European Commission's 7th Framework Programme
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Project acronym: **COMBINE**

Project full title: **Comprehensive Modelling of the Earth System for Better Climate Prediction and Projection**

Instrument: Collaborative Project & Large-scale Integrating Project

Theme 6: *Environment* Area 6.1.1.4: *Future Climate*

ENV.2008.1.1.4.1: *New components in Earth System modelling for better climate projections*

Start date of project: 1 May 2009 Duration: 54 Months

Publishable Summary – Third Periodic Report (1 May 2012 – 31 October 2013)

Summary description of the project context and the main objectives

The main objective of the COMBINE project was to advance the capabilities of climate prediction and projection based on comprehensive Earth system models. The project brought together the leading European centres in Earth system modeling thus making use of an ensemble of seven Earth system models.

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, developed 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.

At the start of the project the consortium had available climate and impact models, as used to contribute to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The experimental protocol of the Coupled Model Intercomparison Project – phase 5 (CMIP5) 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.

COMBINE included research on critical dynamical, physical and biogeochemical processes in the Earth system and the related feedbacks, which eventually determine the amplitude of natural climate variability and anthropogenic climate change. The COMBINE project therefore aimed at developing new model components for the carbon and nitrogen cycles; aerosols coupled with clouds and chemistry; stratospheric dynamics; and the cryosphere comprising ice sheets, sea ice and permafrost. An assessment of the sensitivity of physical and biogeochemical feedbacks and climate change to such processes added in Earth System models was then a final objective of the project.

COMBINE investigated the potential predictability of climate on time scales up to a decade and developed initialization and correction methods to practically realize this potential. This research aimed at a better quantification of the potential predictability based on an ensemble of Earth system models and standardized CMIP5 experiments, and at the development of procedures to exploit this potential in current Earth system models, using ocean and sea ice analyses and accounting for systematic biases of models. The project assessed the sensitivity of decadal predictions to the choice of the initialization and correction methods, as well as to adding selected new components to the Earth system models.

COMBINE aimed at linking Earth system simulations for the past and future to global and regional impacts, thus closing the circle between the development of socio economic scenarios and the projection of climate change by comprehensive Earth system models.

Work performed since the beginning of the project and main results achieved

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 increased 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 (also 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 projections 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.

Description of expected final results and their potential impacts and use

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 projections has established the high quality European participation to the Coupled Model Intercomparison Project – phase 5 (CMIP5) and provided new information for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). New knowledge and expertise has 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, for example, 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. It is expected that these data will be used in research for many years.

One of the key processes addressed by COMBINE was the nitrogen limitation of the 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 emission rather than the more hypothetical response of the climate to an idealised doubling of the atmospheric CO_2 concentration. 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 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 representative concentration pathways (RCPs). 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.