CS/01

ASTER - Results

Assessment of modelling uncertainties in long-term climate and sea-level change projections

DURATION OF THE PROJECT
15/12/2005 - 30/06/2010

BUDGET
1.149.995 €

KEYWORDS
Uncertainty on climate change, future climate change, sea level change, ice sheet modelling, ocean circulation, carbon cycle.

CONTEXT

Climate change represents one of the greatest environmental, social and economic threats that the planet is facing. The warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level (IPCC, 2007). However, the range of possible future climate change in model projections remains large, mostly because of several sources of uncertainty. A large unknown is how the human activities and, subsequently, the emission of greenhouse gases will evolve in the future. Large uncertainties also arise from the design of the climate models themselves. For example, choice in the approximations and parameterisations must be decided. Another source of uncertainty comes from the physical parameters, which are not perfectly known. As a consequence, policymakers and decision-makers are facing a large range of possible future climate change. Efforts are made to reduce this range or to point towards the most likely realisation.

OBJECTIVES

We used LOVECLIM, an Earth system model of intermediate complexity to perform simulations of the Holocene, the last millennium and the third millennium climates, as well as sensitivity experiments to identify the behaviour of the model under increased greenhouse gas concentrations and freshwater hosing. Moreover, we identified several parameter sets that yield different responses of the LOVECLIM model to a scenario of doubling of CO_2 concentration and to freshwater hosing, although the simulated present-day climate remains within the range of observations. The parameter values were chosen within their range of uncertainty. There are nine “climatic” parameter sets, three “carbon cycle” parameter sets and three “ice sheet” parameter sets. Past and future climate simulations were performed with all or a subset of these 81 combinations of parameter sets. The model was run either with fixed-prescribed ice sheets or with an interactively coupled Greenland and Antarctic ice sheet model. Simulations of past climates were conducted in order to identify the subset of parameter sets that allow the best reproduction of observations and reconstructions. Simulations of future climate change then provided a range of model responses that were validated against past climate changes.

CONCLUSIONS

Several improvements have been made to LOVECLIM in the course of the project. The land surface scheme has been adapted to better represent the impact of vegetation on climate change. The bucket depth is now dependent on the vegetation, which has a direct impact on the runoff and soil water availability. Consequently, the transpiration is computed separately for each vegetation type. Moreover, a canopy resistance term has been added, which depends on incident solar radiation, atmospheric humidity and leaf area index. This refined parameterisation induces significant changes in vegetation: e.g., forest area increases over Western Europe and most of North America at the expense of grass and desert extends over most of North Africa and also over Eastern Europe.

When coupling LOCH[1] to CLIO[2] , it appeared that the uptake of anthropogenic CO2 was much too large. The semi-implicit scheme for the computation of the Coriolis term in the equation of motion was then replaced by a totally implicit scheme in order to solve that problem.

The biological module of LOCH has been modified to incorporate a silica dissolution scheme with temperature-dependent rate and depth control. Furthermore, the equation ruling the biomass pool, which export production depends on, includes now a 3-D transport term and allows to consider up to three phytoplankton groups, characterized by their own growth and grazing rates. Finally, the atmospheric module of LOCH now allows for a prognostic computation of carbon isotopes in the atmosphere and the fractionation during soft tissues formation is parameterised to be inversely related to dissolved CO2 concentration.

The Northern Hemisphere Ice Sheet Model (NHISM) has been interactively coupled to LOVECLIM. NHISM is a three-dimensional thermomechanical ice sheet model that includes an improved scheme for marine calving to better simulate ice sheet expansion and contraction over the shallow marine shelf basins surrounding the Arctic Ocean. In addition, a novel hydrological runoff model was devised to route the meltwater from the ice sheets to the appropriate CLIO oceanic grid boxes.

The scheme transports meltwater through the contemporary lake and river system, taking into account isostatic changes of the surface topography, ice-dammed lakes and changes in lake storage.

[1] LOCH is the oceanic carbon cycle component of LOVECLIM.
[2] CLIO is the ice-ocean component of LOVECLIM.

With this new model, the global ice sheets and the climate were simulated during the last deglaciation between the Last Glacial Maximum (LGM) at 21 kyr BP and the beginning of the Holocene at 10 kyr BP. The experiment had prescribed ice sheet configurations and freshwater fluxes from an off-line precursor experiment with NHISM forced by ECBilt[3] -CLIO. It was found that large peaks of continental fresh water released in the Arctic and North Atlantic Oceans at around 17 kyr BP and 14 kyr BP could generate important reductions of the oceanic meridional overturning circulation with ensuing local and global cooling of the climate.
Those improvements had led to making available, for both the project and the scientific community, a new version of the model (LOVECLIM1.2, http://www.climate.be/loveclim).

In order to investigate the parameter uncertainty in LOVECLIM, we varied values of key physical parameters in order to estimate the range of model response for standard sensitivity experiments, to assess the ability of the model to simulate past climates according to the parameter sets and to compute the range of response for climate projections.

More specifically, we selected nine "climatic" parameter sets, three "carbon cycle" parameter sets and three "ice sheets" parameter sets because they yield present-day climate simulations coherent with observations. For the 81 combinations of the parameter sets, we measured the increase in global annual mean surface temperature after 1000 years in a sensitivity experiment in which the atmospheric CO2 concentration increased by 1% per year from the pre-industrial value until a doubled value was reached and was subsequently held constant (used as an estimate of the climate sensitivity) and the percentage of decrease in the maximum value of the meridional overturning streamfunction below the Ekman layer in the Atlantic Ocean (MOC) after 1000 years in a water hosing experiment in which freshwater is added in the North Atlantic (20°-50°N) with a linearly increasing rate of 2□10-4 Sv/yr (used as an estimate of the MOC sensitivity to a freshwater perturbation). Sensitivity to doubling of CO2 concentration ranges from 1.6 to 3.8°C and MOC is reduced by 15 to 75% in the freshwater flux experiments in ECBilt-Clio-VECODE[4] stand-alone (ECV) experiments. In most cases, sensitivities do not exhibit significant changes after the coupling with the carbon cycle model. However, some departure from the values obtained in ECV experiments is shown for the largest climate sensitivity. The reason may be found in different initial conditions; indeed, experiments with interactive carbon cycle departed from the equilibrium state of the corresponding experiment without any carbon cycle. Those various initial states probably explain the large difference in MOC streamfunction reduction with parameter set 51. Furthermore, in fully coupled (LOVECLIM) experiments that considered doubled CO2 concentrations and/or freshwater hosing of magnitude 0.1-0.2 Sv, we found a significant reduction of the climate sensitivity at the millennial time scale due to the effect of additional freshwater fluxes from the ice sheets. The meltwater induces MOC weakening in the Northern Hemisphere and, subsequently, a local relative cooling, which is amplified by sea ice related feedbacks. A similar mechanism operates in the Southern Hemisphere, but is found to be of smaller magnitude. This mitigation effect increases with ice sheet sensitivity and with the initial climate sensitivity of LOVECLIM itself. It is therefore suggested that it is of great importance to include dynamic ice sheets into global Earth system models.

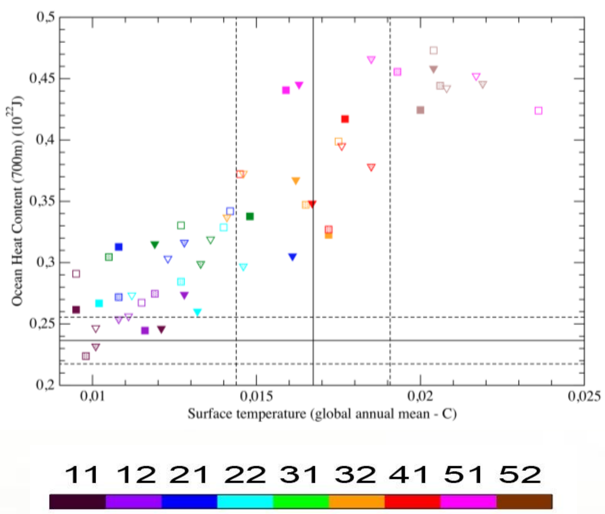

Figure 1: Trend in oceanic heat content in the upper 700 m (1022 J.yr-1) (1950 – 2003 AD) wrt trend in global annual mean surface temperature (°C.yr-1) (1979 – 2005 AD). Each dot represents one simulation. Trends are computed as the slope of the regression line through the annual values. Each colour corresponds to one climatic parameter set. Squares (triangles down) correspond to Efor (Conc) simulations; symbols are for carbon cycle parameter sets (1: full; 2: semi-empty; 3: empty) (see description of the parameter sets and of the experiments in the main part of the report). The full black line represents the trend computed from observation (Levitus et al. (2009) for the heat content and Brohan et al. (2006) for surface temperature). The dashed lines represent the uncertainty related with the variability in the data (one standard deviation).

The analysis of global variables representative of the last millennium climate displays relatively similar results for all the parameter sets and thus did not allow us to select among them the most appropriate one for simulating climate over that time interval. Therefore, we rather focused on the last century. Moreover, we concentrated on global scale model features and on the model ability to reproduce the trend in selected variables over the last few decades. Simulations with the carbon cycle parameter set 3 do not properly reproduce the observed atmospheric CO2 increase although it does not prevent a reasonable temperature increase.

[3] ECBilt is the atmospheric component of LOVECLIM
[4] VECODE is the vegetation and continental carbon cycle component of LOVECLIM

Moreover, no parameter set allows the model simulating simultaneously a correct time evolution of ocean heat content in the upper 700 m, and of Northern Hemisphere sea ice extent or of annual mean surface temperature (Figure 1). This drawback should be investigated in further studies. Generally speaking, simulations with high climate sensitivity have a better global score than simulations with low climate sensitivity. Amongst the best simulations, parameter set 321 performs well for both setup (prognostic or diagnostic CO2 concentration) and both sulphate aerosol forcing reconstructions considered in our study. Moreover, other parameter sets (322, 511, 512) also display good performance for both setups and for at least one of the sulphate aerosol forcing.

Five parameter sets (112, 212, 312, 412 and 512) were used in transient simulations of the Holocene climate (from 8 kyr BP to 2000 AD). Compared to observations covering the second half of the 20th century, parameter sets 112 and 212 lead to a serious underestimation of the decline in summer Arctic sea ice extent, while parameter set 312 yields only a slight underestimation. Moreover, the model results for the parameter set 512 are in disagreement with the very few reconstructions of the summer Arctic sea ice extent during the early Holocene. However, the agreement with the PMIP2 simulated global pattern of summer temperatures during the mid-Holocene (Braconnot et al., 2007) seems to be the best with parameter set 21. Some equilibrium simulations of the LGM climate were also performed. Only the parameter sets leading to low climate sensitivity (i.e. 11, 12, 21, 22) yield reasonable results. The LGM cooling in high latitudes is too strong for the high climate sensitivity parameter sets[5]. This is a direct consequence of the relatively high polar amplification simulated by LOVECLIM. These results clearly illustrate the difficulty to identify a parameter set that would properly simulate strongly different climates such as the LGM or Holocene one, and the global warming of the last century.

Therefore, in the simulations of future climate, we continued to use several (or all) parameter sets, even if some should be dismissed for their poor ability to simulate climate over one of the past periods considered in this study. Several simulations over the third millennium were performed with LOVECLIM, with the different parameter sets, using SRES greenhouse gas scenarios (B1, A2, A1B) until 2100 AD and greenhouse gas concentrations maintained at their levels as in 2100 AD until the year 3000 AD. According to these simulations, the global mean temperature increases by 1.7 to 3.2°C after 1000 years for scenario A1B with medium carbon and ice sheet sensitivities, depending on the climate sensitivity (Figure 2).

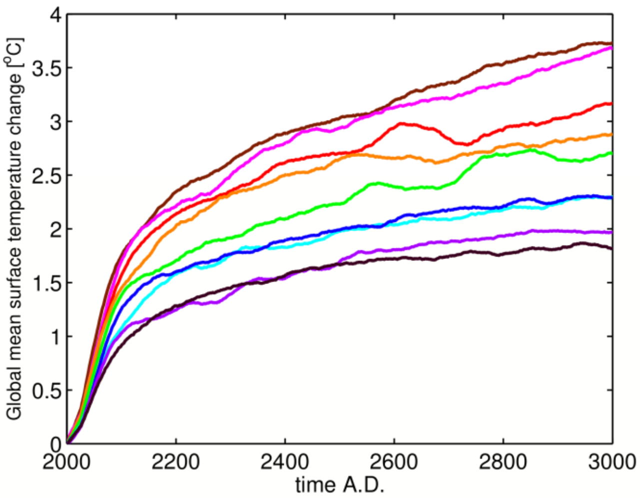

Figure 2: Global mean temperature changes during the third millennium for scenario A1B. Each colour corresponds to one climatic parameter set. Only medium carbon cycle and ice sheet parameter sets (2) are shown.

A large range of ice sheet, glacier, and sea level projections were then performed focusing in particular on the 21st century and the third millennium. The ensemble approach samples the range of uncertainties inherent in crucial ice sheet model parameterisations for basal sliding, flow enhancement, surface ablation and basal melting below Antarctic ice shelves. This is complementary to the usual approach to run model experiments for a wide range of forcing scenarios that were restricted to (prolonged) SRES scenarios B1, A1B and A2. In these experiments, the Greenland ice sheet was found to lose between 15 % (scenario B1, low climate and ice sheet sensitivities) and 95% (scenario A2, high climate and ice sheet sensitivities) of its mass after 1000 years of climate warming (Figure 3). Almost all of the melting occurs by surface ablation, whereas iceberg calving quickly decreases as the ice sheet recedes from the coast. For Antarctica, volume changes varied between slight growth for a low scenario and low climate and ice sheet sensitivities, and a volume loss corresponding to a 6 m sea level rise for the high scenario and high model sensitivities after 1000 years (Figure 3). On the millennial time scale, changes in the Antarctic ice sheet are mainly driven by changes in accumulation and ice shelf melt, with a significant contribution from marginal ablation for the experiments producing the largest warming. For all scenarios and all model sensitivities, virtually all of the ice contained in mountain glaciers and small ice caps has disappeared after 1000 years of climatic warming (Figure 3). For the same range of experiments, sea level rise from oceanic thermal expansion was found to vary between 0.6 and 4 m (Figure 3). We conclude from these experiments that a global eustatic sea level rise of at least 2 m is very likely to occur before the end of the third millennium. For scenario A1B and medium ice sheet and climate sensitivities, the value is ~9 m (Figure 3). The upper bound in excess of 20 m is however considered very unlikely to occur, in part because of the large polar amplification in LOVECLIM.

[5] See the main part of the report for a detailed description of the parameter sets

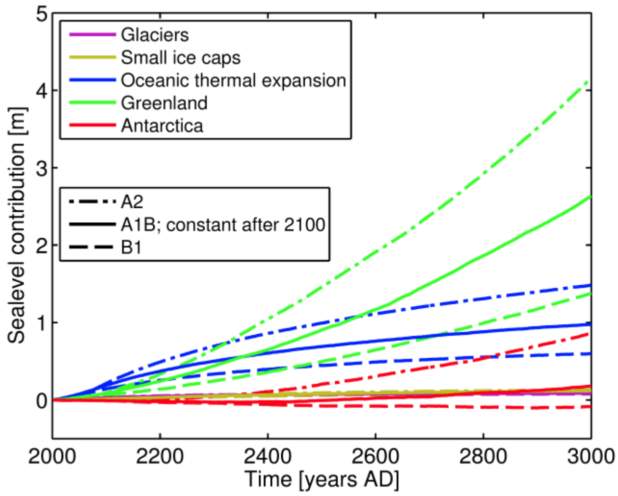

Figure 3: Global sea level contributions from different components for prolonged SRES scenarios B1, A1B and A2. These experiments considered medium ice sheet and low climate sensitivities.

CONTRIBUTION OF THE PROJECT TO A SUSTAINABLE DEVELOPMENT POLICY

The work made under ASTER is a contribution to the ongoing international scientific effort to better understand climate change and to quantify more accurately the uncertainties related with climate and sea level projections. This is needed in order to provide a sound basis for policies designed to address the challenge of climate change. Identifying and reducing the uncertainties is deeply in line with the recommendation of the scientific community for the coming years, in particular for next IPCC assessment report. Therefore, work performed under ASTER is expected to be included into IPCC AR5.

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www.climate.be/ASTER/

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