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INTEGRATED ASSESSMENT OF CHANGES IN THE THERMOHALINE CIRCULATION – INTEGRATION

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Summary

The aim of the INTEGRATION project is to study the effects of a weakened thermohaline circulation (THC) in the North Atlantic on various ecosystems in the European region as well as on economy and society. Two scenarios are investigated: a moderate weakening and a complete breakdown of the THC. Preliminary scenario simulations with the Climber-2 model suggest that the latter could lead to a cooling by several degrees localised over the northern Atlantic region. These two climate scenarios are downscaled in order to drive several impact models.

Initial results of the phytoplankton model show a small direct effect of sea surface temperature on primary production, while that of changes in mixed layer depth and CO_2 could be larger. The main effect of THC changes is expected to be through changes in nutrient supply.

Cod stocks in the Barents Sea will most likely be negatively affected, both due to the local cooling and the decreased advection of copepods, an important prey. Simulations with a bio-economic fishery model show almost entirely negative consequences, with greatest economic losses for trawl fishery.

In agriculture, the cultivation zone for wheat shifts northwards with global warming; this movement will be reversed by a THC breakdown. In a global vegetation model, the tendency of soils to be a net carbon sink during global warming is reversed, so that in the breakdown scenario they temporarily become a net carbon source.

Future greenhouse gas emission scenarios that avoid a THC breakdown and are at the same time economically viable span a wide range, which is however subject to large uncertainty. The analysis of parameter uncertainty is carried out through modelling and by an elicitation of experts' opinion. The dialogue with stakeholders revealed the importance of risk communication, especially with respect to the long time scale of oceanic circulation changes.

These early and preliminary results demonstrate that the range of tools and models and their interfaces is now operational and the project is shaping up well to a coherent whole. Development continues on many aspects of the models, and we expect to succeed with the final integrated assessment according to plan.

Aim of the research in the framework of DEKLIM

The topic of abrupt climate change has gained strongly increasing scientific, political and public attention in the past few years. While the early discussion about global warming and its impacts and consequences has focussed on ”best guess” scenarios, i.e. the most probable outcome of greenhouse gas emissions, it has now been recognised that ”low probability / high impact” risks are an important and policy-relevant aspect of climate change. This is reflected in the recent launch of major research funding networks on this field in several countries, among them DEKLIM. INTEGRATION focuses on one specific low probability/high impact risk: the possibility of a major ocean circulation change in the Atlantic. While this risk is much discussed, there is thus far very little scientific information on the impacts of such an event.

The objective of this study is to investigate the risks of two types of ocean circulation change: (1) A substantial weakening of the Atlantic thermohaline circulation (THC) by 20-50%, involving a reduced North Atlantic Current and associated heat transports, as simulated by most climate models for the coming 50-100 years. (2) A (practically irreversible) complete shutdown of convection and the THC, as simulated in some ”pessimistic” model scenarios for the 22nd century (Rahmstorf and Ganopolski, 1999).

It is not our objective to investigate the causes and mechanisms of such circulation changes, but rather the risks they engender. Since very little is known about the impacts of such changes at the European scale (see, however, recent summaries by the IPCC), the first objective of the study is to collect and evaluate basic information on possible consequences for marine and terrestrial ecosystems and society at large. This is done both by expert elicitation and dedicated modelling. The second objective is to perform an integrated assessment according to a coherent methodology. For this purpose, we have involved relevant stakeholders from the start of the research and combine their points of view with expertise from various disciplines (such as climatology, oceanography, marine biology, fisheries, forest ecology, agriculture, economics, sociology) so as to clarify the risks we are faced with. In this way we are developing an approach that can serve as a model for future integrated assessments on other aspects and scenarios of climate change.

The proposal responds to point 2.C of the DEKLIM objectives (Climate impact research), especially to the topics ”climatic sensitivity of ecosystems and socio-economic systems” and ”climate-related resilience and governance research”. In accordance with section 1 (”Zuwendungszweck”) it seeks to investigate climate instabilities, especially abrupt climate changes (link to point 2.A and 2.D), to identify related critical thresholds and impact-related stress constraints and to evaluate them in an integrated and interdisciplinary manner. The integration method applied – the tolerable windows approach – is capable of taking into account socio-economic information about possible impacts as well as consequences of mitigation measures. Non-quantifiable expert knowledge facilitates the normative but nevertheless educated definition of climate-related guardrails which can be used by policy-makers involved in climate negotiations. The project especially contributes information to the assessments of the IPCC. While scientific journal publications are the primary goal, the results will constitute a knowledge base that supports decision makers in the difficult choices they will face in the negotiations to prepare the second and subsequent commitment periods of the Kyoto Protocol.

The project investigates three topics:

- The possible effects of oceanic circulation changes in the North Atlantic – and of the climate changes which trigger these oceanic processes – on two impact chains. The first chain runs from oceanic circulation to plankton to fish to the economy, the second one from oceanic circulation to climate change over Europe to terrestrial ecosystems to the economy and to society at large. We perform these analyses by employing deterministic models for various elements – oceanic circulation, phytoplankton, zooplankton, fish, regional climate, agriculture, forestry, unmanaged ecosystems, relevant economic sectors – that are based on empirical data and theoretical reasoning.

- The uncertainties involved in these impact chains. They come in four kinds: uncertainty about model parameters, uncertainty about model structures, uncertainty about model coupling and uncertainty about knowledge claims other than models. We are using state-of-the-art methods to deal with them, like Latin-hypercube sampling or expert elicitations.
- The integration of knowledge about the various phenomena and processes involved – including knowledge about relevant uncertainties – in a comprehensive assessment. We investigate the possible arguments for setting specific thresholds of acceptable vs. unacceptable risks with regard to the future of the North Atlantic ocean circulation, explore which corridors of greenhouse gas emissions are tolerable for different thresholds, and identify major implications of these corridors for energy use and for policy-making. In addition, the overall monetary impact of THC changes is estimated. The dialogue with stakeholders is essential to gauge their risk aversion and to communicate and discuss the findings of INTEGRATION.

Recent and completed activities, principal results and planned activities

Two strong conceptual brackets link the individual thematic fields: the data exchange between the models, and the integrated assessment. The interfaces for driving the impact models with climate scenarios, as well as for driving one impact model with the data from another, have been defined and tested with the Climber-2 scenarios. The model overview table (see appendix) displays all models and their interfaces. The integrated assessment has the function of vertically integrating the single impact analyses, from the physical to the biological to the socio-economic impacts, including mitigation strategies and uncertainty analysis. Preliminary results from the individual fields, as well as the planned activities, are described in the following subsections.

Climate scenarios and downscaling

The two impact chains are fed by scenarios of future climate development from various climate models, comprising earth system models of intermediate complexity (EMICs) as well as fully coupled general circulation models (GCMs). The EMICs used are Climber-2 and Climber-3α; ECBilt-Clio, GFDL, and ECHAM5/MPI-OM1 are the employed GCMs. From Climber-2, two scenarios are available and have already been used by different impact modules. These two scenarios are documented in Rahmstorf and Ganopolski (1999). Both depicting the global climate development from 1800 to 2300, they differ in the value of one parameter that is particularly uncertain in most climate models: the hydrological sensitivity. While the standard scenario shows a gradual decline and subsequent recovery of the THC, the other one, with an enhanced hydrological sensitivity (EHS) leads to a total breakdown of the THC, with a substantial cooling in the North Atlantic region after 2150. The scenario data are used to directly drive some of the impact models (phytoplankton, economic impacts), while for other impact models a downscaling is performed.

Scenarios with Climer-3α will be computed as soon as plausible scenarios for the greenhouse gas (GHG) emissions after 2100 are available. We will use equilibrium emission scenarios that are under development at the ETH Zürich.

Downscaling is normally applied to general circulation models (GCMs). We have extended the technique to EMICS by formulating an approach that empirically links some core Climber-2 variables, as observed in the North Atlantic / European sector, with another group of observed high-resolution fields relevant for European agriculture. For the former, we chose appropriate fields from the NCEP reanalysis data set, adjusted to the Climber-2 grid. For the latter, we chose the 0.5°-grid of monthly climate time series compiled by the Climate Research Unit (CRU).

After the downscaling model had been “trained” on the NCEP/CRU combination it was employed to downscale the Climber-2 output. This created a dataset on a high-resolution (0.5° x 0.5°) grid that gives a meteorological development (thermal and hydrological variables, cloudiness) consistent with the Climber-2 scenarios.

The marine impact chain

Plankton

In order to estimate impacts of circulation changes on the marine food chain, one needs to model the development of phytoplankton within a marine environment. The variable availability of nutrients, expressed in their stoichiometric ratios (carbon:nitrogen:phosphoros - C:N:P), influences phytoplankton growth and algal succession. Two model versions are used to evaluate the climatic impact on the development of phytoplankton and the associated biogeochemical fluxes. One model version has been developed in order to better decouple C- from N-fluxes within a marine ecosystem (Schartau et al., 2003). This model is specified as C:N-Regulated Ecosystem Model (CN-REcoM). A second version deals with the succession of diatoms (silicifying algae) and coccolithophores (calcifying algae). This particular model version is named REcoM&Co (‘Co‘ = coccolithophores; Schartau et al., 2002). In the course of several model runs, the basic version of REcoM&Co has been further modified and improved.

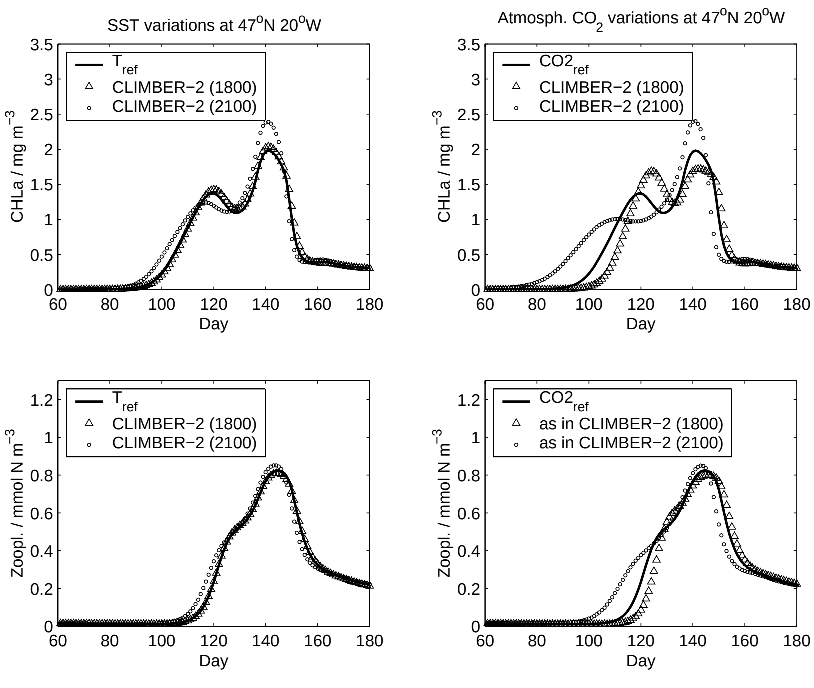

Fig. 1: Response of modeled phytoplankton (Chlorophyll_a, CHLa) and zooplankton biomass in CN-RecoM to Climber-2 temperature variations (SST) and changes in atmospheric CO_2 concentrations at the JGOFS time-series station NABE-47 (47°N, 20°W). T_{ref} / $CO2_{ref}$ = reference values from year 1989 (14.6°C, 370 ppmv). Climber-2 SSTs/CO_2 concentrations for the years 1800 and 2100 are 14.1°C, 280 ppmv and 17.1°C, 930 ppmv.

Sensitivity experiments with REcoM&Co were performed with different initial dissolved inorganic N:P ratios. They revealed a high sensitivity to variations in the N:P ratios, which regulated the occurrence of the coccolithophores. As soon as REcoM&Co is ready to be implemented to the recently developed Climber-3α, it is expected that changes in ocean circulation will redistribute N and P with depth, which will eventually have consequences for algal succession.

The CN-REcoM version has been set up for open ocean conditions. Extensive sensitivity analyses for integration periods of several years have been carried out along a meridional N-S transect in the North Atlantic (60°-29°N, 19°W). In order to investigate climatic impacts, we varied mixed layer depth (MLD) and sea surface temperature (SST). It was concluded that the modeled phytoplankton reacts more sensitive to small changes in mixed layer depths than to temperature variations.

Recently we conducted time-slice CN-RecoM experiments with differing boundary conditions for CO_2 and SST (Fig. 1). For CO_2 we used the same concentrations as for the Climber-2 scenarios, and for SST the output from the Climber-2 standard scenario. First results suggest that the sensitivity of CN-REcoM to temperature is less pronounced than to changes in CO_2 concentrations.

Additional efforts are now put towards an implementation scheme that allows a simplified coupling of REcoM versions to MOM/ISIS, the ocean and sea-ice model of Climber-3α. As a precursor to this implementation, a simpler phytoplankton model has already been incorporated into MOM/ISIS. The validation (Fig. 2) gives satisfactory results.

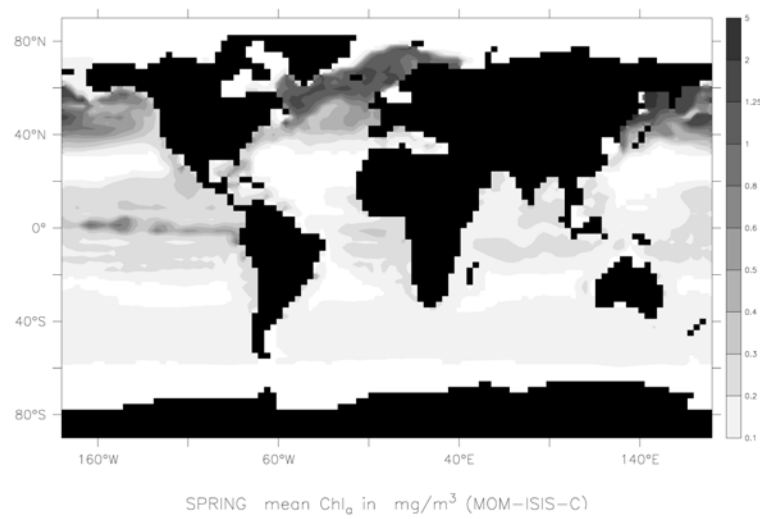

Fig. 2: Mean Chlorophyll_a concentration between April and June simulated by the MOM-ISIS-C model applying a constant Chlorophyll_a : Carbon ratio of 1:50. A pronounced spring bloom of phytoplankton appears in the northern North Atlantic and the subarctic West Pacific. Along the equatorial divergence zone in the Pacific, Chlorophyll_a concentrations show a permanent maximum. The underlying marine ecosystem model is similar to that by Six and Maier-Reimer (1996) save the iron limitation. In contradiction to remote sensing observations, in the Kara and Laptew Seas the excessive sea ice cover simulated by the ISIS model prevents phytoplankton from growing. The overall spring Chlorophyll_a distributions compares well with the SeaWIFS data.

Fish stock

Individual growth of cod larvae and juveniles show functional relationships to biotic and abiotic parameters. In the Nordic Seas ecosystem the prey copepod species *Calanus finmarchicus* is a particularly important component of the biota. The abiotic parameters are ocean climate parameters like advection, temperature, wind-induced turbulence, and light conditions induced by cloud conditions and latitude.

To assess the effects of changes in THC on fish stocks, the effects on the population of the *Calanus finmarchicus* are therefore a key issue, and the temperature as well as the advection are important factors to regulate its production, spatial distribution and habitat extent (Sundby, 2000). Individual-based model (IBM) approaches describing growth and spread of *Calanus* population over many life cycles have been successfully developed at IMR Bergen.

The modelling of spawning grounds and larval drift routes of cod is done with ROMS, a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. A number of substantial improvements within ROMS have been achieved within INTEGRATION (Vikebø et al. 2003a,b). An IBM has been implemented into the larval drift module to simulate how growth and survival are influenced by changes in the ocean climate. The IBM enables us to simulate individual growth of larvae and juveniles from the functional relationships to biotic and abiotic parameters. Preliminary results take into account advection and temperature.

In order to model future distribution and abundance of juvenile fish in scenarios with reduced THC the model must reproduce former years in accordance with measurements. Two different years with distinct western and eastern distribution of 1/2-year old cod were chosen: 1985 and 1986. Monthly mean NAO index for the month of May shows that 1986 had the highest index throughout a 30-year period. High NAO index gives strong south-westerly winds, which cause an enhanced inflow of Atlantic Water (AW) to the Barents Sea and may very well be the reason for the distinct easterly distribution of 1/2-year old cod that year.

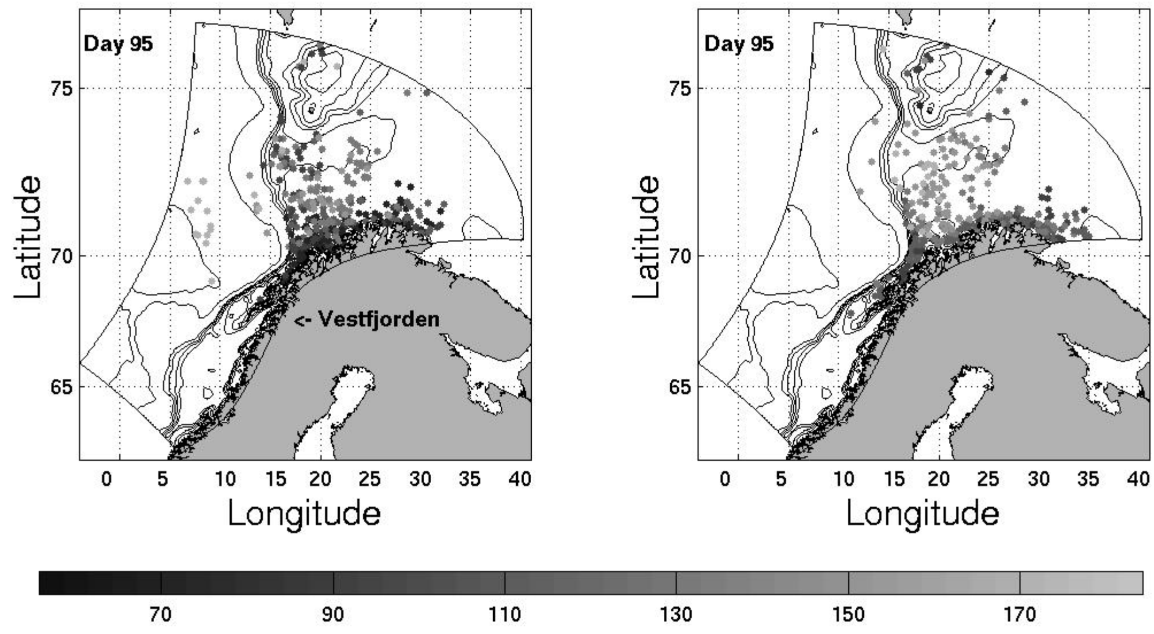

Fig. 3: Individual-based modeling using ROMS, showing the distribution of larvae 3 months after spawning, with atmospheric forcing from 1985 (left) and 1986 (right) and particles released inside and outside the Vestfjorden, the main spawning site. The scale indicates larvae weight in milligram.

Both simulations (Fig. 3) capture the spreading of larvae from the major spawning grounds of the Vestfjorden, the importance of tides at the spawning grounds, the increase of transport time due to complex bank structure at the shelf, bifurcation north-west of Tromsøflaket and inflow of AW in the Bear Island trough and south of the bank structure connected to the Bear Island. Average longitude for the larvae gives a more eastern distribution for 1986 than for 1985 (22.8 compared to 20.7 degrees) and in general a higher weight of the larvae in the western parts of the Barents Sea, consistent with measurements.

Concerning the inflow of AW into the Barents Sea, a situation with a weaker THC is comparable to a low NAO index year, giving a wider NAC which spreads westwards, thereby decreasing the inflow of Calanus-rich AW to the Barents Sea. Temperature in the surrounding waters at the nursery grounds of cod will decrease, resulting in a negative impact on cod growth, and thereby recruitment. A substantial decrease of the THC will also affect the distribution of cod, reducing the north- and eastward extension of the nursery grounds.

Ongoing work is now focused on further development of the IBM, which will calculate transport, distribution, and growth of the fish up to stage 1/2-year old cod. The next steps include an evaluation of the IBM against measurement of 1/2-year old cod as well as running ROMS with THC breakdown scenarios from ECBilt-CLIO.

Marine fisheries

The bio-economic model of fisheries has been set up to comprise the most important economic processes that govern the use of the renewable resource fish, and the general biological processes that influence the population dynamics of the fish stocks. The current version of the model focuses on the marine fisheries of Arcto-Norwegian cod and capelin in the Barents Sea. The cod stock is of great economic importance for the marine fisheries of Norway and Russia. Capelin is exploited commercially as well but is also one of the main food sources for cod. The model considers three different types of fishing fleets, such that the different fleets each have characteristic impacts on the fish stocks.

Depending on the scenario of environmental change, the sizes of the fish stocks are negatively affected. In some cases, the stock sizes are reduced to levels at which an exploitation of the stock is no longer economically viable. This in turn would lead to the breakdown of the marine fisheries in this part of the world. Due to the longer lifespan of cod, any change in population dynamics caused by environmental change is more pronounced than in capelin (for details see Link, 2003, and Link and Tol, 2003).

In the near future, the model is transferred to a new programming environment, which allows for more flexibility in the optimization procedure. In this way it will be possible to address other aspects of economic impacts. It is further planned to include other fish species that are commercially exploited in the North Atlantic, like herring and mackerel. This activity will lead to an assessment of the impact on the entire fishing industry, not just single fisheries.

The use of results from the ROMS model will make it possible to test the plausibility of the scenarios. Also, the individual-based modeling approaches used in Bergen for zooplankton could be extended to fish stocks and fishery.

The terrestrial impact chain

Agriculture

The agro-economic part of INTEGRATION investigates the effects of THC-induced climate change on cultivation and potential yields. Are changes in land use and crop cultivation to be expected? Within this part of the project we decided to collaborate with the International Institute for Applied Systems Analysis (IIASA), and to use their Agro-ecological Zones (AEZ) model. This model is an excellent and internationally utilized tool for projecting future scenarios of agricultural economics.

AEZ identifies crop specific limitations of prevailing climate, soil, terrain resources, and other essential aspects which are relevant to agricultural production under assumed levels of inputs and management conditions. The model is used for the estimation of the maximum potential and attainable crop yields.

A comparison of the agricultural impacts of the downscaled scenario data (standard and EHS) with those of the CRU data showed that the downscaling model works well. First results for winter wheat under high standards of farm input, technology, and management conditions for the time span of 2000 to 2300 show an enhanced wheat yield in northern Europe and markedly reduced yields in southern Europe till 2150 (Fig. 4). After a THC breakdown the northward movement of the cultivation zone is reversed, reflecting the temperature sensitivity of wheat.

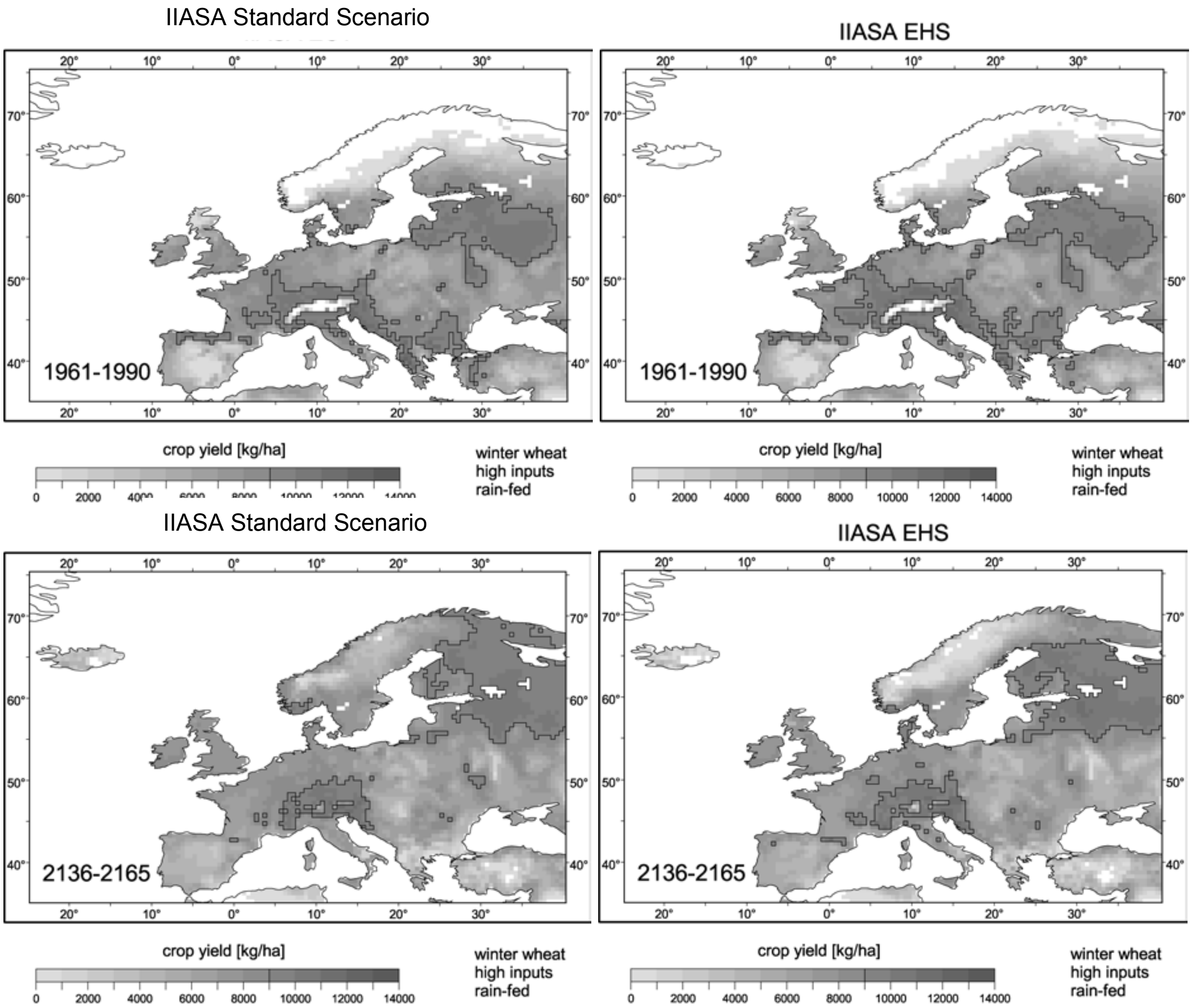

Fig. 4: Yield of winter wheat in the present climate (top row) and around the time of maximum projected atmospheric CO_2 content (bottom row), averaged over thirty years. Regions with a high yield are enclosed by a black line. The standard scenario (left column) has a weakened THC around 2150, while in the EHS scenario (right column) the THC is not far from breakdown (20% of the initial value). In both scenarios the maximum yield regions shift north. The potential yield as depicted here is only limited by temperature, radiation, and precipitation. Soil conditions as a limiting factor will be accounted for in the future.

Future investigations will concentrate on more varieties of crops such as useful plants (potato, rape) and forage plants (silage maize, grass), more detailed analysis under various constraints, inclusion of a soil map, and other aspects like evapotranspiration or length of growing period. Comparisons with other climate scenarios of various GCMs will also be performed.

Forests

Biomass production and frequencies of plant functional types in ecosystems respond to climatic drivers such as radiation, temperature and precipitation. Here, the responses to climate change induced by changes in the THC are studied with the dynamic global vegetation model LPJ (Lund-Potsdam-Jena Model, Sitch et al., 2003). The simulation results serve to evaluate changes in the carbon stocks in ecosystems and changes in the main vegetation systems. LPJ simulations have been performed for the standard and EHS scenario under the change in atmospheric CO_2 concentration as used in the Climber simulations and alternatively at constant present CO_2. In the former case and for the standard scenario the European ecosystems are a net carbon sink during the 21st century due to the CO_2 fertilization effect. This is demonstrated by the simulation with constant atmospheric CO_2 which shows a strong source between 2010 and 2200, while under the dynamic CO_2 scenario the sink turns into a source at the end of the 21st century only. The cumulated sink-strength of European ecosystems is 12.5, 0.3 and 3.9 Gt C in the 21st, 22nd and 23rd century respectively in the standard scenario, with intermittent periods of net carbon release in the 22nd century. For the EHS scenario, net carbon storage during the 21st century is 2 Gt C, followed by a release of 0.3 Gt C in the 22nd century. A strong sink of 15.1 Gt is predicted for the 23rd century when the cooling effect leads to a build up of soil carbon.

In addition to the climate responses of tree species, productivity and species composition in managed forests are modified by forests management operations, as e.g. choice of planted species, thinning operations and choice of rotation length. The interactions of these determinants of forest growth and wood production are studied with the forest growth model 4C (Schaber et al. 1999). In Fennoscandia, where tree growth is mainly limited by thermal conditions, climatic warming will foster growth and wood production and shift the distribution limits of forest tree species northward. A reversal in the temperature trend will induce complex time lagged effects on tree species distribution, growth and soil carbon storage.

The choice of rotation length in response to wood demand on the markets leads to deviations in the age class structure of managed forests from the ideal model of equally sized forested area in the different age classes. The effects of propagation of the current age class structure, which is biased towards younger forests under climate change scenarios including changes in the THC, can be studied with the EFISCEN model.

Uncertainty Analysis

Climber-2 projections may be subject to considerable uncertainty typical of any complex climate model. To study their uncertainty, INTEGRATION and another project hosted at PIK called ”Model Validation and Ignorance Dynamics” (MODIG), have started a close collaboration. MODIG is at present performing a parameter uncertainty study of Climber-2. Its results can be readily utilised by INTEGRATION, and the process of defining common interfaces is under way.

For the AEZ agricultural model, an agreement with IIASA was reached such that the AEZ code will be available for PIK. This allows us to study the effect of Climber-2 uncertainties on AEZ, and on a mid-term perspective AEZ will be fully included into the uncertainty analysis framework developed by MODIG, so as to analyze the parameter uncertainty of AEZ itself.

For analyzing parameter uncertainty in Climber-3α, a different approach needs to be developed, given that the cpu time consumption is about 30 times larger than with Climber-2. A possible technique is to use a tangent model based on a few sample model runs. Some aspects of structural model uncertainty will be studied by analyzing INTEGRATION’s climate model ensemble (both Climber versions plus the three coupled GCMs).

Expert Elicitation

The aim of this work package is to support and complement the model-based uncertainty analysis planned within INTEGRATION by eliciting experts’ subjective probability distributions for uncertain model parameters, variables and outcomes such as the strength of the Atlantic thermohaline circulation (THC) in a specified year. The reason for relying on subjective judgments is that in the case of singular events like a collapse of the THC objective probabilities are not available for many important quantities.

In close cooperation with Granger Morgan (Carnegie Mellon University, Pittsburgh, Pennsylvania) we developed an interview protocol for asking a group of experts to assess the potential impacts of global climate change on the THC. In the design of the protocol, we drew on the experience gained during former elicitations of expert judgments and on the evidence about cognitive heuristics and biases known to operate when people are asked to make judgments under uncertainty. The current version of the protocol consists of five major parts: 1) The operation of the THC under present-day climatic conditions; 2) The effects of future climate change on the THC; 3) The impacts of specific changes in the THC on the climate of the North Atlantic area, sea level rise and oceanic carbon uptake; 4) Research needs and priorities in the field of oceanography and climatology; and 5) The inherent predictability of the THC and the feasibility of an early warning system.

As interviewees, we selected a group of a dozen experts in the field of oceanography. The next step will consist in testing the interview protocol with experts in the field (not the final interviewees), running the full-scale interviews and evaluating the results. The interviews will be conducted in early 2004.

Risk assessment

A stakeholder workshop was held to discuss the stakeholders' perception of the risks of low probability / high impact climatic changes such as a breakdown of the THC. Stakeholders present represented, among others, the UK Climate Impacts Programme, the Icelandic Environmental and Food Agency, and the Danish Ministry of Environment and Energy.

The discussions showed that two aspects specific for this type of risk are particularly problematic. The first is the question of probability. The media tend to either exaggerate a risk (falsely claiming that a collapse of the THC is highly likely), or dismiss it altogether (on the grounds that it is unlikely anyway). It can be difficult to communicate to the public and policymakers that a risk may require serious consideration even if the probability is low – a situation similar to, e.g., the risk of a nuclear accident. Hence, communication of the type of the risk – which differs from other risks that come with anthropogenic warming, e.g. the risk of higher temperature extremes in cities, etc. – is important. One aspect of this is the fact that the probability is not only (probably) low, but also highly uncertain.

A second aspect of the risk is the long time scale involved. Our actions now may in their consequence trigger a THC collapse in a hundred years from now. Most stakeholders are concerned with shorter time scales, i.e. climatic impacts that can already be felt in the next few decades.

Our project will help to clarify both the time scales involved and the uncertainties and probabilities, and will in its publications aim to communicate these aspects in a widely understandable form.

Integrated assessment

Reduced-form THC box model and corridor calculations

We developed a reduced-form model of the THC suited for the inclusion into optimizing integrated assessment frameworks such as the Tolerable Windows Approach (TWA), which are particularly demanding in terms of computational efficiency. The model is a four-box model of the Atlantic, similar to that described in Rahmstorf (1996, Clim. Dyn.). Although highly simplified compared to the comprehensive, coupled ocean-atmosphere circulation models, the box model has proven to be able to reproduce key features of their transient behavior (for a detailed discussion see Zickfeld et al. 2003).

For the calculation of the emission corridors we coupled the THC box model to a reduced-form climate model, the so-called ICLIPS climate model. The emissions corridors were then derived along the methodological lines of the TWA as described in Zickfeld and Bruckner (2003a). The boundaries of the so-obtained corridors demarcate CO_2 emissions limits for the 21^{st} century beyond which either THC changes exceed x% reduction or the mitigation burden becomes economically intolerable. Up to now, the socio-economically motivated guardrails are cast in the form of constraints on the emissions.

Results obtained within our integrated assessment framework indicate that uncertainties in the physical parameters and the guard-rails translate into large uncertainties in the range of allowable CO_2 emissions (Zickfeld und Bruckner 2003a,b). If probability distribution functions (PDFs) can be attached to the uncertain model quantities, it is possible to calculate emissions corridors obeying the guardrails with a given probability, as demonstrated in Fig. 5.

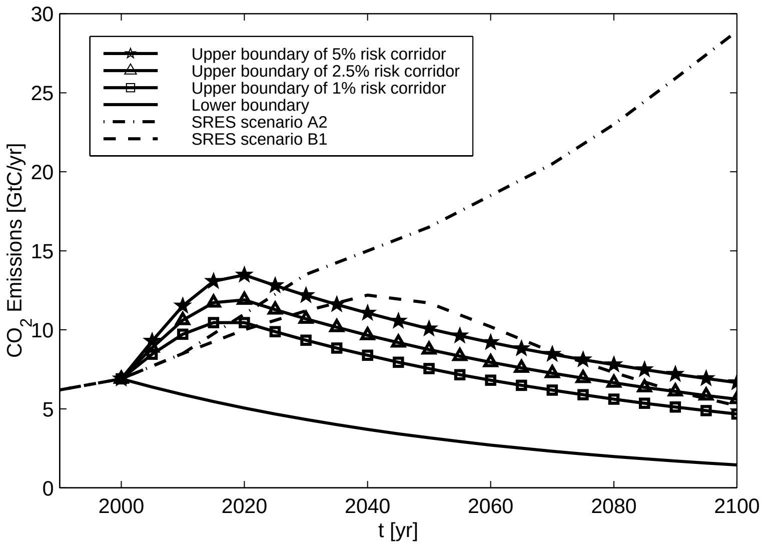

Fig. 5: Emissions corridors avoiding a complete collapse of the THC with a given probability. The corridors were calculated for different values of the climate sensitivity (i.e., 7.7 °C, 8.5 °C, 9.4 °C), corresponding to the 95, 97.5, 99 percentile of the PDF for climate sensitivity determined by Forest et al. (2002, Science 295). Note that any emissions path leaving the x% risk corridor would lead to a collapse of the THC with a probability greater than x%.

It is planned to include an integrated energy-economy model that will enable stakeholders to specify guardrails in domains that may be more meaningful to them, such as greenhouse gas mitigation costs. Also, the inclusion of a model of the energy-economy sector will allow one to explore different policy instruments (e.g., carbon taxes) leading to the compliance with the predefined constraints.

Overall economic impacts of a shutdown of the thermohaline circulation

The general economic impacts of a THC weakening or breakdown are assessed by using FUND, an integrated assessment model including impacts of climate change on agriculture, forestry, coastal zones, malaria, dengue fever, schistosomiasis, cardiovascular disorders, respiratory disorders, energy consumption, water resources, and unmanaged ecosystems. We are working to add diarrhea, amenity and international tourism. The model operates with 16 world regions, one of which is Western Europe. The model can, in principle, handle any scenario of climate change, including ones with a shutdown of the thermohaline circulation. The current version of the FUND model is ready for use in INTEGRATION. Work has commenced to translate the Climber grid to the FUND regions.

Cooperation within DEKLIM and with other programmes

Due to its interdisciplinary nature, INTEGRATION has established close links with projects from various research fields.

For the climate scenarios, there are collaborations with the MPI in Hamburg, the KNMI in the Netherlands, GFDL at Princeton and the ETH Zürich.

The most important links for the phytoplankton modeling within INTEGRATION are: TOPAZ, Towards an Operational Prediction system for the North Atlantic European coastal Zone (EU-5th framework project); CODENET, Coccolithophorid evolutionary biodiversity and ecology network (EC TMR Research Network, 1998-2001); and the Dynamic Green Ocean Project, Corinne le Qéré (MPI for Biogeochemistry, Jena). The work on fish stocks will benefit and contribute to a number of projects funded by the Norwegian Research Council: ECOBE, Effects of North Atlantic Climate Variability on the Barents Sea Ecosystem; ADAPT, Adaption to the Ecosystem: Co-evolution of Life Histories of Calanus and Herring in the Norwegian Sea; and CLIMAR, Climate and production of marine resources.

Collaborations in further directions exist to: International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria (agro-economic modeling); MODIG, a BMBF-funded project about model validation and ignorance dynamics (uncertainty analysis); Granger Morgan, Carnegie Mellon University, Dept. of Engineering and Public Policy (expert elicitations); Thomas Slawig, TU Berlin, Institute for Mathematics, and Thomas Bruckner, TU Berlin, Institute for Energy Engineering (corridor calculations); Klaus Keller, Pennsylvania State University, Department of Geosciences (integrated assessment framework); Mike Hulme, Tyndall Centre for Climate Change Research, Norwich, UK (abrupt climate change, policy relevance, adaptation).

INTEGRATION works together with two EU-projects on vulnerability assessment (VA). The impacts of a THC-induced sea level rise will be assessed in cooperation with the EU-project DINAS-COAST. This project aims at a VA of coastal zones, covering the sectors flooding risk, coastal wetlands, adaptation, and socio-economic impacts. The THC-specific aspects of this VA will be based on climate and sea-level rise scenarios developed by INTEGRATION. These scenarios will also be used to extend the scope of ATEAM, a EU-project that aims at a VA of 30 different ecosystems in Europe.

Policy relevance and application

The result of INTEGRATION will be the first comprehensive integrated assessment study dealing with abrupt climate change. It will provide researchers as well as stakeholders and decision-makers with information crucial for evaluating the risks of changes in ocean circulation, and possible mitigation measures to avoid such risks.

The preliminary results suggest a strong impact on fisheries and forestry in Northern Europe. Arcto-Norwegian cod is a major component of the resources for the Norwegian fisheries industry, which is the second largest exporter after oil and gas and is of vital importance to maintain settlement in the communities along the North Norwegian coast. The bio-economic fishery model is the first attempt to look at the economic consequences of climate-change-induced changes in fish stocks, which turn out to be mostly negative. Forestry in Fennoscandia is expected to benefit from global warming; a THC-induced reversal of the warming trend will give rise to complex reactions in tree growth and timber industry.

For climate change decision-making the quantification of uncertainty associated with a given outcome is of crucial importance. This is true even more in the case of abrupt climate changes such as a collapse of the THC, which may be irreversible on a time-scale of centuries. The uncertainty estimation developed in INTEGRATION, both model-based and through expert elicitation, is thus an essential and innovative element that helps policy makers to assess climatic risks.

The tolerable windows approach (TWA) was explicitly conceived to assist climate change decision-making. In view of the negotiations for the second commitment period of the parties to the UN Framework Convention on Climate Change (FCCC), it provides a useful tool for exploring the consequences of and trade-offs among different levels of climate change constituting "dangerous interference with the climate system" and socio-economic sustainability (cf. Article 2 of the UNFCCC). In particular, the modeling tools and results achieved in INTEGRATION may be useful for setting minimum standards for climate protection such as the avoidance of so-called low probability / high impact events like a collapse of the THC.

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Appendix: INTEGRATION's Model Overview Table

(for the table see the next two pages)

Legend

[1] Linkage to Climber: COUP: fully coupled; SCEN: driven by climate scenario; SLI: computation of time slices

Model name *Institute*	**System modelled**	**Required input variables**	**Temporal / spatial grid for input**	**Link-age** [1]	**Output variables**	**Temporal / spatial grid of output**	**Comments**
Climber-2 *PIK*	Atmosphere, ocean, vegetation, carbon cycle	GHG concentrations (with carbon cycle: GHG emissions)	GHG time series	n/a	Oceanic: T, S, v; (2D, 3 basins) Atmospheric: T, q; Vegetation plus many diagnostic variables	monthly means, yr 1800 - 2300 atmos: 10x50 ocean: 2.5 deg	
Downscaled Climber-2 *PIK*	land surface climate	Climber-2 output: SAT, SLP, vertical velocity at 700 hPa, specific humidity at 700 hPa	Climber-2 output	n/a	SAT, diurnal SAT range, cloudiness, precipitation, wet-day freq., vapor pressure	monthly means, yr 1800 - 2300 Europe, 0.5 x 0.5 deg	
Climber-3α *PIK*	Ocean, Atmosphere, Land surface (MOM: Six/Maier-Reimer for phytoplankton)	GHG concentrations from Climber-2 *or from other atmosphere models*	GHG time series	n/a	Oceanic: T, S, v; (3D) Atmospheric: T, q; plus many diagnostic variables	horizontally: 5x5; in MOM: 4x2 (lon x lat) ΔT=1 day	mit nur 2 Tracern: cpu time 20 min/yr
REcoM *AWI*	Phytoplankton, Calcification Zooplankton only passively ("grazing pressure")	Climber-2 output: 2D transect in Atlantic SST, pCO_2, MLD, cloudiness (interpolated from 10 deg atmos)	0 ... 80N 2.5deg latitudinally monthly means yr 1800-2300	SLI *(COUP)*	variables for phytoplankton biomass and succession, forms and ratios of N, P, C	meridional transect at 20W	later: coupling to MOM3/Climber-3α
ROMS *IMR*	regional OGCM: Norwegian coast, Barents Sea Individual-based model: Arcto-Norwegian Cod larvae and early juveniles	T, (S,) volume flux of Norwegian Atlantic Current, atmospheric forcing (wind stress, heat flux, cloudiness), zooplankton Cal. finm. availability (spatially/ temporally	atmospheric forcing 60N to 70N, monthly means	SLI	T, S, 3D var. U, V, and W; variables describing the cod stock	Hourly means, timeslices of Feb.-Sept. per year Ocean grid: between 3x3km and 15x15km	zooplankton availability needs to be parameterized
SYSTMOD *IMR*	adult population dynamics cod/ capelin/ herring; fishery management analysis	stock size(t_0),T(t); zooplankton(t);	Annual or monthly time series	SLI	stock sizes per year	Time series	conceptual model

Link fishery model *Uni HH*	Bioeconomy: fish and fishery	Planned: SYSTMOD Output: stock size of several fish species, split into age classes	time series ΔT=1 year (at least) length: 100 yr	n/a	stock size (cod, capelin), catch rates (3 competing fleets), ...	point model	
AEZ *IIASA / PIK*	agricultural yield	downscaled Climber-2	downscaled Climber-2	SCEN	potential wheat yield *other crops planned*	monthly means, yr 2000 - 2300 Europe, 0.5x0.5deg *later: 1/12x1/12deg*	
LPJ *PIK*	potential or actual vegetation; functional vegetation types (grasses, shrub, trees, crops,...) terrest. carbon cycle	downscaled Climber-2: SAT, precip, CO_2, solar radiation	downscaled Climber-2: 0.5 x 0.5 deg, monthly means	SCEN *(COUP)*	fractional cover for each functional type, 8 crop classes, structure, status of vegetation, litter and soil carbon pools, evapo- transpiration, runoff, light interception, and seasonal cycle	globally: 0.5 x 0.5 deg Europe: 0.1 x 0.1 deg	coupling to Climber-3 in progress
4C *PIK*	tree vegetation dynamics for single species, soil C/N dynamics; budgets of C, N, water	SAT, precip, CO_2, solar radiation	Daily time series *C2W weather generator needed*	SCEN	for tree species: stand structure, carbon pools in living trees, litter and soil, harvested wood, evapotranspiration, runoff, light interception, and seasonal cycle	time series for specific stands	can be initialised for current conditions, if inventory data are available
EFISCEN *PIK*	Forestry, incl. adaptation	SAT, precip	monthly time series aggregated from Climber-2 for each region	SCEN	timber classes, their distribution to different economic sectors	various regions covering entire Europe	initial conditions are prescribed by forest inventory statistics no soil
FUND *Uni HH*	economy in regions; monetized climate impacts; optimal emission control	Aggregated Climber-2 output: SAT, precip	annual means 16 regions worldwide	SCEN	impact functions: agriculture, forestry, sea level rise, energy consumption, water resources, human health, ecosystems	time series per region	
Tourism model *Uni HH*	impact of climate change on tourism	Aggregated Climber-2 output: SAT, precip	annual means one 'grid point' per country	SCEN	various indicators	time series per country	in cooperation with DINAS-COAST project
DIVA *PIK et al.*	Vulnerability assessment of coastal zones	Climber-2 output	Climber-2 output	SCEN	four assessment modules: flooding, coastal wetlands, socio-economic impacts, adaptation	time series per coast segment	in cooperation with DINAS-COAST project
TWA/ integrated assessment *PIK*	impact of emissions on global climate & THC	From stakeholder dialogue: normative guard rails	n/a	n/a	range of allowable CO_2 emissions ("emission corridors") incl. economic restrictions	time series	coupling to economy model in progress