23 **WORKING PAPER**

Visualizing Vulnerability and Impacts of Climate Change

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Abstract

Are there new ways of visualizing and communicating the future likely impacts of climate change? This report looks for any that could be used as a single tool to help bridge two gaps: the gap between scientific consensus and popular belief, and the gap between broad-brush information on impacts and vulnerability, and the level of information that decision-makers and stakeholders need to help them make better decisions. A brief review is given of current spatial modelling of climate change impacts, together with some indications of how impacts work has been combined with landscape visualization. This is followed by an overview of scenarios of future climate change impacts and the issues related to uncertainty. Methods for representing urban and rural vulnerability are discussed, with some treatment of thresholds. The communication of vulnerability in promoting public debate, individual action, and communal and policy action is addressed, particularly in relation to the possible future development of visualization science. The report concludes with a summary of some of the outstanding issues, and possible ways of advancing this important but difficult agenda.

Contents

1. The Problem

For those in a position to know, the basic facts of climate change are not in doubt—the "Summary For Policy Makers" from the Intergovernmental Panel on Climate Change (IPCC 2007) is clear: "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level". The report also concludes that "...most of the observed increase in the globally averaged temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007). The evidence keeps mounting.

A recent paper shows that significant changes in physical and biological systems are occurring on all continents and in most oceans, with a concentration of available data in Europe and North America: "Most of these changes are in the direction expected with warming temperature. Here we show that these changes in natural systems since at least 1970 are occurring in regions of observed temperature increases, and that these temperature increases at continental scales cannot be explained by natural climate variations alone. ...we conclude that anthropogenic climate change is having a significant impact on physical and biological systems globally..." (Rosenzweig et al. 2008).

Although climate change will impact severely on most developing countries, they are responsible for only a small part of the global greenhouse gas emissions that are largely driving the changes in climate and climate variability. Globally, there is a huge imbalance between the emissions that emanate from the North and those that come from the South. For example, the 19 million people living in New York State have a higher carbon footprint than the 146 Mt CO_2 left by the 766 million people living in the 50 least-developed countries (UNDP 2008).

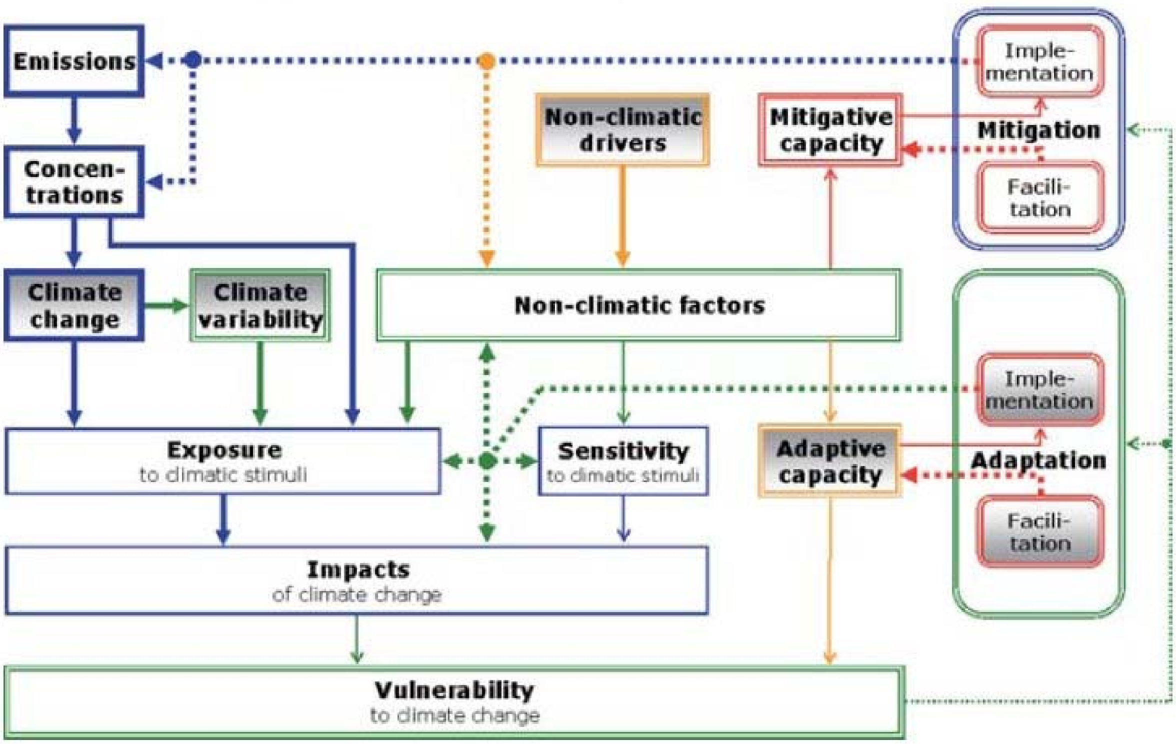
> Climate change will have severe impacts in many parts of the tropics and subtropics. Africa will likely suffer considerable changes in climate and climate variability, with profound reductions in agricultural productivity and knock-on consequences for livelihoods and food security. Climate change will add significantly to the development challenge in Africa.

The survey by Pidgeon et al. (2008) found no great enthusiasm for substantive action on the part of the UK public against climate change, which itself is not seen as a great problem. This is in stark contrast to the likely impacts outlined in the Fourth Assessment Report (AR4; IPCC 2007). Clearly, ordinary people continuously have to be persuaded that climate change is a classic example of "action at a great distance" that needs to be addressed seriously at the local level, everywhere. An example where this is being done is Tearfund's campaign "Don't be Derek" of 2007-2008, which addressed the connection between mitigation actions in the developed world and reducing "harm to neighbours" in the developing world (see http://www.tearfund.org/Campaigning/Derek/). But much more needs to be done.

> Many of the deleterious impacts of greenhouse-gas emissions will eventually be felt in developing countries, rather than in the countries largely responsible for producing them. A disconnect persists between the science of climate change and how the general public sees the problem.

Another apparent disconnect lies between the broad-brush approaches to evaluating impacts and assessing vulnerability, as in recent global and regional assessments (MA 2005; IPCC 2007), with identifying the likely impacts of climate change on specific communities and landscapes and helping local communities adapt. The disconnect is both temporal and spatial. Regarding the temporal disconnect, Washington et al. (2006) argue that addressing the issues associated with long-term climate change through focussing on risk management may be the most effective way of approaching the informational and institutional gaps that currently are limiting progress. Regarding the spatial disconnect, the methodological problems associated with downscaling from coarse-resolution climate models to the scales of interest to local communities, for example, are severely limiting progress on assessing local-level impacts and identifying entry points for adaptation options. The provision of local climate change scenarios, coupled with information on projected impacts of climate change on water availability, agriculture, and infrastructure, are needs that have been identified as being critical for effective adaptation (e.g., see FFL 2008).

This report looks for new ways of visualizing and communicating the likely future impacts of climate change that could be used as one tool to help bridge two gaps. The first gap lies between scientific consensus and popular belief. The second gap lies between broad-brush information on impacts and vulnerability, and the level of information that decision-makers and stakeholders often need to help them make better decisions. There probably are such tools, but designing and implementing something appropriate and effective is far from easy. Much of the visualization work outlined in the report was developed to inform the debate on climate change (the first gap). But the report focuses more on the prospects of using some of these tools to "localize" global and regional scenarios in appropriate ways so that impacts and adaptation options can be assessed at the local scale (the second gap). A great deal has been written about impact assessment, vulnerability, adaptation, etc. Figure 1 shows the conceptual framework proposed by Füssel and Klein (2006), which is a useful way of presenting the major relationships between these and other terms in relation to climate change work.



KEY: Thick solid arrows: physical cause-effect relationship; thick dotted arrows, effect of human actions; thin solid arrows, functional relationships; thin dotted arrows, perception and interpretation of information.

Figure 1. Conceptual framework for an adaptation policy assessment (the fourth level in an evolutionary pathway). For a full interpretation, see Füssel and Klein (2006), from which this is copied.

A key missing piece in this framework is the "user" or consumer of the information generated, which ultimately constitutes the feedback from the vulnerability information at the bottom of the figure to other parts of the system, such as the enhancement of adaptive capacity—i.e., all the many different stakeholders who may affect, and be affected by, the various elements in the framework. With that proviso, the sections of this report can be roughly mapped onto Figure 1. Section 2 contains a brief review of current spatial modelling of climate change impacts, together with some indications of how impacts work has been combined with landscape visualization (this addresses parts of the "impacts" box). Section 3 contains a brief overview of scenarios of future climate change impacts, particularly related to the issue of uncertainty; these scenarios ultimately define the "climate change", "climate variability", and "non-climatic factors" boxes in Figure 1. Section 4 looks at methods for representing urban and rural vulnerability, and includes some discussion on thresholds (the "vulnerability" box). Finally, section 5 discusses the communication of vulnerability in promoting public debate, individual action, and communal and policy action, particularly in relation to the possible future development of visualization science. This is the (missing) feedback link from the "vulnerability" box in Figure 1 to some form of human action that positively affects the system in some future time period.

2. Spatial Modelling and Visualization of Climate Change Impacts

A Brief Review of Current Work

The global average surface temperature increased by about 0.6 °C during the twentieth century (IPCC 2001). Climate model projections from 2001 suggest an increase in global average surface temperature of between 1.4 °C and 5.8 °C to 2100. The range depends largely on the scale of fossil-fuel burning between now and then, and on the different models used. Precipitation increases are likely in high latitudes, while the tropics and subtropical land regions will probably see decreases in most areas (IPCC 2007). Weather variability is likely to increase, although with current knowledge, not a great deal can be said about the extent and spatial variation of this increased variability.

The combination of generally increasing temperatures and shifting rainfall amounts and patterns will impact on sea level, fresh water, ecosystems, human health, and food systems. Quantifying what some of these impacts will be can involve long sequences of models. The outputs from coarse-scale climate models, typically with resolutions of 2º latitude and longitude, are sometimes used directly, particularly to assess global impacts on sea-level rise, for instance. In many studies, these coarse-scale outputs will need to be downscaled using any one of a wide variety of downscaling methodologies, each with particular strengths, weaknesses, and real or potential errors (Wilby et al. 2008).

The problem with all downscaling methods is that weather and climate in any location are governed by physical processes that cannot be taken into account at the coarse level of detail at which climate models currently operate. Daily, weekly, or monthly weather data might then be used that are characteristic of some future climatology (defined on the basis of a specific greenhouse-gas emission scenario) that can be used in combination with a whole range of other models. These may be agricultural sector, partial equilibrium models driven by variables such as population growth, income growth, agricultural trade, yields of crops and livestock, and shifts in human diets. These models provide outputs such as future crop areas, crop and livestock production, commodity prices, food and feed demand, net trade, and poverty rates. The IMPACT model developed at the International Food Policy Food Research Institute (IFPRI) is an example (Rosegrant et al. 2005). Other types of models that can be driven by downscaled climate data include land-use models, crop and livestock productivity models, and fishery models.

In all these cases, outputs are generally spatially disaggregated and are amenable to some form of spatial analysis and spatial display. Much of the agricultural impacts work to date has been carried out at relatively low spatial resolution, often at the scale of the globe, region, or country (e.g., Parry et al. 2004; Cline 2007; Lobell et al. 2008), but higher-resolution impacts work is increasingly being carried out.

> Sometimes impact work uses regional (rather than global) climate models. We need more detailed information on how climate change impacts on agricultural and livelihood systems, so that effective adaptation options can be appropriately targeted. Organizations with a "pro-poor" mandate in developing countries would benefit from this. But our current levels of understanding are limited regarding local-level impacts of climate change.

Uncertainty at the local-level impact of climate change relates to the uncertainties involved in downscaling global (or even regional) climate model output to the high spatial resolutions needed for effective adaptation work, and the problems that exist in objectively evaluating its adequacy.

As noted in section 1, a significant gap also lies between the information that we currently have at seasonal time scales and the information we have at "climate-change" time scales (2050 and beyond). Nevertheless, the outputs of such models are increasingly being used for a wide range of purposes. Most of the visualization of the outputs of impact and vulnerability analysis is in relatively traditional formats, e.g., graphs, charts, and maps. Various types of uncertainty are associated with such modelling. Results will often need to be presented with error bars, if these can be calculated appropriately from model output. The uncertainties in the climate models themselves and the unknowable future are usually addressed by presenting model results for several combinations of climate model and greenhouse-gas emission scenario, and looking at the range of model output that arises. In linked chains of models, however, where the output of one is used as input to another, it is still often the case that these are beset by problems of data availability, and perhaps more importantly, by issues of uncertainty and errors that often remain unspecified, unquantified, and unappreciated by the people looking at the results.

> Information about what is likely over the next 3 to 20 years is largely missing. This presents a critical problem, as this time scale is vital for political negotiation, for assessing vulnerability and the relationship with the Millennium Development Goals, and for agricultural planning.

Maps are a common form of visualization, but with some problems. One is that maps are often not explicitly recognized for what they are: they are essentially probability statements, rather than definitive statements about what may be found in particular places. It can happen that viewers of maps will zoom in to an area they know well, perhaps the area they come from, if it is on the map. If the map does not reinforce what they know (or think

> A common form of visualization is the presentation of model results in the form of maps. However, there are various problems with maps. Credibility in the entire map can be destroyed on the basis of one pixel. A more common problem is that the map will be taken as definitive, and users just accept it as it is. How effective maps are in influencing decision-making behaviour, with or without uncertainty represented explicitly, is another question.

they know) of the area, then credibility in the entire map may be destroyed. Or a map may be taken as definitive and users will suspend all critical faculties in interpreting it. Both situations are clearly undesirable, but could largely be avoided by including information on the uncertainty inherent in the map.

A large literature is available on uncertainty in spatial data, both in terms of classifying the sources of uncertainty in such data (e.g., Thomson et al. 2005), and in setting out methods that can be used to incorporate notions of uncertainty in mapped output for decision-makers. Griethe and Schumann (2005) note that the available techniques for the display of uncertainty have tended to be developed for certain specialized domains, and include utilization of free graphical variables, integration of additional graphical objects, use of animation, interactive representation (e.g., a clickable map), and addressing other human senses such as hearing and touch. A considerable agenda of work in this area still remains, however.

How effective is the use of maps in influencing decision-makers? In an example of presenting stakeholders with vulnerability maps, the actual usefulness of the assessment in directly influencing decision-makers appears to have been extremely limited (Patt et al. 2005). At the time of writing, they had searched for and failed to find any examples of other vulnerability assessments achieving more. This issue is returned to in section 5.

Landscape Visualization

A substantial literature is now developing on the visualization of the impacts of climate change, often using high-performance computing techniques. For example, Dockerty et al. (2006) describe a method based on two forms of visualization—digital photomontage and a real-time landscape model—that can be used as a basis of interaction with stakeholders to look at different scenarios of the possible outcomes of policy options on agricultural landscapes in a region of the UK. This included climate change impacts. Other examples include the work of Dockerty et al. (2005) on Norfolk agricultural landscapes and Brown et al. (2006) on coastal erosion, also in Norfolk. Sheppard (2005) contains a useful overview of a range of studies, including investigation of landscapes and snow cover in the Alps in the middle of this century, and the possible impacts of sea-level rise in the Netherlands by 2020. Another example is FloodRanger (http://www.discoverysoftware.co.uk/FloodRanger.htm), originally developed to help visualize flood risk in the UK. It is an educational game about managing flood defences along rivers and coasts. The objective is to defend urban areas and sites of special scientific interest while maintaining levels of housing and employment for an expanding population. It uses a virtual terrain loosely based on the east coast of England, and the user/player can select among different climate change scenarios.

Nicholson-Cole (2005) and Sheppard (2005) both provide an overview of the ways in which landscape visualization may be able to be used for promoting environmental awareness and action, summarised below. They include the benefits that it can be a means of integrating science and intuition, engaging lay-people and involving their personal experience, and is highly flexible in presenting different options or choices. These would seem to constitute powerful justification for continued attention to developing visualization techniques for understanding and communicating information about future landscapes under different scenarios of climate change.

Potentially beneficial attributes of landscape visualization for promoting environmental awareness and action (from Sheppard 2005).

Integration of science and intuition	The combination of the predictive capabilities of modelling and GIS with the intuitive and experientially rich media of photography and realistic representation, with meaningful socio-cultural associations for communities that may help strengthen more informed perspectives in decision-making.
Engagement of lay-people	The attractiveness of virtual reality and its novel applications to conventional planning problems may be helpful in getting multiple stakeholders to engage in public processes.
Personal salience	The ability to localize and ground the information by detailed depiction of recognisable and well-known sites as they would be seen by local residents or users, as opposed to a detached plan or aerial view or an expert's conceptualisation.
Presentation of choices for the future	The ability to present alternative futures side-by-side and over time, posing 'what-if' questions in the search for preferred or acceptable environmental solutions over the long term.
Flexibility of tool	Digital visualization techniques can be modified or customized to emphasize important information or condense complex details, to fit the presentation to the needs and capabilities of the user.

At the same time, some issues need to be borne in mind in landscape visualization. Nicholson-Cole (2005) and Appleton and Lovett (2005) identify the following:

- Landscape visualizations are necessarily generalized and the level of detail, although variable, can never be equal to that of reality.
- Diverse interpretations of the same virtual landscapes may sometimes be possible.
- Situations will occur where there is a level of dependency on prior knowledge to interpret images of landscape scenarios where an "informed" choice is required, although this raises difficult issues of different kinds of knowledge and power relations in policy-making.
- Images can trigger strong emotional responses, sometimes inadvertently, that can focus attention on issues that researchers might regard as secondary or incidental.
- There is a potentially trivialising effect by viewing landscape scenarios through an interface that is more usually associated with "fun" than "function".
- The background and age of the sample being exposed to landscape visualizations in a multimedia or a virtual-reality setting can have significant implications for the kind of interaction people will have with the images. Some groups are more accepting than others of these kinds of information interface, and others (e.g., those with wide experience of video-gaming) may have high expectations that may be disappointed.

Landscape visualization is one of a group of methods and tools sometimes referred to as "visual representation", which may be of different types and complexity. For example, there are specialized stand-alone environments such as the Macaulay Institute's (2008) Virtual Landscape Theatre, consisting of a large curved screen and a system of multiple computers and projectors. This is used for various purposes, including obtaining feedback from stakeholder groups on different types of landscape changes, such as changes in woodlands and vegetation, wind farm developments, and urban expansion. Ball et al. (2008) present some examples in landscape planning. A simpler but more widely available (web-based) example is using Google Earth (http://www.dfid.gov.uk/news/files/climate-google-earth.asp). It is a useful platform for presenting a wide array of spatial data, and probably a great deal of visualization work could be done using this kind of medium.

Several writers have noted that tensions may occur in the use of landscape visualization and similar methods, particularly at the intersection of values about landscape and change and the processes by which these are communicated and understood by a wider audience (MacFarlane et al. 2005). In a study of coastal erosion in the UK, Brown et al. (2006) note that, for local people, issues relating to loss of property and livelihood are obviously of high concern. For coastal managers, this raised fears that the transfer of this sensitive information to the general public could potentially undermine ongoing planning procedures. In effect, the awareness-raising value of the visualizations was being deemed counter-productive. This is not an uncommon theme in the literature. Dietz et al. (2004) found considerable reluctance to place model results explicitly in the public domain, despite general support for the modelling process.

This raises the broader issue of involvement and inclusion in consultation and decision-making processes. Clearly, "consultation" merely involving one-way communication of preferred options (and restricting wider access to other visualizations for some reason deemed undesirable) is no consultation at all. Yet relatively wide participation in decision-making may lead to unintended consequences, some of which may well be negative from a broader, societal perspective. Giupponi et al. (2008) argue that some methods and tools can reduce the risks of unintended consequences from wide participation (e.g., expert opinion, stakeholder identification, cognitive mapping, and network analysis).

Most importantly, however, they argue that genuine consultation has to be done within a methodological framework that provides an appropriate operational protocol. They outline one such framework, built around problem identification, analysis of the actors involved, analysis of the problem itself, participatory modelling and design of whatever decision support is needed, analysis of alternative options, and implementation of the preferred options with subsequent monitoring and possible modification if needed (Giupponi et al. 2008). Whatever its details, it does seem that some sort of framework is needed to effectively facilitate the involvement of a wide range of stakeholders from different backgrounds in information exchange and decision-making. An appropriate framework may be able to address some of the information sensitivity, credibility, and stakeholder inclusion issues that can dog more ad hoc approaches to consultation. This appears to be a key researchable issue, particularly in relation to using some of the tools of visual representation, and this issue is briefly revisited in section 5.

3. Pragmatic Scenarios of Climate Change

This section contains a brief discussion of scenarios because the future impacts of climate change, and the actions that people will need to take to adapt, are largely dependent on a whole raft of assumptions about the future. Glenn (2006) states: "A scenario is a story with plausible cause and effect links that connects a future condition with the present, while illustrating key decisions, events, and consequences throughout the narrative". He notes that projections are often confused with scenarios. Good scenarios include projections and forecasts based on the cause-and-effect linkages of the specific scenario. Much work has been done on scenarios of climate change in the last few years, most notably the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000) that was assembled for the IPCC's Third Assessment Report in 2001. These scenarios are still being used (including for the Fourth Assessment Report of 2007), and a few of their general characteristics are shown below.

A1. A future world of rapid economic growth, global population that peaks in mid-century, and rapid introduction of new, more efficient technologies. Convergence among regions and increased cultural and social interactions and reduced regional differences in income. Three energy-system alternatives: fossil intensive (A1FI), non-fossil energy sources (A1T), a balance across all sources (A1B).

A2. A very heterogeneous world based on self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

B1. A convergent world with the same global population as A1 but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and introduction of clean, resource-efficient technologies. An emphasis on global solutions to economic, social and environmental sustainability, but without additional climate initiatives.

B2. An emphasis on local solutions to economic, social, and environmental sustainability. Global population increases at a rate lower than A2, with intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1. Oriented towards environmental protection and social equity with a focus on local and regional levels.

Basically, the "A" scenarios have more of an emphasis on economic growth, the "B" scenarios on environmental protection. The "1" scenarios assume more globalization, the "2" scenarios more regionalization. Table 1 summarizes the impacts on climate change that these scenarios give rise to, in relation to the greenhouse gas emissions associated with them. These cover the entire range of the climate change impacts discussed in IPCC (2007).

Table 1. Projected globally averaged surface warming and sea level rise at the end of the 21st century. From IPCC (2007).

	Temperature change (°C at 2090-2099 relative to 1980-1999)		Sea level rise (m at 2090-2099 relative to 1980-1999)
Case	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations	0.6	0.3 - 0.9	-
B1 scenario	1.8	1.1 - 2.9	0.18 - 0.38
A1T scenario	2.4	1.4 - 3.8	0.20 - 0.45
B2 scenario	2.4	1.4 - 3.8	0.20 - 0.43
A1B scenario	2.8	1.7 - 4.4	0.21 - 0.48
A2 scenario	3.4	2.0 - 5.4	0.23 - 0.51
A1Fl scenario	4.0	2.4 - 6.4	0.26 - 0.59

The SRES scenarios have attracted some criticism, partly because the projections for human population have become out-of-date surprisingly rapidly. While some have criticized the population and economic details, the scenarios are generally internally consistent and constitute a useful set of standards, and the range of future greenhouse gas emissions is undisputed (Tol et al. 2005). Of course much work has been done not based on the SRES scenarios, for example Outsights (2004) looked at possible impacts on poverty to 2030, using four distinct but not climatically explicit scenarios.

For climate change impact work, much is to be said for using the SRES scenarios. They have been built on in many ways. For example, they formed the basis of a set of scenarios that combined climate change impacts with different socio-economic futures for the UK (Hulme et al. 2002). They were used also as one of the bases of the scenarios of the Millennium Ecosystem Assessment (MA 2005), although the MA scenarios were transformed with additional detail, to define four scenarios: Global Orchestration (GO), TechnoGarden (TG), Order from Strength (OS), and Adapting Mosaic (AM). In terms of greenhouse gas emissions, GO is essentially equivalent to SRES A1B, TG to B1, OS to A2, and AM to B2. These MA scenarios (and hence the appropriate SRES scenarios) were used also in the International Assessment of Agricultural Science and Technology for Development (IAASTD 2009), although they are not reported on directly in the report itself. The MA scenarios were used as a basis for looking at possible futures of the livestock sector in developing countries to 2030 (Freeman et al. 2007). There are many other examples. The SRES scenarios have been used to look at the possible impacts of climate change on malaria distribution (Van Lieshout et al. 2004), and to assess the implications of sea-level rise on changes in flooding by storm surges and potential losses of coastal wetlands through the twenty-first century (Nicholls 2004), for instance.

Within the context of the various emissions (see page 11) and the likely effects on climate (Table 1), the SRES scenarios afford considerable latitude in allowing the analyst to add in additional detail from a specific perspective, whether it is environment goods and services, agricultural knowledge, science and technology, or even livestock.

> While it is perfectly possible to create new scenarios of the future that include specific assumptions about greenhouse-gas emissions, the analyst will need access to a climate model in order to be able to run them and evaluate the impacts on future climate.

What are the problems with such scenarios? Several can be highlighted in general:

- Coherence, or do things hang together? Analysts and stakeholders often find it difficult to see all the links and relationships between factors, so coming up with scenarios that are logically consistent and internally coherent may be problematic.
- Comprehensiveness: it is often unclear to what extent unexpected occurrences should be taken into account. For example, the rises in food prices of the last 6

months or so (or the sudden emergence of a new technology) may make much scenario analysis quickly outdated.

- Downscalability": scenarios are often global in scope, and they usually will have to be adapted and built on, for applying to regional and local situations. Placing global trends within appropriate regional or local contexts is not easy, as it is often far from clear how particular combinations of global drivers may actually play out at these other levels. The need to "localize" global or regional scenarios, to make them appropriate for specific local contexts, is returned to in section 5.
- Interpretability / uncertainty: many people find it difficult to immerse themselves in a scenario world, either to set one up or to interpret an existing one. Scenarios say nothing explicitly about what will happen, merely what may happen with certain combinations of circumstances (although we all may have private thoughts about the likelihood of specific scenarios actually occurring). This may add considerable uncertainty to scenarios, and raises the question, how best can these then be used for decision-making?

> The problem of uncertainty in scenario analysis would seem to be similar to the uncertainty problem with maps. These are all intrinsically probabilistic, even if the uncertainty and probabilities are not expressed explicitly, which often they are not.

We are now seeing a move towards approaches based on conditional probability (M. Rounsevell, personal communication, 2008), although criticisms have been raised about that approach in terms of the possibility that probabilistic scenarios may over- or under-estimate uncertainty and lead to bad adaptation decisions (Hall 2007). The uncertainties associated with projections of future climate change cause real difficulties for those who have to make decisions on adaptation measures. The literature is starting to see methods and frameworks presented that allow the identification of adaptation strategies that are robust (i.e., insensitive) to climate change uncertainties. An example is Dessai and Hulme (2007), in relation to a case study of water resources management in the East of England. They conclude that, in their case, the results are robust for various reasons, but they doubt the results are generalizable.

> The context of the problem is crucial—robust adaptation decisions have to be negotiated between the decision-makers and stakeholders involved, a process that will inevitably put greater emphasis on communicating uncertainties, using a transparent modelling and assessment framework, and embracing participatory approaches.

4. Representing Urban and Rural Vulnerability

Vulnerability Indicators

The vulnerability and vulnerability assessment literature is expanding at an astonishing speed. Now we are even seeing "retrospectives" that attempt to chart the history of the multiple interpretations of vulnerability (e.g., Adger 2006; Füssel and Klein 2006; Füssel 2007). Even as some consensus seems to be developing on, for example, what vulnerability is and reconciling "end-point" and "starting-point" approaches (O'Brien et al. 2004a), and for all the work on "conceptual frameworks", the suspicion arises that in fact nearly all vulnerability studies are context-specific. Adger (2006) identifies three characteristics for a "generalized" social vulnerability measure: it needs to incorporate well-being defined broadly; it needs to account for the temporal dynamics dimensions of risk (i.e., whether vulnerability is a transient phenomenon associated with exposure to particular risks, or is a chronic state); and it needs to be able to account for the distribution of vulnerability within the vulnerable system. The key problem remains: that of reconciling an ideal, conceptual notion of vulnerability with identifying the elements that are actually measurable and that the analyst has data for at the appropriate scale, which can go into defining "well-being" and vulnerability.

> Vulnerability is closely associated with scale: what may be resilient at global or national scale may be vulnerable at a local scale.

A relatively early list of possible indicators is that of Ramachandran and Eastman (1997), who (even in 1997) were talking of "traditional indicators of vulnerability", such as share of drought-resistant crops, rainfall indices, percentage of crop area, infant mortality rate, etc. They proposed that what was needed were indicators of dynamic vulnerability -- changes in availability of marketing facilities, in access to credit, in climate, soil fertility, etc. The "double exposure" work of O'Brien et al. (2004b) and Javed (2005) built on vulnerability profiles of Indian districts (TERI 2003). It combined indicators of climate sensitivity (e.g., monsoon dependence and dryness) with indicators of trade sensitivity (e.g., distance to ports and extent of import-sensitive crops), to assess the vulnerability of each district to climate change and globalization. The Thornton et al. (2006) study used an amalgam of 14 indicators related to the sustainable livelihoods framework (Figure 2), chosen originally in a workshop setting in relation to what participants thought was important, and then modified on the basis of data availability. A recent example is Vafeidis et al. (2008), which describes a global coastal database of 80 physical, ecological, and socio-economic variables (see examples on page 17), designed to support impact and vulnerability analysis to sea-level rise at a range of scales up to the global, although not at the local level.

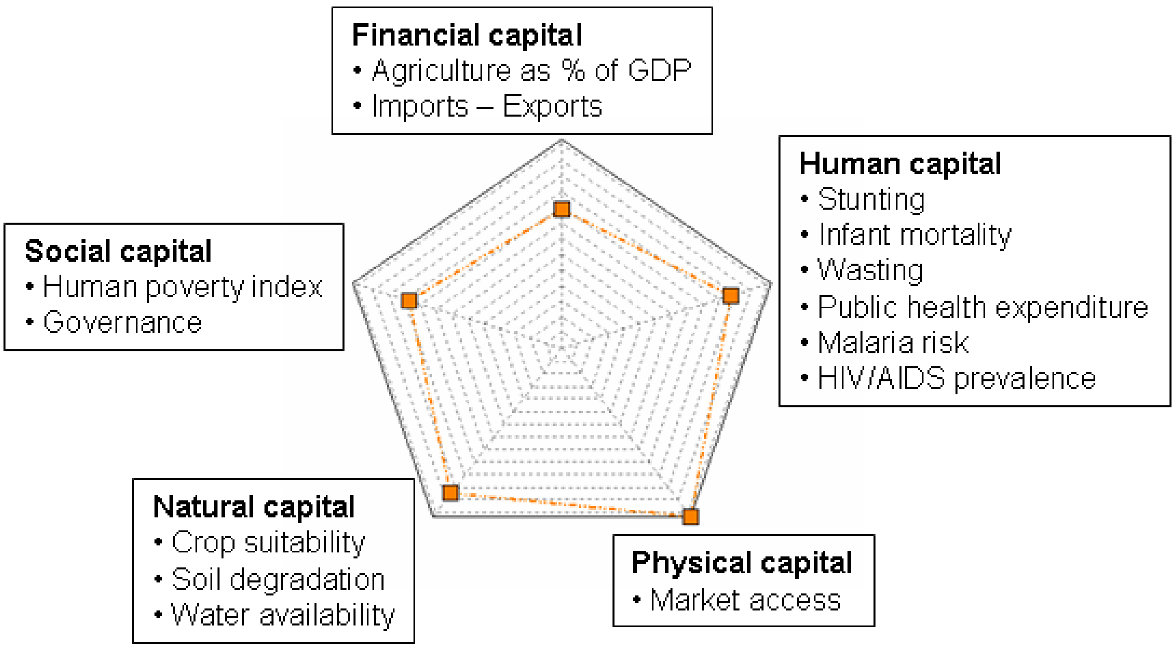


Figure 2. Fourteen indicators used as proxies to characterize vulnerability of households in agricultural systems in Africa, with data at different scales (country, province, 18 km^2). From Thornton et al. (2006).

> Validation is a key problem—why use some indicators and not others? Few studies assess in any objective fashion how different indicators perform in explaining vulnerability or capacity to adapt.

An example of objective validation is Tol and Yohe (2007) that investigates 36 national-level indicators relating to institutions and the rule of law, religion, culture, economics, and education. They conclude that the determinants of adaptive capacity are different for the different measures of vulnerability, indicating that there is no such thing as a general adaptive capacity for all stresses.

"Rather, **the factors from which systems draw to create adaptive capacity is different for different risks**" (Tol and Yohe 2007).

Examples of different types of datasets used for compiling the Dynamic Interactive Vulnerability Assessment (DIVA) Coastal Database (available on line). From Vafeidis et al. (2008).

Dataset	Type
Gridded Population of the World, v. 3 (Center for International Earth Science Information Network, www.ciesin.columbia.edu)	Raster layer
World elevation and bathymetry (National Geophysical Data Center, www.ngdc.noaa.gov)	Raster layer
Geomorphic type	Analogue map
Landform type	Analogue map
Tidal range	Raster layer
Wetlands database	Tabular data
Second-level administrative boundaries (Digital Chart of the World, www.maproom.psu.edu/dcw/	Polygon layer
World heritage sites (UNESCO, whc.unesco.org)	Tabular data
Surge heights	Model output
Uplift/subsidence	Point layer
Land use (IMAGE model, www.mnp.nl/en/themasites/image/index.html)	Raster layer
GDP per capita (World Resources Institute, www.wri.org)	Tabular data
Tourist arrivals/departures (World Resources Institute, www.wri.org)	Tabular data
World rivers	Tabular data
Tidal basins	Point layer
Storm surges	Tabular data
Wave climate	Raster layer

As well as the validation issue, and despite the spate of recent literature on "conceptual frameworks" for assessing vulnerability, another suspicion arises that in fact these still have missing pieces, particularly relating to the full dynamics of vulnerability. Recent literature in the area of poverty traps and the existence and importance of multiple thresholds (e.g., see Barrett and Swallow 2006) suggests that we have not heard the last by any means of vulnerability assessment frameworks, particularly at the local scale. There may be parallels with the concept of adoption, which has undergone radical transformation in recent years from a relatively simple "yes/no once and for all" idea to something much more complex (and realistic), to reflect households' continuous shifting of livelihood activities in the face of enormously dynamic external and internal circumstances.

Urban Vulnerability

In addition to the considerable existing literature on coastal and rural vulnerability, much work is being undertaken on urban vulnerability (not of course that these are mutually exclusive) (see Box 1). There are very good reasons for this. The year 2008 is something of a watershed in human history: half the global human population (3.3. billion) is now living in urban areas (UNFPA 2008). This number will increase to almost 5 billion by 2030, by which time perhaps 15% of these people will be living in about 60 megacities worldwide (cities with more than 5 million people). More than two-thirds of current megacities are located in developing countries.

As Kraas (2008) notes, the urban vulnerability issue has at least two sides. On the one hand, urban areas are global risk areas, subject to increasing socio-economic vulnerability due to increasing poverty, socio-spatial and political-institutional fragmentation, and often extreme forms of segregation, disparities, and conflicts. On the other hand, urban areas can offer a multitude of potentials for global transformation, due to a potentially wide range of available human resources and globally linked actors. A look at some of the issues associated with global change and urban areas (see list below) shows clearly that there may be enormous complexities in urban vulnerability that go way beyond the necessities of food, water, energy, etc.

Concentrated urban areas ("megacities") as hotspots of global change

Geo-ecological change
Hazards, pollution, sea-level rise, global warming and urban heat islands, land consumption, sustainability, securing of socio-physical urban ecosystem

Geo-economic change
Globalizations, transnational companies, international labour division, transformation processes, urban markets, informal sector

Geo-social change
National and international migration, urban diseases, social justice, human security, transnational social spaces, urban life styles

Geo-cultural change
Urban ethnicity, organisation of global urban scapes, global media, social movements, urban cultural diversity and hybridity

Geopolitical change
Resource security, global urban regulation, geo-political competitiveness, social stability, participation, social justice, re-emerging nationalism, welfare, trans-national nongovernmental organizations

Box 1: The Changing Urban Climate

"The populations, infrastructure and ecology of cities are at risk from the impacts of climate change. Built areas exert considerable influence over their local climate and environment, and urban populations are already facing a range of weather-related risks such as heat waves, air pollution episodes and flooding.

Climate change will compound these problems, but building designers and spatial planners are responding through improved building design and layout of cities. For example, green roofs and spaces provide multiple benefits for air quality, mitigating excessive heat and enhancing biodiversity. Hard engineering solutions will continue to play a role in adapting to climate change, but so too will improved forecasting and preparedness, along with risk avoidance through planning controls." (Wilby 2007).

Potential climate change impacts on London. From LCCP (2002), as in Wilby (2007)

Issue	Key impacts
Higher temperatures	• Intensified urban heat island, especially during summer nights • Increased demand for cooking (and thus electricity) in summer • Reduced demand for space heating in winter
Flooding	• More frequent and intense winter rainfalls leading to riverine flooding and overwhelming of urban drainage systems • Rising sea levels, storminess and tidal surges require more closures of the Thames Barrier
Water resources	• Heightened water demand in hot, dry summers • Reduced soil moisture and groundwater replenishment • River flows higher in winter and lower in summer • Water quality problems in summer associated with increased water temperatures and discharges from storm water outflows
Health	• Poorer air quality affects asthmatics and cause damage to plants and buildings • Higher mortality rates in summer due to heat stress • Lower mortality rates in winter due to reduction in cold spells
Biodiversity	• Increased competition from exotic species, spread of disease and pests, affecting both fauna and flora • Rare saltmarsh habitats threatened by sea level rise • Increased summer droughts cause stress to wetlands and beech woodlands • Earlier springs and longer frost-free season affect dates of bird egg-laying, leaf emergence and flowering of plants
Built environment	• Increased likelihood of building subsidence on clay soils • Increased ground movement in winter affecting underground pipes and cables • Reduced comfort and productivity of workers
Transport	• Increased disruption to transport system by extreme weather • Higher temperatures and reduced passenger comfort on the London Underground • Damage to infrastructure through buckled rails and rutted roads • Reduction in cold weather-related disruption
Business and Finance	• Increased exposure of insurance industry to extreme weather claims • Increased cost and difficulty for households/business in obtaining flood insurance cover • Risk management may provide significant business opportunity
Tourism and Lifestyle	• Increased temperatures could attract more visitors to London • High temperatures encourage residents to leave London for more frequent holidays/breaks • Outdoor living, dining, and entertainment may be more favoured • Green and open spaces will be used more intensively

The list infers the existence of several indicators of vulnerability, and two in particular are worth mentioning: migration and human security. The study of migration and what drives it has a long history. Todaro (1969) even at that date refers to a relatively large literature on the modelling of urban migration rates as a function of differential wage rates. Much econometric work has been done since then, although Lall et al. (2006) note that little structural testing has been made of the theoretical models produced, so the general adequacy of such approaches is not really known. In any case, shifts in migration patterns are a strategy of adaptation to complex transformations related to environmental, socio-economic, political, and cultural factors, and climate change clearly is going to have an increasing impact on population mobility (Tacoli 2007), although in ways that are not particularly well understood.

The nature of the relationship between environmental change and human conflict is receiving increasing attention (Homer-Dixon [1991] is a relatively early contribution to the debate). Good grounds exist for viewing climate change as essentially a problem of human security. Barnett and Adger (2007) argue that climate change will increasingly undermine human security in the future, primarily by reducing access to, and the quality of, resources that are important to sustain livelihoods. They also note that if climate change undermines the capacity of states to provide the opportunities and services that help people sustain their livelihoods, then in some circumstances violent conflict may well result.

> A considerable agenda of work is needed to increase our understanding of the nature of climate-change-induced insecurity and how it may be effectively handled in rural and urban settings, particularly the role that institutions can play.

Indeed, both Kraas (2008) and Parnell et al. (2007) call for increasing, serious engagement with all the issues associated with the vulnerability to global change of urban populations in developing countries. In terms of attempting to quantify urban vulnerability, Fragkias (2006) notes that several state-of-the-art integrated, large-scale urban models are being used as planning support systems, but to date these have almost exclusively been focused on cities in developed countries. Thus a strong research tradition exists that could be tapped into, in the search for quantifiable indicators of urban vulnerability, although this tradition would seem to be a long way from the domains of natural resources management (NRM) and rural livelihoods work.

Vulnerability Thresholds

Many vulnerability studies present information on what is in effect "relative" vulnerability, or the identification of hotspots or areas or sub-populations that are particularly vulnerable. Luers et al. (2003) assessed the vulnerability of agricultural systems in a region of Mexico using thresholds. They measured vulnerability in the face of a stressor such as climate change as a function of (say) expected crop yield relative to a threshold of damage, among other things. Defining the threshold is clearly context-specific: in the study of Luers et al. (2003), the yield threshold is set at 4 t of wheat per ha, which is the "approximate minimum yield required for farmers to break even ... based on the average management practices".

> Some work attempts to make use of thresholds of vulnerability, as another way of identifying particularly at-risk subpopulations. Results are not that sensitive to the choice of threshold; there is much more sensitivity to the choice of climate model and emission scenario. If there is no such thing as a general adaptive capacity for all stresses, then it is unlikely that there will be such things as generalized thresholds either.

Another example of a threshold approach is Jones and Thornton (2009). They attempt to identify those areas in the arid-semiarid mixed crop-livestock systems of sub-Saharan Africa where contractions of the growing season due to climate change may be severe enough to induce rural people to modify their livelihood strategies away from cropping to a greater reliance on livestock. Many of these areas are already marginal for cropping. For currently cropped areas, they estimated possible changes in the growing season using a threshold of 90 "reliable crop growing days" per year (a measure of length of growing period that accounts for the probability of failed seasons). Using various combinations of climate model and emission scenario, they mapped and characterized those areas that are currently above this threshold under current conditions, but are likely to fall under this threshold in 2050. It appears that these "transition zones" are already characterized by higher-than-average rates of poverty, particularly those areas that are far from markets.

Various writers in the literature are not sanguine about the prospects of generalizing thresholds for vulnerability analysis (i.e., if indicators exceed a threshold value, then some action is indicated). Meze-Hausken (2008) notes that people have different thresholds and do not respond to the same stimuli in the same way. Admittedly, this was discussing human responses to climatic thresholds (although there would seem to be direct analogues to considerations of local vulnerability). She suggests that a threshold is more realistically seen as a bandwidth or transition zone, and the level of acceptance, and the cultural, technological, and genetic aspects of adaptation will affect the adaptations taken up (and indeed whether any adaptation is undertaken at all).

Further, for any threshold approach, there is the problem of validation: i.e., for the thresholds used, do they actually reflect real-world shifts in behaviour, such as changing a crop type or a move to more livestock dependence? Such observations are generally difficult to make, and may be difficult to attribute to the stressors under consideration. As Meze-Hausken (2008) says, "When populations are vulnerable and thresholds are exceeded, only then will there be a measurable response."

5. Communicating Vulnerability

The communication of vulnerability information to users and decision-makers may take many forms. Recent years have seen considerable innovation in the ways in which development-related information (of which vulnerability can be seen as one example) has been presented to a wide variety of stakeholders. Many tools are available for knowledge exchange, such as the use of web-based platforms to link stakeholders, capacity-building workshops, and the dissemination of printed material. There is a lot of variety in print material, including the obvious books, briefs, and technical notes, as well as more innovative material such as cartoon strips. An example is the series of cartoon books, "Wambui finds out", in which a young girl learns about various aspects of livestock (http://www. smallstock.info/Coping/tools/wambui/wambui.htm). Concerning other media, radio and theatre have long been used for informing people about HIV/AIDS, and the February 2008 bulletin of Climate Change Adaptation in Africa (CCAA) contains a story about a project to write and produce a soap opera for radio as a tool to help smallholder farmers in northern Nigeria adapt to climate change. The same bulletin also contains a story about a scriptwriting competition on topics related to climate change. A broadcaster from a Rwandan radio station subsequently won this with a script on managing rainwater to prevent soil erosion and provide water for crops.

Visual Representation Tools

The major focus of this section is on another set of tools that come under the general rubric, visual representation. This includes landscape visualization, briefly touched on in section 2, and a range of other methods.

> Methods of visual representation have been proposed as a means of enhancing the communication process between scientists and non-scientists, as well as of eliciting environmental perceptions and preferences. A lot of development and application is taking place in the realms of surgical and medical education.

In NRM, several methods have been used in planning, from on-the-spot sketching of participants' opinions and preferences within the context of a participatory workshop, via visual preference surveys using pre-assembled pictures or photos, to the sophisticated use of three-dimensional GIS modelling, with models and analyses carried out either by third parties or by stakeholders themselves (Cruz et al., 2007). The appropriateness of such methods in different situations will depend on various factors, such as the skills and experience of all the stakeholders, the nature of the issue being addressed, the resources available, and the stage of the process reached (Al-Kodmany 2002).

The still-rapid development of computer hardware and visualization software makes the concept of interactive and dynamic landscape visualization or virtual reality, or "collaborative environments" within which several stakeholders could engage at the same time, a realistic option for the future. Such tools would offer new and unique opportunities for the transfer of information, for the assessment of different options, and for evaluating tradeoffs between competing objectives. Much of the computer science needed for this already exists, and quick literature searches indicate that a lot of development and application is taking place in the realms of surgical and medical education. (Presumably, many developments are occurring in the computer gaming industry, but references to information in the public domain related to such developments are understandably few.)

The prospect of converting existing, spatially explicit integrated assessment modelling frameworks into virtual reality tools is intriguing, to say the least. An example candidate for such treatment would be the Savanna ecosystem model, linked with a simple household model that is now in an agent-based framework (Boone et al. 2008). This linked model tracks wildlife and livestock movements in a landscape, as well as the growth and distribution of the feed resources on which they depend, and relates these to household activities (cropping, household movement, and other economic activity) in the same landscape. Outputs from this integrated assessment modelling work have been used in public meetings in Kajidao, Kenya, using simple maps and graphics, and were found to be highly effective discussion tools in such forums (Boone et al. 2006). Embedding this two-dimensional spatial model within a three-dimensional virtual reality framework could allow multiple users and stakeholders to watch the impacts unfold of a whole range of "what-if" questions, in compressed time. It might reasonably be thought that such a tool could be of immense use in promoting public debate, and spurring individuals, communities, and policy-makers to action, concerning climate change and what may be done to mitigate it and adapt to it.

Points to Ponder

> Computer science is at the stage where increasingly realistic landscape visualization can be done, coupled with appropriate virtual reality interfaces, so that these virtual worlds can be explored and in which, presumably, they can be experimented. The associated data problems with sophisticated visual representation methods will be compounded, both in terms of what data are readily available at appropriate scales, and in terms of model uncertainties and errors and how these can appropriately represented.

Amalgamating complex biophysical models with realistic landscape visualization is assumed not to present enormous challenges. Some highly preliminary research work in this area has been done in the international agricultural research centres—for example, the International Livestock Research Institute and the International Potato Centre were involved with the beginnings of a "virtual laboratory" for the System-Wide Livestock Programme in the early 2000s. But if substantive work in the area has not been done as yet in the public domain, it is reasonable to suppose that this is because of the costs involved and of questions related to added value, rather than technical limitations *per se*.

Some of the problems identified with landscape visualization as a tool were listed in section 2. Sheppard (2005) notes "the conventional role of visualization as an informative tool in decision support is associated with the supposed neutral role of science in not imposing value judgements on the public". But whether such neutrality can (or should) be preserved here is an overarching ethical issue, if visualization is in fact to be used for the purpose of influencing attitudes and behaviour concerning climate change. Sheppard (2005) concludes that the persuasive use of visualizations (in concert with other methods) is justified if they can be effective, and may even be vital in communicating climate change urgently. He suggests various standards that should be adhered to, particularly related to disclosure (i.e., so the content of the visualizations is crystal clear) and defensibility of the methods and data used. As he says, "we should test carefully every potentially powerful weapon in the fight against climate change, especially those which promise rapid results. Visualization tools are potentially too powerful either to be ignored or used without careful consideration." It is hard to disagree with this.

> Even with highly sophisticated and innovative methods of communicating vulnerability, what are the prospects for such information actually having an impact in changing people's behaviour, for example in relation to greenhouse gas mitigation or climate change adaptation?

Patt et al. (2005) are sceptical about the impact of their vulnerability maps of Europe, even on the decision-makers who paid for the work to be done and would have, one would imagine, a vested interest in seeing the work used. The issues surrounding the use of computer-based information, and the apparent gaps between information provision and behavioural change, have long been discussed (and lamented). Here, we clearly need the psychologists' help. Midden et al. (2007) argue that technology can be a powerful tool to motivate people to change behaviour in almost any domain of daily life. They argue convincingly that behavioural scientists can contribute considerably to reducing overall environmental impact by analyzing human behaviour and technology in concert (among many examples, they note the influence of on-board computers in cars that display fuel consumption figures and increase most drivers' fuel efficiency). They note with surprise the "modest attention that the role of technology receives in psychology and in policy making"—precisely the same comment might be made about the role of psychology in technology and NRM.

What is Feasible in the Relatively Near-Term?

This subsection sets out some options that might be able to edge this agenda forward in the short term. This is built around a table in Sheppard (2005), which originally presented a typology of selected climate change impacts in terms of their potential to be readily and realistically visualized. This has been expanded here to include some of the vulnerability indicators discussed in section 4. It includes a subjective estimate of their ability to be readily assimilated by lay-viewers and an indication of sources of this type of information, in relation to the types of organizations that are (or may be) doing such work (Table 2). Clearly, the appropriateness of different indicators in any situation will depend on the needs and experience of the target audience. The indicators are divided rather arbitrarily (for ease of viewing) into those that are related primarily to the biophysical, socio-economic, and urban environments. So, for example, an indicator such as "sea-level rise" can be readily linked to future scenarios of change (e.g., the SRES scenarios), it is readily visualized, and the implications of it can be assimilated by lay-viewers. In terms of data sources, this kind of modelling work is being done by Advanced Research Institutes, although the Dynamic Interactive Vulnerability Assessment (DIVA) Coastal Database referred to earlier (Vafeidis et al. 2008) cannot be used directly, for example, as its resolution is not high enough for localized application. Torresan et al. (2008) confirm this by assessing vulnerability in a coastal region of Italy using DIVA and much higher-resolution data for the case-study area. They conclude that information based on data at the scale of DIVA is incapable of providing the understanding necessary to manage the complexities of their study area.

Table 2 contains a selection of indicators that are judged to be particularly appropriate at local levels. Thus it does not contain variables such as education level or explicit indicators of governance, for example, which may nevertheless be important indicators of vulnerability, but usually at different scales (national, regional). An indicator such as market access is not easily linked to scenarios, not easily visualized, and probably not easily assimilable, and yet it is spatially explicit and in many situations may be a key contributor to vulnerability indices.

Table 2. Selected indicators (associated with climate change impact and vulnerability) and their ability to be linked to future scenarios, realistically visualized, and readily assimilated, and possible generic data sources at relatively local scales such as the district. Modified and expanded after Sheppard (2005).

Indicator[1]	Readily linked to future scenarios?[2]	Easily visible to lay-viewer at landscape level?[3]	Readily assimilable by lay-viewer?[4]	Indicative data source[5]
Primarily biophysical:				
Sea-level rise (coastline)	Yes	Yes	Yes	ARIs modelling output
Permanent and seasonal flooding	Yes	Yes	Yes	ARIs modelling output
Changes in crop, livestock suitability	Yes	No	No	CGIAR/ARIs modelling output
Changes in seasonal patterns, lengths, timing	Yes	Yes	Yes	CGIAR/ARIs modelling output
Increased storm severity	No	No	Yes	RCM modelling (ARIs)
Soil erosion from concentrated precipitation	No	Yes, through time	No	RCM + hydrology modelling (ARIs)
Changes in water courses	No	Yes, through time	Yes	RCM + hydrology modelling (ARIs)
Lake level drop	No	Yes	Yes	RCM + hydrology modelling (ARIs)
Drought induced vegetation stress	Yes	Yes, through time	No	ARIs modelling output
Drought induced vegetation die-back	No	Yes	No	ARIs modelling output
Vegetation succession or invasion	No	Yes, through time	No	ARIs modelling output
Wildlife species gains or losses	No	Yes, through time	No	ARIs modelling output
Crop failures	Yes	Yes	Yes	CGIAR/ARIs modelling output
Primarily socio-economic:				
Market access	No	No	No	?
Price changes	Yes	No	Yes	CGIAR/ARIs agric. sector modelling
Poverty (or income) rates or proxies	Yes	No	Yes	CGIAR/ARIs agric. sector modelling
Changes in households' livelihoods	No	No	No	CGIAR/ARIs localized scenario analysis
Changes in human disease risk	No	No	Yes	ARIs modelling outputs
Institutional change	No	No	Yes/No	?
Migration	No	Yes, through time	Yes	ARIs econometric model outputs?
Primarily urban-related:				
Landscaping stress	Yes	Yes	Yes	ARIs modelling outputs
Power brown-outs	Yes	Yes	Yes	ARIs modelling outputs
Air and land pollution	Yes	Yes	Yes	ARIs modelling outputs
Human security	No	No	Yes	?

1. The grouping of indicators is approximate and serves primarily to break the table up for ease of viewing.
2. Linkage to future scenarios: none is easy, but "Yes" indicates that this is easier, "No" that it is harder.
3. Indicators vary widely in their visibility or "imageability". "Yes," indicates relatively easy visibility at landscape level; "Yes, through time" indicates that time-lapse visualizations would probably have to be used, and "No" indicates that the indicator is either visually subtle or it would need "augmented realism" (of some form) to become apparent at the landscape level.
4. A subjective judgement as to the ease with which the implications of a change in the indicator can be understood and taken in by the lay-viewer: "Yes" indicates relative ease, "No" relative difficulty, and "Yes/No" indicates that it would depend on the exact nature of the indicator.
5. "Indicative data source" simply indicates the type of institution that is (or could be) working in the area. "?" indicates a potential gap (or ignorance on the part of the compiler). Acronyms used: ARI, Advanced Research Institute; CGIAR, Centres associated with the Consultative Group on International Agricultural Research; RCM, Regional Climate Model.

Little work appears to be underway on looking at changes in market access and infrastructure, at least in the NRM sphere and, together with local institutional changes and human security, may represent something of a gap in data availability. In thinking about "visualizing futures" case studies to investigate the use of visual representation in communicating climate change vulnerability information, and what these case studies might look like, several points may be made in an attempt to draw together the foregoing discussion.

Table 2 is indicative only and is not exhaustive. The scoring of attributes is admittedly rather subjective, but this is a suggestive result. In terms of identifying a case-study location to test visualization approaches, it might be best to start in an urban or possibly a coastal setting, rather than in a rural setting where there would seem to be more challenges in being able to engage the viewer directly, all other things being equal. As Table 2 also makes clear, in identifying the types of organizations that are or may be working on generating the data with which case studies could be carried out, data requirements seem to become increasingly specialized at the relatively local level, such as the district. An example was cited above concerning the need for data at much higher resolutions than is appropriate for global or broad-brush studies (Torresan et al. 2008), and this is probably a general result. For many of the indicators in Table 2, particularly those associated with hydrology (rain-induced soil erosion and changes in water courses and lake levels), **regional climate models would almost certainly be necessary, simply because global climate models are too coarse to be able to represent the effects of local topography and water bodies on climate**. Given current data limitations, case studies will need to be located in relatively data-rich environments, at least for the time being.

> The indicators associated with urban vulnerability appear to have both high visualization potential and high assimilability by laypersons. By contrast, what makes rural people, who are dependent on natural resources, vulnerable to climate change, may not be readily visualizable, and the implications of spatial changes in indicators may be quite subtle for lay-people to grasp.

> It may be many years before climate models are sophisticated enough to provide reliable climate and weather data at spatial and temporal resolutions that many would consider "ideal" for local decision making. Even so, various things can be done in the meantime.

As noted above, it makes sense to use the SRES scenarios, but for any case study these (or any other global or regional scenario) will need to be downscaled appropriately to the local level. The climate downscaling can be done in several ways (Wilby et al., 2008), none of which is entirely without problems.

In many regions, inter-annual climatic variability is strongly related to the El Niño Southern Oscillation, and thus will be affected by changes in its behaviour (or in the Indian Ocean Dipole; see Conway et al. 2007). Increased understanding of these types of relationships thus should be able to provide some information concerning the likely nature and extent of changes in climatic variability in the future. Perhaps most importantly, the judicious use of sensitivity analysis to assess the robustness of impact and vulnerability assessments to climate change uncertainties (e.g., as in Dessai and Hulme [2007]), offers a practical and effective means of dealing with the climate downscaling issue.

Just as important as climate downscaling is the need to "downscale" all the other drivers of change, so that plausible futures for local conditions are derived. This process may not be easy, but there are examples of how it may be done effectively. Nicholls et al. (2008) explore the development of relevant climate and non-climate drivers, with an emphasis on the latter, to come up with better methods of doing integrated assessments of coastal vulnerability that are linked to the SRES scenarios. They note the importance of a process in doing this that is explicit, transparent, and open to scientific debate concerning their realism. If existing scenarios cannot be appropriately downscaled, then local scenarios may need to be generated or invented that are appropriate for the case study-situation (i.e., bottom-up rather than top-down).

Effective ways need to be found to incorporate uncertainty in the visualizations. Alternatively, effective ways need to be found to communicate the uncertainty in the visualizations to users. Various methods are available for doing this in mapping work (and quite a lot has been done in flood mapping, e.g., Smemoe et al. [2007]), but whether much has been done on this in the realms of three-dimensional modelling and visualization would need to be ascertained. Thought needs to be given as to how to represent and incorporate factors not inherently visual or spatially explicit. Appropriate methods need not necessarily be complicated: Wissen et al. (2008) demonstrate that even simple diagrams of non-spatial factors (e.g., bar charts) that are linked to fairly complex spatial representations can help stakeholders make complicated connections between spatial and non-spatial factors.

Future-orientated visualization work appears to need a genuinely multi-disciplinary mix of inputs if it is to have any chance of success. Inputs are required from:

- Climate science, to help define plausible scenarios of future climate in specific locations;
- The virtual reality computing community and the visualization sciences, to lead the technical aspects;
- The vulnerability sciences, in defining appropriate urban, rural, and coastal measures of vulnerability that are both intelligible and quantifiable;
- The agricultural, economic, and ecosystems sciences, to run the models needed to quantify the impacts of climate change in the case study location (or to downscale impacts from existing modelling activities); and
- The psychological sciences, to understand the links between technology and human behaviour.

In this way, the visual representations that are produced can inform debate and action effectively and ethically. Three possible next steps are suggested, that could help move the agenda forward.

.1 Assemble a "Framework for Action"

This report has identified several areas in which more work is required, but one of the most critical is in defining an appropriate framework for the application of visualization tools that is genuinely consultative and can be made to be specific to the local context. Examples from the literature indicate that this is not a simple task. An activity that would be well worthwhile is a comprehensive review of the relevant literature on application frameworks, so that one could be adapted or

> The line between fostering credibility in an analysis and sparking incredulity is very fine, and even if information exchange or provision is effective, translating this into action is far from guaranteed.

modified. This would help ensure that future application of visualization tools to the information- and decision-related issues surrounding climate change is not ad hoc, but rather part of a coherent and logical process. Some of this literature will be in the realm of psychological research and extension science, rather than NRM, and will doubtless need some interpreting. The work required here could be undertaken in a relatively short time over several months.

2. Design and Implement Case Studies

Once an appropriate framework for action has been identified, a few case studies in selected locations could be undertaken. As noted above, these could be located in a variety of settings. Urban and coastal case studies suggest themselves, but also, perhaps, one in a more visually challenging (Table 2) setting. An example could be in one of the hotspots in the arid-semiarid agro-pastoral systems of sub-Saharan Africa, which Nyong (2005) and Thornton et al. (2006) identified as being particularly prone to climate change impacts and with populations that are already relatively vulnerable. Another potentially useful setting for a case study would be in vulnerable mountain communities, where snowmelt, landscape instability, and upslope movement of species and the timberline, for example, could be easily visualized.

Case-study sites also could be chosen with a view to representing some differences in data availability (although data-poor environments might best be avoided) and in the dynamism of the local socio-economic context (i.e., how difficult would it be to downscale global scenarios to the local situation). Another criterion that may be important in the selection of case studies is in relation to the level of uncertainty associated with climate change projections for the region. There is little model consensus on even the direction of likely rainfall changes in West Africa this century, but much more consensus for East and southern Africa, for instance. These case studies would need to be monitored carefully to track actual consequences of the use of visualizations on learning and subsequent behaviour. Case studies might take between 1 and 2 years to complete, depending on the scope, and monitoring might need to continue for several months beyond this.

3. Is There a Broader Role for the Use of Visualization Tools?

Reviews and consultation documents on research and capacity development needs for climate adaptation in developing countries (e.g., Nyong 2005; Ziervogel et al. 2008) share several common elements. Three are worth mentioning here. One is the need for capacity development to go beyond the development of competency, which has often been the limit of "traditional" capacity building, to the creation of opportunities. Second, few well-documented examples of decision processes have drawn on the knowledge base of climate change and resulted in decisions or changed behaviour improving human well-being in direct or indirect ways. Third, it is widely agreed that new approaches are needed to deal with the complexities of adaptation research and implementation that are built around multi-disciplinarity and inclusion.

There are intriguing possibilities in the use of appropriate implementation frameworks containing visualization tools that could play some role in addressing these three issues, among others. There may be ways in which these tools could be used for training and capacity development, in showing how the loop can be closed between (climate) information providers and potential information users, for example, or demonstrating how risks can be evaluated for different groups of stakeholders. There seems to be no basic reason why sophisticated tools could not be assembled into games that could be used for teaching, not only in relation to risk assessment and the "what" of adaptation, but critically the "when"—at what stage is action needed? As it is not possible to experiment with real systems, the use of virtual systems for training in such areas, while currently fanciful, might be enormously useful. As noted above, any case studies will have to address multi-disciplinary and inclusion issues, and monitoring and evaluation of case studies could help provide the examples that can inspire others to take similar approaches in other situations.

When seen in a broad context, the development and implementation of visualization tools in concert with other methods may well be able to address some of the key requirements that are voiced time and again by stakeholders in developing countries concerning adaptation. Some experience would first need to be gained via case studies. But, in time, a comprehensive, blue-sky assessment of the potential uses, and limits, of integrated frameworks containing visualization tools in adaptation work, which goes far beyond this document, would be of considerable value in helping elaborate a plan of work for the future in this intriguing area of activity.

6. Concluding Remarks

A wide variety of visualization methods exists, and in general these have considerable potential in helping communicate what the likely impacts of climate change may be in the future and for assisting all stakeholders in assessing options to address the impacts, both locally and globally (at a distance). Different methods will be appropriate in different situations and for different stakeholders. These range from simple pictorial representations of impacts of climate change on local landscapes that can be designed and discussed with local communities, through to using tools such as Google Earth to map climate change impacts and vulnerability, given its wide availability and the relative ease with which tailor-made applications can be added on to the basic engine. Perhaps eventually they might even include more sophisticated computer-based visualization tools that show local climate impacts in a virtual world. Designing and implementing effective visualization activities in a case-study context is not likely to be easy, however. Such efforts will need to be truly multidisciplinary; several data and other technical problems have to be overcome, and ethical issues have to be addressed, relating to transparency, avoidance of bias, and stakeholder inclusion, that may very well make or break such activities. Nevertheless, the potential benefits are such as to make the effort well worthwhile.

Acronyms & Abbreviations

AM	Adapting Mosaic
AR4	Fourth Assessment Report (of the IPCC)
ARI	Advanced Research Institute
CCAA	Climate Change Adaptation in Africa
CGIAR	Consultative Group on International Agricultural Research
DFID	Department for International Development, UK
DIVA	Dynamic Interactive Vulnerability Assessment
GO	Global Orchestration
IAASTD	International Assessment of Agricultural Science and Technology for Development
IDRC	International Development Research Centre, Canada
IFPRI	International Food Policy Research Institute, USA
IPCC	Intergovernmental Panel on Climate Change
MA	Millennium Ecosystem Assessment
NRM	Natural Resources Management
OS	Order from Strength
RCM	Regional Climate Model
SRES	Special Report on Emissions Scenarios
TG	TechnoGarden

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