Accepted for publication in *Global Change and Regional Impacts*, Water Availability, Vulnerability of Ecosystems and Society in the Semi-Arid Northeast of Brazil, Gaiser, Krol, Frischkorn, and Araújo (Eds.), Springer, 2003.

Integrated modelling of climate change impacts in Northeastern Brazil

M.S. Krol, A. Jaeger and A. Bronstert

Potsdam Institute for Climate Impact Research

P.O. Box 60 12 03, 14412 Potsdam, Germany

1. Introduction

Societies in semi-arid areas in developing regions are amongst those, most vulnerable to climate variability and potentially most vulnerable to climate change. The vulnerability to climate variability is caused by the strong restrictions that limited water availability poses on the use of natural resources, by the generally low reliability of water availability and, on the other hand, an often appreciable density of population, strongly depending on these resources with little short-term options to reduce the dependency. Reasonable conditions in the wetter years support the persistence of population in the area; marginal or poor conditions in dryer years and arrears in development hamper significant improvements in the quality of life. Regional tradition and adaptation to local conditions serve as experiences to cope with droughts. This may help to survive emergency situations, but does not really reduce vulnerability, as it does not reduce development deficits. Present-day climate conditions already are marginal to sustain societal demands, therefore climate change poses a serious potential threat.

Clearly, the study of climate change impacts in developing semi-arid regions calls for an integrated approach. The climate impacts are not merely an effect of changes in water availability, but emerge from the confrontation of availability and societal demands and the role these demands play in society. Therefore, the study should include not only the physical understanding of climate impacts on the water balance and on crop yields, but should also include the analysis of water use, agricultural economy and societal impacts. In North-eastern Brazil, one of the most marked societal impacts of droughts is the emigration of population from rural areas in the urban centres and to destinations outside the region (Magalhães et al., 1988).

Latest assessments of available climate observations conclude that global climate has been warming over the last century and that human influences play a major role in climate change (IPCC, 2000). For the 21st century, an enhanced warming is projected to take place under a broad variety of assumptions on global developments. Global precipitation is projected to increase, but at low latitudes, where most of the semi-arid regions in developing countries are situated, both regional increases and decreases are projected. Where precipitation increases, an increased inter-annual variability is assessed to be very likely.

Scientific consensus on climate change projections for specific semi-arid regions is not available at present. This may partly be due to the small scale of these regions, compared to the global dimension represented in the climate models supporting the present assessments. Both the spatial resolution of global models and the model skill at the regional scale complicate the interpretation of results. Downscaling techniques are thus required (Section 3).

The research area of integrated modelling in the context of climate change studies is developing rapidly. Integrated models initially originating from natural science models (energy balance, carbon cycle, crop yield), where models for greenhouse gas emissions from energy use and representations of climate change impacts were included, like IMAGE (Rotmans, 1990), IMAGE 2 (Alcamo et al., 1994). In an alternative approach, macro-economic models were extended with cost estimates for impacts of climate change (like GCAM, Edmonds et al., 1994). Later on, integrated models emerged with a more centrally defined integration approach (like ICLIPS, Toth et al., 1997 or TARGETS, Rotmans and de Vries, 1997).

Regional climate impact assessments also tend to include ever more integrative approaches, extending from agricultural impacts (MINK study, Rosenberg et al., 1993) to representation of interests of various socio-economic sectors (MBIS study, Cohen, 1997). Earlier regional studies on North-eastern Brazil (Magalhães et al., 1988) were broad and rich in information but did not arrive at an integrative concept as adopted in the present (Bronstert et al., 2000).

The implementation of this concept in a fully coupled integrated model, forms a very challenging task, see Section 2. The resulting model dynamically describes the relationships between climate forcing, water availability, agriculture and selected societal processes, allowing the analysis of possible climate change impacts (Section 4) or simulation of scenarios of regional development (Döll et al., 2003).

2. The Semi-arid Integrated Model (SIM)

Although there does not exist a generally accepted approach to integrated modelling, some characteristics are commonly found. Basic characteristics of an integrated model are its focus on a problem rather than on individual processes, its focus on dynamic behaviour rather than on exact replication of the present.

Integrated modelling starts with a systems analysis of the problem, the assessment of relationships between water availability and quality of life and migration in rural semi-arid North-eastern Brazil at the meso-/macro-scale in the context of global change, especially climate change. A top-down analysis of the problem identifies which are the basic variables, processes, and external forcing that should be accounted for in the integrated model (Fig 1).

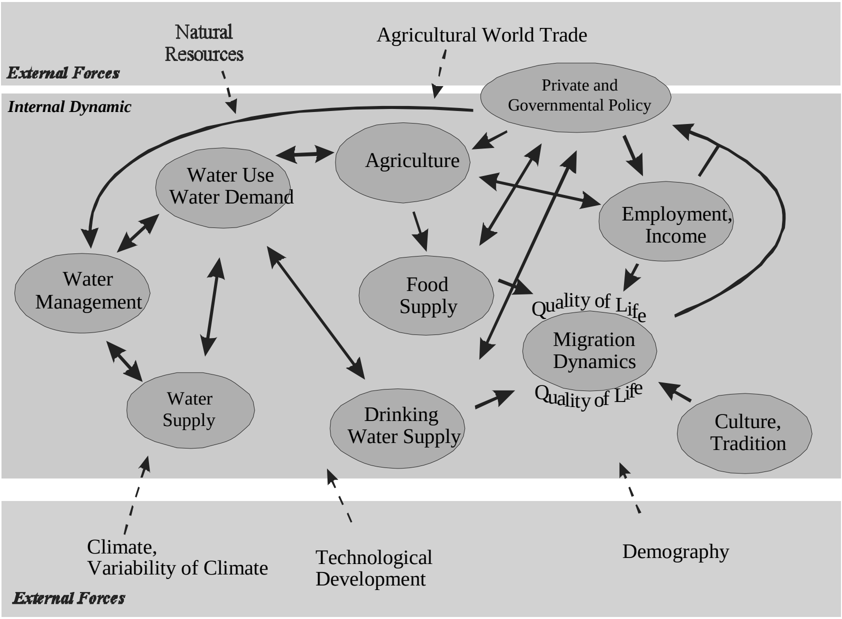

Figure 1. Conceptual model of dynamic relationships between water availability, agriculture and migration in North-eastern Brazil, as influenced by global change.

In this analysis, the focus is explicitly on internal features of the most relevant dynamic behaviour rather than on what is best understood, as for instance the influence of water scarcity on water consumption. The specific challenge is to find a good compromise between the clarity in the representation and the comprehensiveness regarding the main dynamical processes. Special attention should be paid to cross linkages and feedback processes, which already are important in the present functioning of the system (Bronstert et al., 2000), but can especially influence long-term dynamics, as for instance the effects of regional development on the agricultural sector and on water extraction.

A specifically interesting feature of the dynamics is the ability of the system to dampen or enhance the variability resulting from the variable climate forcing. Here e.g. water infrastructure and water policy can cause a reduced variability in availability of water resources, but increased water demands may amplify variability of impacts.

The context of global change forces the analysis to consider long-term behaviour of the system. A reasonable dynamic understanding is preferred over an excellent static understanding, and processes influencing long-term changes are more in focus than processes just explaining heterogeneity at the micro-scale. Clearly, only (aggregated) process-based models can simulate both the effects of individual influences of global change and policy interventions. In this sense, integrated models generally show a mix of deductive and inductive approaches.

In the analysis, geographically explicit integrated modelling is chosen as the most explicit way to approach consistency considerations and regional validity. The Semi-arid Integrated Model (SIM) was constructed for this regional integrated modelling at the meso-/macro-scale (Krol et al., 2001), and is extending the commonly found integrated modelling further into human dimensions.

SIM is built up in a modular way, where each module consists of a disciplinary contribution. Integrative tasks include guaranteeing the consistency between modules, defining interfaces between modules and filling up gaps with plausible and clear basic assumptions. Modules of SIM are:

Climate: Climate scenarios or a historic reconstruction are input to SIM, and results from long-term daily observations combined with climate trends from General Circulation Models (Gerstengarbe and Werner, 2003).

Water availability: A large scale water balance model describes run-off, storage in water reservoirs and soil moisture based on a hydrotope-approach (typical size 10-50 km^2), accounting for vertical and lateral processes depending on topography, soil and vegetation cover, with an explicit representation of the main water reservoirs (Bronstert et al., 2000). A water use model simulates water withdrawal, considering the various water use sectors and their specific intensity and efficiency (Hauschild and Döll, 2000), directly coupled to the agricultural and demographic models.

Agriculture: Crop yields are simulated using FAO schemes for yield response to water stress, as used in CROPWAT (FAO, 1979), considering the 14 regionally most important crops (including maize, bean, rice, cashew) and for impacts of soil-quality (FAO, 1983). Agro-economy is represented as optimising farm income by varying cropping and husbandry activities, under restrictions of available land, technical and financial opportunities, and feed and food requirements, and accounting for production costs and prices (Höynck et al., 2003).

Socio-economy: Migration amongst municipalities and to external destinies is preliminarily modelled to occur when gradients in the quality of life exceed migration costs (fixed and distance-dependent) (Fuhr et al., 2003). Here quality of life is a composite indicator, where mean municipal income per head is the dominant influence. Migration is accounted for in a demographic model, which resolves population development for age and gender.

3. Regional interpretation of climate change projections

Complex physically-based climate models (as General Circulation Models, GCMs) show an increasing ability to simulate present day climate as well as historic trends over the last centuries at the global to continental scale (IPCC, 2000). They project significant global climate warming (1.4 to 5.8 degrees, 1990-2100) and precipitation increase to take place in the current century, under the assumption of a continuous increase in atmospheric greenhouse gas concentrations, as would be caused by a continued intensive use of fossil fuels.

Still, the skill of these models in representing climate at the scale of North-eastern Brazil (NEB) is modest. Of seven climate GCMs, whose climate change experiments were made available for climate impact assessments by the IPCC Data Distribution Centre (IPCC-DDC, 1999), only three are able to represent in their simulations the semi-aridness and strong seasonal cycle, that are characteristic for this region, see Figure 2. One of these three models has a serious flaw in representing global precipitation, hampering serious interpretation of its results on changes in precipitation. This lack in skill may be caused by the relatively coarse resolution of GCMs, 300 to 900 km, leaving 2 to 12 grid cells only to cover all of North-eastern Brazil. An alternative explanation may be the imperfect representation of regionally important physical processes.

Either way, the lack in skill seriously affects the applicability of model results for impact assessments.

The recommended approach to critically review regional performance in selecting model results to be used in assessments (IPCC-TGCIA, 1999) is often ignored, for instance in a specific assessment of plausible climate change in Brazil, including a focus on NEB (Hulme and Sheard, 1999). This can easily lead to inconsistent interpretations; for example, in one GCM, North-eastern Brazil turns from very arid into arid between 2000 and 2100, which by only using climate change output, would be interpreted as a transformation from semi-arid into sub-humid.

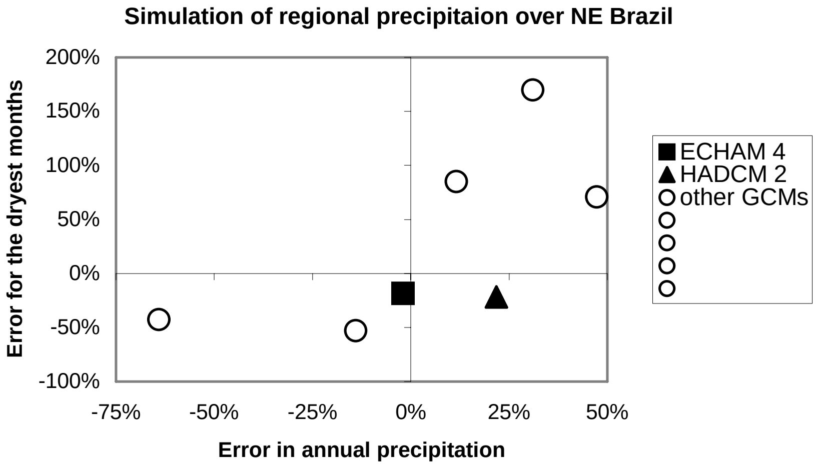

Figure 2. Simulation of regional precipitation over semi-arid North-eastern Brazil in the period 1961 to 1990 by seven GCMs (IPCC-DDC, 1999) compared to the observational database (New et al., 1999), illustrating the skill to represent regional climate characteristics. For one GCM, NEB is hyper-arid, for three GCMs climate does not show a marked seasonality (the driest months are too wet), one GCM gives a reasonable representation of regional climate but overestimates global precipitation by 40%.

The two models involved, still reasonably allowing a regional interpretation of their results for North-eastern Brazil are ECHAM4 (Roeckner et al., 1996) and HADCM2 (Johns et al., 1997). Following the recommendations of IPCC-TGCIA (1999) we selected results from these models for our analyses. For an annual increase of greenhouse gases by 1% per year as of 1990, projections of precipitation changes over NEB (2070-2099 compared to 1961-1990) are –50% for ECHAM and +21% for HADCM.

Given the very small number of models meeting the minimal criteria adopted above for a direct regional interpretation of its climate change results, conclusions on likely precipitation changes in NEB, on median changes or probable ranges of precipitation change cannot be drawn. Still, in climate change studies for semi-arid North-eastern Brazil both the possibilities of a strong decrease in precipitation (-50%) and an appreciable increase in precipitation (+21%) should be considered as plausible to take place in the current century

Assessment of climate change impacts on e.g. surface hydrology and agricultural production for the states of Ceará and Piauí requires, at the coarsest, a resolution of climate data at the scale of sub-regions in Ceará and Piauí with marked differences in hydro-meteorological or agro-meteorological conditions, i.e. the scale of 10-100 km. This seriously hampers the direct (grid-cell based) regional interpretation of GCM-simulated climate change, whose resolution is much coarser. Indirect methods, using Local Area Models (LAMs) of climate or statistical downscaling of large-scale features to derive regional climate may overcome this problem. The latter method was applied in the WAVES project for the generation of regional climate scenarios (Gerstengarbe and Werner, 2003), as no LAMs are presently operational with sufficient skill for climate studies in the study region (Böhm, 2003). Future development of regional LAMs or GCMs with increased resolution could yield improved regional simulations of the climate of semi-arid north-eastern Brazil, as is hinted at by the fact that the 2 models with reasonable reproduction of regional and global climate exhibit the highest resolutions in the model set considered.

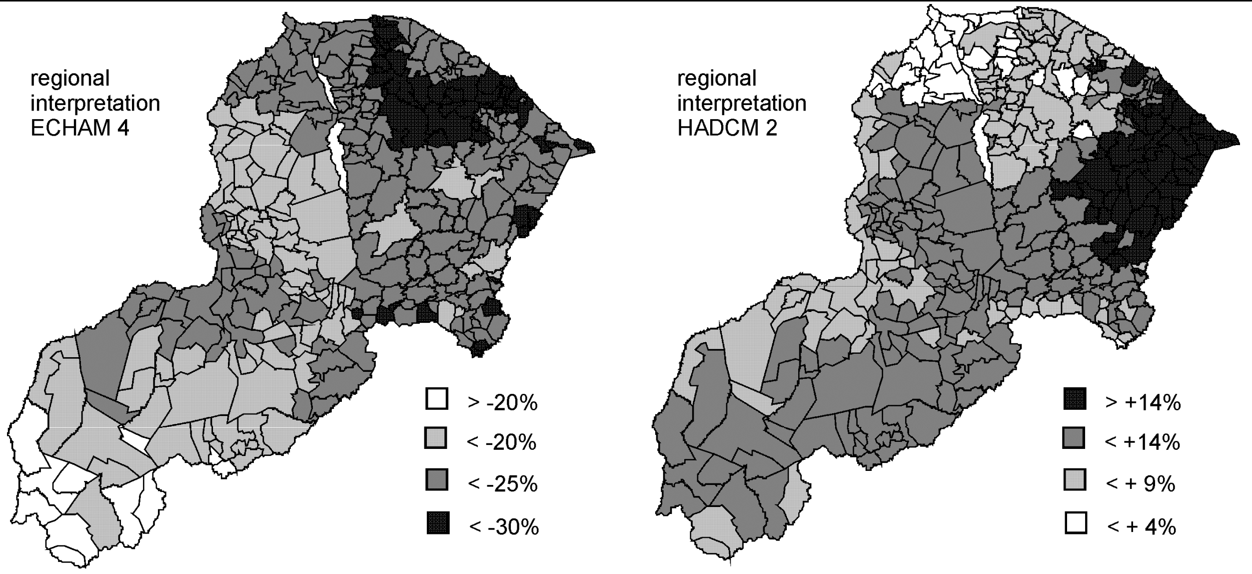

Figure 3. Regional interpretations of GCM results for precipitation trends over the period 2001 to 2050, assuming continued growth of atmospheric greenhouse gas concentrations.

The downscaling method adopted combines observed daily historic climate data at the level of climate stations with long-term climate trends from GCM projections. Here the tendency in annual precipitation at the large scale was taken as the regionally most relevant trend. Simultaneously observed daily data on precipitation and temperature were used to interpret these tendencies into projections of these variables at the station level. Other meteorological variables like relative humidity and short-wave radiation were added using regression relations derived from the few available daily time series of a more complete set of meteorological variables. This resulted in climate scenarios at the level of the climate stations. Interpolation routines were used to transform these scenarios into a climate scenario defined at the level of municipalities. This additional step was necessary, as the municipality was taken as the common spatial unit used in the integrated simulations of hydrological, agricultural and socio-economic processes.

Results for the two selected GCMs show well-defined spatial patterns of precipitation trends, arising from station-specific correlations between local and large-scale precipitation amounts. The difference between the spatial patterns indicates that this correlation is different for anomalously dry years than for anomalously wet years. For a description of the methodology see Gerstengarbe and Werner (2003).

4. Climate change impacts for North-eastern Brazil

Assessing the effects of climate change on NEB, simulations for one fixed reference scenario of regional and global developments with the three different climate scenarios were compared. These combined scenarios are afterwards referred to as the ECHAM scenario, the HADCM scenario and the Constant scenario. The reference scenario 'Globalisation and Cash Crops' (Döll et al., 2003) was selected, being one of the central reference scenarios developed in WAVES. This scenario assumes a continuation of historic trends in demographic and economic development, an increasing on international markets with development focusing on the coastal region and the interior, where water resources are potentially available (especially the downstream river valleys and mountainous areas). Especially in these area water supply is enhanced through additional dam-construction. Agriculturally used area expands gradually; the irrigated area more than doubles.

The first impact of climate change in the causal chain of processes (Fig. 1) is the impact on the availability of water resources. Here precipitation changes have a direct effect on the water balance, affecting run-off generated, river flow and surface water storage.

River runoff shows a strong reaction on the precipitation changes (Fig. 4), with a strong decrease in run-off using the ECHAM scenario, with smaller, statistically insignificant increases for the HADCM scenario. Until year 2025 results are statistically similar to historic simulations.

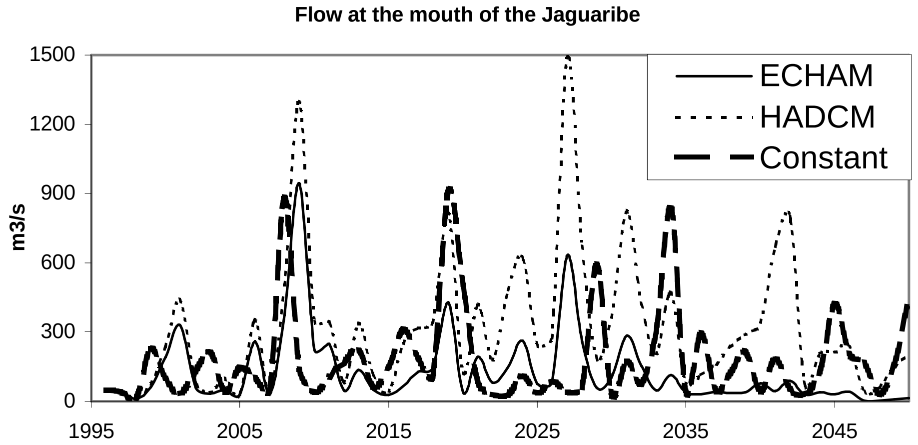

Figure 4. Outflow of the river Jaguaribe, showing a marked reduction in run-off for the ECHAM scenario after 2025, and statistically insignificant tendencies for HADCM and the scenario with constant climate.

Similar tendencies appear for the water storage in reservoirs. Dam construction is one of the main regional strategies to reduce water shortages in the dry period (July to November) and to carry water availability from wetter years to following dryer years.

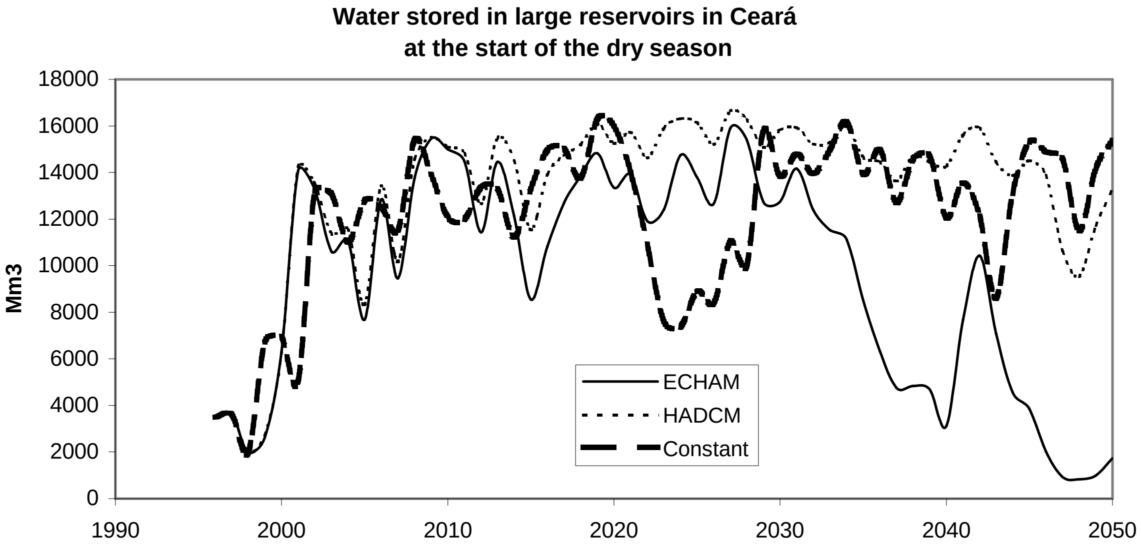

Figure 5. Water stored in large reservoirs in Ceará (>50 Mm3), at the beginning of the dry period for scenarios using climate interpretations based on ECHAM, HADCM simulations and on a constant climate.

In SIM, the larger reservoirs, with capacity over 50 Mm3, are simulated explicitly. The total water volume stored in these reservoirs at the beginning of the dry season (July 1st) shows a strong increase between 1995 and 2015, the period where a marked increase in storage capacity occurs in the scenario (by 7000 Mm3). Total storage capacity in Ceará and Piauí then reaches almost 22000 Mm3, of which 16400 Mm3 is installed in Ceará. Afterwards, in the HADCM scenario and the scenario with constant climate, the reservoirs show a variable degree of stored water, without a significant trend; for the ECHAM scenario, stored volume in Ceará shows a marked decline (Fig 5).

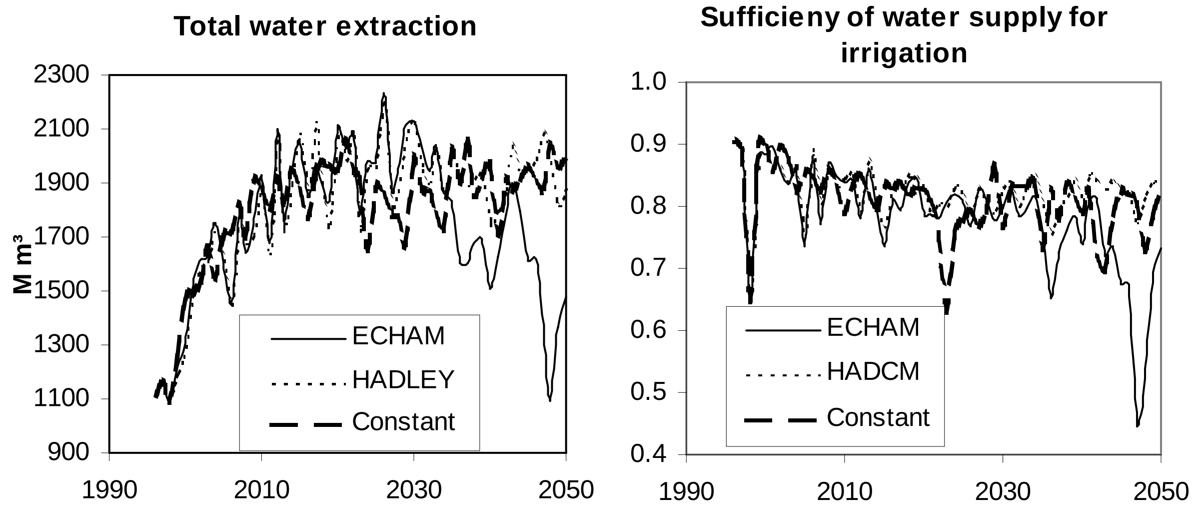

Figure 6, a. Total water extraction in Ceará for the 3 climate scenarios, and b. the relative sufficiency of water supply for irrigation water demand.

The general decline in water availability for the ECHAM scenario after 2025 should be seen in connection to the trends in water use. Due to population growth, increased connection to public water supply systems, intensification of industry and, above all, a strong increase in irrigated area, water demand grows strongly in the reference scenario until 2025, afterwards irrigation area is assumed constant while price increases of water drive increases in water efficiency, combining with increased demands into a stable or declining net extraction (Figure 6a). The decline in water extraction for the ECHAM scenario is caused by unfulfilled demands due to insufficient water supply. The increasing demand cannot always be met in all three assumed climate scenarios. An index of water sufficiency measures, which part of total irrigation water demand can be covered by water availability during the dry season (Fig 6b). Here it shows that the increases in water storage capacity in the reference scenarios allow a 90% sufficiency until 2025, but afterwards sufficiency is only preserved in the climatically favourable scenarios.

Important impacts of climate trends on agricultural production are found both in rain-fed and irrigated production. For the ECHAM scenario, declining rainfall amounts reduce rain-fed yields, especially after 2025, when the climate trend becomes apparent. After 2025 until the end of the simulation, mean maize yield in Ceará falls by 35%. For the HADCM and Constant scenario, no clear trends are found. For the irrigated production of e.g. tomato, the increase in irrigated areas dominates all other effects until 2020. Afterwards, a declining tendency is simulated, due to the decreasing sufficiency of water supply to support the irrigation. For the ECHAM scenario, this tendency is strongest, with mean production losses of 50% after 2025.

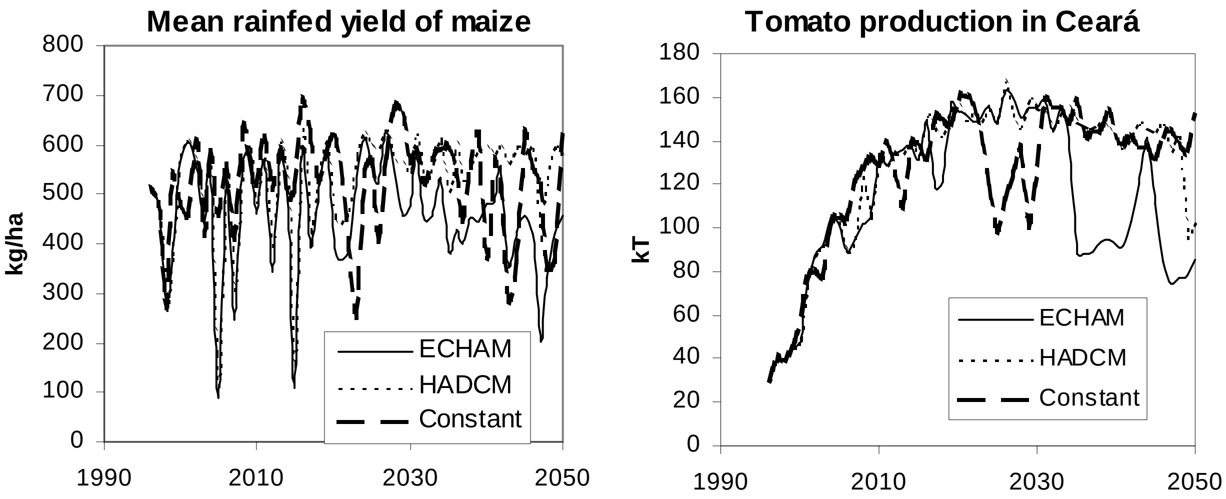

Figure 7. a. Mean rain-fed maize yield in Ceará for 3 climate scenarios, b. total irrigated production of tomato for the three climate scenarios.

Decreases in agricultural production lead to decreasing contributions of the agricultural sector in the economy. An interesting indicator for production losses is the number of municipalities, where the area-weighted loss in yield, relative to local potentials, exceeds 60%. Under this condition, the municipality is considered to be severely affected by drought. For the ECHAM scenario, this number of municipalities shows an increasing tendency after 2025; no clear trends for HADCM and the constant scenario (Fig 8).

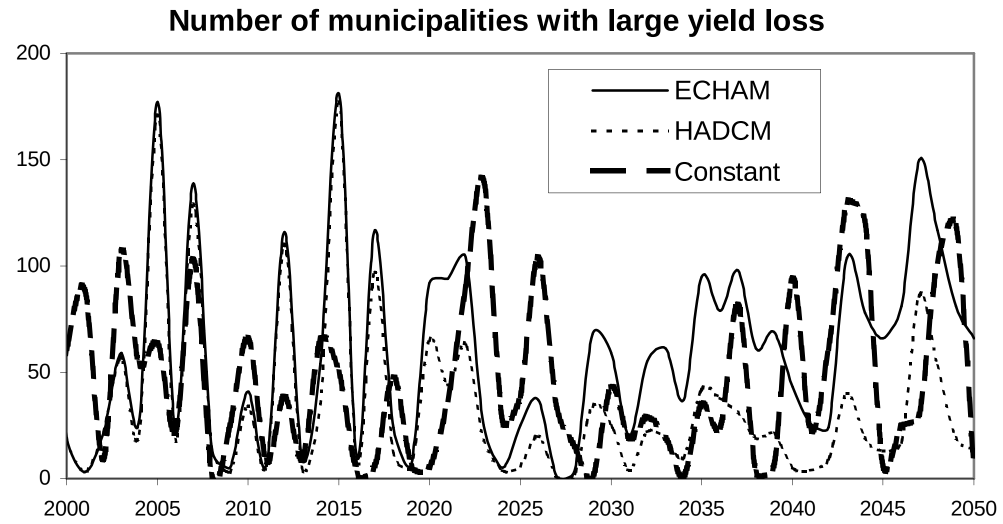

Figure 8. Number of municipalities in Ceará with large yield losses (of 184 municipalities), for three climate scenarios.

Production losses lead to significant losses in municipal income in the rural areas, where the importance of the agricultural sector is assumed to remain big. This implies an increased gradient in income between the rural area and the metropolitan areas in drought years thus driving simulated migration. In this way, enhanced migration in drought years keeps on appearing, even when population development levels off.

5. Discussion and Conclusions

Global climate change will take effect on the climate of North-eastern Brazil. The direction of precipitation changes however cannot be determined with certainty. Both very significant precipitation losses and moderate precipitation increases should be considered plausible.

At current climatic conditions, surface water availability and crop production exhibit a major variability, showing the regional vulnerability. The impacts of precipitation losses, as projected by one of the climate models with best regional performance (ECHAM scenario), would be of big importance for the region, even enhancing the vulnerability.

For the states of Ceará and Piauí, large scale reductions in the availability of flowing and stored surface water leads to an increasing imbalance between water demand and water supply after

2025, under the assumptions of the reference scenario, where future water demands are growing until 2025 but stabilizing then.

Agricultural production would also show negative tendencies after 2025, both by reductions in rain-fed yields and by reductions in irrigated production due to insufficiency of water supply to meet irrigation water demands.

For the climate scenarios with a constant or moderately increasing precipitation, no apparent tendencies in impacts are found.

In the climate scenarios, trends in precipitation are entangled with the natural variability, leaving long periods for tendencies to become statistically significant. This applies to tendencies in the impacts as well. Even for the climate scenario with the most marked trends, significancy of impacts is found after 2025 only. Before, impact levels do not exceed the levels of impacts emerging from natural variability.

This should not discourage to consider possible climate change in preparing policies to increase drought resilience. Measures to increase resilience will largely rely on long-term policies. In discussions with responsible regional agencies, focus was on measures in water infrastructure and its management, water use efficiency improvements, and structural changes in the agricultural sector. All these items refer to long term changes, where possible climate change could have a significant influence. The present analysis suggests, that the efficiency of various measures under different future climatic conditions (which can be considered as the robustness of the measure) might be a more relevant criteria in selecting measures than optimising the measure for present climatic conditions.

Integrated modelling proved an important instrument in evaluating climate impacts. Feedbacks between trends in agriculture, water use, insufficiency of surface water supply have a relevant influence on model results, especially for the scenario with diminishing precipitation volumes. Such feedbacks would not be addressed by single thematic studies or direct sequential couplings of models.

Many uncertainties remain, not only in the possible future climate developments, but also in the regional responses to water shortage and trends in water use; descriptions of specific water use, water management, tendencies in (irrigated) agriculture and societal processes are based on scarce data, and other relevant themes are still lacking representation in the scenarios and models, e.g. planned adaptation strategies as the connection of large catchments to reduce impacts of sub-regional droughts. These uncertainties were partly studies for the isolated contributing models, see various contributions in Araújo et al. (2003), but an ample study of uncertainties in the integrated model is lacking. Nevertheless, model results are well interpretable, and the strong impacts of climate change in the ECHAM scenario are considered to be a stable result, with large regional relevance.

Acknowledgements

The research presented here would have been impossible without the contributions of data, models and discussions from partners in the WAVES project, as amply reported upon in Araújo et al. (2003).

This research was supported by the German Bundesministerium für Bildung und Forschung (BMBF) under grant 01LK9713/4, as part of the WAVES program, funded by BMBF and the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

The analyses were partly made possible by the generous supply of data by many regional institutions, especially COGERH, FUNCEME, and CPRM.

Literature

Araújo, J.C. de, H. Frischkorn, T. Gaiser, and M.S. Krol (Eds.) (2003), this book.

Böhm, U. (2003), this book.

Bronstert, A., A. Jaeger, A. Güntner, M. Hauschild, P. Döll, and M. Krol (2000): Integrated Modelling of Water Availability and Water Use in the Semi-Arid Northeast of Brazil, *Phys. Chem. Earth, B: Hydr., Oc. & Atm* (25)3 pp. 227-232

Hulme, M., and N. Sheard (1999), Cenários de alteraçoes climáticas para o Brasil, Climate Research Unit, Norwich, UK.

Döll, P., M. Krol, D. Fuhr, T. Gaiser, J. Herfort, S. Höynck, A. Jaeger, C. Külls, E.M. Mendiondo, A. Printz, and S. Voerkelius (2003), Integrated scenarios of regional development in Ceará and Piauí, this book.

FAO (1979), Yield response to water, FAO Irrigation and Drainage Paper 33, Rome.

FAO (1983), Guidelines: land evaluation for rainfed agriculture, FAO Soils Bulletin 52, Rome.

Fuhr, D., L. B. Albuquerque, R.L. Chavez, A. Döring (2003), Quality of life and migration in Ceará and Piauí, this book.

Gerstengarbe, F.-W. and P.C. Werner (2003), Climate scenarios and climate modelling, this book.

Hauschild, M. and P. Döll (2000), Water use in semi-arid Northeastern Brazil – Modeling and scenario analysis, Kassel World Water Series 2, University of Kassel.

Höynck, S., Washington, H. Hinterthür (2003), Structure and sensitivity of the agricultural sector in Ceará and Piauí, this book.

IPCC-DDC (1999), GCM climate change scenarios and observed climate datasets, http://ipcc-ddc.cru.uea.ac.uk.

IPCC-TGCIA (1999), Guidelines on the use of scenario data for climate impact and adaptation assessment, Version1. Prepared by Carter, T.R., M. Hulme, and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69 pp.

Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett, and R.A. Wood, 1997: The Second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. *Climate Dynamics* 13, 103-134.

Krol, M.S., A. Jaeger, A. Bronstert, and J. Krywkow, 2001: The Semi-arid Integrated Model (SIM), a regional integrated model assessing water availability, vulnerability of ecosystems and society in NE Brazil. *Phys. Chem. Earth (B)* 26 (7-8), 529-533.

Magalhães, A.R., H.C. Filho, F.L. Garagorry, J.G. Gasques, L.C.B. Molion, M. da S.A. Neto, C.A. Nobre, E.R. Porto, and O.E. Rebouças, 1988: The effect of climatic variations on agriculture in Northeast Brazil, in Parry, M.L., T.R. Carter, and N.T. Konijn (Eds.): The Impact of Climatic Variations on Agriculture, Volume 2: Assessments in Semi-Arid Regions, Kluwer Ac. Publ., 273-380.

New, M.G., M. Hulme and P.D. Jones (1999), Representing 20th century space-time climate variability. I: Development of a 1961-1990 mean monthly terrestrial climatology, *J. Climate*, **12**, 829-856.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Gioretta, U. Schlese, and U. Schulzweida, 1996: The atmospheric general circulation model ECHAM-4: model description and simulation of present-day climate. Max-Planck Institute for Meteorology, Report No. 218, Hamburg, Germany, 90 pp.