Contents

Executive Summary

The European Union FP7 project 'Enhancing robustness and model integration for the assessment of global environmental change' (ERMITAGE) was an eight-partner consortium that ran from December 2010 to November 2013, supported by €3.4m of EU funding from the Commission. ERMITAGE was a response to the need for an enhanced software framework to improve the integration of environmental change and related policy models. Important aspects of the framework include transparency of methodologies, public access and extensibility, policy relevance of results, and the applicability of the framework to sustainable development challenges. These objectives were achieved by building on existing platforms and technologies for model coupling, including statistical emulation, whereby complex computer codes are replaced by simpler models that reproduce their output in a fraction of the computational time.

A major development of the project was the successful, interactive coupling of complex climate change and economic and energy system models. The resulting coupled models were used to analyse the impacts of climate change on heating and cooling demand, the impacts of sea-level rise and the structural changes required to switch from low to relatively high-ambition mitigation scenarios broadly consistent with the 2C global warming target. A further important new development was the coupling of a groundwater recharge module to the land-surface model, permitting the analysis of the sustainability of groundwater under future climate change.

Coupling of energy and macro-economic dynamics to detailed agricultural production dynamics produced a range of notable applied results on the role of bioenergy in mitigation scenarios in the context of competition between food and fuel production and forest protection. A key finding was that under strong mitigation scenarios, it is economically

efficient to maintain the stores of terrestrial carbon in forest ecosystems whilst also increasing the intensity of agriculture, in order to allow for some use of cropland for biofuels at the same time as supporting projected future food demand. In these scenarios, the market value of bioenergy was found to be dominated by its potential as a carbon sink. Applied results also showed that impacts on water and crop yields increase substantially for average global temperature rises above 2°C above pre-industrial levels, although some areas experience substantial impacts on water resources even at relatively low levels of average warming.

The project also addressed fairness in international environmental agreements consistent with constraining global temperature rise to 2°C above pre-industrial levels. Game-theoretic approaches were used to demonstrate that stable burden-sharing regimes could be derived, corresponding to a shared output loss not exceeding 1% of GDP for all groups of countries, rising to 1.8% GDP in a robust-decision analysis allowing for multiple sources of uncertainty. Finally, the project invested significant resources in improving the transparency and accessibility of model analysis and results, building and enhancing portals for access to climate data, models and results designed for a range of users from the public to policymakers and scientists. This work will facilitate continued development and application of the software framework for future users.

Project context

In the 21st century, humanity faces the challenge of feeding a rapidly growing population, which will place substantial additional pressure on the exploitation of land and water. At the same time, agricultural activities and human use of fossil fuels lead to the emission of potent greenhouse gases including CO_2 and methane into the atmosphere, exacerbating climate change which is expected to further increase pressure on water and agriculture in many regions. At the same time rising standards of living are likely to result in dietary changes and expectations for the protection of sensitive ecosystems both of which could increase the demand for land.

ERMITAGE (http://ermitage.cs.man.ac.uk/) is a research collaboration between eight European partners, aimed at allowing a communication between systems representing food, water, ecosystem protection, economy, energy and climate change in order to understand how they interact.

The project's challenge consists of deriving environmental policies that account for society's conflicting demands on energy, agriculture, land and water resources in the face of global change. This requires the use of advanced modelling tools from a wide range of natural science and socio-economic disciplines. For the resulting analyses to account for natural-societal feedbacks and regional disparities, whilst consistently and robustly taking account of high levels of uncertainty, requires a new level of integration between the available models. ERMITAGE has successfully addressed this gap by building on existing modelling tools and platforms to develop a flexible and transparent sustainability modelling framework.

After having integrated the several models (global climate system, the economy and climate change mitigation strategies, and models representing agriculture, hydrology and land use), the scope consists of producing internally consistent future world scenarios, with consequent policies harmonised towards common sustainability goals: secure supplies of food, energy and water, and preservation of natural ecosystems. A lack of such policy integration would instead produce ineffective or undesirable outcomes. In addition to the overarching goals of studying sustainability scenarios, the project has also addressed the joint distribution of uncertain climatic and economic changes, quantifying the regional, uncertain impacts of different policy options. Furthermore, the project has studied the strategic implications of cooperation *vs.* non-cooperation in international environmental agreements using tools derived from game theory and robust decision making applied to the coupled models in the project.

The project has built on earlier coupled modelling software frameworks and technologies including the bespoke framework generator (BFG) system, the grid-enabled integrated Earth system (GENIE) and Community Integrated Assessment System (CIAS) frameworks, as well as statistical modelling and meta-modelling tools and approaches, to develop a new, enhanced modelling framework. The project also focused on improving the transparency and accessibility of model analysis and results, building and enhancing several connected web-based portals for access to climate data, models and results designed for a range of users from the public (via http://climascope.tyndall.ac.uk) to policymakers and other scientific users.

ERMITAGE includes outputs from a range of advanced coupled modules that relate to sustainability goals. The project thus brings together and builds on a strategic collection of recently-developed modelling tools to address emerging sustainability challenges related to agriculture, energy and water availability.

Table 1: Consortium details

ERMITAGE at a glance:	**ERMITAGE partners:**
EC Contribution: EURO 3,383,455.55	The Open University, UK (Coordinator)
Project Start Date: 1st December 2010	ORDECSYS SARL (ORDE)
Project End Date: 30th November 2013	Ecole Polytechnique Fédérale de Lausanne (EPFL)
Coordinator: Dr Neil Edwards	University of East Anglia (UEA)
ERMITAGE website: http://ermitage.cs.man.ac.uk/	ENERIS Environment Energy Consultants S.L. (ENERIS)
	Potsdam Institute for Climate Impact Research (PIK)
	The University of Manchester (UNIMAN)
	STFC Daresbury Laboratory (STFC)

Main Objectives

In accordance with Annex I, the project has overall the following main objectives:

1. Build a transparent modular framework for the coupling and analysis of diverse environmental models with divergent paradigms and programming languages, with an accessible, web-based interface (WP4).

2. Develop simplified forms of complex models of both natural and socio-economic systems that facilitate more interactive coupling between models as well as statistical analysis of model projections. In detail:

- An emulator-based model coupling that is a robust lower-dimensional surrogate for full model couplings which allows for nonlinearity and spatially complex feedbacks (WP 3).

- A modular coupling between:

  - An intermediate complexity climate system model and a land-surface model that represents both natural and managed terrestrial ecosystems; feedbacks between these systems and the associated uncertainties will be analysed (WP 5)
  - An intermediate complexity climate system model and a complex macro-economic model using emulation and meta-modelling techniques; the cascade of uncertainty through the coupled system will be quantified (WP 6, WP 8).
  - An energy-economy and a land-use model; the sensitivity of the resulting coupled system will be analysed (WP 7).

- Construct a hierarchy of climate impact and integrated policy assessment models for the purposes of downscaling the results from the coupled framework analysis for more effective use by regional and local policymakers (WP 9).

3. Analyse and quantify feedbacks between the natural and socio-economic systems, paying particular attention to biofuels, hydroelectricity and other sustainable energy sources (WP8).

4. Analyse the options for burden-sharing in the context of international environmental agreements and quantify the strategic implications of international cooperation *vs* non-cooperation (WP10).

5. Engage with policymakers and relevant stakeholders to ensure the relevance of results for global and regional policy (WP 2, WSs 1 to 3).

6. Develop robust scenarios for the sustainable use of land, energy and water, taking account of climate change impacts, mitigation actions, population growth, bioenergy demand, and ecosystem conservation. (WP 11).

S&T results foreground

WP3: Statistical emulation and robust optimisation

WP3 Summary of project work and results

In the first substantial work of WP3 a new climate model coupling "PLASIM-ENTS" was developed. This is a coupling of the Hamburg Planet Simulator atmosphere, slab ocean and slab sea ice to the GENIE sub-model of terrestrial vegetation ENTS that provides a much improved representation of atmospheric dynamics compared to the original GENIE-2 atmosphere.

The new model was used to generate an ensemble of climate simulations as a basis for the construction of reduced-form statistical representations (emulators) of climate change for the purposes of coupling to other models. To facilitate robust policy analysis the ensemble was designed to cover the full range of possible future scenarios and a wide range of uncertainty in model parameters. Using this ensemble, dimensional-reduction emulation techniques were applied to reproduce the temporal history (2010 to 2100) of a range of seasonally and spatially resolved outputs including temperature, precipitation, and heating and cooling degree days, in response to any given scenario of temporal forcing over the relevant period. The emulator, PLASIM-ENTSem, has been subjected to detailed validation and submitted for publication.

A separate strand of work has focused on producing a statistical emulator for the output of the dynamic global vegetation and crop model LPJmL, for which a two-stage statistical emulator based on regression and principal component analysis has been developed, suitable for coupling to a range of other models. The emulator projects decadal changes in primary productivity and in the yields of four major crop types, as a function of climate input and the efficiency of CO_2 fertilisation and management practices.

Emulators have also been constructed for the carbon-cycle model GENIE-1 and the macroeconomic model GEMINI-E3. A variety of coupled models have been constructed and applied using these emulated forms, including two different approaches to coupling climate dynamics with the perfect-foresight energy-economy model TIAM-WORLD and a coupling with the dynamic economic system model FTT:Power-E3MG.

WP3 Detailed description of work

Deliverables:

- D3.1, M18- GENIE Emulator. Emulation of GENIE as a modular component of the enhanced framework platform.
- D3.2, M24 GENIE Emulation and coupling report: Report on the emulated form for LPJmL and REMIND-R as modular components of the framework, and on oracle-based coupling of a complex economic model with environmental modules via the framework software.

Task 3.1: Emulation as a coupling tool

One of the principal obstacles to coupling complex climate models to impacts models is the high computational expense of the various models. Replacing the climate model with an emulated version of its input-output response function circumvents this problem without compromising the possibility of including feedbacks and non-linear responses. This approach yields two further benefits in the field of integrated assessments. First, the emulation can allow for the construction of gradients of the response function. These may be required, for instance, in an optimisation-based application. Second, a calibrated statistical emulation, based on ensembles of simulations, also provides a quantification of uncertainty and modelling errors. We have constructed an emulator of the modelled spatio-temporal surface climate response, using principal component analysis to give an empirical orthogonal function decomposition of ensembles of plausibility-calibrated simulations with the model PLASIM-ENTS. This work has been detailed in deliverable D3.1, published as a discussion paper, (Holden *et al.* GMDD 2013) and subsequently rigorously validated and further refined. Substantial work towards coupling to other modules and inclusion of the model in the software frameworks, has also been carried out and is reported under other Work Packages.

Task 3.2: Input reduction and emulation of land-surface and economic models

The work of this task, in contrast to Task 3-1, focuses on emulation in the ostensibly more challenging setting in which both inputs and outputs to a given module within a coupled framework are high-dimensional, the primary example being the land-surface and crop model LPJmL for which the inputs are surface climate fields including temperature and precipitation, and the outputs are spatial fields of productivity and crop yields. A first approximation can be obtained by treating the problem as a large spatial field of quasi-independent samples of vegetation responses, thereby avoiding the problem of 2D input and output fields. This approach has proved highly efficient and flexible, and is described in detail in Deliverable D3-2 submitted at M24. Since then, the land-surface and crop emulator LPJmLem has been further refined using an approach that explicitly addresses the high dimensionality of the output. The final emulation is thus a two-stage process in which the first stage is quasi-local, as described above, while a second stage applies a 'correction' to the prediction based on a weighted average of known 2D error fields from the training data used to build the emulator. The second stage substantially improves the proportion of variance explained by the emulators and the combined approach has been written up for submission to an applied statistics journal (Oyebamiji et al in prep.) and the final emulator coupled to GEMINI-E3 and incorporated in the CIAS framework as reported under the relevant Work Packages.

In addition to LPJmL, three other emulation exercises addressing models with large input spaces have been carried out and reported in Deliverable D3-2 relating to the carbon-cycle model GENIE-1, the macro-economic model GEMINI-E3 and the energy sub-model of the hybrid energy-economy model REMIND-R. In the case of GENIE-1, the emulator takes as input a time-series of CO_2 emissions and produces a time-series of atmospheric CO_2 concentrations, requiring dimension-reduction techniques for both input and output. An option exists to emulate the entire carbon cycle response of the GENIE-1 intermediate complexity Earth system model, or to exclude the land-surface component, for the purposes of coupling to a more complex land-surface model such as LPJmL or its emulator. This work builds on the construction of a plausible ensemble of carbon cycle runs of GENIE-1, produced within the protocol of the IPCC AR5 EMIC intercomparison and thus contributing to AR5 and to a series of related papers (Eby et al. 2013, Zickfeld et al. 2013, Joos et al. 2013). Emulating the future carbon-cycle response necessitated the extension of GENIE-1 to include land-use dynamics as documented in Holden et al. (2013a, Biogeosciences). The plausibility-constrained ensemble produced through this work has the potential to provide additional data on uncertainty and carbon dynamics, as demonstrated in a further application of the techniques developed in Task 3-1 of singular-value decomposition (EOF analysis) by Holden et al. (2013b, Biogeosciences). Most importantly for integrated assessment, the combination of carbon-cycle emulator GENIEem and climate emulator PLASIM-ENTSem allows for a complete climate system coupling to an economic modelling system including uncertainty estimates and spatial field outputs. This has been demonstrated with a one-way coupling to an economic model outside the core group of models in ERMITAGE via a collaboration with the Cambridge economics group, and reported in a series of papers (Foley et al. subm, Mercure et al. subm a,b).

The emulation of GEMINI-E3 is described in detail in D3-2. This was based on a single ensemble of 400 simulations of GEMINI-E3, with the purpose of deriving analytical payoff functions for the GEMINI regions as output in response to different regimes of regional and global emissions. These data were then used as input to a competitive game between the regions involving the timing of emissions in order to address issues of competition in burden-sharing regimes. This work is being published in Haurie et al. (2013).

Initial investigative work regarding the emulation of the energy sub-system of REMIND-R was also reported in D3-2. The motivation for this was the fact that the energy sub-system needs to be solved repeatedly within REMIND and can thus dominate the computational demands of the model. However, the production of a sufficiently general and accurate reduced-order representation for incorporation into the full model proved more challenging than anticipated, while further work on the emulation of the full model itself, in addition to the other five models considered as emulation targets within the project, was not possible within the time available. Nevertheless, it may be noted that the relative ease of construction of emulated forms of GEMINI suggests that emulation of more demanding economic models may be tractable.

In addition to the above models, a further modelling exercise has been carried out to assess the potential of a new approach to the generic problem posed in this Task, namely the emulation of a model with high-dimensional input and output. This approach extends the EOF decomposition of output fields to both input and output spaces and derives the connection between the leading-order modes of input and output from an ensemble of simulations. The approach has been tested by application to the climate (input) and vegetation (output) fields within the coupled model PLASIM-ENTS and appears highly promising. The technique has been written up for submission to an applied statistics journal (Holden et al. in prep).

Task 3.3: Meta-modelling of coupled climate-economic dynamics

Note this work represents the technical aspect of emulation and meta-modelling contributing to Task 8-3, where the work is briefly summarised.

Coupling of detailed economic and climate models has been successfully demonstrated and is described in detail in Deliverable D3-2 and in several publications. Two alternative methods, both of which successfully achieved a coupling between the techno-economic model TIAM-WORLD and the climate model emulator PLASIM-ENTSem (or a similar emulator of the dynamical-atmosphere version of GENIE) are detailed in D3-2, a highly general oracle-based method and a highly efficient direct method. Both are designed to find an optimal solution for the TIAM-WORLD objective function that satisfies a constraint on global warming at 2100 as computed by the climate module. The coupling variable is a time-series of radiative forcing values, with the iteration process determining a time-series of radiative forcing (equivalent to a temporal schedule of emissions) that optimises the objective function representing discounted global welfare. The oracle-based method generalises earlier work by Drouet et al. (2006) in which a master program controls the iteration between climate and economic sub-models, generating a sequence of iterates that progressively reduces the space of possible solutions by utilising sub-gradient information produced through a set of finite-difference calculations performed on the objective functions at each iteration. In contrast to the work of Bahn et al. (2006) and Drouet et al. (2006) the use of emulators appears to render the gradient calculation and hence the overall iteration considerably more stable, making possible the coupling of much more complex component modules. The direct method is much simpler and avoids the calculation of climate module gradients altogether by using the internal climate module of the original TIAM-WORLD model to calculate the climate function gradients that guide the iteration, but replacing the climate function values themselves with those produced by PLASIM-ENTSem. The direct method has been used by Labriet et al. (subm) to address the effects of climate-driven changes in heating and cooling demands on the energy system.

Task 3.4: Propagation of uncertainty and multi-model feedback analysis

The assessment and coherent treatment of uncertainty is a key theme of the project, closely allied to the use of emulators, which intrinsically quantify uncertainty through extensive sampling of the underlying simulator. The coupled framework has allowed a coherent treatment of uncertainty from physical climate and socio-economic sources in several applications including the sea-level rise impact study described by Joshi et al (subm) and detailed in D6-3; the agricultural impact study also detailed in D6-3, and the series of papers (Foley et al. subm, Mercure et al. subm a,b) using the climate emulators coupled to the Cambridge-based FTT:Power-E3MG model. Uncertainty propagation in the context of the meta-game analysis of international environmental agreements studied in D10-2 is considered in D10-3 which generalises this analysis to a robust decision-making setting, allowing for uncertainties from a range of sources. The impact of structural uncertainty represented by the range of different models on policy choices is addressed by the integrative analysis of D11-2 and to a lesser extent by the multi-model analysis of bioenergy options in D7-2. Feedback analyses are implicitly addressed through the two-way coupling of modules and comparison of multiple coupled and uncoupled options in all the coupled analyses described in the above work packages.

WP3 Policy implications

Since WP3 is a methodological work package, any applied conclusions and policy implications arise through specific applications that are detailed in other work packages.

WP4: Modularisation and Middleware

WP4 Summary of project work and results

The objective of work package 4 was to provide appropriate software infrastructure to the project to support the development and running of the (coupled model) scenarios being developed in the project and the viewing of the subsequent results. The focus of the infrastructure support has been the ERMITAGE portal which brings together tools extended or developed in the project that cover the major aspects of coupled model use: 1) Creating Coupled Models, 2) Viewing Coupled Models, 3) Configuring and Running Coupled Models, 4) Storing the results generated by Coupled Models, 5) Viewing the results generated by Coupled Models, and 6) Analysing coupled model results.

The BFG2 coupling system has been extended to support the ERMITAGE models and scenarios. BFG2 is freely available for download and the BFG2 functionality has also been made freely available online via the BFG2 portal. The BFG2 portal has also been developed to allow the viewing of the couplings between models in the coupled-model scenarios. A prototype Controlled Vocabulary has also been developed in collaboration with the PIMMS project to describe the science of the ERMITAGE models and couplings. Both the CIAS integrated assessment system and its data viewer, ClimaScope, have been extended to better support the ERMITAGE scenarios and output data. A new freely available integrated assessment system - CIAS-Live - to support the running of fast models interactively from web pages has been developed and installed at two institutions. Storage space has been made available by BADC to store data produced by the project. Finally, a new output data analysis system - VedaViz - has been developed.

Where appropriate the coupled model scenarios developed in the project and the data produced by them have been integrated with the tools described above. All of the tools in WP4 will continue beyond the lifetime of the ERMITAGE project and will enable ongoing access to the models, couplings and data developed in the project. Where possible the tools, model descriptions and data have been made openly available to promote their use and ensure that ERMITAGE provides not only a legacy of coupled models but also a legacy of tools that can be used to understand and further extend the coupled models developed in the project.

WP4 Detailed description of Work

Initially, an analysis of the ERMITAGE coupling requirements was performed for the purposes of coupling using BFG2. From this analysis it was decided to support scientific models written in the Fortran, C and Python computer languages directly in BFG2. This decision required the extension of BFG2 to support both C and Python as BFG2 was originally limited to Fortran. Python was chosen as it is a powerful scripting language which can be relatively simply interfaced with GAMS and R (GAMS and R are two of the languages that models in the project are written in) rather than supporting GAMS and R directly in BFG2. Together the chosen languages cover all of the scientific model languages being used in ERMITAGE. It was also decided to extend BFG2 to support both "component" and "program" compliant models to make it easier to integrate the different types of models in the project. Further, it was also necessary to extend BFG2 to support convergence loops. BFG2 is openly available and the latest version can be downloaded from the following website (http://cnc.cs.man.ac.uk/projects/bfg.php). A BFG portal (linked from the ERMIATAGE portal) has been developed which allows BFG2 to be run directly without requiring the downloading and installation of software. The portal also allows coupled model descriptions to be viewed, both textually and in graphical form. In addition, the BFG portal allows the editing of coupled model description metadata. The BFG2 software itself has undergone a number of revisions, each of which has been added to both the BFG portal and the CIAS system.

The CIAS portal is a web-based portal that allows remote configuration and execution of coupled models, and visualisation of data from model output. CIAS links its component modules through a supporting software infrastructure, SoftIAM, based on BFG2, which enables flexibility in the assembly and composition of individual modules to form complete coupled models, and flexibility in their deployment onto the available software and hardware resources. CIAS allows model coupling and sharing of data between disparate computing platforms and multiple computer languages. The robustness of the CIAS portal has been improved to better support an increased number of users, its appearance has been updated to make it more useable and an interactive graphical map interface has been added to CIAS which allows the user to create a custom emissions scenario, or choose from the list of existing scenarios.

ClimaScope is a data visualization engine overlaying data from climate models (e.g., CLIMGEN, PLASIM-ENTS) with other data sets (e.g., poverty indices, GDP). It provides easy access to climate and climate change data and, eventually, will provide climate impact data. For a selected climate change model pattern and emissions scenario, ClimaScope provides maps and data on the projected climate changes. Conversion software has been developed to allow outputs from ERMITAGE models to be input into ClimaScope.

The CIAS-Live system has been developed to support models that run in near interactive times (approximately 30s or less). Such fast running models allow stakeholders to explore, in real-time, a range of different scenarios. The near-instant feedback from models within the CIAS-Live portal enables users to visualise the effects which changing the parameters of those models can have on the output. The CIAS-Live system extends the BFG2 metadata to include widgets (such as sliders for inputs and graphs for output). The developer can simply connect models and widgets together to create new presentations. CIAS-Live is freely available and has been designed to be easily deployable. It is currently running at two sites, the Open University and Manchester University.

VedaViz is a powerful tool for constructing and sharing views of model results. A major challenge in using a complex model is the sheer volume of results data to be reviewed and hopefully understood. Large numbers of scenarios, variables, model years, and perhaps regions and even different models mean that simple, static two-dimensional graphs are not enough to meet the challenge. VedaViz allows the user to quickly select and rearrange dimensions to create a variety of graphs, maps, and motion charts to help find the story in the data. An introduction to VEDAViz can be found here http://www.youtube.com/watch?v=Bz9GCqfflfI.

All models used in the ERMITAGE project are now available within the BFG and CIAS systems and a large number of couplings are available for viewing in the BFG portal and for running in the CIAS portal. Three ERMITAGE models have been integrated into the CIAS-Live system (PLASIM-ENTSem, LPJmLem and a burden-sharing code that solves a game-theoretic model of climate negotiations). Climate data output from the CIAS portal is available on ClimaScope and downscaled PLASIM-ENTSem data has successfully been imported into the system for display.

A prototype controlled vocabulary (CV) which uses the Metafor Common Information Model (CIM) to describe the science of the models and their couplings has been developed in collaboration with the PIMMS project and a number of models are being described using this CV to demonstrate its benefit in terms of the transparency of model documentation for users.

Finally, the British Atmospheric Data Centre (BADC) have provided a 2TB ERMITAGE group workspace for storing ERMITAGE output data (http://badc.nerc.ac.uk/help/jasmin_workspaces.html). This has been used to store some of the openly accessible ERMITAGE output data for use beyond the end of the project.

WP4 Policy Implications

This workpackage has not had any direct policy implications, rather it has enabled the other workpackages to investigate policy choices and provided access to the results of the project.

WP5: Land Use and Climate

WP5 Summary of project work and results

The main objective of WP5 was to improve connectivity between models and emulators of the global climate system (MAGICC, ClimGen, PanClim, GENIEem, PLASIM_ENTSem), a model of the land surface that simulates coupled vegetation dynamics, carbon and water fluxes (LPJmL), and an agroeconomic model that simulates land use allocations as governed by biophysical and economic constraints (MAgPIE). In the first step, LPJmL was linked in a one-way coupling to the models of the climate system in order to allow for comprehensive global impact simulations. In the following step, these impacts were provided to MAgPIE to project changes in land use under the constraint of climate impacts on potential crop yields and water availability; and feedbacks from the land surface to the climate (through emissions from land use changes and re-allocations) were quantified. All of these couplings form part of the overall framework built in WP11.

Specifically, LPJmL was used to perform global-scale impacts assessments for key sectors such as ecosystems, water, and agriculture. One result is that the population living in water-scarce regions will increase by almost half a billion at a mean global warming level of 2 °C above pre-industrial, due to climate change-induced decreases in precipitation and increases in temperature (i.e. even without considering future population growth). Moreover, a majority of the world's land ecosystems will likely face substantial biogeochemical and vegetation structural changes if global warming surpassed 3–3.5 °C, with many biodiversity hotspots being affected at a warming around 5 °C. Crop yields will decline in many regions with higher values for the rise in higher global mean temperature, but direct CO_2 effects upon plants – a highly uncertain process – may counteract these decreases. We also found that more intensive crop management could significantly buffer adverse effects of climate change on crop yields, but not everywhere, and many countries would no longer be able to produce enough food for their inhabitants with domestic water and land resources. Uncertainties in all these projections were studied by the use of nearly 20 General Circulation Models (GCMs), and by either including or excluding CO_2 effects. We also studied effects of climate change (for a selection of GCMs and RCPs) on groundwater recharge and storage, based upon a newly implemented groundwater scheme developed for LPJmL.

Selected outcomes of these simulations were provided to MAgPIE, which projected land use changes and associated greenhouse gas emissions in response to the LPJmL-simulated biophysical climate impacts (crop yields, water supply). Resulting emissions of CO_2 together with fossil fuel and industrial emissions from the REMIND energy economy model were provided to the GENIEem and PLASIM_ENTSem emulators to estimate the feedback to the climate, and the thus modified climate was considered in LPJmL for renewed impacts assessments. GENIE was also enhanced by a land use scheme; with it, a study was performed to constrain the CO_2 fertilisation effect. Overall, the full loop climate change – climate impacts – land use change – emissions from land use change – feedback to climate – impacts on land surface has been successfully closed. Notably, a substantial part of this coupling has been performed online in CIAS, for the first time performed via international remote connection, which demonstrates the principle of applicability and user-friendliness.

WP5 Detailed description of work

Climate scenario generation: We provided a large ensemble of scenarios of future climate change by a coupling of the MAGICC model and ClimGen and PanClim pattern-scaling models (see full description in D5.1). Specifically, a successful coupling between the MAGICC6.0, the ClimGen-v1.02 and the LPJmL_vs.3.2 models has been accomplished. ClimGen and PanClim were used to disaggregate global mean temperature trajectories delivered by MAGICC to 0.5°-resolution grids of climate variables, the target resolution for LPJmL. This pattern-scaling approach was applied for about 20 General Circulation Models.

In this context, we also improved the disaggregation from the monthly climate data provided by MAGICC-ClimGen to daily data (see D5.2).

Climate change impacts assessments: We used the whole, comprehensive set of climate change scenarios as an input to the LPJmL biosphere model so as to provide quantitative global assessments of climate change impacts upon freshwater resources, ecosystems and agriculture/crop production. The analyses were focused on key earth system processes and societally relevant domains: the overall status of, and biogeochemical fluxes in, land ecosystems (Gerten et al. 2013; Ostberg et al. 2013); the carbon release from (thawing) permafrost regions (Schaphoff et al. 2013); the production of calories from crops (Rastgooy 2013; see next section); and the availability of freshwater (Gerten et al. 2013).
Schaphoff et al. (2013) found that soil carbon release in the permafrost zone will for a while be buffered by additional carbon input due to higher net primary production; but around year 2100 there will be a net release whose size depends on the mean global warming level. The net release would continue for centuries even if the warming reached until 2100 would be halted at that time – hence we identified a long-term response to climate change, which in addition represents a positive feedback to the climate system.
Ostberg et al. (2013) demonstrated that the area affected by significant changes in key ecosystem properties will strongly increase with mean global warming. Building on this, Gerten et al. (2013) show that some regions would face strong ecosystem changes already at a warming of 'only' 2 °C above pre-industrial, i.e. the agreed climate mitigation level. A warming by 3.5 °C – not unlikely to happen if countries cut their emissions only according to their current reduction pledges – and especially a warming by up to 5 °C will expose a major fraction of the land surface, including many of the current biodiversity hotspots, to significant change. Water availability will decline and water scarcity will be aggravated in many regions even at a warming of 2 °C.

Analysis of CO_2 and management effects: We assessed effects of climate change upon crop yields globally, also studying the role of the direct CO_2 effects on plants and the potential of more intensive management to buffer adverse climate impacts (full description in Rastgooy 2013). Results show that climate change will significantly affect the ability of countries to produce a given calorie amount, such that many countries will lose their capacity to be self-sufficient. CO_2 effects, if fully realised in the field, could buffer a part of the adverse impacts, as could a more intensive management of current crop yields. Nonetheless, even if management was substantially improved, countries especially in Africa and the Near and Middle East will be dependent on international trade to ensure food security for their inhabitants – especially in view of population projections for the future.

Groundwater representation: To improve simulations of freshwater availabilities, scarcities and withdrawals, the hydrologic scheme of LPJmL was modified. We newly introduced (i) a groundwater store scheme, a groundwater recharge term, and a function that couples simulated surface runoff to a database of mean slope gradient. Results using this new module have been extensively validated, and simulations of potential future changes in groundwater stores and recharge rates performed, using MAGICC-ClimGen climate change simulations as forcing (see details in D5.3).

CO_2 fertilisation constraint: We derived an independent constraint on the strength of CO_2 'fertilisation' of the terrestrial biosphere by calibrating GENIE parameters constrained by the past (since 1850) increase of atmospheric CO_2 concentration. A probabilistic prediction for the globally averaged strength of CO_2 fertilisation was derived, implicitly net of other limiting factors such as nutrient availability. For this, we enhanced GENIE by a scheme representing land use changes and built an emulator of past CO_2 change used to sample the multi-dimensional input parameter space. A Bayesian calibration of the emulator output suggests that the increase in gross primary production owing to a doubling of CO_2 very likely exceeds 20%.

Land use change and feedback to the climate: We implemented a heretofore unresolved feedback loop in ERMITAGE, which comprises effects of global climate changes on water availability and crop yields, the subsequent effects on cropland allocation and management intensity, the increase in CO_2 emissions through this land use change, the sole effect of these additional emissions on the climate system, and eventually the effect of these land use change-induced climatic changes on the land surface (water resources, crop yields) relative to an 'undisturbed' reference climate (all details and initial results are shown in D5.3). The completed coupling involves the models MAGICC–ClimGEN–LPJmL–MAgPIE–REMIND–GENIEem–PLASIM_ENTSem–ClimGEN–LPJmL. In brief, we first ran LPJmL forced by climate fields derived from RCP6.0 and patterns from the GCM GFDL-CM2.0, as generated by MAGICC and ClimGEN. Based on this we computed impacts on potential water availability and crop yields, which were used in MAgPIE to derive scenarios of cropland reallocation along with associated CO_2 emissions. These were used to estimate feedback effects on the climate, with emissions being translated into a climate signal by the emulators GENIEem and PLASIM-ENTSem.
We compared a baseline simulation forced by fossil fuel and industrial CO_2 emissions, provided by the REMIND energy economy model, with a simulation that also considers the CO_2 emissions from land use change. Results show that the land use-related emissions – enforced by land use changes in response to the 'original' climate change – would slightly change the climate in many regions. The study demonstrates that a closing of the loop climate – land surface – climate is successful with ERMITAGE models and procedures, and that important feedback loops in impacts and adaptation studies and related policies can be represented.

WP5 Policy implications

WP5 contributed substantially to the policy-relevant outcomes of the overall couplings and analyses in ERMITAGE, in that it provided the climate–land surface couplings using several state-of-the-art models. The achieved couplings and the climate impacts assessments that were performed with them demonstrate that water scarcity is likely to significantly aggravate in regions such as the Near and Middle East, southern Europe and parts of the USA even if mean global warming could be restricted to 2 degrees above pre-industrial (with even stronger impacts at higher warming levels). Thus, water management in these regions will be strongly challenged, especially since population is expected to grow simultaneously in many of these regions. In addition, we found that much of the Earth's terrestrial ecosystems will experience profound changes in response to climate change, with many biodiversity hotspots, including the Amazon region, being affected at warming levels between 3 and 5K. Crop yields were also shown to decrease in response to climate change in many countries, so that major efforts in crop management will be required to ensure food security in the future.

WP6: Linking climate and economic models

WP6 Summary of project work and results

The work done in WP6 concerns i) the development of coupling algorithms between GEMINI-E3 and other ERMITAGE models (PLASIMem and LPJmLem) and their integration into the CIAS platform and ii) the exploitation of these coupling frameworks to analyze the impacts of climate changes on the economy related to sea level rise, energy demands and agriculture.
One of the main achievements in the study of sea level rise has been to combine information at local level using GIS tools with top down model GEMINI-E3. We found that this kind of integrated approach is important while conducting economic analysis of climate change (Joshi et al., 2013). In addition, uncertainties coming through different models are identified and analyzed by developing different scenarios for sea level rise. In the paper by Labriet et al. (2013), we showed the importance of examining the impact of climate on energy demand

for heating and cooling from energy and macroeconomic perspectives. In the case of impacts of climate change on the agricultural sector, a link between the emulator of LPJmL and GEMINI-E3 has been established. We showed how agricultural production might be affected due to uncertainties in yield change and economic parameters related to the agricultural sector.

WP6 Detailed description of work

The work done in this WP concerns mainly i) the development of coupling algorithms between GEMINI-E3 and GENIEem (Task6.1) ii) the modelling of impacts of climate changes on the economy through the coupling procedure done in Task 6.1 and iii) uncertainty analysis and iv) the integration into the CIAS platform of the coupled models developed in the first part of the project. This latter contribution is described in detail in the WP4 section.

Development of the coupling framework:

In the first part of the project we have developed a coupling algorithm between GEMINI-E3 and GENIEem. The objective of this coupling has been to use the emulators of GENIE to define emissions constraints into GEMINI-E3 in order to assess a climate policy scenario satisfying a given temperature increase limit in 2050. As the economic model GEMINI-E3 is a time-step optimization model, one could not build a coupled model that computes endogenously an optimal emissions path with respect to the economy. For this reason, we have implemented a soft coupling approach, which looks for some acceptable and realistic emissions profiles producing a given temperature rise. These emissions profiles are finally used in GEMINI-E3 as an upper bound vector on the emissions for the assessment of climate policies.

As the number of “acceptable” emissions trajectories is potentially unlimited, the coupling restricts its search to a subset of trajectories. We have thus selected two general classes of functions for generating new emissions trajectories. The first one is the simple class of linear functions while the second class contains more complex polynomial functions. For each proposed trajectory, GENIEem can compute a temperature increase and the coupling algorithm selects the one that meets the given warming target.

The algorithm written in Python linking all models together is now operational. It has been converted into an equivalent BFG compliant code in order to be integrated on the CIAS platform. A battery of climate and economic outputs will then be displayed on this platform for each user request.

Modeling impacts of climate change in GEMINI-E3:

Three independent studies has been conducted on GEMINI-E3 to assess i) the consequences of sea level rise on the economy, ii) the impacts of climate change (CC) on heating and cooling demands and iii) finally the effects of CC on the agriculture sector in terms of crop yield changes.

In the first study, an integrated stochastic analysis approach is used to evaluate the potential physical and economic impacts of sea level rise (SLR) combining a climate system model PLASIM-ENTS, computable general equilibrium (CGE) model GEMINI-E3 and geographical information system (GIS) tools. First, a temperature profile required to calculate SLR is provided by PLASIM-ENTS and a semi-empirical relationship developed by Rahmstorf et al. (2012) is used to calculate SLR. Then, physical impacts of SLR specifically on cropland area loss, urban area loss, number of people affected and protection costs are estimated using GIS tools. It is important to emphasis here that the uncertainties relating to temperature, parameters of the semi-empirical relationship linking SLR and climate and the parameters of coastal development are also considered in our methodological approach. Finally, this information is incorporated in the GEMINI-E3 model to conduct economic analysis with and without protection cost.

In the case of energy, worldwide estimates of heating and cooling energy demand due to climate change are produced using PLASIM-ENTS, TIAM-WORLD and GEMINI-E3 models.

Heating degree days (HDDs) and cooling degree days (CDDs) required to estimate the change in energy demands are provided by PLASIM-ENTS. Since GEMINI-E3 describes only total energy consumption by household without representing the different purposes (heating, cooling, cooking, lighting, etc) the respective shares of energy consumption for heating and cooling are taken from the outputs of TIAM-WORLD. The baseline scenarios of TIAM-WORLD and GEMINI-E3 are harmonized in relation to regional mapping, population and economic growth, energy prices and GHG emissions. Details regarding the energy study can be found in the WP8 section.
Finally in the third analysis, macroeconomic impacts of climate change on the agricultural sector are studied using the emulator of LPJmL and GEMINI-E3. To estimate the yield changes, LPJmL was forced by 18 climate change pattern generated with the ClimGen statistical pattern generator, which in turn has used trajectories of global mean temperature constructed by the MAGICC model. Hence, uncertainty on crop yields is derived from the 18 GCM climate scenarios with RCP6. Moreover, uncertainty in the economic side is captured through elasticity parameters (i.e. substitution between land and other factors, substitution between agricultural products etc). This uncertainty analysis is carried out through Monte Carlo simulation of these uncertain parameters in GEMINI-E3.

Improvement of the GEMINI-E3 model

A new version of the GEMINI-E3 model has been built. First, the model database has been updated to the new GTAP database version 8. Consequently, the reference year of the model is moved now to 2007 instead of 2001. Secondly, a new classification of sectors and regions has been defined in order to make easier the communication with other ERMITAGE models and the representation of impacts of climate change on sectors. The new regional classification that describes the world with 14 regions has been defined with respect to the TIAM-WORLD classification in order to facilitate the exchange of information.

Other works:

GEMINI-E3 model was also used to perform different scenarios related to mitigation policies in WP11. Statistical emulation of GEMINI-E3 was also developed and used in WP10, this contribution is detailed in the WP10 summary.

WP6 Policy implications

The simulation results from GEMINI-E3 showed that there could be significant impact due to sea level rise. Nonetheless, protecting the coastal regions could significantly decrease the impacts of SLR. One of the main insights of this study is that the economic impact of SLR is as much affected by uncertainties of coastal development as by uncertainties of SLR drivers. This suggests that not only there is a need for protecting coastal region by building dikes etc. but also there is a need for proactive adaptation strategies in the development of coastal regions such that impacts of sea level rise could be ameliorated.
The simulation results from impact of climate change on energy demand from heating and cooling showed that the macroeconomic impacts are limited at global level. This stems mainly from the fact that expenditure for heating and cooling represents only a small share of total energy consumption. However, the welfare impacts are quite diverse, with negative impacts coming from terms of trade and positive impacts coming from decrease in heating expenses. The rebound effects that moderate the impact of climate change are non-negligible.
The simulations results from the agricultural study showed that the future management practices are a crucial issue when we want to analyse this impacts of CC on crop production. If one assumes improvement of existing practices in the future in particular in emerging and developing countries, one could alleviate the potential negative impact of cc on crop yields. This shows the importance of adaptation and also the question of its funding especially for farmers of developing countries.

WP7: Economy and land use

WP7 Summary of project work and results

This WP focuses on improving the modelling of interactions between the economy/energy system and the land use system. After having described the interfaces on a conceptual basis, the implementation has been focused on those identified as the most sensitive to the interaction between the involved subsystems - namely: (1) GDP-Food link, (2) Trade link, (3) Bioenergy link, (4) Emissions link. While applying existing models, model adaptation and improvement was needed for running the coupled framework. The main achievement of this WP is the established soft coupling between two energy/economy models (REMIND and TIAM) and a land use model (MAgPIE). This coupling was also used as part of a full loop coupling incorporating climate, land-use, energy and macroeconomic system models (WP 11). The objective of representing feedbacks between the relevant models in a way that supports the assessment of climate change policies within the overall framework has been achieved.

Couplings between REMIND and MAgPIE and between TIAM and MAgPIE were used for detailed analyses of the role of bioenergy under different mitigation scenarios. From the scenario analyses we can draw the following conclusions: Bioenergy is a key component of long-term climate change mitigation strategies aiming at low stabilization. Its versatility and capacity to generate negative emissions when combined with CCS (BECCS) adds degrees of freedom for the timing of emission reductions. However, BECCS implies a strong reliance on the combination of two uncertain components (CCS and biomass potential). When CCS is not available, biomass continues to play an important role in the energy system, but in other forms (gasification and production of biofuels without CCS).

The provision of bioenergy crops for energy production is one major contribution of the agricultural sector to reduce GHG emissions and mitigate climate change. But the agricultural system is a major source of greenhouse gas emissions itself. Effective climate policy that includes GHG pricing also in the agricultural sector can help to reduce these emissions and to protect forest areas. Intensification of agricultural production ensures that even with additional demand on land for bioenergy crop production less forest has to be converted. At the same time, residual emissions in the land-use sector still occur. Increasing intensity of agricultural production is associated with increasing N2O emissions from fertilizer application and methane emissions from livestock production. Therefore, under climate policy, agricultural production costs by the end of the century are dominated by costs for emission permits which may lead to a steep increase in the food price index.

WP7 Detailed description of work

Task 7-1: Design and implementation of the macroeconomic – agricultural link

Research focused on the interaction between the agricultural part of the land use system and the macroeconomic subsystem of the energy/economy system. We identified and conceptualized three interfaces: (1) GDP/food link, (2) Trade link, (3) Investment link, (4) Emission link. The investment link was assessed to be less important, meaning that the capital demand from the agricultural system can easily be met by the macroeconomic system without any significant feedback on the capital prices. With respect to the GDP/food link, a regression analysis was conducted. The derived food demand functions allow to compute within MAgPIE the calorie consumption and the animal calorie share for a GDP trajectory that is given or determined by REMIND. MAgPIE, in general, meets the food demand – either by land expansion or by investing in technological change (increase of yield per hectare). The subsequent question, however, is: at which prices can food be supplied? A first food price analysis was conducted, including an empirical study for India. While real food prices do not yet show a sustained increase, the expenditure share (of more than 50%) on food in low income groups clearly indicate the potential of adverse impacts of increasing food prices. In a first step of capturing the trade link, we integrated the agricultural trade balance (as computed in MAgPIE) into the macroeconomic budget equation in REMIND. This resulted in a significant shift in the trade pattern of big agricultural importers (Middle East, Africa, India) and exporters (Latin America).

Task 7-2: Design and implementation of the energy system – agricultural link

Research was related to the bioenergy link, the emissions link, and to technical work of model coupling. Within the implementation of the bioenergy link, the land-use model MAgPIE determines at what price it can provide the biomass that is demanded from the energy system. Within the emission link, regional trajectories for GHG prices (CO2, CH4 and N2O) are calculated by REMIND and passed to MAgPIE. Based on bioenergy demand and GHG prices MAgPIE calculates the resulting regional CO2-, CH4-, and N2O-emissions from land-use and land-use change. MAgPIE is able to perform allocative abatement, meaning that it can reduce emissions by changing the land allocation pattern. The resulting emission trajectories are then reported back to REMIND and serve as emissions baselines from which further abatement is possible according to marginal abatement cost curves.

In order to get this coupling working a concept was developed to link models with different spatial and temporal scales. A low-pass-filter-based interpolation avoids simulation artifacts that depend on differences in resolution. The derived region mappings between REMIND/TIAM and MAgPIE allow for a fast convergence of the coupled system. Technically, the coupling is implemented as a soft-coupling, i.e. models are used as they are and coupled by iteratively exchanging files. This implementation has the advantage that all developments in the standalone versions of the model can directly be made available in the coupled system.

In addition to the manually-prepared coupling, the REMIND-MAgPIE coupled model has been integrated into the Bespoke Framework Generator (BFG) system. The BFG system produces a portable, reconfigurable and flexible coupling of the two models concerned by employing metadata which describes the points and rates of interaction between its client models. This metadata can then be processed in order to generate an intermediate layer of code which facilitates communication between the coupled models, irrespective of the technical details of the execution environments, or of the physical locations in which the models are deployed. This procedure results in a flexible and modular coupling of the REMIND and MAgPIE models in which each model is a self-contained entity, interacting with its coupled partner-model in a well-defined and structured manner that remains semantically equivalent to the manual coupling in that it expresses the same scientific interactions.

Task 7-3: Harmonization of the energy system module of REMIND-R and TIAM-World

In preparation of a coupling between MAgPIE and TIAM, using the same interface as developed in task 7-2, we started the harmonization of TIAM-WORLD and REMIND with a comparison of the results obtained from common scenarios assessed by both models (Asian Modeling Exercise and Energy Modelling Forum). This harmonization was continued as a prerequisite of the comparison analysis carried out in task 7-4.

A major aim of the ERMITAGE project is the transfer of knowledge between different modelling groups and the provision of robust policy recommendations based on scenario analysis with different model configurations. Based on the existing coupling between REMIND and MAgPIE which has been further improved during the course of the ERMITAGE project, an interface between TIAM-WORLD and MAgPIE was implemented that allows users to run comparable scenarios of mitigation policies. In the process, new supply curves of second-generation energy crops of TIAM-WORLD were constructed, based on data obtained from MAgPIE.

Research results from Task 7-1 (Design and implementation of the macroeconomic – agricultural link), Task 7-2 (Design and implementation of the energy system – agricultural link) and Task 7-3 (Harmonization of the energy system module of REMIND-R and TIAM-World) have been compiled and documented in Deliverable D7.1.

Task 7-4: Sensitivity and scenario analysis

Within a series of scenario runs, the sensitivity of climate change mitigation strategies to the interaction between the land-use system and the economy-energy system was explored. In a first scenario analysis, we run REMIND and MAGPIE in a full coupled mode based on recent SSP2 scenario assumptions. We analysed one Baseline and two different policy scenarios which aim at stabilizing the greenhouse gas concentration at around 450ppm and 550ppm CO_2 equivalent, respectively. In both policy scenarios, the expansion of modern bioenergy use starts around 2030, about 30 years earlier than in the Baseline scenario, and evolves dynamically thereafter. The combination of bioenergy conversion and CCS (BECCS) is so attractive that bioenergy use without CCS is crowded out. Bioenergy with CCS is one of the major mitigation options owing to its ability to produce negative emissions from the renewable carbon sink biomass. In contrast to that, fossil CCS is less favoured as it entails residual CO_2 emissions. At the end of the century in both policy scenarios BECCS has a share of about 30-35% in primary energy. In climate change mitigation scenarios, the value of bioenergy is determined by both its energy value and the value of potential negative emissions created. Evaluation of the revenues gained from biomass conversion demonstrates that under stringent climate targets and in presence of BECCS the value of negative emissions tends to dominate over the value of the energy produced.

The bioenergy demand puts substantial additional pressure on the land-use system since around 225 EJ additional agricultural production are required in 2100. Around 450 million hectares of total cropland are dedicated to bioenergy production by the end of the century. In the BAU scenario, carbon emissions from land-use change amount to 100 Gt C in 2100. N_2O emissions and CH_4 emissions add a warming potential of almost 300 Gt C. Carbon pricing in the 450ppm scenario effectively protects forests, resulting in half of the carbon emissions from land-use change being avoided up to 2100 and the land-use sector only contributing 55 Gt C to global anthropogenic carbon emissions in the 21st century.

In another set of model experiments, we explored the sensitivity of mitigation costs to the biomass potential. It turned out that mitigation costs nearly double when the global bioenergy potential is reduced from 300 EJ to 100 EJ, whereas increasing the biomass potential beyond 300 EJ does not substantially reduce the mitigation costs.

In a comparison analysis based on the alternative couplings between REMIND and MAgPIE compared with TIAM-WORLD and MAgPIE we again focussed on climate change mitigation scenarios that aim to limit the increase of atmospheric greenhouse gas concentration to 450 ppm CO_2eq with alternative assumptions on the biomass potential and the availability of CCS technology. REMIND and TIAM-WORLD propose two different future states of the world in the case of no climate policy; one with more pronounced electrification and a market entry of renewable energy technologies and one with a moderate increase of the electricity share and a negligible share of renewables in primary energy. The resulting challenges for climate change mitigation scenarios are mixed. In REMIND the mid-term increase of coal will impose higher mitigation efforts, whereas the penetration of renewables eases the challenge. For TIAM-WORLD, the opposite applies.

In the mitigation scenarios, when CCS is available, REMIND tends to delay emission reduction slightly more compared to TIAM-WORLD, using more CO_2 sequestration in the long term, while mitigation starts earlier in TIAM-WORLD but is less dependent on CCS. When CCS is not available, emission reduction starts earlier in REMIND, associated with a temporary but immediate decline of energy consumption, while such a reaction is not observed with TIAM-WORLD. Indeed, mitigation options other than CCS, which are not cost-efficient in REMIND appear to be cost-efficient in TIAM-WORLD, like the use of hydrogen produced by electrolysis and the gasification of biomass. These options, which result in lower negative emissions in TIAM-WORLD compared to REMIND, provide a viable alternative strategy to BECCS and give some more flexibility to the energy system.

Results and findings from the work under Task 7-4 are summarized in deliverable D7.2.

WP7 Policy implications

- Bioenergy is a key component of long-term climate change mitigation strategies aiming at low stabilization
- While most attractive in combination with CCS, bioenergy can also contribute to mitigation if CCS not available
- Optimal future use of bioenergy (biofuels, electricity generation, hydrogen production) differs depending on the stringency of the climate target, the availability of CCS technologies and the biomass potential
- Climate policies that include emissions pricing of the land use sector help to reduce induced land use change emissions and to protect forest areas

WP8: Climate and Energy Technology

WP8 Summary of project work and results

WP8 focused on improving the modelling of feedbacks between the climate and the energy systems, as represented by the intertemporal optimisation-based integrated assessment models exemplified by TIAM-WORLD. Three feedbacks were explored: the impact of climate change on heating and cooling, on hydroelectricity and on biofuels. The work was done in close collaboration with other teams and WPs of the project, reflecting the very essence of coupling models to answer complex questions.

Tasks included: literature review on the impacts of climate change on the energy system; definition and implementation of the coupling of TIAM-WORLD and the emulator of GENIE and PLASIM-ENTS based on local temperature, precipitation and evapotranspiration.; comparison of meta-modelling approaches based on direct coupling and oracle-based framework; development and implementation of the coupling of TIAM-WORLD and MAgPIE; uncertainty analysis in deterministic and stochastic modes with TIAM-WORLD; about 2000 runs were done during the project, including those used for debugging.

Obtained results are:

- Availability of integrated and user-friendly modelling frameworks to couple TIAM-WORLD with climate and agriculture models.
- Assessment of climate impacts on heating and cooling and on hydropower.
- Improved modelling of bioenergy supply in TIAM-WORLD.
- Better understanding of the adaptation of the energy system.
- Implementation of couplings in BFG and CIAS (link with WP4).
- Application of the coupled models in other WPs such as 7, 10 and 11.
- Preparation of online results via CLIMASCOPE, VEDAVIZ, for example:

http://vedaviz.com/Portal/Playground.aspx?p=TWSSP2_REM-Comp16Oct&g=19931a

WP8 Detailed description of work

Deliverable

D8.1. Uncertainty analyses in TIAM (May 2013) by M. Labriet, A. Kanudia, R. Loulou, M. Biberacher (ENERIS); N. Edwards, P. Holden, B. Pizzileo (OU); S. Joshi Ram, M. Vielle (EPFL); J. Dietrich, M. Leimbach (PIK); F. Babonneau (ORDE).

Task 8-1: Evaluation and representation of the linkage between climate change and the energy system. Partners: ENERIS (TL), OU, PIK, UEA, UNIMAN

Literature review: Literature review on the impacts of climate change on the energy system helped to understand the nature and range of the impacts of climate change on the energy system and to define the relevant climatic parameters.

Heating and cooling: The coupling of TIAM-WORLD and the emulators of GENIE and PLASIM-ENTS was defined and implemented: the techno-economic TIAM-WORLD model provides greenhouse gas concentration to the climate model, which sends back spatio-temporal estimates of local temperature increases (degree-days) to TIAM-WORLD. Information exchange between models is handled by a fully automated script that launches models, reads output of one and creates input for the next. This can be done on a single computer or across a distributed network using the Community Integrated Assessment System tool (implementation in BFG and CIAS was done in collaboration with WP4).
The modelling framework developed with TIAM-WORLD was used to couple PLASIM-ENTS and GEMINI-E3. The analysis also contributed to the refinement of the seasonal representation of heating and cooling needs across regions in TIAM-WORLD.

Hydropower: The coupling of TIAM-WORLD and the emulator of PLASIM-ENTS was completed. It required the use of datasets such as topography, precipitation, evapotranspiration (the former from public data; the other two ones from PLASIM-ENTS) to compute hydropower in a Geographic Information System.

Bioenergy: The coupling of TIAM-WORLD and MAgPIE was developed and implemented for the assessment of interactions between bioenergy supply and other land uses: TIAM-WORLD provides regional bioenergy supply to MAgPIE, which sends back to TIAM-WORLD the prices of the corresponding regional bioenergy supply quantities and associated emissions. Emulated biomass supply-curves were also built, based on MAgPIE, and were integrated in TIAM-WORLD.

Runs and results management: The coupling of TIAM-WORLD with other models, the running of many scenarios and the analysis of results were possible thanks to the use of VEDA software (Versatile Data Analyst) developed by Amit Kanudia. Moreover, results from TIAM-WORLD were transferred to UEA for their use in CLIMASCOPE. To enhance the understanding of the significance of TIAM-WORLD results by users and stakeholders, the description of TIAM-WORLD was incorporated into the PIMMS Metadata Manager.

Task 8-2. Meta-modelling of the feedbacks between climate and energy/technology systems. Partners: ENERIS, OU (TL), ORDE, PIK
Meta-modelling activities were done in collaboration with WPs 3 and 6. The coupling of the emulator of PLASIM-ENTS and TIAM-WORLD was implemented step by step (coupling based on the Global Mean Temperature, then based on locally-defined temperature, and finally locally and seasonally-defined temperatures).
Deliverable 3.2 (Month 24) described two entirely separate approaches to TIAM-WORLD / PLASIM-ENTS coupling, both of which demonstrated a successful and efficient coupling: an oracle-based approach, and a direct coupling approach. The success of both coupling approaches and the rapid convergence achieved strongly suggests that the use of an emulated form for the climate module has circumvented the smoothness and convexity issues.

Task 8-3. Uncertainty analysis. Partners: ENERIS (TL), OU, ORDE, PIK
Two series of experiments were defined in order to explore the impacts of different uncertainties on the energy system within a stochastic analysis framework and integrating the impacts of climate change on the energy system:
1) Uncertainties related to the climate system (impacts of uncertain long-term mitigation levels on the mid-term mitigation options)

2) Uncertainties related to the economy and technology outlook (uncertain economic growth, climate mitigation and technology availability, CCS in this case).

WP8 Policy implications

What are the impacts of future climate changes on the heating and cooling needs and the consequences on the energy system?

At the global level, changes in heating dominate over changes in cooling in the intermediate horizon. Changes in cooling dominate over changes in heating when temperature reaches higher levels. Major reduction in gas and coal for heating and net increase in electricity are observed. Sector emissions reflect these changes, with an increase of emissions from the power sector in some regions, compensated by a decrease of emissions from buildings. This would require subtly different mitigation measures if climate policies were delayed for several decades.

At regional level, impacts and adaptation of the energy system depend on both climatic and energy system characteristics. The increase of electricity needs usually observed in warm seasons results in increases in electricity prices. Fuel substitution is observed in other sectors, where gas (reduced consumption for heating) may substitute electricity (increase demand for cooling), demonstrating the importance of considering system-wide effects.

What is the feedback on the climate induced by changes in heating and cooling?

Feedback is negligible, at least for the parameters and scenarios considered: heating and cooling system compensate each other at global level, and heating and cooling represent a reduced share of total energy consumption. Therefore, a one-way linkage with the climate model and the energy model is sufficient.

What are the impacts of future climate changes on hydropower?

A quite large increase of hydropower potential is found compared to what could occur without considering the impacts of climate change on hydropower (up to 16% at the end of the century, with decrease at some seasons in China, USA and India, and increase in all other regions and seasons). No impact on total electricity generation is found, neither at global nor regional levels. Variations in hydro generation remain small compared to total electricity generation: additional hydroelectricity substitutes coal power plants (both being baseload power plants, their substitution makes sense) and gas and wind/solar plants to a lesser extent. No impact on CO2 is observed. In other words, a one-way linkage with the climate model and the energy model is sufficient.

As an overall conclusion, the hydropower computing methodology and the coupling of PLASIM-ENTS and TIAM-WORLD are fully valid. However, the low geographic resolution of the analysis, much greater than the catchment and topographic precipitation scales, implies a high degree of approximation in the assessment of the hydropower variations.

Are there synergies between different effects of climate change on the energy system?

Yes, there are. The analysis of electricity generation confirms that changes in heating/cooling dominate the impacts on hydropower and on thermal plants at the global level (this is not the case in all regions: in Africa, the hydro feedback dominates the others) and exemplifies possible synergies or trade-off across scenarios: at global level, the additional electricity, needed to supply new cooling demands, is supplied by coal power plants in the case where only the impact of heating/cooling is considered. It is replaced by hydropower when all climate feedbacks are included.

What are the interactions between bioenergy needs and other land uses?

This analysis, based on the coupling between TIAM-WORLD and MAgPIE, and REMIND and MAgPIE, was covered in WP7.

What are the impacts of uncertainties on the energy system?
Uncertainties analyses prove that that the hedging does not vary uniformly within the range defined by two bounding extreme scenarios analysed assuming perfect foresight. For example, a small probability of high mitigation (10%) forces the energy system to adopt decisions quite different from the "Perfect foresight Low Mitigation". In other words, some energy decisions deserve an early implementation "in any case" ("act-now" strategy strongly dominates over a "wait-and-see" strategy) and are of particular interest for decision-makers. Amongst them: coal and gas are substituted by wind, hydro and nuclear. Moreover, stochastic simulations have revealed 'super-hedging' options that carry little weight when high or low mitigation scenarios are analyzed in isolation but add crucial flexibility when both scenarios are possible. Amongst these options, natural gas for electricity and end-uses, biofuels and solar electricity in some regions.

WP9: Global to local interfaces

Summary of project work and results

The work done in WP9 has concerned two vertical integration aspects related to downscaling for adaptation modelling and to TIMES-like models of different scopes. Regarding the latter, we have implemented a downscaling framework to link fundamental outputs of a world version of a TIMES model to some inputs of national versions and, similarly, to link national to regional bottom-up models. A Python code has been implemented to automate the data exchange process between models and preliminary analyses have been performed on TIAM-World, ETEM-Switzerland and ETEM-R. In the task of downscaling for adaptation modelling, we have developed a new version of the ClimGen climate scenario generator capable of coupling to the GENIE Earth System Model. Concretely a mean-conserving linear interpolation and a regridding algorithm have been employed to build a coupling unit between GENIEem and the ClimGen scenario generator. This new ClimGen version has been installed on the UEA CIAS platform.

WP9 Detailed description of work

The WP9 work concerns mainly vertical integration for i) downscaling for adaptation modelling (Task 9-1) and ii) TIMES-like models of different scopes (Tasks 9-2).

<u>Task 9.1: Downscaling for adaptation modelling:</u>
In this task we modified the ClimGen climate scenario generator in order to couple it to the GENIE Earth System Model emulator, GENIEem. This necessary step is required in order to transform the native GENIE data to a compatible spatial (0.5 by 0.5 degree, land only) and temporal (monthly) format and thus pass climate information to 'downstream' impact models within the ERMITAGE framework. The full technical description can be read in D9.1, but we provide a brief summary here.
To transform the GENIE data to the correct time resolution, a mean-conserving interpolation approach is used within the GENIE – ClimGen coupling module. Seasonal mean fields of temperature, precipitation and wet-day count are thus interpolated to twelve monthly values, via regular linear interpolation, but then scaled in order to preserve the original seasonal means. Having calculated the interpolated data, the results are then re-gridded from the GENIE native 5.0 by 5.0 grid to the ERMITAGE standard grid using a Esbensen-Kushnir area filter – which also weights grid cells according the original and target land-sea mask. The new version of ClimGen, v1.20, which includes the coupling module, is also capable of saving future climate data (to 2105) as anomalies, per variable, per cell, in addition to the absolute values. We also modified the output code to enable NetCDF3 and 4 output.
Elements of other tasks identified in 9.1. -- relating to the coupling of climate data to a water resource model -- are described in the WP5 report where they are formally stated as tasks.

(i.e. (i) completion of a daily precipitation generator and (ii) the modification of the LPJmL land vegetation and hydrology model to simulate groundwater stores).

Task 9.2: Vertical linkage between TIMES-like models:
In this task, we have implemented a downscaling methodology to link fundamental outputs of a world version of a TIMES model (i.e., TIAM-World) to some inputs of national versions, such as ETEM-Switzerland and, similarly, to link national to regional bottom-up models (i.e., from ETEM-Switzerland to ETEM-R). In order to implement this methodology, the ETEM-Switzerland model has been specifically developed in WP9 of the ERMITAGE project. The methodology is based on the definition i) of indicators for energy prices and emissions trajectory computed by TIAM-World and ii) of side-conditions for technology penetrations (electric and PHEV cars, renewables, etc) that are simulated at the upper level. We have developed a coupling framework that automates the construction and the exchange of these indicators and conditions between the three different models, thereby simplifying the assessment and comparison of climate policies. As an example of application, we have used the algorithm on a climate policy compatible with a 2^{o}C warming in 2100 to analyse the evolution of renewable electricity generation in Switzerland and evaluate its impact more specifically on the Arc Lémanique region in relation with the development of smart-grid technologies, demand response services and the Swiss decision to phase-out nuclear power by 2035. In that context TIAM-World provides the ETEM models with drivers on energy prices and emissions, and constraints on the transportation sector. We observed that while smart-grid technologies have a limited impact on the reduction of peak load due to the lack of flexibility of the residential demand technologies, they can contribute to the development of renewables with load shifting capabilities. We also remarked that the constraints on the transport sector from TIAM-World significantly reduce the penetration of electric cars in Switzerland. As a consequence, the storage capacities of intermittent electricity from renewables renewables are reduced, leading to a diminution of the penetration of renewables.
Although the present coupling has been implemented and tested specially for Switzerland and the Arc Lémanique region, the methodology can easily be extended to other countries and regions. Moreover, alternative indicators and side-conditions can be defined and built in order to extend the analysis to other sectors of the energy systems.

WP9 Policy implications

- Our vertical linkage exercise shows that smart-grid technologies have a limited impact on the reduction of peak loads due to lack of flexibility of residential demand technologies. However, they can contribute to the development of renewables with load shifting capabilities
- The automatic coupling of GENIEem to the ClimGen scenario generator has enabled a critical coupling in the UEA 'CIAS' integrated assessment module. Without this coupling it would not be possible to automatically iterate the output of energy / economic models back to the GENIEem and climate scenario generator, and then pass the new climate information to the energy / economic models (etc).

WP10: Linking climate and economic models

WP10 Summary of project work and results

Coupled economic and climate models have been exploited in game theoretical frameworks to analyze stability, fairness and robustness of international environmental agreements (IEAs). A cost-effectiveness approach is used to study fairness and robustness aspects while a cost-benefit one is proposed for the coalition stability issue. In the latter, payoff functions are built from simulations of combinations of ERMITAGE's models and damage

costs come from literature. The results show that global cooperation is always worthwhile but at the same time we observe very few and small stable coalitions.
In the cost-effectiveness approach, the damage cost is replaced by a constraint on total emission over the 2010-2050 period compatible with a 2°C warming at the end of the century. Assuming that all groups of countries agree to respect this enforced global budget and thus to contribute individually with some domestic abatements, our analysis tend to show that an acceptable voluntary burden sharing agreement could be obtained among all groups of countries with an associated balanced welfare loss below 1% of their total discounted household consumption. Such an agreement in which 15.3% of the total emission budget of 424GtC is allocated to USA, 8% to EU, 22.5% to China, 7.5% to India, 4.8% to Russia, etc. is considered as a fair agreement in the sense that global contribution is limited, shared equitably among all players and proportional to their domestic household consumption. This burden sharing game has been integrated into the CIAS Live Portal as a public web-application. In a "robust" solution that prevents potential emissions overshooting in such commitments and takes potential errors arising in the various approximations made in our methodology into consideration, the welfare loss rises to 1.8% for each group of countries. In a complementary analysis using a dynamic economic growth game, we found that the impact of climate change on the economy is important in the very long term. As a consequence, one must adopt a cost-effectiveness approach with a 2°C constraint (instead of a cost-benefit one) to favour the early use of low-carbon technologies.
Finally, a study on oil and gas market reaction to IEAs has been performed using the TIAM-World model. In this study we simulate a two-level game where OPEC oil producers are the leader, and the rest of the world constitutes the followers, behaving as a competitive fringe. Numerical results show that OPEC power increases with climate policies and lower extraction costs. However, OPEC has very limited impacts on climate policy costs and would not counteract abatement targets.

WP10 Detailed description of work

The work done in WP10 concerns i) Task 10.1 on the identification of stable IEAs, ii) Task 10.2 that deals with fairness and robustness of burden sharing for GHG emissions reduction and Task 3 that focuses on oil and gas market reactions to IEAs.

Task 10.1: Identification of stable IEAs

Regarding Task 10.1, the aim was to build payoff functions (i.e., abatement cost functions and damage functions) using combinations of complex environment, energy and economy models that are developed through the ERMITAGE project. Those payoff functions are then exploited for the game theoretical stability analysis using the approaches of robust stability and stability likelihood. In deliverable D10.1, we have presented in detail the methodology used for the stable IEA modelling and presented a preliminary analysis using GEMINI-E3, REMIND-R and with the coupled model TIAM-WORLD / GENIEem which has been developed in WPs 3 and 8. For that analysis, the three above-mentioned economy/energy models are used to calibrate marginal abatement cost functions while damage functions come from literature. The results show that there are always significant gains to be obtained from global cooperation on climate policies, both in terms of abatement cost and damage reduction (benefits). However, these gains from cooperation offer, at the same time, opportunities and incentives for free riding. We observe that stable coalitions are very few and small. Finally the analysis also shows that partial cooperation does not help much to improve upon the case of no cooperation.

Task 10.2: Fairness and robustness in burden sharing analysis

First we have used two complementary approaches to evaluate a possible fair sharing of the burden of keeping climate change inside a tolerable region. The outcome of negotiation is assumed to be reduced to the definition of a fair sharing of a safety emission budget over the 2010-2050 period that is compatible with the warming at the end of the century being less

than 2°C. To evaluate this budget we have used first an emulator of a complex climate model, PLASIM-ENTS coupled with either a bottom-up energy model, TIAM-WORLD, or a top-down general equilibrium model GEMINI-E3. Using these different models we have defined two ways to assess the net benefit, expressed in terms of a ratio of surplus over GDP or household consumption. The surplus is computed after the establishment of an ``optimal international emissions trading market". Then we were able to find the sharing of the safety emissions budget that would maximize the minimum of these ratios. In the case of TIAM-WORLD we could allocate the quotas of each player, in each period so that all these ratios are equal, in each period. In the second approach, we used statistical analysis of a sample of numerical simulations performed with GEMINI-E3 to define the payoff functions of the players/regions in a non-cooperative game of strategic allocation of their shares of the safety emission budget, as quotas for each period in the international emissions trading system. This second way of organizing the market has the advantage of avoiding the (restrictive) assumption that a benevolent planner determines the allocation of quotas for each player at each period; it should therefore be more acceptable in the negotiation process. Hence assuming that all groups of countries agree to respect the safety emission budget and to contribute with domestic abatements, our results tend to show that an acceptable voluntary burden sharing agreement could be obtained among all groups of countries with an associated balanced welfare loss below 1% of their total discounted household consumption. In such an agreement, 15.3% of the total emission budget of 424GtC is allocated to USA, 8% to EU, 22.5% to China, 7.5% to India, 4.8% to Russia. All results are reported in D10.2 and D10.3. This burden sharing game based on GEMINI-E3 simulations has been integrated into the CIAS Live Portal (http://ermitage.cs.man.ac.uk/csl/ShowModel?name=burdensharing) allowing any user to test different allocation solutions through this simple web-interface. See D10.2 for more details.
We have then introduced the concept of robust balanced equilibrium applying robust optimization techniques to take into consideration uncertainties created by the statistical emulation approach and by potential emissions overshooting in the implementation of IEAs. In a "robust" solution, we found that the welfare loss rises to 1.8% for each group of countries which is quite reasonable and promising for future negotiations. The results are reported in D10.3.
In a final study, described in D10.3, we have represented the climate negotiations and the resulting agreement as the imposition of a coupled constraint in a dynamic economic growth game, with a climate module and economic loss factor induced by temperature change. The economic growth models have two particular features. The players, i.e. the group of countries involved in the negotiations, can invest in a carbon and in a low-carbon economy. They can also invest in an adaptation capital which tends to alleviate the impact of climate change on economic production. Using a 3-player model, corresponding to the division of the world economy into industrialized (OECD), emerging (BRIC) and developing (ROW) countries, we have simulated different possible solutions to the resulting differential game. The results show that the impact of climate change on the economy is significant in the very long term. This implies that, in a cost-benefit approach, very little is done in early commitment periods (e.g., 2010-2050), even in a Pareto optimal solution. In order to obtain a sensible drive toward the use of low-carbon technologies, one must adopt a cost-effectiveness approach and impose a 2^{o}C constraint on temperature increase in the Pareto optimal solution. Otherwise, even in the long-term, investment in adaptation capital is the favoured (climate) policy.

Task 10.3: Oil and gas markets reaction
For the analysis on oil and gas market reactions to IEAs, we have adapted the TIAM-World model to enable the simulation of a two-level game where OPEC oil producers are the leader, and the rest of the world constitutes the followers, behaving as a competitive fringe. The model had been coupled with the GENIE climate model as part of WP 8 in order to calibrate the climate module of TIAM-World. Additional harmonization with the MAGPIE

model was done to enhance and update the biomass production module of TIAM, as part of WP7 and WP8. In both cases, the harmonization of TIAM's database proved to be sufficient for the purpose of the present task. The modified TIAM-World model was then used in a two-step experimental design. The first step was exploratory, and consisted in assessing the impact of five major parameters that could influence the oil production game, namely: the presence or absence of a severe climate target, the future costs of gas production, the future potentials of synthetic liquid fuels, the future production costs of unconventional oil, and the degree of flexibility of Non OPEC oil producers in increasing their production levels. The results of the first step showed that a) the gas markets are sufficiently decoupled from the global oil market to have a very small influence on the oil game, and b) that the presence or absence of synthetic fuels also has a negligible impact on the oil game. The other three parameters were seen to have sufficient importance to be kept in the final step of the experiment. The final experiment was then focused on a finer investigation of OPEC strategies, that were allowed to vary independently at three periods, while retaining the three remaining parameters as exogenous variables with 2 discrete values each (thus producing 8 alternative scenarios).

The results of the final runs of the model showed that OPEC has market power in all 8 scenarios considered, and that its market power increases when a climate policy is active and/or when future oil extraction costs are low. In both these cases, the explanation of the higher power lies in the fact that global oil demand becomes less elastic (but the reason for such inelasticity differs in the two cases). In spite of the higher OPEC market power in the climate policy scenarios, it was seen that OPEC's power has a very limited impact on the global cost of implementing the climate policy. What is meant here is that if indeed the selected climate target of 450ppmv in 2100 remains the globally desirable one (i.e. one for which the net global social benefits are maximized), then the cost part of achieving it is little affected by OPEC strategic power. This very result indicates that OPEC's strategies are very unlikely to result in a modification of the target itself. This research has shown that under each optimal OPEC strategy, the global cost of implementing a climate target of 450ppmv in 2100 increases by an almost negligible amount within the range -0.004% to 0.012% (relative to the cost without OPEC's strategy), depending on the values of the other parameters. The report also contains a summary analysis of energy savings and energy substitutions that are triggered by each optimal OPEC strategy. The main energy forms that substitute for the reduction in oil production by OPEC are coal and gas, in about the same amounts. See D10.2 for more details.

WP10 Policy implications

- Fair and robust IEAs are possible at reasonable costs: A burden sharing equilibrium solution (ie, a fair IEA) limits the discounted welfare loss to 1% of household consumption of each group of countries with an associated carbon price of 700 US$ in 2050. When considering uncertainties (eg, modeling errors and potential emission overshooting), welfare losses reach 1.8% of household consumption.
- Cost-effectiveness approaches are preferable for early commitments: As the impact of climate change on the economy is important in the very long-term, one must adopt a cost-effectiveness approach with a 2°C constraint (instead of a cost-benefit one) to favour the early use of low-carbon technologies.
- OPEC countries have limited impacts on IEAs: Whilst our analysis shows that OPEC power increases with climate policies and lower extraction costs, OPEC has very limited impacts on climate policy costs and would not counteract abatement targets.

WP11: Sustainable land and water use

WP11 Summary of project work and results

This work package completes the advanced integration of couplings to create 21st century harmonized scenarios. A dozen different alternative couplings were created in order to explore different aspects of the relationship between the economy, climate change, land use change, agriculture and the environment. Several of these pairwise and more complex model couplings have been incorporated into the Community Integrated Assessment System (CIAS) tool (Warren *et al.*, 2008), whilst others are available off-line.

WP11 has thus derived added value by creating long-lasting coupled models available for use in research for the future, drawing together a range of models created at different institutes that allows those researchers to continue to explore these questions. The co-location of many of the models in the same system (CIAS) allows for increased, easy use of the models in the future at a secure and user friendly web portal.

WP11 also derives added value by exploring more complex interactions than are explored in the individual work packages, and by allowing harmonised comparisons to be made when alternative model couplings are applied to ask similar questions.

In particular, it has addressed the challenge of how to achieve a transition from a high carbon world to a low carbon world under a common socioeconomic scenario, using the newly developed framework of Representative Concentration Pathways and Shared Socioeconomic Pathways (RCPs and SSPs, Moss et al. 2010). A variety of economic and technical solutions and instruments were explored, including carbon taxation, burden sharing regimes, and the role of biofuels including their interaction with land use patterns. It was found that high carbon prices on both terrestrial and fossil carbon were required to achieve the transition, but that these prices are minimised if policy action is taken early, if burden sharing regimes are used, and if agriculture is intensified.

WP11 Detailed description of work

The ERMITAGE deliverables produced for WP11 are:

- D11.1, M17, Scenario generation mechanism
- D11.2, M34, Harmonised policy scenarios

WP11 was key to the achievement of the overall ERMITAGE project aim to link together several key component models into a common framework in order to better understand how management of land, water and the Earth's climate system can be synergised. First, key component models of climate change, land use change, and the economy were assembled. In this WP models of multiple systems were coupled together, specifically models of the hydrological; agricultural; ecological; economic; and technical (energy) systems. The complexity of the couplings was gradually increased as the project progressed, working towards the ultimate goal of producing a completely harmonised vision of land, water, climate and the economy for the future.

In the first deliverable of the work package, mechanisms to set up and create harmonised scenarios of the future incorporating the above component models and objectives were creating using the technologies which were produced by WP4 (i.e. BFG2 and CIAS). First, pairs of models were coupled together in order to allow analysis of some key relationships that are important in sustainability science, such as the relationship between the agricultural system and the economy. Most of these pairwise couplings were successfully demonstrated using the BFG2 technology (WP4) and were subsequently incorporated into CIAS, whilst the rest of the couplings were set up so that they could be run off-line.

For the second deliverable, harmonised scenarios of the 21st century were produced using both the pairwise couplings created in the first deliverable, and also a number of more complex couplings that were created by using three or more component models. These more complex couplings were important to allow feedbacks to be explored. This further work allowed the physical feedbacks and changes in natural and anthropogenic emissions to be built into the models to derive economic impacts and combined analyses, the separate reports of which are presented in a number of the work packages. As the model grew in size, computational time became an issue partially resolved by the development of emulators, bringing with them greater flexibility for sensitivity analysis, opening the door to further combinations of opportunities for comprehensive analysis of sustainability given statistical modelling of multidimensional uncertainties (WP3).

Table 1 illustrates the status of the couplings used in WP11 within BFG and CIAS.

Coupling Sequence (feedbacks not shown)	**BFG2 status**	**CIAS status**
PLASIM-ENTSem-GEMINI-E3	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(crop)_GEMINI-E3	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(crop)	✓	✓
MAGICC_ClimGEN_LPJmLEm(crop)	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(NPP)	✓	✓
MAGICC_ClimGEN_LPJmLEm(NPP)	✓	✓
MAgPIE_REMIND	✓	Close to completion
LPJmL_MagPIE	×	×
MAGICC_ClimGEN_LPJmL_MagPIE_REMIND	×	×
MAGICC_ClimGEN_LPJmL_MagPIE_TIAM	×	×
MAgPIE_TIAM	×	×
TIAM_PLASIMEntsEm	In preparation	×

In addition, the WP4 portal CIAS-Live currently includes LPJmL-em, PlasimEnts-em, and Maniclette - a burden sharing model. These are available on http://ermitage.cs.man.ac.uk/csl

The BFG portal provides BFG descriptions of the following:
GeminiE3 ↔ PlasimEnts-em
GeminiE3 ↔ Genie-em
MagPIE ↔ REMIND
PlasimEnts-em → Climgen → LPJmL-em-3f
(A prototype of) Climgen → LPJmL-em-3f → GeminiE3
(A prototype of) TIAM ↔ PlasimEnts-em

The CLIMASCOPE portal climascope.tyndall.ac.uk provides public access to the regional climate change projections produced in the project (WP5).

In particular couplings were run with common or similar datasets for population, GDP and land use. A major focus was the use of the couplings to explore economic instruments and technical solutions necessary to achieve a transition from a higher to a lower carbon world, specifically from the representative concentration pathway RCP6 (Fujino et al. 2006) to that of RCP2.5 (van Vuuren et al 2011) under the common socioeconomic pathway SSP2 (Moss et al. 2010). Five separate couplings were employed, incorporating climatic, technological, economic, land-use, and agricultural models to explore the potential technologies required, the role of biofuels, the required carbon taxation regimes, and the role of potential burden sharing regimes.

Two couplings were used to explore the consequences of climate change for household energy demand through changes in heating and cooling degree days, and one coupling was used to explore the economic consequences of sea level rise, combining forecasts of population, GDP and diminished land availability

Another key question addressed was how the combination of both climate change and climate mitigation policy affects land use and hence feed-back upon climate change itself. We began by projecting climate change impacts (WP5), and then considered the role of CO_2 fertilization, and how crop and water management options might buffer adverse climate change effects on crop yields. Finally, anticipated feedback effects of changes in greenhouse gas emissions developed in the simulations were re-applied within the land use allocation model MAgPIE to assimilate the likely climate change impacts given projected changes in food demand, thus completing the simulation feedback loop from climate change to impacts to land use change and hence back to the climate. Projections of changes in the agricultural system thus eventually incorporated both direct impacts of projected changes in precipitation and temperature, and indirect impacts from land-use change brought about by biofuel cropping and changes in food demand.

WP11 Policy Implications

A set of coupled models has been developed that can be used in future research projects involving policy makers and other stakeholders, based on the Community Integrated Assessment System and other coupling tools.

Regional climate change projections are available at climascope.tyndall.ac.uk, providing a resource for deriving policy advice in the future, particularly relating to adaptation challenges.

A transition from a high carbon world that produces climate change consistent with RCP6 to a low carbon world consistent with RCP3PD is feasible. However, this requires significant increases in carbon prices and a substantial reliance on biofuels.

Couplings suggested that high carbon prices were needed to achieve the transition to RCP3PD. These rose further if biofuel cropping was minimised in order to reduce competition for land with agricultural crops and preserve natural ecosystems and biodiversity. However, these carbon prices, and the consequential effects upon households can be greatly reduced through (i) early policy action (ii) cooperative burden sharing approaches (iii) agricultural intensification.

Reliance on biofuels induces widespread deforestation and other land use change globally, but this can be greatly reduced by the use of a carbon taxation scheme that includes terrestrial carbon as well as fossil carbon, and uses a uniform price for both. Agricultural intensification is important in further reducing pressure on land use, and is therefore necessary to achieve the target.

Climate change was projected to have minimal effects on heating and cooling demand globally, but effects were important regionally, especially in Europe. Sea level rise was expected to have relatively small economic consequences by the 2050s.

Potential impact

ERMITAGE's final results, to be possibly used by policy makers, can be summarised as follows:

- ***Impacts on water resources, ecosystems and crop yields*** will increase substantially with higher global mean temperature rise.
- ***Spatial and temporal impact patterns*** differ among impact sectors, with water resources being reduced strongly in some regions even at a warming of 2C above preindustrial level and changes in heating and cooling possibly significant at local level in higher long-term temperature scenarios.
- ***Multi-sector and multi-effect analysis*** is crucial since impacts of climate change on one sector may be compensated or reinforced by the impacts on another.
- ***Analysis of impacts at regional and local levels*** is important because geographic aggregation may hide large local variations.
- ***Tools to support decision-making in uncertain contexts*** are essential for robust policy-making, and can give substantially different results to approaches that exclude uncertainty analysis.
- ***A transition from RCP6 to RCP2.6*** is feasible but requires high carbon prices and will increase competition between biofuel cropping, food cropping and forest conservation. However, these effects can be minimised by (i) early action (ii) including a price on terrestrial carbon (iii) agricultural intensification (iv) burden sharing (v) ensuring that biofuels are used cost-effectively as part of the energy mix.
- ***Effective climate policy*** that includes GHG pricing also in the terrestrial sector can help to reduce GHG emissions from agriculture and to protect forest areas.
- ***Intensification of agricultural production*** ensures that even with additional demand on land for bioenergy crop production, less forest has to be converted to meet food demand.
- ***Bioenergy is a key component*** of long-term climate change mitigation strategies aiming at low limiting warming to 2C above pre-industrial levels. While most attractive in combination with CCS, bioenergy can also contribute to mitigation if CCS is not available.
- ***If global warming is not kept below 2C*, **major implications for agriculture and water policies might emerge as they would have to deal with large-scale and potentially costly adaptation options.
- ***Our coupling technologies***, successfully used to create 10 alternative coupled models, 7 of which appear in the Community Integrated Assessment System, and several of which use model emulators, have allowed us to tease out relationships between climate mitigation, land use policy and energy policy in a cost-effective manner.

Main dissemination activities and the exploitation of results

Publications

Under preparation:

1. Oluwole K. Oyebamiji, Neil R. Edwards, Paul H. Garthwaite, Philip B. Holden, Sibyll Scaphoff and Dieter Gerten. Predicting climate change impacts on crop-yield. Under preparation.
2. Holden, P. B., Edwards, N. R. and Garthwaite, P. H. Emulating high-dimensional output from high-dimensional input. Under preparation.
3. F. Babonneau, N. Edwards, D. Gerten, S Schaphoff, S. Joshi, O. Oyebamiji, M. Vielle. Impacts of climate change on the agricultural sector. Under preparation

Submitted/ Discussion papers:

4. Holden P.B. et al.: "PLASIM-ENTSem: a spatio-temporal emulator of future climate change for impacts assessment", Geosci. Model Dev. Discuss., 6, 3349-3380, 2013, doi:10.5194/gmdd-6-3349-2013.

5. Deryng, D., Ramankutty, N., Conway, D., and Warren, R. Global crop yield response to extreme heat stress under multiple climate change futures. Submitted.
6. Foley, A. M., J.-F. Mercure, P. Salas, P. B. Holden, N. R. Edwards, H. Pollitt and U. Chewpreecha Modelling the climate impacts of mitigation policies in the energy sector: An integrated assessment framework using climate model emulation, submitted to Climatic Change.
7. Joshi, S. R., Vielle, M., Babonneau, F., Edwards, N. R. and Holden, P. B. Physical and economic consequences of sea-level rise: A coupled GIS and CGE analysis under uncertainties (2013), submitted to Environmental and Resource Economics.
8. Bahn, O. and Haurie, A. (2013). A cost-effectiveness differential game model to assess climate agreements, Ordecsys technical report. Submitted.
9. J.-F. Mercure, H. Pollitt, U. Chewpreecha, P. Salas, A. M. Foley, P. B. Holden and N. R. Edwards, Economic benefits of decarbonising the global electricity sector, submitted. http://arxiv.org/abs/1310.4403
10. Mercure, J. F., P. Salas, A. Foley, U. Chewpreecha, H. Pollitt, P. B. Holden and N. R. Edwards, The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector, submitted to Global Environmental Change. http://arxiv.org/abs/1309.7626

Peer reviewed:

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12. Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., Pastor, A. 2013: Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. *Current Opinion in Environmental Sustainability* 5, 551–558.
13. F. Babonneau, A. Haurie and M. Vielle. A robust meta-game for climate negotiations.Computational Management Science, Volume 10, Issue 4, pp 299-329
14. Maryse Labriet, Santosh R. Joshi, Frédéric Babonneau, Neil R. Edwards, Phil B. Holden, Amit Kanudia, Richard Loulou, Marc Vielle. 2013. Worldwide impacts of climate change on energy for heating and cooling. *Mitigation and Adaptation Strategies for Global Change.* Available online. 10.1007/s11027-013-9522-7
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24. Holden, P. B., N. R. Edwards, S. A. Müller, K. I. C. Oliver, R. M. Death and A. Ridgwell 2013. Controls on the spatial distribution of oceanic $\delta^{13}C_{DIC}$. Biogeosciences, Vol. 10, pp. 1815-1833, doi:10.5194/bg-10-1815-2013.
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30. Popp A., Krause M., Dietrich J., Lotze-Campen, H., Leimbach M., Beringer, T., Bauer N. 2012: Additional CO_2 emissions from land use change – forest conservation as a precondition for sustainable production of second generation bioenergy. *Ecological Economics* 74: 64–70.
31. Neil Edwards, Plausible mitigation targets, Nature Climate Change 1, 395–396 (2011) doi:10.1038/nclimate1267, Published online 23 Oct 2011. (http://www.nature.com/nclimate/journal/v1/n8/full/nclimate1267.html)
32. Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M., Weindl, I. (2012): "Trading more Food - Implications for Land Use, Greenhouse Gas Emissions, and the Food System", Global Environmental Change, 22(1): 189-209.
33. Heyder, U., Schaphoff, S., Gerten, D., Lucht, W. 2011: Risk of severe climate change impact on the terrestrial biosphere. *Environmental Research Letters* 6, 034036.

Paper in Proceedings of a Conference/ Workshop:

34. Gerten, D. 2011: Water availability and scarcity: now and future trends. In: Kowarsch, M. (Ed.)., *Water Management Options in a Globalised World – Proceedings of an International Scientific Workshop, 20–23 June 2011*, Bad Schönbrunn, 9–15. Institute for Social and Development Studies (IGP). (E-Book, http://www.hfph.de/igp/proceedings2011).

35. Gerten, D., Heinke, J., Hoff, H. 2012: Estimating green-blue water availability and needs for global food production. In: Bogardi, J.J., Leentvaar, J., Nachtnebel, H.-P. (Eds.), *River Basins and Change*, 80–84. Global Water System Project & UNESCO Institute for Water Education (E-Book, http://www.gwsp.org/fileadmin/documents_news/GWSP_12_01_E-Lernbuch_Complete_RZ5.pdf).

Article/Section in an edited book or book series:

36. A. Haurie, F. Babonneau, N. Edwards, P. Holden, A. Kanudia, M. Labriet, M. Leimbach, B. Pizzileo and M. Vielle. *Fairness in Climate Negotiations: a Meta-Game Analysis Based on Community Integrated Assessment*, Oxford University Press handbook on the economics of climate change, to appear.
37. Ford, R.W. and Riley G.D.,The Bespoke Framework Generator, in: Earth System Modelling - Volume 3 Coupling Software and Strategies Series: SpringerBriefs in Earth System Sciences Eds: Valcke, Sophie, Redler, René, Budich, Reinhard October 2011, ISBN 978-3-642-23359-3.
38. Leimbach, M., A. Popp, H. Lotze-Campen, N. Bauer, J.P. Dietrich, D. Klein, Chapter in the Handbook on Climate Change and Agriculture (2011), Integrated assessment models – the interplay of climate change, agriculture and land use in a policy tool. In: Handbook on Climate Change and Agriculture, A. Dinar and R. Mendelsohn (Eds.), Edward Elgar, Cheltenham, pp. 204 – 229.
39. N. Edwards, R. Warren, M. Labriet, D. Gerten, 'Integrating Economy and Ecology', International Innovation, December 2012, (Research Media, UK, pp 32-34) ISSN 2041-4552.

Thesis/ Dissertation:

40. Rastgooy, J. 2013: *Effects of Climate Change and Management Improvements on Global Crop Yields – a Model-based Analysis.* Master thesis, Ludwig-Maximilian-University Munich and Potsdam Institute for Climate Impact Research.

University Publication/Scientific Monograph:

41. Alain Haurie, Jacek B Krawczyk, Georges Zaccour. *Games and dynamic games*. World Scientific, Vol. 1, 2012.

Workshops and conferences

1. Neil Edwards presented on ERMITAGE final results at the UK Department of Energy and Climate Change (DECC), 27th November 2013, London.
2. Talk (C. Wallace et al.) Making rain and modelling groundwater. Tyndall Lunchtime Seminar Series, 27 Nov 2013, Norwich (UK)
3. Talk (F. Babonneau) "On using robust optimization in some problems in energy planning". 3ième Colloque de la chaire de recherché industrielle CRSNG/Hydro-Québec en optimization stochastique de la production d'électricité, 25 November 2013, Montréal, Canada.
4. Talk (N. Edwards) "Modelling the models: statistical emulation for climate-economics and the carbon cycle", 18th November 2013, University of Bern, Bern.
5. Talk (A. Haurie) "Cost Effectiveness Differential Game Model for Climate Agreements". Workshop organized by CRM, University of Montreal, Canada on "Biodiversity and Environment: Viability and Dynamic Games Perspectives", November 4-8, 2013.
6. Talk (A. Popp et al.): Land-use transition for bioenergy and climate stabilization Presentation at the EMF30 workshop, 2 Nov 2013, Tsukuba (JP)

7. Bas van Ruijven & Keith Oleson, collaborators of ENERIS. “Comparing energy use for space heating and cooling across IAMs and Earth System Models”. 29 October 2013, Tsukuba, Japan. 6th Annual Meeting of the Integrated Assessment Modeling Consortium
8. Talk (M. Labriet). “Complementary roles of energy and agriculture models: Insights from TIAM-WORLD couples with MAgPIE” and “Modelling HDD/CDD changes in TIAM-WORLD”; *Meetings of LAMP (Latin American Modeling Project) and CLIMACAP (Integrated CLimate Modelling And CAPacity building in Latin America), Bariloche, Argentina, October 21-23, 2013*
9. Talk (D. Gerten): Will there be a global water crisis? Water, climate change and food security. Colloquium: Current Topics in Geoscience. University of Basel, 16 Oct 2013, Basel (CH)
10. Talk (Leimbach, M.) Assessment of climate policy measures from a global point of view. CliPoN Workshop, Leipzig, Germany, 8-9 October 2013.
11. Warren, R. The Community Integrated Assessment System. Short presentation at Fudan University, Shanghai, China, 20 August 2013
12. Talk (D. Gerten): Global climate change impacts on freshwater availability: an overview of recent assessments. Conference: Knowledge for the Future – Joint IAHS-IAPSO-IASPEI Assembly, 22–26 Jul 2013, Gothenburg (S)
13. Talk (Leimbach, M.): Solution algorithms of large-scale Integrated Assessment models. Presentation at 26th European Conference on Operational Research, Rome, 1-4 July 2013.
14. Talk (Alain Haurie) A Meta-Game Model for Fair Division in Climate Negotiations at the SSES Annual Meeting 2013, University of Neuchatel, June 20-21, 2013.
15. Talk (S. R. Joshi) “Impacts of climate change on heating and cooling: a worldwide estimate from energy and macro-economic perspective”. Swiss society of economic and statistics (SSES) Annual Congress, 20-21 June 2013, Neuchatel, Switzerland.
16. Talk (M. Labriet) “Impacts of climate change on heating and cooling: a worldwide estimate from energy (TIAM-WORLD) and macro-economic (GEMINI-E3) perspective”. International Energy Workshop, 19-21 June 2013, Paris, France.
17. Talk (D. Gerten): Quantifying multiple pressures on global water resources: climate change, food production, bioenergy production. GWSP Conference, 21–24 May 2013, Bonn (D)
18. Talk (M. Bonsch et al.): Implementing water management policies– possible caveats and leakage effects. GWSP conference, 21–24 May 2013, Bonn (D)
19. Talk (D. Gerten): LPJmL vegetation model: water availability – water demand – water scarcity. Workshop: Water Futures and Solutions, 6–8 May 2013, Laxenburg (A)
20. Talk (P. Holden et al.): A model-based constraint on CO_2 fertilisation. EGU, 12th April 2013, Vienna (A)
21. Talk (D. Gerten): Water for food under global climate change: scarcities and opportunities. Symposium: Water Issues in Climate Change, 3–5 Apr 2013, La Jolla (CA, USA).
22. Talk (D. Gerten): Climate impacts on global water resources and the biosphere. Guest talk, IASS, 22 Mar 2013, Potsdam (D)
23. Warren, R. REDD is essential to achieve a 2C target. Presentation at the Dept. of Energy and Climate Change, London, UK 22 March 2013
24. P. Holden and B. Pizzileo attended the BADC Workshop Deriving value from the latest Climate Simulation archives, 15 March 2013, Birmingham.
25. Warren. R Climate change impacts avoided by mitigation. Presentation at the Royal Society, at the Avoiding Dangerous Climate Change symposium, hosted by the UK Dept of Energy and Climate Change, 12 Feb 2013
26. R. Warren gave a seminar entitled ‘Applications of the Wallace Initiative in the Study of Climate Change Impacts on Agriculture’ at the Agricultural Transitions Workshop held at UEA, Norwich (UK), 16 Dec 2012

27. Talk (M. Labriet) "Impacts of climate change on heating and cooling: coupling TIAM-WORLD with the climate model PLASIM-ENTS" based on ERMITAGE results. *Semi-Annual Workshop of the Energy Technology System Analysis Program (ETSAP), 10 December 2012, Lisbon, Portugal*
28. Talk (M. Labriet) "Towards climate resilient and low carbon energy systems: tools for action" in the Side-Event "Resilient energy policies", where ERMITAGE was presented. *Conference of the Parties of the UNFCCC, COP18, 3 December 2012, Doha, Qatar.*
29. Talk (M. Vielle): "Economic consequences of climate change". 5th Integrated Assessment Modeling Consortium (IAMC) Annual Meeting, 12-13 November 2012, Utrecht, The Netherlands.
30. Poster presentation (D. Gerten et al.): Potential of crop water management to secure global food production under climate change. IIASA 40th Anniversary Conference: Worlds Within Reach from Science to Policy, 24–26 Oct 2012, Vienna (A)
31. Talk (D. Gerten): Closing the global water-for-food gap. Symposium: Water Constraints on Future Food Production, 5 Oct 2012, Wageningen University (NL).
32. Talk (T. Osborn) "Drought in Mediterranean Europe: future projections from multiple climate models" at the MedCLIVAR 2012 conference, 26-28 September 2012, Madrid, Spain.
33. Neil Edwards gave the talk "Simulating glacial cycles with GENIE: When the WAIS had nowhere to hide" at the GREENCYCLESII Mini-Conference 3: Evaluation of Earth system models using modern and palaeo-observations. September 24, 2012, Cambridge.
34. Poster presentation (S. Schaphoff et al.): Permafrost soil carbon balance in a warming world. 3rd International Conference on Earth System Modelling, 17–21 Sep 2012, Hamburg (D)
35. Talk (D. Gerten): "Water requirements for future global food production, and potentials of on-farm green–blue water management to increase crop production" at the World Water Week Conference, Aug 26–31, 2012, Stockholm (S).
36. Tutorial by Alain Haurie on "Normalized Equilibria in Dynamic Games: Theory and Applications" presenting in particular what is developed in terms of game-theoretic meta-modeling in ERMITAGE at the 15th International Symposium on Dynamic Games and Applications , 18-22 July 2012, Bysice, Czech Republic
37. Talk (D. Gerten): Water and agriculture – the grand challenge. Presentation for a high-level delegation from Qatar, 13 Jul 2012, Potsdam (D)
38. Talk (G. Tarel) "Analysis on burden sharing for GHG emission reduction". Preliminary results of Task 10.2 presented. 25th European Conference on Operational Research, July 8-11, 2012, Vilnius.
39. Talk (R. J. Santosh) "Sea level rise and its economic consequences" at the International Conference on Economic Modeling ECOMOD2012, July 4-6, 2012, Seville.
40. O. Oyebamiji presented the poster "Predicting terrestrial biosphere response to climate change and anthropogenic CO2 emission" at the Uncertainty in Computer Models 2012 Conference 2-4/07/12, University of Sheffield.
41. Talk (A. Haurie) "Incertitude dans les modèles intégrés socio-économiques". Workshop organized by the French Ministry of Ecology, Sustainable Development and Energy on "uncertainties and adaptation of climate change", June 13-14, 2012, Paris.
42. Talk (K.M. Hiscock) "Overview of current drought research and its relevance to the challenges we face" at the UK Groundwater Forum Conference. 13 June 2012, Nottingham
43. Opening plenary talk (A. Haurie), "Dynamic Games and climate Negotiations", presenting in particular what is developed in terms of game-theoretic meta-modeling in ERMITAGE.12th Viennese Workshop on "Optimal Control, Dynamic Games, and Nonlinear Dynamics", May 30th-June 2nd, 2012, Vienna.

44. Talk (C. Wallace et al.) A statistical rainfall disaggregator. National Oceanography Centre Climatology Seminar Series, April 2012, Southampton (UK).
45. R. Warren AVOIDing Dangerous Climate Change. Poster Presentation at Planet Under Pressure, London, 28 Mar 2012.
46. Talk (D. Gerten, R. Warren et al.): Risk of severe and inequitable impacts at 2°C and beyond. Conference: Planet Under Pressure, 26–29 Mar 2012, London (UK).
47. Poster (M. Fader, D. Gerten et al.): Dependence of countries on food imports due to limitations in domestically available land and water resources. Conference: Planet Under Pressure, 26–29 Mar 2012, London (UK).
48. Talk (H. Lotze-Campen, A. Popp, J.P. Dietrich et al.): Cumulative pressures on future global agriculture and the role of technological change. Conference: Planet Under Pressure, 26–29 Mar 2012, London (UK).
49. Lotze-Campen H., Popp, A., Obersteiner, M., Antle, J., Märkl, M. (2012): Pressures on agriculture from increased bioenergy demand and biospheric carbon management. Organized session at Planet under Pressure 2012 Conference, London, 26-29 Mar 2012.
50. Poster (S. Ostberg, D. Gerten, S. Schaphoff et al.): Probability of severe ecosystem change under different temperature targets. Conference: Planet Under Pressure, 26–29 Mar 2012, London (UK).
51. K.M. Hiscock. “Linking Groundwater and Climate: Learning from the Past and Looking to the Future”. Water Futures Conference, Geological Society of London, London, 6-7 March 2012.
52. Talk (A. Popp): Bioenergy costs and potentials with special attention to implications for the land system. AGU Fall Meeting , 5–9 Dec 2011, San Francisco (USA).
53. Talk (D. Gerten): Ways toward more integral water scarcity studies. Summer School: Water resources and the Water Cycle in a Changing World, 4–8 Jul 2011, Oxford (UK).
54. Talk (D. Gerten): Water availability and scarcity: now and future trends. Workshop: Water Management Options in a Globalised World, 20–23 Jun 2011, Schönbrunn (AU).
55. Phil Holden at al. Invited talk: “Emulation and probabilistic climate predictions”, European Geophysical Union, Vienna, 3-8 April 2011.
56. R. Warren. Climate Change and Land Use Change in the Community Integrated Assessment System, CIAS. Seminar at Brown University, USA, 15 March 2011.
57. Talk (D. Gerten et al.): Estimating green-blue water availability and needs for global food production. Conference: The Global Dimensions of Change in River Basins. 6–8 Dec 2010, Bonn (D).

Press releases and interviews

9/1/14 Press release (N. Edwards) Saving coastlines from flooding is an uncertain science, http://theconversation.com/saving-coastlines-from-flooding-is-an-uncertain-science-21825

28/11/13 Press release (N. Edwards) New model framework links the impacts and economics of climate change. http://www.open.ac.uk/research/main/node/751

16/10/13 Klimawandel heißt Wassermangel, Neues Deutschland, interview with D. Gerten, https://www.neues-deutschland.de/artikel/836067.klimawandel-heisst-wassermangel.html

13/09/13 “Water scarcity and biodiversity under threat as temperatures warm”, press release by PIK, http://environmentalresearchweb.org/cws/article/news/54636

13/09/13 Klimawandel bedroht Wasserversorgung vieler Menschen, Die Welt, http://www.welt.de/newsticker/news1/article119976594/Klimawandel-bedroht-

Wasserversorgung-vieler-Menschen.html

13/09/13 "Goal to cap temperature rise will still leave hundreds of millions thirsty", ClimateWire, interview with D. Gerten, http://www.eenews.net/stories/1059987178

12/09/13 "Current pledges put over 600 million people at risk of higher water scarcity", press release by IOP, http://www.eurekalert.org/pub_releases/2013-09/iop-cpp091113.php

12/04/13 "Permafrost regions: from carbon sink to source by 2100", Environmental Research Web, interview with D. Gerten, http://environmentalresearchweb.org/cws/article/news/53024

16-17/07/12 Meeting between OU and UEA with 2 stakeholders (S. Smith and R. Standring)

21/06/12 "Tackling climate change", Audio Podcast

(https://itunes.apple.com/gb/itunes-u/rio+20-united-nations-conference/id538502636?mt=10)

13/02/12 "World's water footprint linked to free trade", Nature News Blog (interview with D. Gerten), http://blogs.nature.com/news/2012/02/world%E2%80%99s-water-footprint-linked-to-free-trade.html

22/11/11 "Growing world trade makes food production cheaper – at the expense of the environment", press release by PIK, http://www.pik-potsdam.de/news/press-releases/archive/2011/growing-world-trade-makes-food-production-cheaper-2013-at-the-expense-of-the-environment

01/11/11 "Africa has highest risk of ecosystem change", feature in Environmental Research Web, http://environmentalresearchweb.org/cws/article/news/47686

07/10/11 "Climate change: a risk for plants and animals worldwide", press release by PIK, http://www.pik-potsdam.de/news/press-releases/archive/2011/klimawandel-weltweites-risiko-fuer-tiere-und-pflanzen

18/08/11 "Energy from biomass pays even with forest protection in the long term", http://www.pik-potsdam.de/news/press-releases/archive/2011/Energy%20from%20biomass

17/08/11: "Bioenergy could be big player by 2100", feature in Environmental Research Web, http://environmentalresearchweb.org/cws/article/news/46891 29

Other dissemination activities

- 30/05/12- Contribution, written by several ERMITAGE partners, to a talk by Patricia Reilly's (DG Res. Commissioner's team) at Globe EU Event on Resource Efficiency Europe: Promoting Cascading Use of Biomass, as requested by the project officer Olivia Chassais.
- 21/05/12, London School of Economics (LSE), London- The project manager, B. Pizzileo and another scientific investigator from OU, Phil Holden, attended the event "Evaluating the Impacts of Climate Change research".
- 27/04/12- Contribution, written by several ERMITAGE partners, to "A selection of EU success stories", as requested by the project officer Olivia Chassais.
- 19-20/04/12, Luxembourg - The project manager B. Pizzileo participated, as part of the DG Research delegation, at the EC initiative, monitored by Eurostat, "Sustainable Development Indicators Working Group". This was encouraged by ERMITAGE project officer, Olivia Chassais, who represents the DG "Research and Innovation".

The event involved European Commission DGs, agencies and international organisations as well as EU Member States, EFTA and candidate Countries.

- 14/09/11, London- The coordinator N. Edwards presented the project at the PURE dissemination and brokerage event (https://connect.innovateuk.org/web/pure)

ERMITAGE website:
http://ermitage.cs.man.ac.uk/

ERMITAGE YouTube Channel:
http://www.youtube.com/ERMITAGE2010

A tally of 32 videos produced!

ERMITAGE Twitter:
https://twitter.com/ERMITAGE_FP7

Month 23th - Progress update:
http://ermitage.cs.man.ac.uk/sites/default/files/Progress_update_M23.pdf

ERMITAGE - Enhancing Robustness and Model Integration for the Assessment of Global Environment Change

Month 23 - progress update

Month 25th – Brochure:
http://ermitage.cs.man.ac.uk/sites/default/files/ERMITAGE_Brochure.pdf

Month 36th - Final brochure:
(http://ermitage.cs.man.ac.uk/sites/default/files/ERMITAGE_Final_brochure.pdf)