model version. Sensitivity studies underlined the importance of scavenging on the aerosol and cloud properties, especially regarding wet deposition, i.e. removal of aerosol particles either by activation to cloud droplets or by collision of aerosol particles with cloud droplets. For instance, the high aerosol loading in the Arctic became into much closer agreement with observations using the improved model where scavenging is better described. These developments resulted in the improved HAM2 aerosol cloud microphyiscs model, which subsequently was coupled to ECHAM6, the atmospheric component of MPI-ESM. This new MPI-ESM-HAM2 model was re-calibrated for a stable pre-industrial climate comparable to that of original MPI-ESM.

To better account for the atmosphere-biosphere interactions in the aerosol-cloud-radiation problem, ECHAM5-HAM and JSBACH land surface and biosphere models were interfaced. This enables not only the model climate to influence vegetation, but also biogenic volatile organic compound (BVOC) emissions from JSBACH to affect aerosol particle growth processes, and thus cloud nuclei, in ECHAM5-HAM. The simulated effect of BVOCs on aerosols and climate is sensitive to the included details of atmospheric oxidation products, dynamics of the condensation process, and the description of secondary organic aerosol (SOA) formation. In COMBINE, two possible SOA formation pathways were established in MPI-ESM. In the first one, biogenic (monoterpene and isoprene) and anthropogenic (toluene, xylene, benzene) precursors are oxidized in the atmosphere to form two products, which can partition in aerosol phase. This scheme involves semi-volatile products, which can evaporate from the aerosol phase. In the second method, only monoterpene is considered as a SOA precursor. In this scheme, no gaseous organic vapours are transported: the precursor is assumed well-mixed in the boundary layer, and oxidation products are partitioned to aerosol phase immediately after oxidation. In general, these two approaches lead to very different results in terms of aerosol-cloud-climate effect. The thermodynamic partitioning mostly increases organic aerosol mass in the larger modes even suppressing nucleation and decreasing CCN formation, whereas kinetic condensation provides additional growth for sub-CCN particles. Numerical experimentation revealed that there is potential for a negative climate feedback mechanism via BVOC-aerosol-cloud-climate interactions. A scenario with 50% increase in BVOC emission due to climate warming and a decreased anthropogenic aerosol and precursor emissions by year 2100 was tested. While the anthropogenic aerosol forcing decreased from -1.6 to -0.2 W/m^2 during the 21st century, the potential increase in BVOC emission can provide an additional negative forcing of about -0.5 W/m^2 in the future.

In addition to fully coupled ESMs to study chemistry-cloud-aerosol-radiation interactions and feedbacks, a faster and simpler system to test ideas and process modules was developed. A stand-alone version of the multi-layer canopy chemistry exchange model (MLC-CHEM) was developed for use within EC-EARTH-ESM. This allows analysis of surface layer observations of tracer concentrations and fluxes as a function of the observed micro-meteorology and vegetation cover, and introduction of new representations of biogenic emissions, dry deposition, chemistry or turbulence. The impact of new modules on atmosphere-biosphere exchanges can thus be flexibly evaluated.

The coupling of the ammonia cycle and nitrate formation to the Earth system was developed and analysed in the IPSL-ESM. Reactive nitrogen plays a key role in atmospheric chemistry and is directly influencing marine productivity, continental biosphere, and soils. Up to now ammonia emissions were not taken into account since they require both atmospheric chemistry and aerosols treated simultaneously in models. The ammonia cycle as well as nitrate formation were introduced in the LSCE model (atmospheric chemistry component of IPSL-ESM) and the results were extensively compared with the measurements that were available up to 2012. The improved model was used to simulate the evolution of the future atmospheric chemical composition and compute the radiative forcings of different aerosols. The future drawdown of aerosol precursors projected with the phasing down of the use of fossil fuel together with the increase in emissions due to agricultural activities will cause nitrate contribution to the forcing to augment significantly in future scenarios. The inclusion of nitrates in IPSL-ESM increases the direct radiative forcing by a factor 1.3 in the year 2000, 1.7 to 2.6 in 2030, and 6.4 to 8.6 in 2100, respectively, depending on the scenario considered.

Stratosphere (WP3)

New representations of stratospheric dynamical processes were included in five project Earth System Models (CMCC, EC-EARTH, HadGEM, IPSL-ESM and MPI-ESM), enabling the inclusion of a well-resolved stratosphere in the CMIP5 (COMBINE project stream-1) simulations.

Main outcomes included significant improvements in the simulation of stratospheric variability, such as the quasi-biennial oscillation and semi-annual oscillation, tropical Kelvin and Rossby-gravity wave packets (Lott et al., 2013), and Northern extra-tropical intra-seasonal and inter-annual variability related to stratospheric sudden warming events (Charlton-Perez et al., 2013). The inclusion of stratospheric dynamical processes was found to affect the stratospheric mass circulation and a better representation of the transport and distribution of water vapor in the upper-troposphere lower-stratosphere region.

Several aspects of tropospheric dynamics and circulation also benefitted from the inclusion of a well resolved stratosphere in the Earth System Models. Biases in the blocking index were reduced over the Atlantic and North Pacific, while the correlation between the North Atlantic oscillation index and stratospheric jet strength was improved. There was also a suggestion that the teleconnections between the NAO index and North Pacific and Asia were more accurate in the new models. The downward propagation of anomalies from the stratosphere compared more favorably with re-analyses with the new models (Hardiman et al., 2012). In the Southern Hemisphere the observed trends in the tropospheric circulation patterns could generally be fully reproduced with the new models, with implications for the Southern Ocean circulation trends and the CO_2 air-to-sea carbon fluxes changes (Cagnazzo et al., 2013).

Cryosphere (WP4)

Greenland ice sheet models (ISMs) were incorporated in four ESMs (IPSL-ESM, CNRM, EC-EARTH, and MPI-ESM). The IPSL and CNRM models incorporated the GRISLI ISM, while the EC-EARTH and MPI-ESM incorporated the PISM ISM. The newly coupled model systems were tested and validated. Most groups achieved the objective of developing mass and energy conserving coupling schemes, in which, neither flux nor anomaly corrections are applied. However, these model systems simulate the present day's Greenland ice sheet with inevitable biases, which can be due to biases from the climate model or from the ice-sheet model. Nevertheless, they are valuable tools for studying the interaction and feedbacks of the Greenland ice sheet in a changing climate. A prototype model of the Antarctic ice sheet has been coupled to the EC-EARTH ESM.

Multi century simulations were carried out for the Greenland ice sheet, after the coupled ESM-ISM systems had been spun-up and properly initialized. While the performance of the MPI-ESM-PISM and the EC-EARTH-PISM models conforms to our understanding, with a stable ice sheet under preindustrial condition, and a substantially shrunken ice sheet in a warming climate, the Greenland ice sheet simulated by the IPSL-ESM-GRISLI model is very stable, even under the warm climate of quadrupled CO_2. Further analysis showed that the lack of sensitivity of the IPSL-ESM-GRISLI is due to the lack of vertical resolution near the surface in the LMDZ model, the atmosphere module of IPSL-ESM-GRISLI, which prevented the ice sheet to melt even under CO_2 quadrupling.

The parameterization of the snow albedo is another key parameter in explaining the differences in simulated Greenland ice sheet responses (Figure 2). No work on this aspect was planned in COMBINE, though the results from COMBINE showed clearly that a better represent of snow on the ice sheets will be crucial to improve the results in future Greenland ice sheet simulations.

Improvement in the representation of sea-ice was achieved either by implementing multi-category sea-ice, or by revising surface processes such as snow over sea-ice and melt ponds, or by implementing wave-sea-ice interactions (Lecomte et al. 2011, Massonet et al. 2011). All these processes are particularly important in a warmer world. Implementing several sea-ice categories into a previously mono-category model was by far the most difficult task but resulted in significant model improvement and differences in projected sea-ice characteristics for warm scenarios. Significant changes in the atmospheric circulation over the Arctic sea-ice were obtained for these different sea ice schemes (Koenigk et al. 2013). More work is needed to better assess the impact of these new sea-ice parameterizations.

The impact of the representation of permafrost on the hydrological cycle has been addressed with the ORCHIDEE model. The new soil freezing scheme, implemented in ORCHIDEE, considerably improves the representation of runoff and river discharge in regions underlain by permafrost and subject to seasonal freezing (Gouttevin et al. 2012). A thermodynamical parameterization of the liquid water content appears more appropriate for an integrated description of the hydrological processes at the scale of the vast Siberian basins.

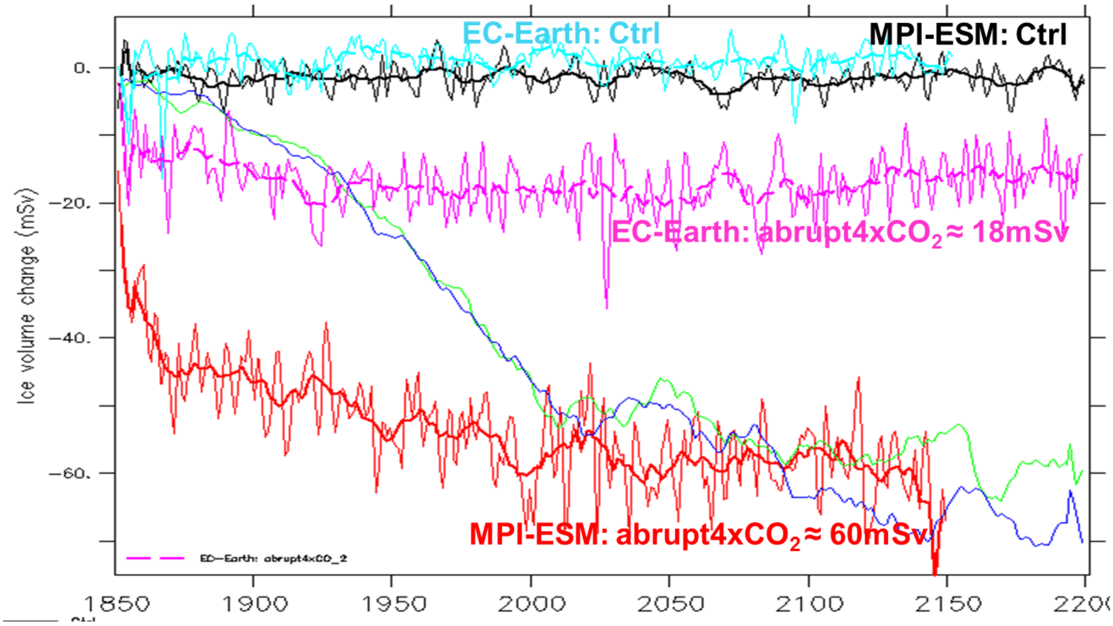

Figure 2: *Simulated net ice loss rates for two fully two-ways coupled ice sheet – climate model systems in the COMBINE: EC-EARTH – PISM and MPI-ESM – PISM, respectively. The ice loss rates are nearly zero for the control run (pre-industrial climate state) for the EC-Earth – PISM (light blue/cyan) and the MPI-ESM – PISM (black line). Under the scenario abrupt4xCO2 the ice loss rates for the EC-Earth – PISM is approximately 18 mSv (magenta line) and reaches almost 60 mSv for the MPI-ESM – PISM (red line). For these above described time series, the thin lines represent yearly values while the thick lines are running means of 13 years. The tiny blue and green lines highlight the loss rate within the MPI-ESM – PISM under the scenario where the atmospheric carbon dioxide concentration raises, from the pre-industrial value, by 1% per year until quadrupled; afterwards the CO2 concentration is kept constant. The green line considers the full two-way coupling, while the blue line represents the response of the ice sheet without any feedback into climate model. Thicker lines are running means of 13 years. The larger difference in the ice loss rates between the two abrupt4xCO2 runs by the two model systems are mostly due to the differences in the snow albedo parameterizations in the two model systems.*

Initialization (WP5)

Gridded ocean re-analyses (NEMOVAR-COMBINE, ORAS4, CMCC, ORA-S3, GECCO and SODA) spanning the relevant period were provided to the different COMBINE partners intending to produce decadal forecasts and predictability investigations. These data sets were used either directly or via relaxation techniques to initialize the decadal forecasts. The ORAS4 reanalysis shows interesting signals in Ocean Heat Content, including the increased role of the ocean in heat absorption, a plausible explanation for the recent hiatus in surface warming (Figure 3).

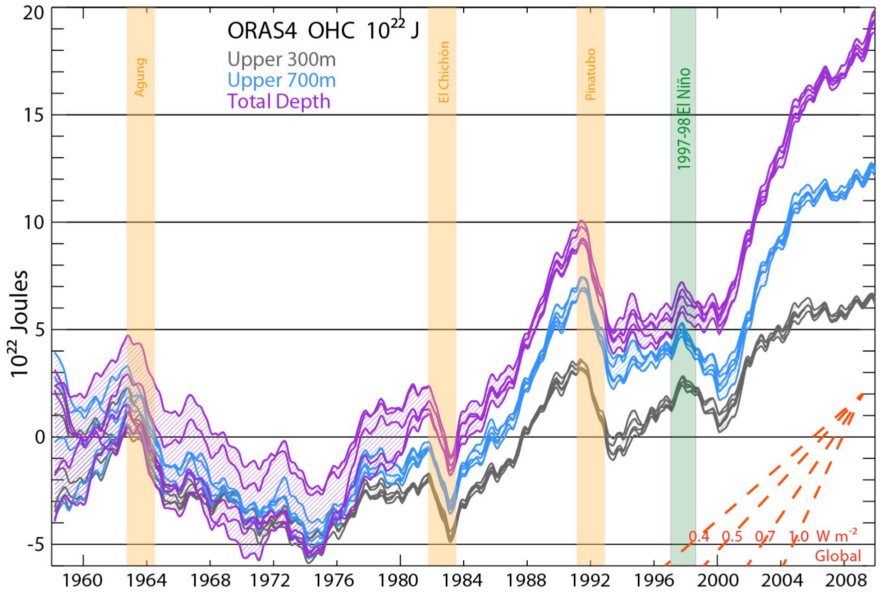

Figure 3*: Global Ocean Heat Content integrated from 0 to 300 m (grey), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members. The time series show monthly anomalies smoothed with a 12 month running mean, with respect to the 1958–1965 base period. Volcanic eruptions and the 1997/8 ENSO are marked by the vertical bars (orange and green respectively). The warming hiatus appears to affect only the upper ocean, and disappears when the whole ocean column is considered. From Balmaseda et al. (2013).*

There is growing evidence that anomalies of Arctic sea ice can influence the atmospheric circulation, impacting northern hemisphere climate especially in Europe and North America. Initialization of sea ice in climate predictions is essential in order to capitalize on this potential source of skill. Prior to COMBINE, sea ice was not initialized in any operational seasonal forecasts, or in most decadal predictions. During COMBINE, sea ice initialization has been developed for the Met Office, CNRM, and EC-EARTH prediction systems. Encouraging levels of skill have been achieved for predicting both summer and winter Arctic sea ice extent several months ahead, with detrended correlations exceeding 0.6 by some systems. Initialization of sea ice thickness was found to be important, especially for predicting summer sea ice. This highlights the need for continued high quality measurements of sea ice thickness, such as those provided by CRYOSAT. During COMBINE, re-analyses of Arctic and Antarctic sea ice have been developed, and shown to be effective for initialization of hindcasts covering the historical period in which actual sea ice thickness measurements are not available (Mathiot et al. 2012). Initialization of Arctic sea ice anomalies contributes to the skillful retrospective forecasts of the North Atlantic Oscillation (NAO) achieved by the latest version of the Met Office seasonal forecasting system, and additional model simulations are beginning to shed light on the physical processes through which sea ice anomalies can influence the atmospheric circulation.

Three different strategies used to deal with model error in seasonal and decadal forecasts have been evaluated: The so-called full initialization, anomaly initialization and flux correction. In the full initialization the coupled model is initialized to a state close to the real-world attractor and after initialization the model drifts towards its own attractor, giving rise to model bias. The anomaly initialization aims to initialize the model close to its own attractor, by initializing only the observed anomalies. The flux correction strategy aims to keep the model trajectory close to the real-world attractor by adding empirical corrections. Both anomaly and full initialization approaches are currently in use in decadal and seasonal forecasts, but their relative merits were unclear. Independent evaluations (Magnusson et al. 2012, Magnusson et al. 2013, Smith et al. 2013] show that at seasonal time scales the full initialization produces more skillful forecasts, while at decadal time scales there is little difference between the approaches. The flux correction strategy has been further explored using the ECMWF system, and results show that the erroneous model mean state is responsible for a degraded forecast skill. The best forecast skill is obtained when the model mean state is corrected by empirical corrections. By correcting the mean state, the interannual variability and teleconnections are improved, resulting in higher forecast skill. These results suggest that the current forecast practices of removing the forecast bias a-posteriori or anomaly initialisation are by no means optimal, since they cannot deal with the strong nonlinear interactions. An important conclusion of this study is that the predictability on annual time-ranges could be higher than currently achieved if model error is reduced. The conclusion from the ECMWF model that the correction of the model mean state by some sort of flux correction leads to better forecasts needs to be assessed in other models. This may also lead to further model improvements since flux correction may be a powerful tool for diagnosing coupled model errors and predictability studies.

Decadal climate prediction (WP6)

European modeling groups lead by the COMBINE project were successful in pushing the state-of-the-art in decadal climate prediction from being an explorative activity of individual groups to its current status of being an internationally coordinated activity of near-term climate predictions (under CMIP5). For the first time, groups agreed to carry out the same series of hindcast and prediction experiments. The CMIP5 decadal prediction experiments were carried out by 5 project ESMs (CMCC-CM, EC-EARTH, CNRM-CM5, MPI-ESM-LR and HadCM3). Within COMBINE, the climate prediction experiments were then examined to highlight several aspects of decadal predictions, using the multi-model approach (Bellucci et al. 2012, Bellucci et al. 2013). The predictive capabilities of the multi-model ensemble were examined both at the global and at regional scales, with additional focuses on the influence of the initialization strategy on predictive skill, and on the level of mutual agreement across different model predictions (measuring uncertainty). All of the analyses were conducted on well-observed variables, including sea surface temperature, near surface air temperature and precipitation over land.

Although most of the skill (measured through the anomaly correlation coefficient; ACC) associated with surface temperature fields is dictated by the prescribed boundary conditions, after removing the long-term trends a significant residual predictive skill is found over large oceanic and continental areas. In particular, the multi-decadal variability of sea surface temperature (SST) in the Atlantic basin appears to be skillfully reproduced by individual forecast systems, showing considerable predictive capability up to ~10 years. Similarly, long-term predictability is found for near-surface air temperature over Northern Africa and the adjacent Mediterranean and Middle East. Contrastingly, compared to surface temperatures, precipitation exhibits much lower predictability, except at a few limited areas, including the African Sahel, parts of North America, and Eastern Europe (Figure 4). These results are consistent with a plausible, strong connection between the Atlantic multi-decadal variability and the surface temperature and rainfall changes occurring over regions adjacent to the Atlantic basin. This link may be a signature of the Atlantic Multidecadal Oscillation (AMO) teleconnection pattern, as suggested in a number of previous studies (e.g., Knight et al. 2006). An important finding of the predictive skill analysis of the multi-model COMBINE ensemble is that the multi-model ensemble mean generally outperform the individual forecasts (when this is not the case, it is at least comparable to the best of them). This finding has been well documented for seasonal forecasting, but here is found to hold also at the decadal range, supporting the need for large multi-model ensembles of diversified models to provide valuable decadal predictions.

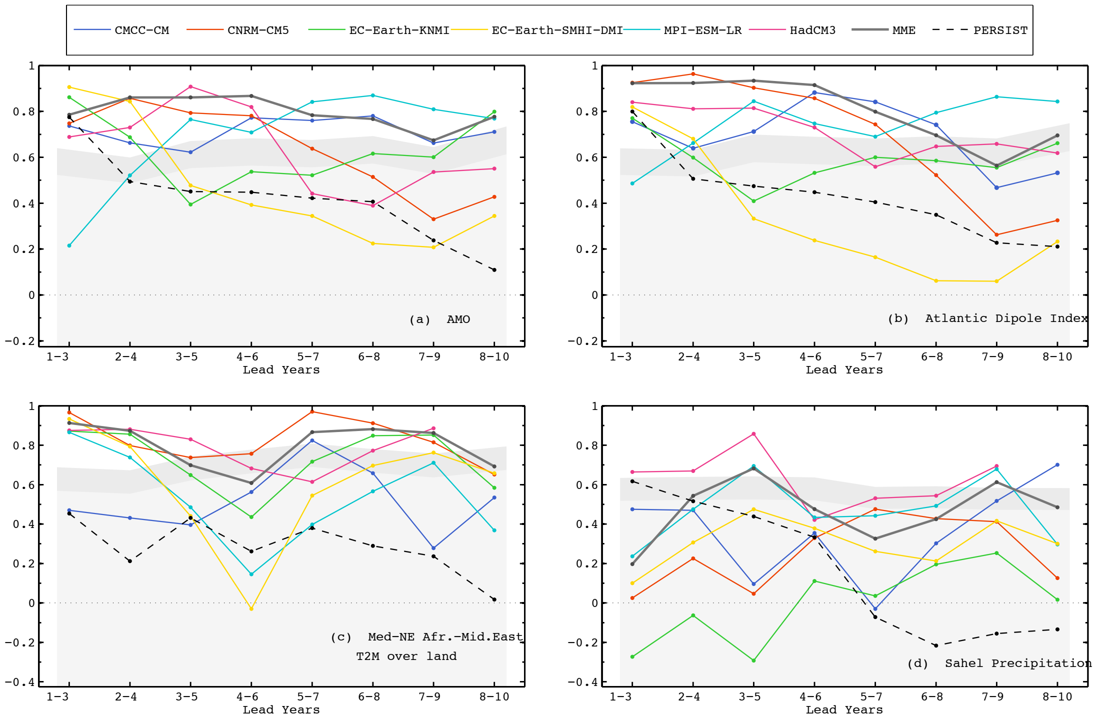

Figure 4: *ACC as a function of lead time for different climatic indices: (a) AMO, (b) Atlantic SST Dipole, (c) T2M averaged over an area including parts of the Mediterranean, NE Africa and Middle East [20–45N, 10–50E], (d) PREC averaged over the Sahel [8–18N, 15W–15E]. The two thresholds displayed by grey shading correspond to the 90% and 95% levels of statistical significance, accounting for autocorrelation in the time series.*

One of the open questions for decadal prediction relates to the identification of an optimal (i.e., skill-maximizing) initialization strategy. By clustering the 6 analysed decadal prediction systems in two groups according to the initialization method (full-value and anomaly initialization), it was possible to frame this issue (so far only examined for individual systems: Smith et al. 2013, Hazeleger et al. 2013) in a multi-model perspective. From the comparison between the predictive skill patterns associated with these two groups, the Equatorial Pacific emerged as an area particularly sensitive to the details of the initialization method. In particular, the anomaly initialization seems to exert a deteriorating impact on the skill in the Equatorial Pacific, while a sensible improvement is obtained in the full-state initialised systems. Should this result be confirmed (possibly by extending the same analysis to a larger set of systems), there would be implications for the design of multiple model ensembles for operational decadal climate predictions (Smith et al. 2013), as the balance between anomaly and full-value initialized systems may strongly affect the regional skill of the multi-model mean. Finally, the consistency across the different model predictions of surface temperature was assessed. The model-to-model RMSE pattern indicated that the largest departures between different decadal prediction systems occur at the same locations where the largest year-to-year variability is found (in particular, over the areas dominated by intense western boundary currents and their open ocean extensions). The pattern of temporal coherence across different systems reveals a general agreement between models in predicting the near-term evolution of surface temperature fields (referring to the sign of the corresponding anomalies), displaying positive correlations between different decadal predictions over most of the global domain.

The present analysis adds to the growing evidence that the current generation of climate models adequately initialized have significant skill in retrospectively predicting years ahead not only the anthropogenic warming but also part of the internal variability of the climate system. The high skill detected in the Atlantic sector, and extending over the potentially linked surrounding areas (including the Mediterranean and Sahel climatic hot-spots), emerges as a particularly robust feature of CMIP5 models. This finding discloses a promising future for the recently established decadal prediction field of research, envisaging the possibility of valuable assessments of climatic fluctuations at the regional scale over a multi-year horizon.

In addition to the CMIP5 decadal prediction experiments (denoted “stream-1” within COMBINE), a second set (stream-2) of experiments were carried out and analysed. Particular emphasis was given to the comparison of stream-2 against the benchmark set of stream-1 predictions. The legacy of this deliverable is a multi-model set of decadal prediction integrations, performed using dynamical models of varying levels of structural complexity and implementing different initialization strategies, that are / will be analyzed in current / future projects (we envisage, both at the European and international scale). In synthesis, the analyses performed so far on the individual sets of decadal integrations reveal the following: (i) there are indications that the inclusion of a well-resolved stratosphere in a dynamical model determines an improved predictive skill over certain areas, in most of the analysed systems; (ii) there is no clear evidence in support of the fact that a better constrained sea-ice initial state leads to an improved predictive skill (and reduced RMSE); iii) an improved representation of land-surface (through the inclusion of a dynamic vegetation model) leads to a limited (but sizeable) enhancement in the predictive skill featured by surface temperatures.

Two other sets of experiments were conceived, to investigate the potential predictability of the climate system. For the potential predictability experiment sets (again stream-1 and 2), no common experimental set-up had been designed, leaving individual partners free to tailor the experimental setting around the particular purpose of the experiment. This was because, potential predictability experiments are generally designed to provide insight in the physical mechanisms leading to the predictability of the Earth System and are conducted in an idealized setting to ease the set-up and analysis of the experiments. The Earth System components investigated for their potential predictability were: Dynamic vegetation, improved representation of sea-ice and of stratospheric dynamical processes. In addition, the impact of different approaches of ocean initialization had been investigated, in collaboration with the work-package on initialization. In general, a small but positive impact has been found for each of these components. The incorporation of a dynamical vegetation module induced a small but detectable impact of a dynamically generated leaf area index on potential predictability of surface air temperatures. The new sea-ice modules improved the predictability of sea-ice but the impact on other variables was small and limited to the Arctic region. A well resolved stratosphere increases the potential predictability. This increase is however geographically localized and only for certain variables. In addition the well-resolved stratosphere is able to simulate and predict new modes of variability such as sudden stratospheric warming events and the Quasi-Biennial Oscillation. Hence, a well-resolved stratosphere in decadal climate prediction models includes pathways of stratosphere-ocean links not previously addressed (Reichler et al. 2012). The results of COMBINE however also reveal that further development of these new components is necessary, to fully take advantage of them.

Climate projection and feedbacks (WP7)

Through the COMBINE project, the climate projection experiments for CMIP5 from the European side (7 ESMs: CMCC-CESM, EC-EARTH, CNRM-CM5, HadGEM, IPSL-ESM, MPI-ESM, an NorESM) were accomplished. As in the case of the prediction experiments, two series of model set of experiments were conceived for the project projection experiments: the stream-1 projection experiments with model configurations as used in CMIP5 and the stream-2 experiments with improved process descriptions. The stream-2 simulations consisted of a subset of the CMIP5 runs, including new processes, components, or improved process descriptions as developed in the work-packages related to the carbon & nitrogen cycle, aerosol processing, ice-sheets and sea-ice. Note that the inclusion of a well resolved stratosphere in the European ESMs was already achieved for the CMIP5 / experiments. In the case of the stratosphere, the investigation of the impact of this new component was carried out with respect to CMIP3 (Charlton-Perez et al. 2013, Manzini et al. 2013). The projection stream-2 experiments are one of the main legacies of the project, because they provide for a first foundation for the next cycle of CMIP (phase 6) to take place in the next years. It is expected that these experiments will be augmented by new ones and explored in ongoing and future European projects. In addition to supply for the 2 streams of experiments, their results were analyzed for feedbacks and impacts and.

The radiative feedbacks in the stream-1 / CMIP5 simulations were analysed using the comprehensive partial-radiative perturbation (PRP) and Kernel methods. These detailed quantitative methods have been put into the context of the international contributions to the entire CMIP5 multi-model archive by exploiting the Gregory method using a linear regression approach from coupled simulations in which carbon dioxide concentrations are abruptly quadrupled. Details of the feedbacks in idealised simulations in equilibrium and in transient conditions were investigated (Tomassini et al. 2013). After the new components were developed by the COMBINE work packages, a new suite of simulations (stream-2) was conducted consistently with the simulations performed for stream-1 with the old model systems. Model systems employing improved representations of the carbon/nitrogen cycle, of aerosols and clouds, and of sea-ice and Greenland ice sheets (cryosphere) were analysed in comparison to the respective old simulations. Climate sensitivity and radiative feedbacks are mostly affected by aerosol microphysical processing of clouds, and sea-ice representations. Overall, climate sensitivity is slightly smaller in the improved models compared to the old model systems.

In a warming climate, the Greenland ice sheet shrinks substantially due to mainly the melting at the ice surface that exceeds the increased precipitation. The melt water fluxed into ocean results in slowdown of the recovery of the Atlantic meridional circulation that has weakened in a warmer climate. Concerning other cryospheric components considered in the project, the representation of melt ponds has a minor effect on global climate.

For CMIP5 models and in preparation of IPCC AR5, the carbon cycle feedbacks were determined for the COMBINE models alone and then also for the COMBINE models together with all other relevant Earth system models worldwide in cooperation with the Canadian climate centre (Arora et al. 2013). To this end, with each COMBINE ESM system which includes the carbon cycle the following experiments were carried out: A spin-up to quasi-equilibrium (at least over several hundreds of years), a control simulation over 140 years, and a fully coupled 1%-CO_2-concentration-increase-per-yr scenario (until 4x CO_2 in the atmosphere). In addition experiments over this 140 yr period were performed where only the biogeochemical model components or only the physical model component experience a CO_2 increase in the atmosphere. This enables an approximate separation of the effects of rising CO_2 concentrations on air-land as well as air-sea carbon fluxes and the effects of climate change (here temperature increase) on air-land as well as air-sea carbon fluxes. The overall carbon cycle feedback to climate change was confirmed to be positive. The land uptake in models, which did include for the first time in CMIP experiments a limitation of plant growth on land through nitrogen availability revealed a lower uptake of carbon from the atmosphere than the bulk of the other models.

The separation of feedback effects due to rising CO_2 (biogeochemical feedback) and due to warming (physical feedback) for the oceanic Earth system component was investigated by Schwinger et al. (2013). The error in linearising the ocean carbon cycle climate effect into a linear feedback factor can be as large as the associated climate feedback itself. For a quantification of the overall climate feedback through the carbon cycle this is a relatively small amount, however, this situation could potentially change in future when less diffusive higher resolution models become available. The fully coupled models showed a stronger effect on the ocean carbon cycle feedback to physical forcing than the other model runs. This underlines the necessity for Earth system models including the carbon cycle.

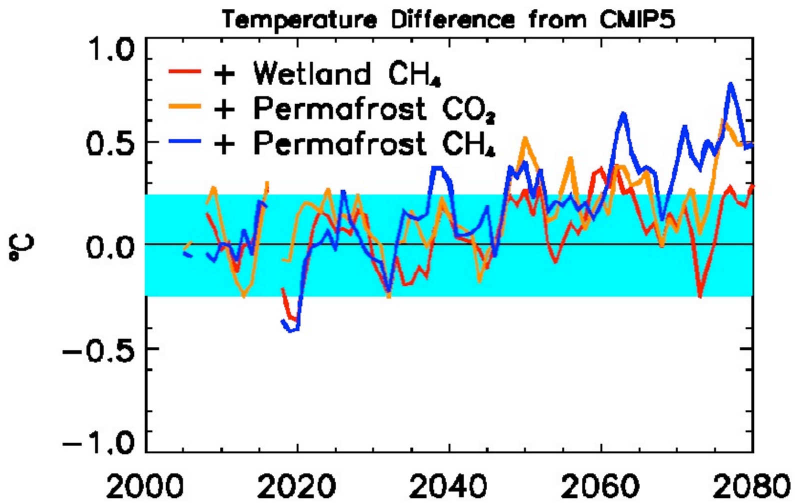

Figure 5: *Change in global average temperature relative to the standard CMIP5 RCP8.5 simulation with prescribed concentrations when accounting for the additional warming from CH_4 and CO_2 emissions from wetlands and permafrost. The blue band on left panel shows two standard deviations for global temperature. (Result from the UK Metoffice model HadGEM2-ES).*

Addition of nitrogen limitation for terrestrial biomass production results in a reduced uptake form carbon by the land biosphere under elevated CO_2 in the atmosphere. This was corroborated through dedicated model experiments including nitrogen limitation and also N_2O cycling in ocean, land, and atmosphere. Inclusion of wetland methane (CH_4) production, as well as release of CH_4 and CO_2 from melting permafrost areas under climatic warming results in substantially increase positive feedbacks in the order to 0.5-1 degrees more warming in the late 21st century (Figure 5).

Impacts and Scenarios (WP8)

Information and data produced by the scenarios of future climate change projection simulated by the project ESMs were analyses with integrated assessment and impact models, focusing on important sectors such as climate policy, hydrology / water resources and primary production.

Analyses showed that feedbacks could have a considerable impact on the climate strategy and its costs. Permafrost has a positive feedback on climate change; biomass fires either have a positive or negative feedback on the climate system. Wetlands and ozone feedbacks show the lowest feedback parameters and consequently lowest impact on costs. Climate sensitivity and carbon cycle assumptions have the strongest impact. Mitigation costs vary by a factor 8 depending on assumptions on the climate sensitivity. However, climate feedbacks and their implementation are subject to large uncertainties and the strength of the response of climate feedbacks to climate change is still unclear.

Analyses of the climate model outcomes confirmed that many meteorological and hydrological extremes would increase due to higher greenhouse gas concentration in the atmosphere. Heat waves will increase throughout the world. Also rainfall intensity is projected to increase in large parts of the world. In large areas the number of days with rain is decreasing and the amount of rainfall per event / rain-day is increasing. These changes have a large impact on hydrological extremes and water resources availability. Both flood and drought risks are increasing in significant parts of the globe.

The total future water resources availability is estimated to increase in large parts of the globe when using the ensemble average of several Earth System Models (Figure 6). However, the analysed climate impacts on global hydrology and water resources showed a wide diversity between the simulation runs with input data from the different ESMs. Some models such as HadGEM predict a relatively large scale drying while the EC-EARTH model shows a much wetter future globe. Despite the global increase of water availability there will be regions such as Central America and Northern Africa where under all scenario assumptions renewable water resources are diminishing. Linking the water resources to the development of human population until 2100 shows that per capita water availability will drop significantly in many regions of the world, meaning that there is the danger that even a regional increase of water availability often cannot compensate the rising water demand by human activities. This leads to the conclusion that a growing part of the world population is threatened to face situations of water scarcity, especially in regions with already high pressure on existing water resources such as the Middle East or India.

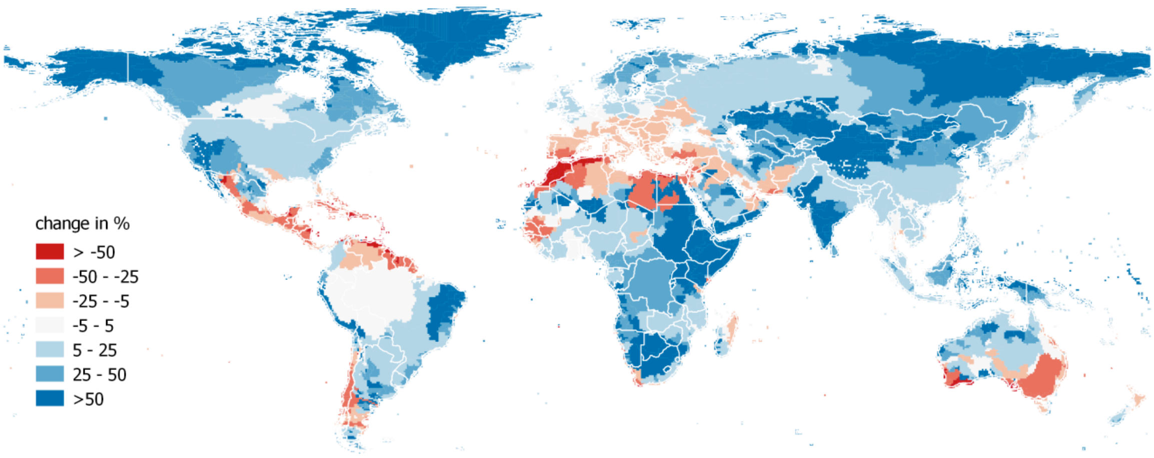

Figure 6: *Change in the average annual water availability on watershed level (ensemble mean) between the time periods 1971-2000 and 2070-2099 for RCP8.5. The calculations were conducted with the WaterGAP2 model using bias corrected climate input from five different Earth System Models used within COMBINE.*

Analyses with LPJ showed that the total plant production is projected to increase due to climate changes. To a large extent this is due to the direct impacts of higher atmospheric CO_2 concentration on plant growth. Without this direct CO_2 impact plant production is only increasing in the high latitude regions of the Northern hemisphere, some mountainous regions and parts of Africa where rainfall is increasing.

The regional analyses on the Arctic showed that, patterns and amplitudes of future temperature change are quite similar between regional and global model simulations. However, some interesting differences occur: The warming over the ocean is generally smaller in regional climate model and the warming over land is larger in winter and spring but reduced in summer. In terms of precipitation there is more small-scale variations in the regional climate model results over land areas, probably due to the higher resolution and better-resolved topography compared to the global models. The regional downscaling simulates a substantially larger increase in summer precipitation compared to the global future projections.

The Amazon case showed that, the impacts of climate change increase when effects of land-use change and fire are considered. The effects of fire and changes in land use and climate result in a warmer and possibly drier climate. This has an important impact on future biome distribution in Amazonia.

The analysis of climate models data for the Mediterranean regions indicates that projected shorter rainy periods could seriously affect the water resources by significant reduction of water availability with wide ranging consequences for local societies and ecosystems. The results show that the quantitative impact of these changes on water availability can be substantial at watershed level, especially in a Mediterranean island like Crete.

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Potential impact, main dissemination activities and exploitation of results

Potential impact

The COMBINE project generated new knowledge in the field of fundamental climate research through its advancement of the capabilities of an ensemble of European Earth system models. The use of these models in climate projection has established the high quality European participation to the CMIP5/ IPCC AR5 process. New knowledge and expertise as also been generated in the establishment of the European climate prediction systems, including the development and assessments of new initialization techniques of the ocean and by pioneering analysis and initialization of sea-ice. These advances are providing for the scientific base of the European initiative for climate service observation and modelling (ECOMS), comprising the EUPORIAS, NACLIM, and SPECS projects.

COMBINE directly contributed to IPCC AR5 through (a) the relevance of the research in COMBINE to climate change studies and (b) by using the experimental design proposed for the internationally coordinated experiments for the scientific work in this project. Hence, climate predictions and projections carried out in COMBINE added to the CMIP5 data archives, which are accessible to the international climate research community at large.

One of the key processes addressed by COMBINE was the nitrogen and carbon cycle. Understanding the carbon cycle is a crucial link between human activity and climate. The concept of "TCRE" - transient climate response to emissions – is one of the major advances highlighted in IPCC AR5 since AR4. It quantifies the climate response to human activity in terms of carbon emissions rather than the more hypothetical response of the climate to an idealised doubling of atmospheric CO_2 concentrations. AR5 presented an uncertainty spread of TCRE but on top of this there are many missing processes – with permafrost, wetlands and nitrogen being among the most important. COMBINE took steps to address these.

The nitrogen limitation of the carbon cycle, as quantified within COMBINE, will have substantial impacts on the value of TCRE and hence the emissions compatible with any climate target (e.g. Jones et al. 2013). All of the new processes addressed by COMBINE that are related to the carbon/nitrogen components (nitrogen limitation, wetland emissions and fire) represent positive feedbacks in the context that they will increase atmospheric concentrations of greenhouse gases for given emissions. Conversely therefore they all mean lower compatible emissions to follow a given concentration pathway, such as RCP2.6.

Thawing permafrost will release both CO_2 and CH_4, wetlands response to future environmental changes will likely emit more CH_4, and the role of nitrogen limitation will mean less uptake of CO_2 from the atmosphere by the terrestrial biosphere. The impacts of these have been shown on climate, and on socio-economics.

The better representation of the stratosphere in models can improve the reliability of climate predictions and projections at a regional level, which is essential for assessing the socio-economic and societal impacts.

The cryosphere is undergoing rapid changes in the recent decades. The feedbacks associated with the cryosphere, such as between snow and ice albedo and the surface temperature, or between the sea- and land-ice melting and the oceanic convection and deep ocean circulation, or between permafrost melting and methane emissions, significantly contribute to climatic changes related to human activities. Furthermore, melting of ice sheets and the resulting sea level rise is one of the most severe societal threats of global warming. Retreat of the Arctic sea ice has impacts on weather and circulation beyond the high latitudes. The better representation of the sea ice and the inclusion of the ice sheets in the ESMs can better quantify the rapid and long-term feedbacks of the cryosphere changes, and improve the reliability of the climate projections.

As climate changes, there is a growing need from many sectors of society for skilful and reliable predictions of the coming seasons to decades. Initialization of climate models is essential for forecasting on these timescales, in order to predict natural internal variability, and to correct model responses to previous external forcing factors. The initialization schemes developed in COMBINE have enabled many centres to contribute to the CMIP5 decadal simulations for assessing the skill of near term climate predictions.

A main objective of COMBINE was to evaluate whether either the use of an improved initialization strategy or the inclusion/better representation of a specific climate component determines a sensible change in the predictive skill of a given decadal prediction system. The outcomes of these activities contributed to enhance state-of-the-art climate prediction systems through a better understanding of the main drivers of decadal predictability and by testing different initialization strategies, thus responding to the increasing demand for reliable near-term forecasts from a wide range of end-users and decision-makers. Infrastructure planning, water management and the implementation of adaptation strategies are just a few examples of the sectors which will benefit from an improved climate forecasting service on interannual to decadal timescales.

For a quantitative understanding of global climate change, a more reliable quantification of climate sensitivity, and its components, the radiative feedbacks, is necessary. We were able to quantify the impacts of the individual new or improved model components on climate sensitivities and disentangle the pathways of how these effects act. There is a slight indication from the improved models in comparison to the old versions that climate sensitivity is slightly smaller than previously simulated.

A melting of the inland ice sheets and the subsequent sea-level rise is one of the most severe long-term threats of global warming. Widespread Arctic sea ice melt, in turn, is one of the most imminent severe threats of global warming. Both effects are now more reliably simulated (sea-ice) or newly implemented into the comprehensive Earth system models at all (Greenland ice sheet).

The inclusion of carbon and nitrogen dynamics in Earth system models employed for future climate projections is necessary for a realistic estimate of compatible emission in order to achieve a specific greenhouse gas level in the atmosphere and a respective limit of global warming. The carbon and nitrogen cycles overall contribute to a positive climate feedback and hence reduce the allowable greenhouse gas emissions in order to reach a specific climate target.

The climate change can potentially have large socio-economic impacts. The feedbacks in the climate system have a large impact on the linkages between carbon emissions and future global temperatures. With more positive feedbacks there is a need for more mitigation to achieve the two-degree target. As a result the mitigation costs increases with more positive feedback and reduce with more negative feedbacks. This project quantified these costs and shows the socio-economic importance of properly quantifying.

The impact analyses showed the serious changes in extremes especially in scenarios assuming high emission pathways. Under RCP8.5 the changes in hydro- and meteorological extremes are much higher than under the RCP4.5. This shows the need for mitigation to avoid serious impact on important resources such as food and water. The potential impacts were made particularly clear for in the Mediterranean case study showing large impacts of future climate change on water resources and agricultural production.

Main dissemination activities

A major dissemination event was the COMBINE International Science Conference, jointly organized with the 3rd International Conference on Earth System Modelling (3ICESM) of the Max Planck Institute for Meteorology, 17-21 September 2012, Hamburg, Germany. The synergy generated by the joint event has provided for a vibrant discussion week and a great opportunity for the dissemination of the COMBINE project results, including drawing the attention of the international Earth System model scientific community outside Europe, to the project results. The conference brought together 476 scientists from 27 counties.

Scientific results from the research pursued in the COMBINE project are mainly disseminated to the international research community by peer-reviewed articles. Additional routes of more immediate dissemination were the project newsletters, the project technical reports and the web site. Particular emphasis has been put in circulating among the partners the benefits and requirements of making their publications available free of charge via the publisher or a repository (i.e., comply with open access). As our institutional repositories are being established, it is expected that virtually all COMBINE publications will be open access within six months from their publications. However, as these repositories are under constructions, open access may be delayed in some cases.

Many results from the COMBINE project were presented in international conferences, such as those of the European Geophysical Union and the American Meteorological Society. Further activities included the dissemination of COMBINE results in and the provision from the COMBINE generated knowledge for the scientific foundation of specialized international workshops under the auspices of the International Geosphere-Biosphere Program and the World Climate Research Program.

A side event: “Shaping tomorrow's carbon cycle research: Knowledge gaps, international collaboration, and funding priorities” with contributions from several projects, among them COMBINE, took place at the 9th International Carbon Dioxide Conference, Beijing, China, 3-7 June 2013.

Of particular interest ware the opportunity for several COMBINE partners to present their most recent advancements on decadal prediction and predictability issues at the (1) International workshop on seasonal to decadal prediction, 13-16 May 2013, Toulouse (France): The goal of the workshop was to review our current abilities to make skillful predictions on seasonal to decadal timescales. The availability of results from the Climate system Historical Forecasting Project (CHFP) and the decadal prediction component of the Coupled Model Intercomparison Project (CMIP5), together with very active investigations in both operational and research communities, supported the timeliness of the workshop; and the Joint THOR-

COMBINE decadal prediction meeting, November 2009, KNMI, Utrecht (NL). This meeting, jointly organized by THOR and COMBINE, gathered several scientists from both projects communities. The goal of the meeting was to make an inventory of methods and discuss best practices for decadal predictions.

Several COMBINE partners were active in the IPCC AR5 WG1 report, specifically with Jones, Friedlingstein, Lohmann as Lead Authors and Heinze as Review Editor. Therefore COMBINE was represented during the AR5 writing process. Jones and Friedlingstein also led a carbon cycle special issue of Journal of Climate, which featured several COMBINE presentations: http://journals.ametsoc.org/page/C4MIP

Exploitation of results

The European and International scientific climate research community will benefit / is already benefitting from a number of scientific & technical development which have resulted from COMBINE and form the future legacy of the project. Current and future plans of exploitation of COMBINE results (project foreground) include their provision for the scientific & technical base of the European initiative for climate service observation and modelling (ECOMS), comprising the EUPORIAS, NACLIM, and SPECS projects, as well as for any other current and future project on climate and the Earth system. A large fraction of the model-data produced by COMBINE simulations (the outputs from the COMBINE stream-1 runs) are on the public CMIP5 archive, and so available to the international scientific community for analysis in the years to come. COMBINE scientific & technical development will also be exploited by the next cycle of CMIP.

COMBINE scientific & technical development (models) and result (model-data & analysis-data) include:

- Online carbon & nitrogen coupling interface model (MPI-ESM, MPG).
- Offline carbon & nitrogen coupling interface model (ORCHIDEE-CN, CNRS and JULES-FUN-ECOSSE, METO)
- Permafrost models for IPSL-ESM (CNRS), HadGEM2-ES (METO) and EC-EARTH (KNMI)
- Fire models for IPSL-ESM (CNRS), HadGEM2-ES (METO)
- Extensions of the atmospheric model ECHAM5/6 for several applications: stochastic cloud generator module (McICA, FMI), ECHAM5/6-HAM with aerosol activation (FMI) and aerosol cloud processing (ETHZ), ECHAM5/6-HAM-JSBACH with BVOC emissions (UHEL). ECHAM based modules will probably be used by other ESM using ECHAM as the atmosphere model.
- MLC-CHEM multi-layer canopy chemistry exchange model (WUR)
- LSCE-IPSL model with ammonia cycle and nitrate formation (CNRS)
- Stratosphere-resolving models are being adopted as the climate model's standard configuration (CNRM, HadGEM, IPSL-ESM, MPI-ESM).
- The Earth System Models that are fully coupled to ice sheet models for Greenland: MPI-ESM – PISM (MPG), EC-EARTH – PISM (DMI), IPSL – GRISLI (CNRS), CNRM-CM5 – GLISLI (MF-CNRM).
- New generation of the sea ice model with multiple ice categories: LIM3 (UCL), and its coupling to the ocean model NEMO-LIM3. NEMO-LIM3 will probably be used by other ESMs using NEMO as the ocean model.
- Improved seaice model LIM2 (EC-EARTH) to represent melt pond albedo effect (SMHI).
- Improved sea ice model GELATO5, for CNRM-CM5 (MF-CNRM).
- Development of the NEMOVAR ocean data assimilation system. This is a fundamental component for the ocean and sea-ice initialization. The sea-ice initialization for EC-EARTH developed in COMBINE will be used and further

improved in the next version of the EC-EARTH model (as part of the EU SPECS project).

- ECMWF and Met Office ocean analyses are publicly available at the EasyInit data server. The ocean re-analyses produced under COMBINE are entering the international CLIVAR/GSOP-GODAE Ocean Reanalysis Intercomparison project.
- Partial-radiative perturbation and radiative Kernel tools (MPG): Software package based on the radiation code of the MPI-ESM that allows diagnosing quantitatively radiative feedbacks from climate simulations.
- Soft-coupled model version of LandSHIFT and WaterGAP2 has been developed that allows accounting on the effect of water availability on the spatial pattern of irrigated cropland (Uni Kassel).
- Bias corrected datasets at half-degree grid for the land surface for the following variables: wind speed, maximum temperature, minimum temperature, mean daily temperature, surface downwelling shortwave radiation, surface downwelling longwave radiation, precipitation and snowfall (WUR). The datasets are available for the 1970 to 2100 time period and are based on the model output of six ESMs (MPI-ESM-LR, IPSL-CM5A-LR, HADGEM2-ES, ECEARTH, CNRM-CM5, CMCC-CESM) for both the RCP4.5 and 8.5.
- COMBINE stream 1 model outputs are on the CMIP5 archive (MPG, METO, ECMWF, KNMI, SMHI, CMCC, CERFACS, DMI, CNRS, MF-CNRM, UCL, UiB)
- COMBINE Stream-2 model outputs: All the data produced as part of WP6/WP7 activities (not including those available on CMIP5 archiving system) were stored locally (at individual partners' data server) and are available upon request. This choice followed several discussions within the Data Panel, where the option of storing data on an external central server was deemed to be unfeasible. The model outputs are maintained by each participated partners and available on request.

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