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A comprehensive view on climate change: coupling of earth system and integrated assessment models

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Abstract
There are several reasons to strengthen the cooperation between the integrated assessment (IA) and earth system (ES) modeling teams in order to better understand the joint development of environmental and human systems. This cooperation can take many different forms, ranging from information exchange between research communities to fully coupled modeling approaches. Here, we discuss the strengths and weaknesses of different approaches and try to establish some guidelines for their applicability, based mainly on the type of interaction between the model components (including the role of feedback), possibilities for simplification and the importance of uncertainty. We also discuss several important areas of joint IA–ES research, such as land use/land cover dynamics and the interaction between climate change and air pollution, and indicate the type of collaboration that seems to be most appropriate in each case. We find that full coupling of IA–ES models might not always be the most desirable form of cooperation, since in some cases the direct feedbacks between IA and ES may be too weak or subject to considerable process or scenario uncertainty. However, when local processes are important, it could be important to consider full integration. By encouraging cooperation between the IA and ES communities in the future more consistent insights can be developed.

Keywords: integrated assessment, climate change, earth-system model, model linkage, integration

1. Introduction

Climate change is a complex and comprehensive process that can only be understood on the basis of the combined insights from various scientific disciplines. Natural scientists contribute to an improved understanding by looking at issues like the global energy balance, the carbon cycle and changes in atmospheric composition. At the same time, economists, social scientists and engineers provide insights into the drivers of anthropogenic climate change and the options for adaptation and mitigation, and yet other scientists, including geographers and biologists, study the impacts of climate change. Along these lines, it is possible to identify three research communities, sometimes referred to as the 'earth system' (ES), 'vulnerability, impact, and adaptation assessment' (VIA), and 'integrated assessment' (IA) communities[7]. Clearly, important linkages exist between these different areas of research, and in the past the three research communities have already exchanged information on a regular basis. The ES community, for instance, uses the outcomes of IA models in the form of emission and land use scenarios as input to their models (e.g. the IS92 scenarios [1, 2], the SRES scenarios [3] and more recently the representative concentration pathways (RCPs) [4, 5]). Both the IA and VIA communities, in their turn, use climate model output for assessing climate change impacts or socio-economic responses. Many IA modelers have also used simplified climate models, such as the MAGICC model [6, 7], which are calibrated to state-of-the-art ES models.

In recent years the need for integration of information has become stronger [4, 8]. Moss *et al* [4], for instance, explicitly mention the need for a stronger collaboration between the research fields to better account of the possible feedbacks between human systems and the earth system on the global scale. Papers have also shown how climate impacts may influence macro-economic development [9, 10], or how (anthropogenic) land use and land cover change can interact with climate [11–16] and air pollution [17]. Also from a policy-making perspective, integration of knowledge is required. The focus towards more integration can also be seen in current research trends. The ES community, for instance, has extended its focus from a primary interest in the climate system itself to related topics such as the carbon cycle, land use, hydrology and even urban systems. At the same time, the IA and VIA communities are also looking into these same topics, partly as part of joint scenario development [18, 19]. As result, the research agendas of these communities are starting to overlap and closer collaboration becomes increasingly useful. Examples of advanced cooperation can already be found. Voldoire *et al* [11] included the IA model IMAGE in the ES model CNRM-CM3 to look into the interaction of land use change and climate. Bahn *et al* [20] coupled the IA model MERGE to the intermediate complexity ES model C-Goldstein. Hibbard *et al* [21] describe the research priorities in the field of land use modeling from a multidisciplinary perspective. Van Vuuren *et al* [5] describe how the new RCP scenarios have been constructed in a cooperation process involving researchers from the ES and IA communities.

In light of these trends, in this letter we focus on the integration of IA and ES modeling activities in order to improve the understanding of important linkages between human development and environmental change. We discuss the different forms of linkages between IA and ES models, which each have strengths and weaknesses (see further in the letter). It is therefore useful to consider which forms of integration are most suited for different purposes. In the letter, we discuss different research areas where IA and ES models could be coupled and relate these to the various options for information exchange.

[7] These communities are more or less consistent with respectively WG1, WG2 and WG3 of the IPCC.

2. Forms of integration

In both IA and ES research, models are used as tools to quantitatively explore the linkages between various relevant issues and possible future changes. Partly because ES models can build upon more stable 'natural laws', models in the ES field tend to be somewhat more complex than those in the IA field. The cooperation between the IA and ES model communities can take many forms ranging from activities that stimulate information exchange, dedicated joint research programs, data collection or even shared model components. In figure 1, we have schematically indicated the current research areas of the two communities. We use the figure to start describing possible linkages between the communities such as for emissions, land use and climate parameters. Some of these linkages mostly work in one direction. Other linkages, however, lead to feedbacks that either dampen or strengthen the original signal. While many linkages and feedbacks exists within the human and natural earth systems, they also occur between these systems. Obviously, in models, these can only be accounted for if 'code' exists that describes them. Unfortunately, this is not an easy thing to do as it often involves rather 'weak knowledge' that does not automatically translate well into formal equations [22]. For instance, most IA models do not include an impact of climate change on the energy demand for heating and cooling or an impact of extreme droughts on crop yield, based on the fact that knowledge is assumed to be too uncertain. For improving the IA–ES coupling, a critical condition is therefore also to improve the individual model systems that represent the possible responses to either IA or ES information. Here, making some first basic assumptions about how these components could interact, e.g. using simple linear approximations, could provide insight into the potential relevance of interactions justifying or denying more detailed follow-up studies with the coupled approach.

Focusing specifically on the information exchange between IA and ES models (the horizontal arrows in figure 1), we can recognize four different ways in which the interaction can be organized.

(A) Information can be exchanged in one direction from ES to IA models and/or vice versa (as is currently mostly done). Such interaction can be further refined in the spatial, temporal or variable dimension (to take account of more detailed information available within each community).

(B) The representation of the Earth system within IA models can be further improved by advancing the climate, vegetation, carbon cycle and atmospheric chemistry representation within the IA models.

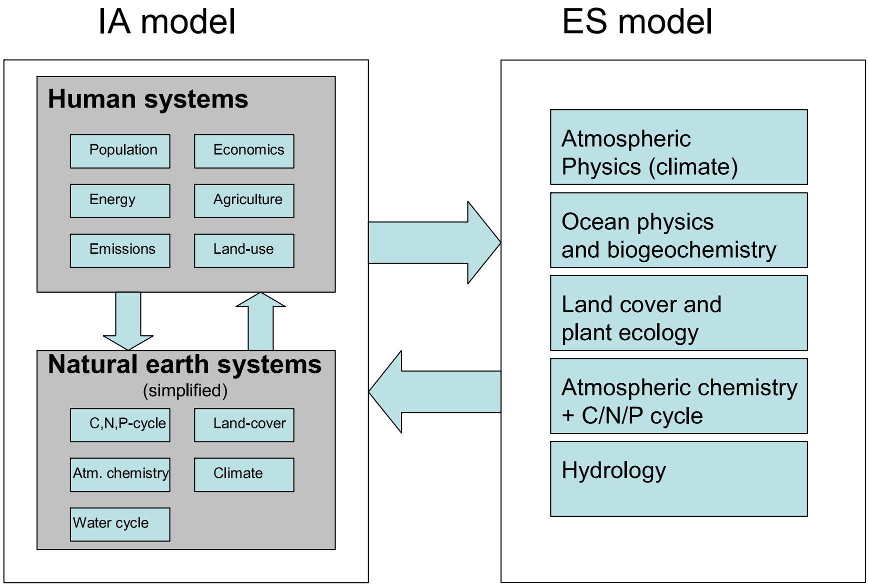

Figure 1. Overview of some main components of IA and ES models. This letter discusses the possible exchange of information (coupling) between these types of models as indicated by the horizontal arrows. The two vertical arrow illustrate the linkage between the human system and natural earth system components that already exists in IA models.

Table 1. Advantages and disadvantages of the different types of IA–ES collaboration.

Method	Advantages	Disadvantages
A (off-line information exchange, one-way)	• Work with existing terminology and tools • Transparent information exchange • Flexibility • Separate research strategies	• Feedbacks are only captured via (one-single) iterations • Potential inconsistencies
B (improved IAMs)	• Allows for good representation of uncertainty • Model complexity tailored to question • Detail in treatment of socio-economic processes	• Lack of detail in treatment of biophysical processes (often meta-modeling)
C (improved ESMs)	• Higher resolution analyses than in IAMs • Detail in treatment of biophysical processes	• Lack of detail in treatment of socio-economic processes • Limitation of model runs limits representation of uncertainty
D (full coupling)	• Assessment of feedbacks • Highest degree of consistency	• Technical difficulties • Lack of representation of uncertainty • Inflexibility • Complexity/intransparency • Limitations in knowledge may hamper progress

(C) The representation of societal elements within ES models can be further improved by advancing, for instance, the modeling of agricultural and water management options within the ES models.

(D) IA and ES models can be fully coupled online, allowing for more or less instantaneous two-way interactions.

These four different interactions also represent increasing levels of complexity (from A to D). We briefly discuss the advantages and disadvantages of each of these approaches (see table 1 for a summary). Spatial and temporal scales also play a critical role here. While IA models tend to describe socio-economic processes at the regional scale, ES models mostly use a more detailed geographical grid. A similar situation holds with respect to time, where socio-economic models often tend to focus on longer time scales (e.g. year) than ES models (parts of a day). If necessary, the difference in scale can be accounted for using downscaling techniques [23, 24], but this may be complex especially for time-related issues. Another scale issue is that also regional IA and ES models exist. While some of the arguments might also apply for these models, regional modeling systems may introduce additional constraints as well.

The simplest form of information exchange is a one-way exchange of information (A). Successful examples of this form include the ES model simulations on the basis of IA scenarios (emissions, land use) and the extensive use of climate output (temperature and precipitation) to assess water scarcity, yields or health impacts in IA and VIA work (even within IA 'model frameworks' one-way coupling is sometimes used [25, 26]). An important advantage of the method is that the various research communities can continue to work with existing tools and terminology and pursue their own research strategy. The interaction between the research communities occurs via a limited number of 'pipes' that can be clearly defined, allowing for a transparent information exchange (soft coupling). The method also allows for a high degree of flexibility: ES models can use the output of different IA models, and IA models can use the output of different ES models. This allows a mapping of various sources of uncertainty in a transparent way and without the constraints related to some of the more complex methods of interaction (such as limited flexibility due to calibration). A disadvantage is that the method can only capture feedbacks through iterations involving potentially large numbers of model simulations to reach an 'equilibrium' solution. This is not a practical solution given the computational time involved in ES model simulations. The method will thus often lead to some inconsistencies (e.g. crops might be grown in the IA simulation under conditions unsuitable for these crops in the ES simulation). In fact, identifying these inconsistencies might be an important reason for type A coupling (and form the basis for more integrated analysis). Identification and quantification of the consequences of these inconsistencies should be an important feature of type A (and B/C) coupling exercises.

The second approach (B) builds further on the idea that IA models have already been designed as a tool for integration: they include a representation of both the human and natural subsystems. This approach therefore aims at strengthening the interaction by improving the natural system representation within IA models. Often, IA models only calculate changes in global mean temperature, and correlate impacts directly to this parameter (if calculated at all). A more advanced method is to downscale the outcomes of a relatively simple climate model using the patterns retrieved from sophisticated modeling systems or observations. Evidence so far suggests that pattern scaling works well for temperature, but less well for other variables such as precipitation [27–29]. While it is even more difficult to capture variability, e.g. temperature and precipitation extremes, some methods exist and the results might not necessarily be worse than the skill of ES models. Approaches have been designed to correct patterns of temperature increase for regional sulfur emissions [30]; similar methods could possibly be developed to capture the spatial impact of albedo change, tropospheric ozone and other aerosol components (processes that are generally not yet included in IA models). Within this approach, there is ample room to represent uncertainty, as the simplified climate models included in IA models can be calibrated to reflect the range of outcomes of different ES models [31]. There is also a relatively high level of flexibility in designing model experiments focused on the specific research question. The success of this pathway depends on whether processes currently included in ES models can be simplified, by either a simpler process model, statistical modeling or by meta-modeling such as the development of emulators or improved pattern scaling techniques. Obviously, the model design will be limited in detail in its treatment of physical processes.

Approach C builds on the observation that ES models are now beginning to include components traditionally considered part of human systems. For instance, representations of urban land cover have been included in earth system models in order to calculate urban heat island effects or the impact of albedo increases in urban areas [32, 33]. In addition, vegetation models included in ES models are beginning to incorporate not just natural vegetation, but also various crop types relevant to the representation of managed land. The incorporation of irrigation and the ability to specify nitrogen-based fertilizer application further extends the human management aspects covered by ES [34]. These extensions provide an opportunity to test the implications of alternative human decisions in ES models. For example, sensitivity analyses exploring the magnitude and extent of a particular aspect of land use could be carried out without requiring new inputs from IA models [13]. The increasing computing facilities allow to apply these ES models at increasingly higher spatial resolutions. Obviously, this method will be more complete in its coverage of physical processes than socio-economic processes. The size of ES model runs may limit the treatment of uncertainty.

The fourth approach (D) is full online coupling of ES and IA models. Given the differences in complexity and computational requirements of ES models, this effectively implies the integration of the IA model into the ES model. The technical difficulties involved in this depend on the type of IA model. For a recursive IA model, in which decisions that are simulated depend on information about current and past conditions, the IA model can be stepped forward in time along with the ES model (although technical problems might still need to be solved). However, for an intertemporal optimization IA model, in which decisions that are simulated also depend on information about future climate conditions, integration will require whole new modeling techniques (e.g. using a simplified version of an ES model (preferably the one used in the integration) to provide information of future conditions, or running the IA model in some myopic way). This type of integration allows potentially full assessment of the feedbacks between the human and earth system while retaining the full capabilities of the ES model. It could achieve the highest degree of consistency. The method, however, also involves the highest additional costs. First of all, it introduces additional complexity in the models, among others because models originating from very different scientific disciplines are coupled, each with specific terminology, focus etc. Second, as the approach typically combines only one ES model and one IA model, there is a loss of flexibility and representation of the full uncertainty space: the range of outcomes originating from using different ES or IA models is not taken into account. While theoretically many ES models have been formulated in a modular fashion with coupling software, in practice setting up the coupling is likely to be too labor intensive to allow for couplings with different models.

A third risk to the approach is that the high level of complexity may also lead to intransparency.

Currently, the trend in model development seems to suggest that there is a 'natural' evolution from A towards category D-type models. However, there are clear strengths and weaknesses to each of these approaches as indicated above. In that light, it is possible to formulate a set of criteria that may be used to assess which type of integration is most suitable to address a given scientific question.

(1) If a one-way linkage between the human and the earth system is dominant because feedbacks are weak, very slow, or non-existent, category A type cooperation is the most appropriate.
(2) If interactions in both directions are known to be significant and the relevant processes can be represented by relatively simple formulations, category B is the best way forward. Most environmental change processes that take place at an aggregated scale (e.g. radiative forcing by long-lived greenhouse gases) or that can be derived from changes at an aggregated scale, fall into this category.
(3) If the main focus is on the natural system and the relevant human system processes can be represented by relatively simple formulations, category C seems the best way forward.
(4) If interactions are known to be significant (or exploration of this possibility is the goal), the relevant processes have a relatively large spatial and temporal variability and these processes cannot be adequately represented in simple models, category D is the desired option. Non-linear threshold behavior (e.g. collapse of a system under specific conditions that may become more likely with climate change) could be a reason to consider category D-type modeling as well.
(5) Uncertainty is important in the choices. If the uncertainty in involved processes and interactions is large, category A or B is probably most useful, at least as a first step allowing the flexibility to explore the full uncertainty range (certainly in light of the natural variability in ES runs). If results of these explorations suggest the possibility of a strong feedback effect, C or D analysis could be a useful next step. Exploration of uncertainty in feedbacks will be more difficult in type D calculations, given their higher computational demands.
(6) Criteria 2 and 5 considered together can also be formulated as follows: it is only useful to consider category B, C or D if potentially strong feedbacks are involved and the processes involved are rather well established.

3. Examples of potential human dimension–physical system interactions

We now discuss some IA–ES interactions that we believe warrant further exploration. This list does not intend to be complete; above all we aim to show how IA–ES cooperation can be encouraged and what forms of cooperation (A, B, C, D or a combination of them) could be most suitable given the considerations and criteria in section 2.

3.1. Impact of climate change on energy use

Climate change can influence production and use of energy in several ways; it can influence (1) the potential of renewable energy, (2) the required cooling of power plants, (3) the additional energy demand for adaptation/mitigation measures (e.g. desalinization) and (4) heating and cooling energy demand [35]. Regarding the first factors: climate change impacts on the costs and potential of renewable energy resources are uncertain and may in fact be positive or negative [36]. In general, these impacts are considerably smaller than the uncertainties associated technology development of these resources. Impacts of climate change on cooling of power plants can be important (some estimates suggest a loss of efficiency of 0.5–0.8% for 1 °C of warming [36]) but various adaptation options exist. Regarding the impact on heating and cooling demand, Isaac and van Vuuren [37] show that climate change could result in a decrease in heating demand (by over 30% in a default scenario) and an increase in cooling demand (by about 70%). As globally these effects go in opposite directions, the impact on global greenhouse gas emissions was found to be small: in their default scenario, Isaac and van Vuuren estimate the total amount of additional CO_2 emitted in the 21st century to be less than 1% of the total anthropogenic emissions. Consistent results for specific regions are reported by Aebischer *et al* [38] and Hadley *et al* [39]. For a standard climate sensitivity and forcing estimate, this amount of CO_2 would result in an additional warming of about 1.4×10^{-2} K. We thus arrive at a feedback factor (i.e. the further warming due to the changed heating and cooling) of around 1% of the original warming. The (small) greenhouse gas consequences of most of these issues can be accounted for in category A or B/C type integration. It should be noted, however, that the impacts on cooling and heating mostly occur in different regions. Therefore, the impacts on climate might be somewhat larger at the regional level as a result of impacts on air pollutant emissions (aerosols, ozone formation) and the subsequent implications for climate [40].

3.2. Impact of climate change on transport and shipping routes

Climate change could impact transport routes. The most important could be the potential opening of the northern shipping route (allowing shipping through the Arctic between Europe, North America and Asia) [41] leading to an increase of local emissions of greenhouse gases, short-lived pollutants and ozone precursors [42]. Given the special role of the Arctic region in climate change dynamics, this could have important local feedbacks on climate [43], which in turn could have economic consequences. It is still very uncertain when and how fast diversion traffic will emerge. Corbett *et al* [44] assume a scenario where it is 1% of global shipping in 2020, 2% in 2030 and 5% in 2050. According to Granier *et al* [45] the NO*x* emissions from Arctic shipping could be in the range 0.65–1.3 Tg N yr^{-1} in 2050. Corbett *et al* arrive at a contribution of 0.7 Tg N yr^{-1} in 2050. It requires model simulations to accurately simulate the resulting impacts on tropospheric ozone and aerosol concentrations and the associated radiative forcings. As a first-order guess we make the crude assumption that the RF from the ozone produced by Arctic shipping in 2050 is of a similar order of magnitude to the RF due to the ozone produced by present-day global shipping, which according to Eyring *et al* [46] is about 2.6×10^{-2} W m^{-2}. This results in an estimated additional warming from Arctic ship emissions of 0.02 K or a feedback factor (i.e. additional warming as a result of climate impact on transport routes) of about 1%. Obviously, the direct and indirect effects of the particulate matter resulting from the Arctic ship traffic should also be taken into account, but it is likely that category A coupling approaches would suffice to further explore the strength of these couplings, prior to applying more complex methods.

3.3. Interaction between climate change and land use

One of the most important reasons for strengthened IA and ES interaction might be the feedbacks between land use/land cover and climate [21]. The importance of representing dynamic vegetation in ES models is well known and it is equally known that human activities play an important role in land use/land cover trends [11–15, 47]. This may lead to several relevant IA/ES feedbacks. For instance, climate change may impact decisions (simulated within an IA model) on where to grow crops and which management approaches to apply, which in turn influence climate via emissions and albedo [48, 49].

We elaborate this further using some examples. For instance, in South and South-East Asia climate change [50] and its consequences for the monsoon [51–53] could significantly alter the suitability of crop growth in this area and require adaptation measures [54] such as more irrigation [55, 56]. In the Amazon Basin, deforestation contributes to climate change via well-mixed greenhouse gases but also local dynamics (changes in the local hydrological cycle) [57–59]. In both examples, category A approaches could give a first overview of the significance of interactions and feedbacks, but more complex approaches could be subsequently used to further explore these feedbacks (the choice between these approaches would depend on the focus on economic and policy mechanisms versus the focus on issues like climate variability and local feedbacks; strong local feedbacks could even warrant type D approaches). Clearly, changes in agricultural management are highly important for climate–land use studies [47]. For instance, current agricultural in Sub-Saharan Africa (90% rain-fed agriculture) is highly vulnerable to droughts [48]. While irrigation could be a measure to reduce this vulnerability, it also affects climate by increasing latent heat flux, reducing surface temperature (a negative climate feedback). In this case, a D-type approach might be used to appreciate the changes in agricultural production and local climate in this region. Interactions could also be related to land use decisions influencing the occurrence of fires. This could influence climate and human activities directly or indirectly [60]. Of key interest are also the biogeochemical and biophysical feedbacks of land use related mitigation options such as bio-energy [61] and afforestation [15]. In fully integrated analyses, the human decisions could be based on observed impacts, including those related to albedo and regional heat and fresh water balances. Such changes are reported to be relevant at least at the regional scale, but possibly even globally [62]. While category A and B cooperation can be used to further explore the importance of the various feedbacks, they would warrant category D linking if feedbacks are strong. A final example relates to the implications of land cover patterns for atmospheric chemistry and, indirectly, climate change. These interactions are very complex possibly warranting a highly integrated approach, but first explorations so far have shown these effects to be rather small and only of local relevance [17].

3.4. Interaction between air pollution and crop growth

Another class of interactions is those between emission of air pollutants, deposition, concentration levels and vegetation processes. For instance, ozone concentrations can have a considerable impact on the growth of both natural vegetation and crops [63–65]. This, in turn, could lead to different trends in the agricultural production and, subsequently, land use change emissions. Similar relationships exist for nitrogen. There are, however, still large uncertainties involved in our understanding of the processes involved in this interaction including biogenic sources of reactive nitrogen and carbon, jointly determining ozone production in pristine conditions, and dry deposition and, particularly, deposition impacts. Therefore, at this point in time it seems that type A cooperation would be most useful to explore the strength of different impacts, followed by more complex linkages.

3.5. Interaction between climate policy and air pollution policies

The interaction between climate policy and air pollution control has received increasing attention. While originally the focus was mostly on ancillary benefits and trade-offs of reducing greenhouse gas emissions on air pollutants (e.g. [66–68]), more recently focus has shifted to the joint benefits of reducing black-carbon and ozone precursors emissions and to optimal strategies for reducing aerosols emissions [69]. In many cases, the impacts of reduction of emissions of air pollution precursors on climate are highly non-linear and require further improvement in terms of the representation of spatial and temporal variability in these emissions, dispersion, and deposition of these pollutants (for instance while climate change mostly focuses on long-lived GHGs, for air quality issues fine geographic scales and short time scales are relevant). Still, it would seem logical to further pursue assessments to the first-order interactions between these two global change themes by type A and B/C cooperation.

3.6. Droughts, availability of water and impacts on societies

A key factor of interaction is the availability of water. Water is needed for agriculture, energy production, residential water demand and industry and will be influenced by climate change. These impacts could, certainly locally, be so strong that they would influence the human activities sufficiently to create feedbacks. Both IA and ES researchers are currently integrating water availability and use into their models. It should be noted, however, that given the uncertainty in precipitation patterns, research will have to be more focused on determining the possible strength of these linkages than on real predictive power. Based on progress in these developments it is useful to study these feedbacks using B/C and D types of cooperation.

3.7. Mitigation policy responses to realized/projected climate change

Often scenarios are designed by selecting a long-term climate target. In reality, however, it is much more likely that policy decisions are based on short-term trends and observations. In IA research, work has been done on how observation may reduce uncertainty after some time, influencing the optimal decisions on climate policy [70] (type B). Using more complex climate models adds the opportunity to focus on variability, but if relevant there are likely simpler ways to achieve this. It is therefore not likely that this requires fully integrated models.

3.8. Extreme and catastrophic events

All possible disruptive consequences of climate change on the human economy qualify theoretically for type D coupling. For instance, if the shut-down of the thermohaline circulation (THC) leads to severe climate impacts [20, 71], it would certainly also impact economic growth (and thus create a feedback). Other examples of such tipping points are major catastrophes in the agricultural sector or very strong sea-level rise leading to loss of economic activities in coastal zones [72, 73]. So far, however, most studies suggest that such extreme events have a low or unknown probability of occurrence and, moreover, are poorly captured by models (given the associated non-linearities). Moreover, we also have little knowledge on how economies react to such events, including the potential for adaptation or maladaptation [74]. Research will therefore be mostly explorative at this stage, for instance by using indications of possible outcomes from ES models to explore the sensitivity in IA models, despite the model limitations mentioned above (type B). Such information could include possible ranges of signal strength and in some cases (for extreme events) an indication of probability.

3.9. Avoiding particular (regional) climate change outcomes or impacts

Research may also focus on mitigation or adaptation responses to specific regional climate outcomes (such as coral bleaching as a result of sea surface temperature increase). Clearly, such impacts cannot be modeled using a simple model that produces only globally averaged outcomes. Even global models with high spatial resolution may be insufficient, since in many cases additional model dynamics will be needed (in the example above, for instance, regional ocean acidification). Interaction with socio-economic modeling could help with understanding the possibilities to avoid these impacts, especially if responses to these impacts could involve specific local dynamics. In this context, it is important to note that at the local scale, other processes are often more important than at the global scale [40]. While many of them might not have a strong enough forcing to affect the global climate, they can define climate risk at the regional scale. This involves innovative research as these processes are often still missing in global models. Regional impacts might possibly be dealt with using B- or C-type cooperation—although it would likely require developing new emulation or pattern scaling techniques. Alternatively, one could consider more complex, D-type, cooperation with full integration of models, when local interactions between climate and impacts are relevant (such as wide-spread irrigation; [75]).

3.10. Other areas of research

Other possible couplings may exist. For instance, it has been suggested that climate change could also be a factor in determining future migration flows (either as an underlying driver of economic impacts or more directly in short-term events) [76, 77]. Migration would obviously result in significant feedbacks to the original scenario drivers. Another topic includes the impact of climate change on tourism (and thus transport and, locally, economic growth).

4. Conclusions

In this letter, we have indicated that there is a need for further cooperation between the different communities studying climate change. In this context, we have specifically focused on the potential of enhanced collaboration in the form of coupling IA and ES models. As discussed in section 3, there are many examples of areas that are useful to study from both disciplines and where interactions are likely to exist. The cooperation can differ from coordinated exchange of information, the introduction of simplified representations of new processes in the models used by the IA and ES communities, and finally full model integration. These cooperation modes all have strengths and weaknesses (see table 1). The most suitable type of cooperation depends on factors like the expected strengths of the interactions, the existence of feedback mechanisms, the role of uncertainty and the advancement of science. In this light, we have discussed a set of criteria that might be used in deciding which mode of cooperation is most suitable. While full integration can potentially deal with feedbacks and consistency issues, it also leads to rather complex models and little flexibility in exploring uncertainty.

Next, we discussed a wide range of areas where IA and ES model coupling would make sense. Important areas, for instance, include the land use and land cover dynamics, the interaction between climate change and air pollution, and the role of water and droughts. Also, the impact of climate change on energy use and production, and the role of extreme events could be very relevant. Using the considerations on the most suitable forms of cooperation, we found that often simplified representations of IA and ES dynamics will be sufficient to deal with the possible linkages. In some cases, feedbacks seem to be too small to warrant more complex coupling. In other cases, linkages mostly occur via global mechanisms that can also be captured by more simple approaches. Finally, simpler approaches are more flexible in exploring uncertainty. Still, based on further cooperation between the two communities, it is likely that more complex model linkages will become more important in the future. Full integration seems to be most useful for studying local impacts, including those related to land use, as here one would benefit from the high resolution of ES models. Some of the local feedbacks are strong enough to make a difference, maybe even at higher levels of aggregation.

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