CLIMATE IMPACT RESPONSE FUNCTIONS: AN INTRODUCTION

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Abstract. The concept of climate impact response function is introduced and placed into the context of integrated assessment models to analyze policy options under climate change constraints. An example of developing such response functions is presented that entails a global model of potential natural vegetation driven by a climate change pattern derived from a general circulation model. A large array of strenuous issues are introduced that will be addressed by the set of papers included in this Special Issue.

1. Introduction

The principal objective of climate change mitigation is to reduce the amount of anthropogenic carbon dioxide and other greenhouse gas (GHG) emissions in order to achieve "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Article 2) and to avoid intolerable human-induced adverse climate impacts on societies. Taking Article 2 as the guiding principle for climate policy and the requirement to prevent "dangerous anthropogenic interference" raises the question "what is dangerous" (see Moss, 1995; Parry et al., 1996). This boils down to searching for and identifying "unacceptable" climate change impacts.

The question sounds relatively simple conceptually, but it becomes extremely complex and highly contentious in practice. A given exposure to and impact of climate change may turn out to be perfectly acceptable to one society and fully unacceptable to another, even if their levels of economic development and other relevant circumstances are similar. This is explained by the mixture of (i) scientific uncertainties involved in biophysical impact assessments, (ii) attitudes towards risk taking and risk avoidance determined by a multitude of socioecomic and cultural factors, and (iii) normative judgements involved in deciding what is (un)acceptable as follows from the combination of the previous two.

To help societies make informed judgements about what and how much climate change might be dangerous requires tools that synthesize the best available information about the relationships between changes in relevant attributes of climate over a plausible range and the implications of those changes for social activities, economic sectors, and valued environmental components. These relationships are depicted as climate impact response functions (CIRFs) and are the central theme of the contributions to this Special Issue. The papers were originally presented at a workshop held as part of the project on Integrated Assessment of Climate Protection Strategies (ICLIPS) at the Potsdam Institute for Climate Impact Research

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in Potsdam, Germany. Originally, discussions started with the explicit search for climate-related thresholds in different impact sectors that could direct policymakers' attention to possible danger zones. As the ideas evolved in the discussions and through the review process, emphasis has shifted to the more general issue of establishing CIRFs and the difficulties involved in depicting highly complex climate-society interactions.

This paper introduces the themes addressed by the various contributions. We begin by providing some background information about climate impact assessments and CIRFs in Section 2. Section 3 presents a simple example of developing CIRFs to assess the response of potential natural vegetation of the world as captured by global vegetation models. Section 4 introduces the papers in this Special Issue that explore a diverse set of questions involved in CIRFs and in the search for potential climate change thresholds. Finally, concluding remarks are offered in Section 5.

2. Climate Impacts: From Point Estimates to Response Functions

The convenient and customary direction of climate impact assessments is "bottom-up". In agriculture, they typically start with one or more crop(s) in one or more small region(s), then aggregate at the level of economic (sub)sectors and larger regions, and finally, if regional coverage permits, synthesize results at the scale of the national economy. Some studies (see Fischer et al., 1993) extend the analysis all the way up to the global economy by taking farm and national level impacts from many countries and several world regions and use a global agricultural-economic model to analyze effects on and adjustment processes within the world food and agricultural system. Point estimates of the impact functions pegged to the $2\times CO_2$-equivalent GHG concentrations and other prominent benchmarks have been the norm for a long time in other impact sectors as well. Most studies referred to in Volume 2 of the IPCC Second Assessment Report (IPCC, 1996a) follow this pattern.

While these point estimates provide useful first grade assessments of the nature and magnitude of risks involved in climate change, they are less helpful for climate policy that needs to find the appropriate balance between mitigation and adaptation efforts, the latter largely determined by the size of the impact. Article 2 of the FCCC cited above explicitly links GHG mitigation guidelines to "tolerable" impacts by requiring that the concentration of those gases be stabilized at a level that would not jeopardize food production and would let ecosystems adapt naturally. This framing of the problem requires assessments of impacts over a broad range of plausible climate regimes so that social actors can make an informed judgement about what degrees and/or rates of climate change might imply unacceptable consequences.

The ICLIPS project explicitly attempts to help decision makers derive climate protection objectives by combining CIRFs and their own judgements. CIRFs synthesize the best available information from sectoral and regional climate impact models with due caveats about uncertainties. CIRFs describe how climate sensitive sectors respond to changes in relevant climatic attributes across a whole range of plausible climate change patterns under a broad diversity of socioeconomic conditions. This implies that CIRFs integrate both bio/geophysical sensitivity and socioeconomic vulnerability, although the bulk of the research so far has focused on the first component. Nevertheless, user judgement is required to weigh the risk of pure biophysical changes against perceptions of future development and adaptive capacities.

Two major types of systemic responses to climate change can be identified from studies in various impact areas. Some sectors are characterized by a smooth response function within plausible intervals of relevant climatic variables. In this cluster, it is important to distinguish between impact sectors dominated by human management (such as agriculture, agroforestry) and those dominated by natural biogeochemical processes (natural ecosystems, hydrology). The profound difference between the two cases is related to the fact that the vulnerability of sectors under the influence of human management is changing over time as it is closely associated with the development level, institutional capacities, and technological capabilities of human society. The sensitivity of natural systems to climate change, in contrast, is changing much more slowly.

The special difficulty involved in the assessment of climate impacts and hence in the formulation of response functions for managed systems is the need to distinguish between the biophysical sensitivity and socioeconomic vulnerability of these systems. Taking agriculture as an example, biophysical sensitivity is primarily climate-driven. Phases of crop growth, the amount of yield, or the risk of crop failure heavily depend on vagaries of weather. A persistent shift in weather patterns as manifestation of global climate change will, ceteris paribus, inevitably affect yields and risks of crop failure. Orthogonal to this axis, socioeconomic vulnerability of the society behind this agricultural system is largely development-dependent. The vulnerability concept combines two components: to what extent is society affected by implications of climate change in the first place, and what is the adaptive capacity of the society to respond to and mitigate impacts of climate change.

The tolerable level of climate change forcing in the particular system depends on the perception and judgment of social actors, especially those directly affected. In this case, it is a social decision problem to demarcate beyond which level implications of climate change are perceived as dangerous. This implies a desirable level of maximum permitted anthropogenic forcing of the global climate system.

Many components of the Earth's geophysical system have shown major qualitative changes and these are well detectable in the Earth's geological history. New results indicate that some of these changes occurred in a split of a second by geological measures. While the exact mechanisms of these changes are still poorly understood, there is increasing concern that anthropogenic greenhouse forcing could trigger such changes in the future. Examples of these changes include the North Atlantic deep-water formation, the so-called conveyor belt phenomenon delivering huge amounts of heat to the Northeast Atlantic and keeping Western and Northern Europe much warmer than they otherwise would be. Additional examples include the South Asian monsoon patterns, sea-ice albedo, and breakdown of ice shields.

This second type of climate change impacts can be characterized by discontinuous response functions. These systems are assumed to undergo a phase change beyond a given forcing. This level of forcing implies a threshold at which the system would switch from one qualitative behavior to another. Here the social decision problem is whether human societies would want to refrain from crossing such thresholds.

Recently, increasing attention has been given to the issues of climate-related surprises and catastrophic climate change which cut across the above classification. A CIRF can be highly non-linear or even discontinuous but not surprising if the non-linear response of the particular system to external forcing is known or at least suspected. In contrast, even a minor, linear effect can be a source of surprise if no causal relationship was suspected before. Schneider and Turner (1996) propose a typology of surprises in the broader field of global environmental change while Schneider and Root (1996) look at possible surprises induced by climate change in ecological systems. In the literature, the term catastrophic climate change is mainly used to characterize discontinuous CIRFs possibly because of the suspected large magnitude of impacts.

In summary, in the case of continuous CIRFs, unacceptable climate change can be determined by the level of impacts beyond which adaptation is not affordable (this could be relieved by some sort of side payments) or beyond which adaptation is impossible (mainly in the case of ecosystems). In impact sectors with potential phase transitions (possibly triggering others) beyond certain thresholds, crossing those thresholds could constitute a “dangerous interference”.

It is worth noting that there are various other efforts to derive CIRFs. One particular line of research attempts to capture biophysical changes from the current value of various climate attributes as they can be measured from their relative economic importance. Mendelsohn et al. (1994, 1996) pioneered this approach for the farm sector in the United States. The approach has been extended to other regions as well (Dinar et al., 1998).

Whatever the approach, CIRFs are intended to help various social actors determine the extent of climate change beyond which the impacts they are concerned with would be unacceptable. These climate change constraints serve then as input to integrated assessment models conceived in inverse mode. This means models determine permitted corridors or even cost-efficient paths of GHG emissions that satisfy the predefined climate change constraints.

3. Climate Impact Response Functions: A Simple Example

This section presents an early attempt to step beyond point estimates and derive CIRFs for the potential natural vegetation of the earth over a plausible range of climate change.

3.1. COMPONENTS OF THE ANALYSIS

Harvey Brooks proposed an attractive metaphor to characterize global environmental change and the emerging necessity to manage various aspects of that change. He asserted that by the second half of the 20th century, as a result of human intervention, the earth cannot be considered as pristine nature that should be preserved intact. It "is more like a garden than a primeval forest" (Clark, 1986:11) and it should be managed accordingly. We will borrow this metaphor for the purposes of this section and assume a global gardener who has various valued plants in his garden. (He is taken to be equivalent to policymakers who carry the responsibility for determining the necessary level of climate protection.) The gardener has been listening to the rather contradicting predictions about what might happen to those plants as a result of anthropogenic climate change. He would like to know the effects on his plants associated with various rates and magnitudes of climate change in order to decide at what level should the process be halted in order to avoid catastrophic or simply unacceptable losses.

For the purposes of this analysis, the case of global terrestrial cover of natural vegetation has been adopted. Biogeographers identified associations of plant species that are considered to interact with each other as components of a well-defined system. Their geographic locations are largely determined by climate (usually represented by the two most important attributes: temperature and precipitation). Version 1.1 of the BIOME model (Prentice et al., 1992) has been used to study the response of terrestrial vegetation systems to climate change forcing.

The BIOME model takes soil properties and climate to determine what plant functional types (PFTs) can occur in any terrestrial location in the absence of permanent ice. The spatial resolution follows the Leemans and Cramer (1991) climate data sets that were gridded at 0.5 x 0.5 degrees of latitude and longitude. This resolution has been kept for the analysis to be presented in this section. Ecophysiological data determine the climatic requirements for each PFT as a minimal set of threshold values.

The parameters adopted in the BIOME model differ from one PFT to another, allowing more than one PFT to occupy the same climate space. However, competitive exclusion controlled by differences in productivity prevents certain PFTs to grow together although climate would allow them to coexist. The competitive exclusion is implemented in BIOME 1.1 as a dominance hierarchy that prescribes which PFTs will outcompete others. For example, conifers will be outcompeted and disappear where climate allows growth of both warm-temperate evergreens and cool-temperate conifers.

The set of PFTs that can occur in a given region define the "biomes" which will occupy the region. In the following analysis this means the whole 0.5 by 0.5 degree grid cell. In some cases, the biome involves only one PFT (e.g., tropical rain forest consists of tropical evergreen PFT), while in other cases, several PFTs coexist in a biome (e.g., taiga consists of a boreal evergreen conifer PFT and a boreal summergreen PFT). Cramer and Solomon (1993:99) recall an important feature of BIOME 1.1: "[U]nlike most other vegetation-oriented climate classifications, the definition of PFTs as entities with overlapping niches, and biomes as free associations among PFTs, allows the BIOME model to recombine PFTs to form biomes not found on the contemporary landscape". This feature allows biomes to assemble and disassemble in the model just as it has been happening in reality over the past few millennia.

The units of analysis (the plants in the gardener metaphor) are the 20 major biomes covering the terrestrial part of the earth. The list of biomes and their initial areas in BIOME 1.1 is presented in Table I. The impacts of changing climate on these biomes are analyzed with the help of a climate change pattern derived from the ECHAM3 model developed by the Max Planck Institute for Meteorology in Hamburg (Roeckner et al. 1992; DKRZ, 1993).

The ECHAM3 model has been developed from the ECMWF model (Simmons and Chen, 1991) by implementing a series of changes in parameterization to adjust the model for climate simulations. The model is formulated in spherical harmonics and truncated expressions are adopted for the representation of dynamical fields. The transform technique is used in such a way that non-linear terms, including parameterizations, are evaluated at a set of almost regularly distributed grid points (Gaussian grids). The reference resolution is T42, but the model is set up to use resolutions in the range T21 to T106.

A flexible coordinate is used in the vertical that enables the model to use either the usual terrain-following sigma coordinate or a hybrid coordinate for which upper-level model surfaces "flatten" over steep terrain, becoming surfaces of constant pressure in the stratosphere. Moist processes are treated in a consistent way in both the dynamical equations and parameterization schemes.

3.2. DERIVING CIRFS

The analysis presented here is rather simple. Two points are taken to characterize the necessary climate parameters. The starting point is "present climate" as defined by the Leemans and Cramer observed climate for 1931-60. The end point is defined by the difference between the $3\times CO_2$ equilibrium climate as calculated by an equilibrium experiment conducted with the ECHAM3 model and its control run: this difference was added to the observed climate. All relevant climate variables (mainly monthly values) are derived from these data sets. A linear interpolation is

TABLE I

Biomes and their current area in BIOME 1.1 (1×CO_2 climate)

Plant functional types (biomes)	Current area (10^3 km^2)
Ice/polar desert	1944.1
Semidesert	5594.9
Northern tundra	6611.3
Southern tundra	2583.1
Northern taiga	2566.1
Southern taiga	10854.8
Northern cold deciduous forest	1178.2
Southern cold deciduous forest	2483.6
Cool grass/ shrub	4757.6
Cool confer forest	3400.6
Cold mixed forest	653.6
Cool mixed forest	5820.2
Temperate deciduous forest	6016.9
Broadleaved evergreen forest	5812.5
Warm grass/shrub	10823.5
Hot desert	20974.2
Xerophytic woods/scrub	10743.7
Tropical dry forest	16990.1
Tropical seasonal forest	8307.2
Tropical rain forest	8214.4
Total	136690.6

performed between the two endpoints in 100 steps. The procedure developed by Leemans (1989) and Smith et al. (1992) was adopted by applying gridded climate differences (anomalies) between the GCM results and the observed gridded climate values.

The BIOME model is then driven by this derived transition pattern (i.e., not by a transient experiment result from the GCM). For each time step, the model determines the dominant potential vegetation for each grid cell. This provides 100 time slices (or snapshots) of a moving picture, namely how relatively small changes in climate alter the dominant vegetation type in any of those 0.5 by 0.5 degree-sized terrestrial grid cells.

Two cases have been defined for the purposes of this analysis. They are the two extremes, and as such, they are admittedly unrealistic. The first case is that of the pessimistic gardener: if the current biome (plant in the garden) becomes infeasible under the climate prevailing in the actual step in the climate change sequences, then the area will be lost. This means that once the current vegetation disappears, nothing will replace it, the area becomes idle, i.e., no plants will grow in that particular location of our garden any more). This is very pessimistic, and clearly unrealistic, but shows the upper limits of the losses mankind might face if remnants of the disappearing biomes (and their ingredients) prevented the establishment of ecosystems that would be viable under the new climatic conditions.

The second case depicts a gardener who is an optimist. Here it is assumed that any change in climate will be followed by the appropriate and immediate adaptive response by the natural vegetation in any region. That is, according to the metaphor, the optimistic gardener expects his plants to prop up in any new location as soon as the climate becomes suitable for them. This means that as climate changes, the dominant biome that became infeasible at a given location will be replaced immediately by the new biome type: no hindrance posed by the decaying components of the old vegetation, no delay in establishing the new biome. This is a close-to-realistic assumption for some biomes while a rather unrealistic assumption for others.

3.3. RESULTS

It is rather difficult to tell at this point how the future of various components of the global terrestrial vegetation will unfold at different geographical locations between the two extremes bounded by the optimistic and pessimistic cases. However, the wide range defined by these extremes might help us specify future research questions better and target our modeling efforts finer.

This section summarizes the results from the this initial attempt to develop CIRFs measured in natural or physical units. In the analysis below, these units are land areas where biomes are predicted to change as a result of climate change (plotted on the horizontal axis in Figures 1 through 10).

We take each biome group in turn and present both the optimistic and pessimistic cases next to each other. Pessimistic functions show cumulative losses of current biomes as a function of climate change expressed in percentage of the current land area occupied by the biome at hand. It follows from the definition of the pessimistic case that these functions are monotonously increasing. The optimistic functions represent cumulative outcomes of the transformation processes: when climate becomes feasible for a particular biome at a new location, this area is netted out against areas where that biome becomes infeasible. The measure is again the percentage change relative to the current area occupied by the biome.

What happens to the boreal vegetation classes in the pessimistic case? Much of them will be basically lost in their current locations already by the time we reach the $2\times CO_2$-equivalent climate (see Figure 1). This is particularly true for the Northern taiga. Comparing this to the optimistic case (Figure 2), however, one can see that the region with climate appropriate for the Northern taiga will be gradually disappearing as climate changes. Other boreal vegetation types are doing relatively well, that is the areas lost in their current locations will be more than compensated by new regions where the new climate will be favorable to cold mixed forests and Southern taiga.

The second group of boreal vegetation behaves similarly under the pessimistic assumptions (Figure 3). Northern cold deciduous forests and Southern tundra vegetation disappear rather fast from their current location. The decline is slower for Southern cold deciduous forests and Northern tundra. These four biomes will be declining even under the extremely optimistic case (Figure 4). The Northern cold deciduous forests will be simply falling off at the edge: no matter how fast they can adapt to the changing climatic conditions and move to areas becoming available to them, close to 80 percent of their current area will be occupied by other biomes even under $2\times CO_2$-equivalent conditions.

Grassland and desert ecosystems prevail under a broad range of climatic conditions. It is not particularly surprising that in a warming world desert vegetations favoring low temperatures (cool grass and ice/polar desert) will suffer major losses under the pessimistic scenario (see Figure 5). They will be replaced by other ecosystems whereas they will have no region with suitable climate to migrate to under the optimistic case (Figure 6).

Temperate forests provide the most contrasting picture between the pessimistic and optimistic world views. They will be gradually disappearing from part of their current locations, although these losses appear to be moderate compared to other vegetation types (see Figure 7). More than 70 percent of the broadleaved evergreen forests will be unaffected even under $3\times CO_2$-equivalent equilibrium climate. The biome worst hit in this group is cool coniferous forests with 50 percent losses under $2\times CO_2$-equivalent climate.

Although cool coniferous forests remain a major loser even under optimistic assumptions, all other temperate forest ecosystems practically preserve the size of their current area up to the $3\times CO_2$-equivalent climate (Figure 8). This is obviously the case where natural migration ability of the ecosystem is favorable, that is, the rate of climate change is slower than the pace of natural migration. Presence or absence of natural (water bodies, mountains) and anthropogenic (managed forests, pastures, cultivated land) barriers to ecosystem migration will determine where reality will unfold between the optimistic and pessimistic cases.

Tropical forests also present an interesting case. It may come as a surprise at the first glance that even some tropical biomes (xerophytic and tropical seasonal) become infeasible in significant fractions of their current areas in a generally warmer and wetter world (Figure 9). These moderate losses turn into modest gains under the optimistic assumptions (Figure 10). The fate of tropical forests has provoked fierce debates over the past two decades. Figure 9 shows that they will not be significantly affected even under the $3\times CO_2$-equivalent climate. Moreover, if we assume that tropical rain forests will migrate into regions that open up for them as a result of climate change, their potential area could increase by up to 25 percent. This shows an important cross-linkage among causes and processes of global

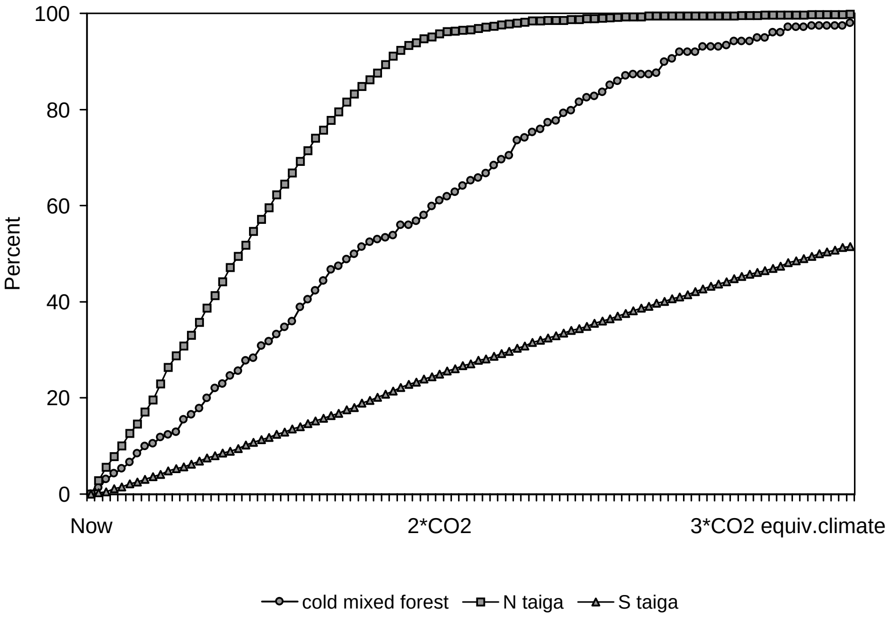

Figure 1. Response functions for boreal vegetation 1: pessimistic case.

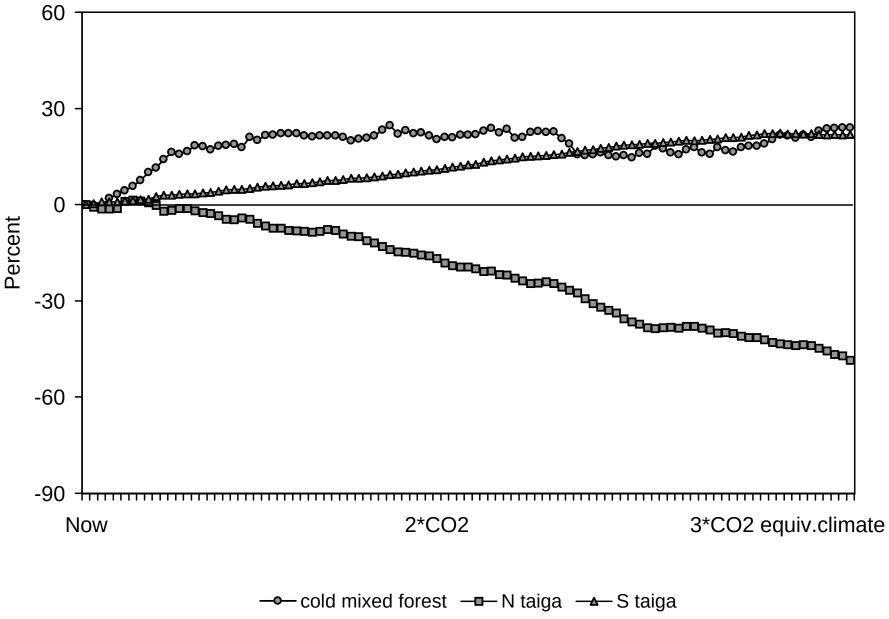

Figure 2. Response functions for boreal vegetation 1: optimistic case.

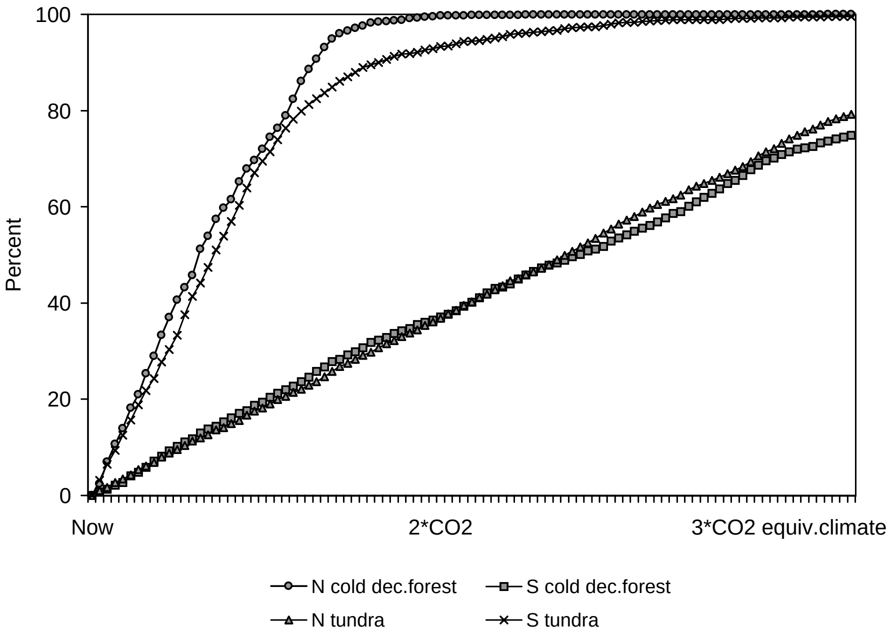

Figure 3. Response functions for boreal vegetation 2: pessimistic case.

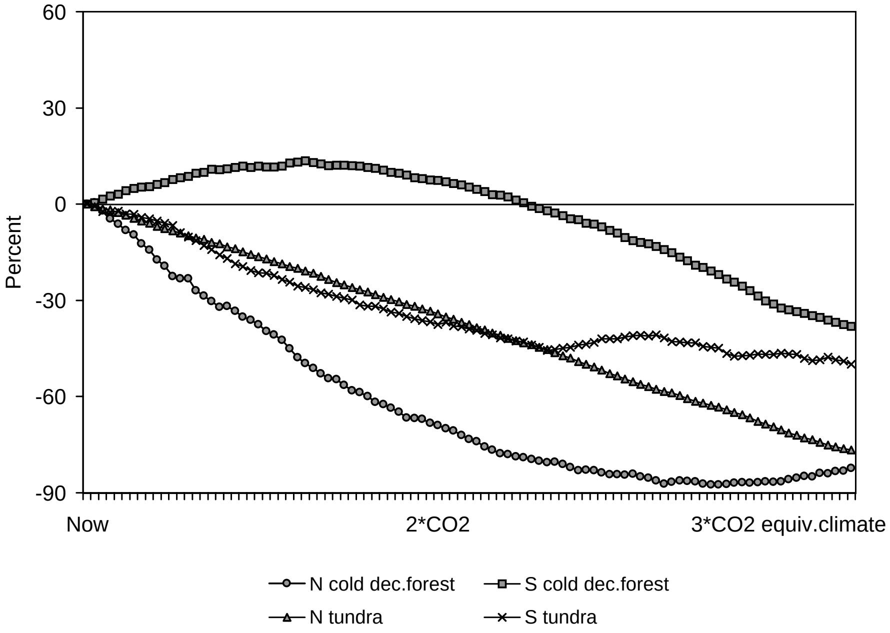

Figure 4. Response functions for boreal vegetation 2: optimistic case.

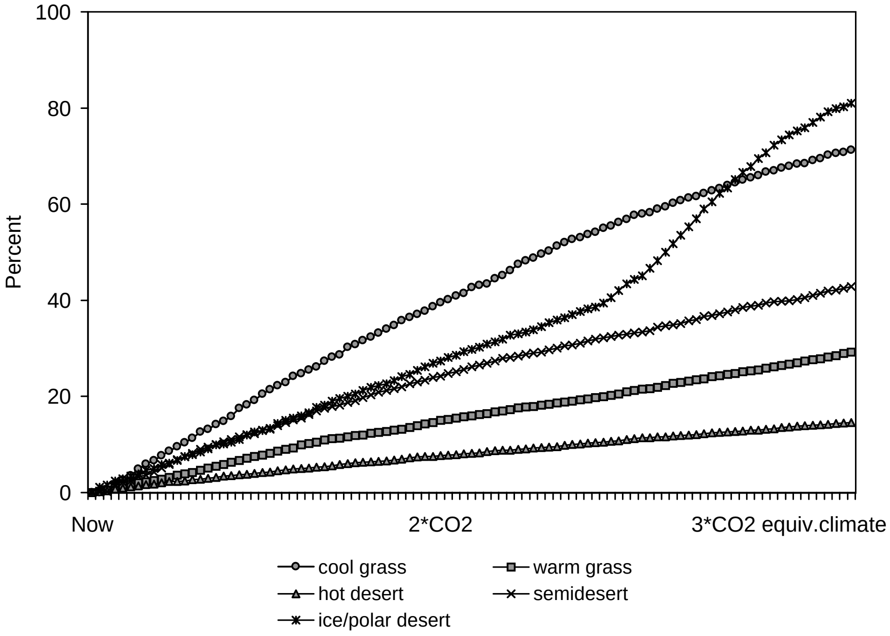

Figure 5. Response functions for grasslands and deserts: pessimistic case.

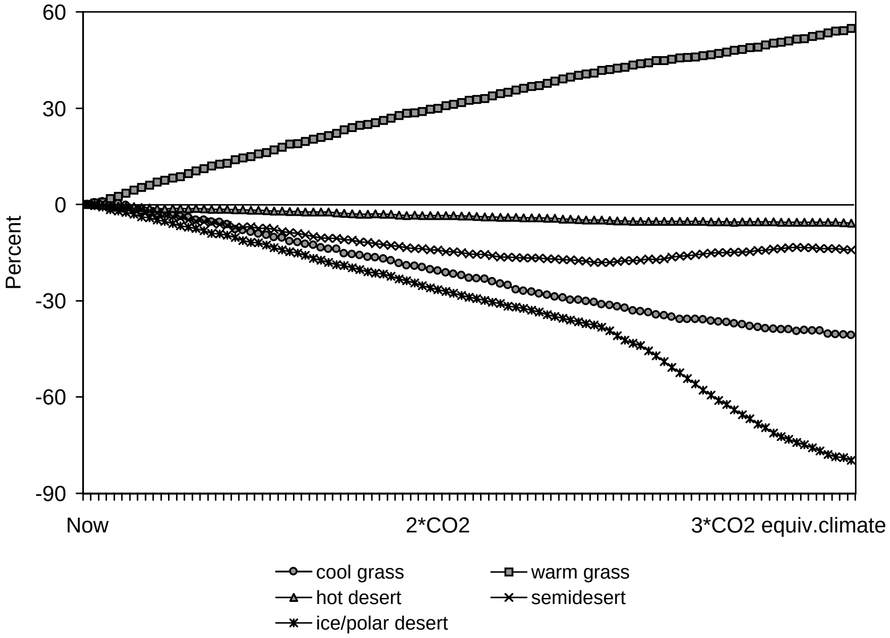

Figure 6. Response functions for grasslands and deserts: optimistic case.

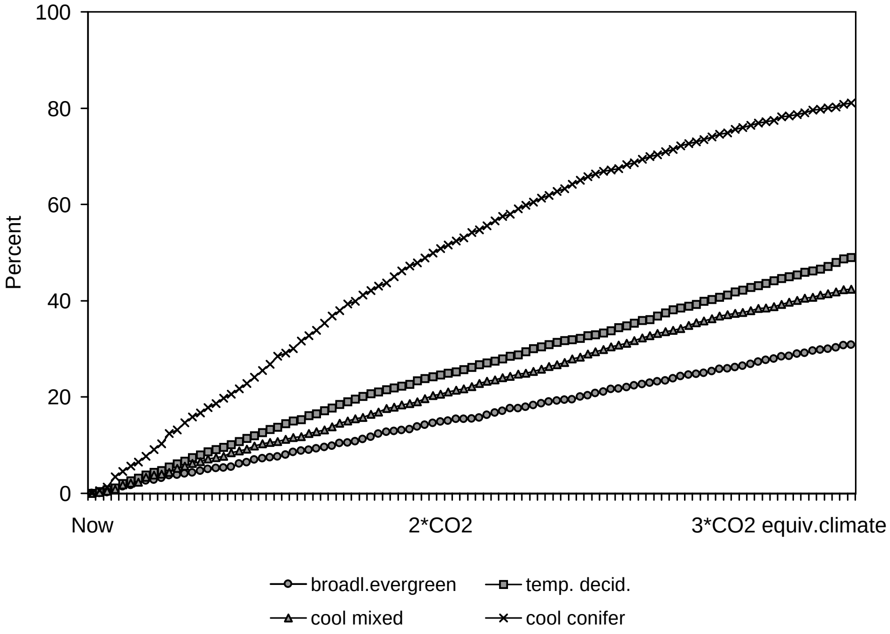

Figure 7. Response functions for temperate forests: pessimistic case.

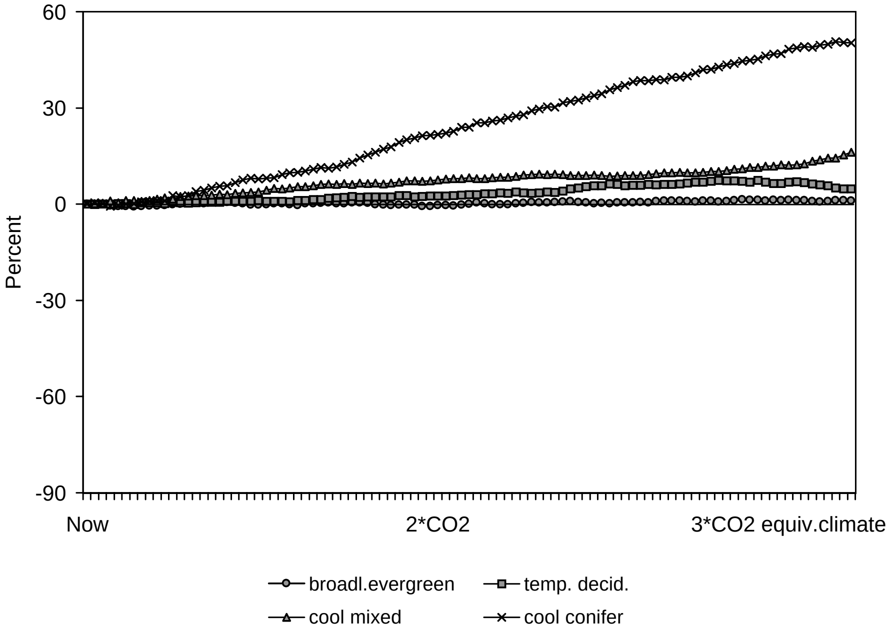

Figure 8. Response functions for temperate forests: optimistic case.

environmental change. If tropical rain forests constitute such an important natural asset of mankind, should not we consider other elements of global change seriously when we look at management options?

3.4. INSIGHTS FROM AND POSSIBLE USES OF THE RESULTS

These results obviously stem from a very crude analysis and provide just an illustrative example of CIRFs. Lot more research will be needed to reduce these exceedingly wide ranges in order to get a more realistic assessment of plausible futures. The list of things to do in terms of future research includes:

- using more appropriate climate change patterns to derive the vegetation model: instead of the simple interpolated climate path, one should experiment with climate change patterns derived from transient GCM runs by using advanced statistical techniques to extract more information;
- adopt new versions of the BIOME model which have more vegetation dynamics in them and include the first elements of the feedback relationships between terrestrial ecosystems and climate;
- perform additional, more detailed analyses on the transition clusters identified by the modeling exercise described above: which biomes are typically replaced by which other, what are the natural dynamics of these transitions (going from biome A to B might be easy, transition from biome M to N might be much more difficult), what are the management options to foster that transition (i.e., what could the gardener do to help his plants get to places in the garden where they can thrive under the new conditions);
- analyze the temporal gaps: there might be a significant temporal gap between old ecosystems decaying and the new ones getting fully established. What happens to the site in this transition period: how will be soils affected, what changes might undergo the local hydrology. These processes and, again, the options available to manage them will be decisive in the actual ecosystems processes.

Our gardener might deduct several types of information from improved versions if this kind of analysis.

First, the analysis can identify sensitive regions. There is a number of “thoroughfare regions” where we can observe biomes changing several times as climate changes from $1\times CO_2$ to $3\times CO_2$-equivalent climate. Is it realistic to expect that those changes in natural ecosystems can take place at the rate implied by the rates of climate change? The model behind the present analysis is well suited to identify these regions even in its crude form. The gardener would be well advised to focus his limited research capacities on these regions.

Second, this kind of analysis can identify “sensitive biomes”, i.e., those that would need to be fast movers because climatic conditions favorable for them move fast and they would need to reestablish themselves at several new locations over time. The question again: can they really migrate that fast? Is there a chance to help

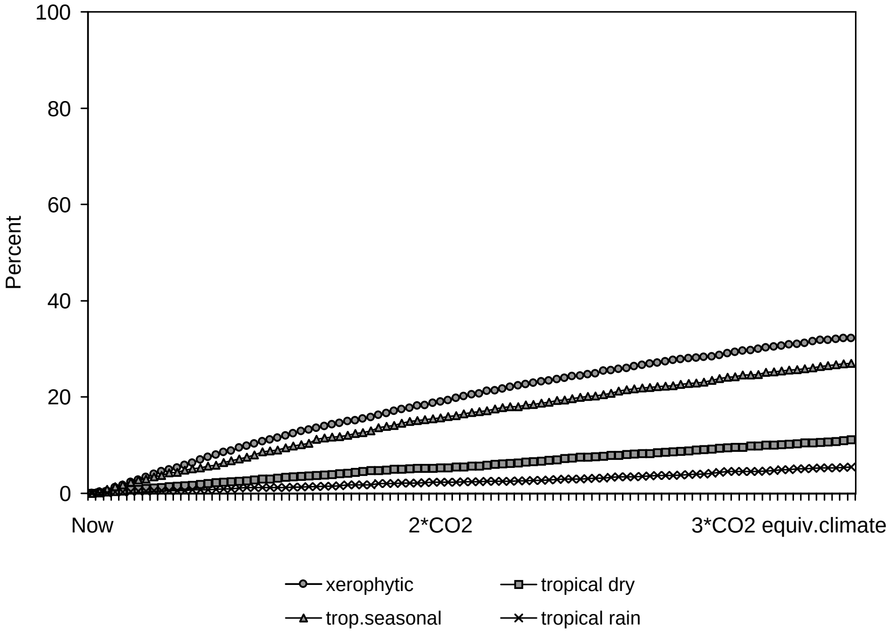

Figure 9. Response functions for tropical forests: pessimistic case.

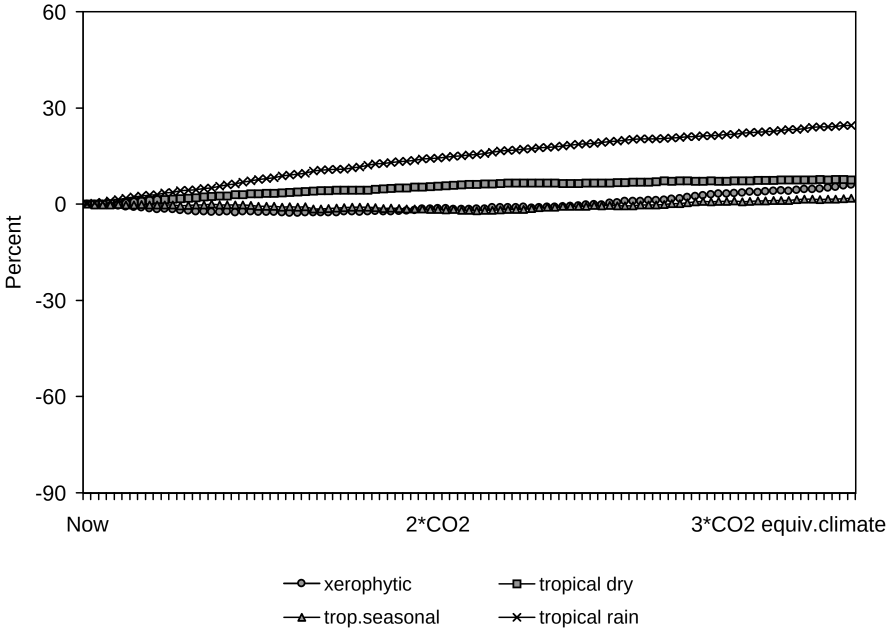

Figure 10. Response functions for tropical forests: optimistic case.

them migrate as conditions change for them? Here again, even this rudimentary analysis can identify biomes for which more detailed analyses are required.

Third, this analysis can provide a framework for discussing and identifying levels of willingness-to-accept losses in physical units and feed those data into an inverse model in order to check how much would it cost to stop climate change at a predefined level of ecosystem transformation.

This information will then become a key input to the inverse-mode integrated assessments mentioned in Section 1. Instead of choosing rather arbitrary concentration targets (IPCC, 1996b; Wigley et al., 1996) or targets derived from geological history (WBGU, 1995), this approach can help frame the debate on critical thresholds of climate change. It can help identify acceptable loss or transformation levels. One example: if the gardener says that the maximum amount of boreal forests he would like to lose in their current locations (because, according to his perception and experience with his plants, migration of higher fractions of boreal forests would entail unacceptable ecological risks), then Figure 1 provides a tolerable level of climate change for that biome. The associated permissible global climate change defines a set of permitted emission paths. By using appropriate emission-economy models, one can derive cost-minimizing optimal emission paths that would keep the level of anthropogenic climate forcing within the tolerable climate window. Finally, one can look at the related costs and ask: is it really worth it? If the costs associated with that particular level of climate protection are perceived to be too high, the gardener (i.e., policymakers) can go back to the response functions, consider adaptation options and/or reconsider the acceptable levels of changes/losses.

Although it has been emphasized from early on that the above is a rather simple modeling exercise, it is appropriate to note a few caveats. The emphasis in the above analysis is on the concept of CIRFs rather than the exact numerical results or their direct policy applicability. One might argue to what extent are CIRFs of potential vegetation relevant for real-world problems, but in our view they are useful at least as indicators of possible changes. Potential vegetation is also a good indicator of potential land use. Cramer and Solomon (1993) define climatic limits of global agricultural zones and use the same model to determine how global distribution of potential agricultural land would change under $2\times CO_2$-equivalent climate simulated by different general circulation models.

Another caveat is related to the spatial and temporal scales characterizing different studies. The global 0.5 by 0.5 degree resolution adopted here is widely used but it is admittedly coarse. Moreover, models looking at different scales tend to emphasize selected aspects and processes. Cramer and Steffen (1997) address a number of difficulties involved in studying the responses of ecosystems to climate change on different time scales.

In recent years, a lot of work has been devoted to developing dynamic global vegetation models. Woodward and Cramer (1996) outline how to develop such models using PFTs. Steffen et al. (1996) present model simulations involving transient changes to structure and composition in vegetation distribution. Feedback processes between atmospheric composition, climate and large-scale changes in natural vegetation constitute yet another factor underlying the importance of dynamical processes.

4. Selected Issues Related to CIRFs and Thresholds

The first set of papers in this special issue look at selected large-scale geophysical systems. They establish responses of those systems to different climate change forcing and search for possible thresholds beyond which the response would be discontinuous. The dynamics of the North-Atlantic Deep Water Formation and the thermohaline circulation are the most intensely researched topics of all possible phase-transition phenomena. Cubasch et al. (this issue) conduct experiments with the ECHAM3/LSG ocean-atmosphere general circulation model. The authors detect four major feedback processes that influence the NADW formation but act in opposite directions with the possibility that they partially cancel out each other. The experiments conducted by Cubasch et al. do not detect the dramatic cooling of Western Europe as established by some other general circulation models and many specifically formulated reduced-from models. The authors point out plausible explanations, but all these indicate deep uncertainties still prevailing in this critical area. Rahmstorf (this issue) presents an enlightening overview of the NADW issue that helps to put the Cubasch et al. study in a broader context.

There is a wide consensus among climate modelers that current general circulation models are much better at simulating present-day temperature and future temperature changes under different forcing assumptions, especially at global and continental scales, than at simulating existing precipitation patterns and expected changes in them. In the second part of their paper, Cubasch and his colleagues report recent results on precipitation change as simulated by the Hamburg climate model. The authors draw some interesting conclusions regarding the nature and magnitude of precipitation changes, including the possibility of drastic changes towards more extreme temporal distribution of precipitation in some regions.

Although obvious relationships exist between the two phenomena (the North-Atlantic Deep Water Formation and the change in precipitation, especially in the North Atlantic region), the present analysis by Cubasch et al. does not attempt to link them explicitly. This kind of self-restraint is certainly justified in the midst of profound uncertainties and with a view to the difficulties involved in harmonizing the time horizons required for conducting meaningful experiments of the two problems. Nevertheless, targeted linkages of selected problem areas might improve our understanding of the complete system and are likely to raise important questions for future research in the individual components involved.

Impacts of climate change on the sea ice cover of polar oceans and their possible interactions with other geophysical processes are another important issue and also an example of the integration mentioned above. Lemke et al. (this issue) present results from sensitivity experiments involving thermodynamic and dynamic-thermodynamic models of sea ice processes. Their general conclusions is that unrealistic simplifications of sea ice model components tend to produce higher sensitivity values with respect to perturbations in the atmospheric and oceanic boundary conditions. The authors also observe that sea ice processes react smoothly to changes in radiative forcing.

Another important linkage among different domains of climate change impacts entails the possible melting of ice sheets in response to higher temperature and the resulting sea level rise. Greve (this issue) adopts an ice-sheet model to investigate the response of the Greenland ice sheet to climate change characterized by an increase in the mean annual air temperature above the ice shield ranging from 1°C to 12°C and several parameterizations of snowfall and surface melting processes. The author argues that only semi-quantitative response predictions are possible due to current uncertainties about inputs from snowfall and surface melting, and the response of the bedrock. This is yet another example of how much uncertainty characterizes our knowledge even for a geographically limited and well-studied area like the Greenland Ice Sheet. Greve finds that the response of Greenland ice is likely to be smooth, in contrast to the West Antarctic ice sheet that may be more prone to discontinuous response to anthropogenic climate change due to its structural characteristics.

Hydrological impacts of climate change and the associated changes in water resource availability have been one of the central fields of climate impact research. Arnell (this issue) examines the difficulties of defining and using thresholds in general and illustrates those intricacies by a series of examples from the impacts of climate change on the water sector. Arnell uses a somewhat different terminology from what has been proposed above. He calls an externally defined threshold “response threshold” while he terms an intrinsic threshold “force threshold”. Both can involve non-linearities in the water sector. Intrinsic thresholds tend to be connected to hydrological processes while management standards (e.g., water quality, level of flood protection) are examples of externally defined thresholds marking the border between the need for action or inaction.

Next to hydrology and water resources, impacts of climate change on agricultural production and food supply is the area of preeminent concern. Van Minnen et al. (this issue) present CIRFs developed to assess the impacts of climate change on potential crop production and cropping area. These functions portray the relationship between temperature, precipitation and their seasonal and spatial variability on the one hand and crop yields and crop suitability on the other. National-level response functions are aggregated from appropriately weighted regional impact data for Germany and the Democratic Republic of Congo. Although these CIRFs cover only biophysical relationships in their current form and do not embrace adaptation, they provide useful basic information for policymakers regarding the nature and magnitude of climate change that would pose big challenges for agricultural production for their country.

Climate impact assessments have been conducted with sectoral orientation for a long time. Sectoral studies typically ignored baseline and/or climate-induced changes in other related sectors or considered them in the form of exogenous assumptions at best. Integrated regional climate impact assessments have been emerging relatively recently. Some studies formulate possible changes in the most closely linked climate-sensitive sectors (e.g., agriculture - hydrology, agriculture - soils) in the form of scenarios and use them as boundary conditions in sensitivity analyses. Very few studies accomplished integrated regional assessments like the MINK study (see Rosenberg, 1993). Strzepek and Yates (this issue) present an integrated national climate impact assessment for Egypt. The main trigger in their study is the potential impacts on the water resources of the Nile river. The authors use a suit of models to trace repercussions of these changes from agriculture all the way to the national economy. Equally important, the study involves different baselines scenarios of socioeconomic development upon which scenarios of climate change impacts are superimposed. This is a major step beyond many climate impact studies that assess impacts of future climate on present-day economy, society, and technology. This approach makes the evaluation of adaptation options much more realistic as well.

The importance of these two factors, climate-independent baseline scenarios of future socioeconomic development and adaptation, become apparent when we look at the history of climate-society interactions in the context of climate variability. Tol and Langen (this issue) seize an exceptional opportunity to present and analyze changing vulnerability with respect to a climate-related environmental risk in the same geographical region but under changing economic, institutional and technological circumstances. Their study is an excellent account of the history of flood management over a millennia. Key messages of the paper are related to the interaction between vulnerability, adaptation, development, and institutions. Appropriate reflection of these social, economic and political processes in CIRFs will be a difficult task.

Yet adaptation is critically important to consider in climate impact studies. Yohe (this issue) discusses three types of adaptation: response to short-term fluctuations, reaction to long-term change, and activity switching. Moreover, he demonstrates the importance of distinguishing between biophysical climate sensitivity (and the associated “virtual” thresholds) as well as actual socioeconomic vulnerability (in which case actual thresholds are significantly influenced by social, economic, technological, and other factors).

The concept of CIRFs has been formulated in the context of the TWA. TWA is still a new approach and many of the underlying ideas as well as the actual ways of implementation continue to evolve. Most improvements emerge from the experience in the ICLIPS research network, but many of them stems from comments on and critique of the TWA work by others. Dowlatabadi (this issue) contemplates on the intricacies involved in the TWA in general and in selected applications. He uses the ICAM model to illustrate the impact of uncertainties in targeting climate policy.

Some of his points call attention to unresolved issues and require hard thinking in future development of TWA while others stem from the specifications of the ICAM model. It is important to note here, however, that a clear distinction should be made between the TWA as a general decision analytical framework, a specific model system developed to address a certain problem (in the ICLIPS project it is climate change), and a given application of the instrumentarium in which users have proposed specific normative decisions based on their own perceptions of tolerable changes.

5. Concluding Remarks

Probably the most important source of information for climate policy is related to question at what level would want mankind stabilize the climate system with respect to anthropogenic interference. This requires assessments of possible implications of climate change in different regions. Traditional approaches to climate impact assessments have produced point estimates, like those associated with a $2\times CO_2$-equivalent climate. Recent efforts attempt to establish the response of particular impact sectors or regions over a plausible range of climate change patterns and synthesize these relationships in CIRFs.

CIRFs are intended to help social actors to make their judgements about “dangerous” or “critical” levels of climate change. While CIRFs themselves cannot reduce the uncertainties involved in climate change or impact forecasts, they can at least provide a consistent framework for synthesis and thus may help frame the debate about long-term climate protection objectives. Just as any decision related to the climate change problem, the appropriate approach to long-term objectives and strategies to reach them is sequential decision making under uncertainty and learning. As new information becomes available about various primary impacts, adaptation possibilities and other factors involved in CIRFs, long-term climate change targets will need to be adjusted accordingly. Developers and users of CIRFs should keep this simple rule in mind.

Contributions in this special issue discuss the merits, shortcomings, and the difficulties involved in deriving CIRFs and in identifying critical thresholds. They have been introduced and discussed in the context of various geophysical, ecological, and socioeconomic impact sectors. On balance, it appears to be a useful effort to complement existing approaches and frame the climate change risk by developing response functions and defining critical thresholds for climate change. The increasing number of sectoral and regional climate impact assessments are likely to provide an improving knowledge base to formulate models and derive better versions of such response functions.

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