Proceedings of the Institution of Civil Engineers
Engineering Sustainability 162
September 2009 Issue ES3
Pages 155–167
doi: 10.1680/ensu.2009.162.3.155

Paper 800008
Received 14/02/2008
Accepted 25/11/2008

Keywords:
environment/research & development/social impact

Julian Hunt
Professor of Climate Modelling (Emeritus), University College London and Visiting Fellow Malaysian Commonwealth Centre, University of Cambridge, UK

Institution of Civil Engineers

Integrated policies for environmental resilience and sustainability

J. Hunt PhD, Hon FICE, FRS

Policies for resilience against disasters use forecasts for short and longer term environment hazards, both natural and artificial. Although the methods used are increasing in reliability, significant uncertainties remain in the underpinning science and in the data. The vulnerability of communities to environmental risk is increasing because of economic and social factors, which also need to be better understood. This paper shows why, over the long term, engineering, medical and social policies for improving resilience are most effective when they are firmly linked to those for sustainable development. Policies need to be coordinated globally to meet agreed United Nations objectives and also to ensure that environmental actions in one region can benefit and do not damage sustainable development in other areas. Analyses and simulations of emerging and other possible scenarios, using economics and complex systems modelling, can test and propose strategies for resilience and sustainability, including the merits of different types of integration. This approach provides new insights for public discussion and decision making. There are new ways that universities, research institutes, non-governmental organisations and the private sector can contribute to multi-disciplinary technical advances and to promoting public participation in the complex changes affecting communities everywhere.

1. CONCEPTS FOR DEALING WITH ENVIRONMENTAL RISK

World leaders have agreed that dealing with the practical and political aspects of environmental risk and climate change is intimately linked with meeting the other urgent challenges of poverty, security and maintaining global economic development.[1,2] This paper reviews these developments, especially the contribution of improved prediction methods and practical innovative steps for combining resilience against environmental hazards with long-term sustainability.

The guiding concept that emerged during the United Nations (UN) decade for natural disaster reduction (1990–2000)[3] was that planning, science and follow-up action need to distinguish between the impact of hazards measured by the frequency severity of natural or accidental events, and vulnerability, which is a measure of the severity of how environmental events impact on communities.[4] As one disaster follows another with progressively more damage (as recorded by the insurance industry), especially to poorer communities (as UN statistics have recorded), it is clear that increasing vulnerability is the main cause—much more so than increasing hazard.[5] The lesson learnt from the European heat wave in 2003 (with 35 000 ‘excess’ deaths) and hurricane Katrina in New Orleans (killing 2000 or more) is that even industrialised countries are not always well prepared either nationally or locally. In the aftermath of hazard events, urgent actions are needed both to recover and to enable the capacities of communities and physical systems (such as dykes) to be renewed—essential for reducing the impacts of future events. Where social capacity and environmental resilience is inadequate, the costs of recovery and the insurance losses are that much greater.[6]

The degree of resilience within a system or organisation may be defined by how effective it is in reducing the social, economic and ecological losses caused by hazards. Environmental sustainability[7,8] broadly defines the objective, over many generations, of reducing the adverse effects of hazards on societies, through minimising their overall impacts on the natural environment. Other recent definitions are given in Ref. 9.

Environmental risks are also increasing because of the changing nature of the environment, both locally and globally.[10,11] The most important practical conclusions are firstly that current long-term changes to the world’s climate are caused largely by human activities and secondly that environmental risks associated with natural hazards and their consequences, such as diseases and crop failure, are likely to become progressively more serious over the next few hundred years.[12] Within the time period of about 30 years in which the global climate responds to human influence, it is essential to start mitigating human effects on the global environment. This requires a range of measures to reduce and eventually stabilise greenhouse gas (GHG) emissions at a global level equivalent to those in the 1980s, which were less than about half of today’s emissions.[10] The UN conference in Bali[13] and government agencies (e.g. the UK Department for Environment, Food and Rural Affairs)[14] have also recognised that local adaptation measures are necessary to reduce the impacts of local hazards over the next few decades before mitigation measures are likely to become effective. The causes and consequences of hazards, social impacts and societies’ responses are shown schematically in Figure 1. The sequence of responses of societies and governments, and how they interact

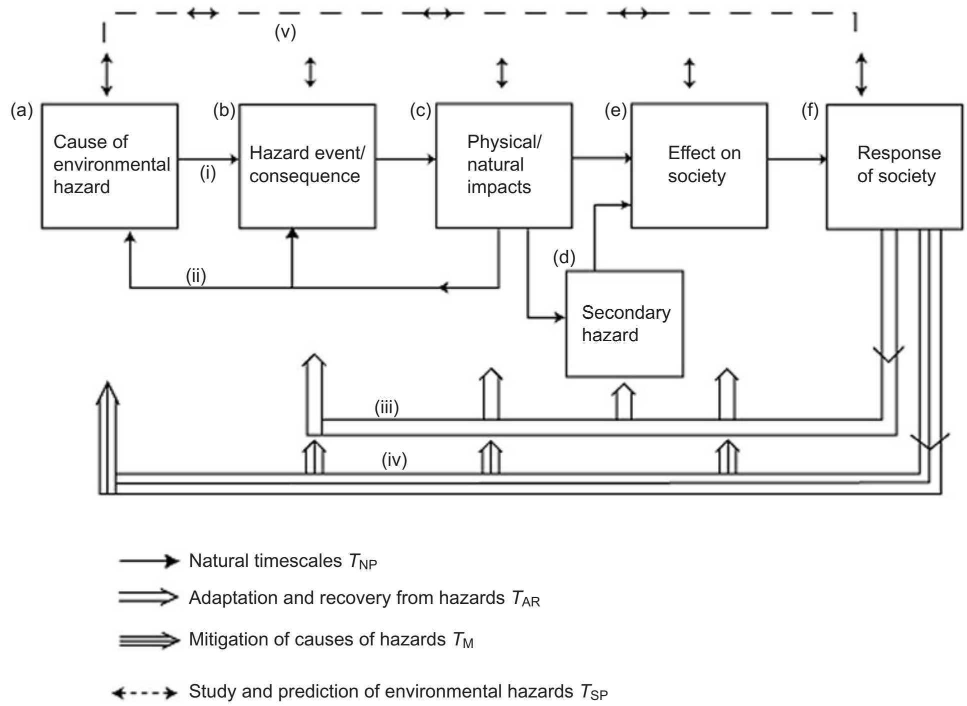

Fig. 1. Environmental hazards and interactions of causes, consequences and responses. (a) Geophysical extremes (e.g. hurricanes, earthquakes, tsunami) and artificial local and global environmental change (technology, population, etc.). (b) Short-term hazards (e.g. winds, floods, earth vibrations) and longer term hazards, both local (e.g. agricultural desertification, acidification) and global climate or environmental change. (c) Damage to infrastructure, environment or ecology (back reaction (ii) can affect (a) and (b)). (d) For example, natural flooding from winds, landslides from floods, ecological damage, artificially enhanced vulnerability from structures, pollution from damaged infrastructure. (e) Applicable to all types, e.g. loss of life, damage to health, economic damage. (f) Study, explanation and prediction of hazards, leading to policy and action (back reaction (v)). Other reactions include (iii) development of resilience and adaptation of society/infrastructure/economy to (b), (c), (d), (e) and (iv) mitigation of hazards (a) and consequences (b), (c), (d), (e)

on varying timescales, are shown schematically in Figure 2. These figures are discussed further in Section 5.

2. SCIENCE AND TECHNOLOGY OF ENVIRONMENTAL RISKS

Natural disasters still cause a large number (about 70 000) of lives lost globally per year.[15] Man-made environmental hazards are even more dangerous; air pollution leads to more than 20 000 'excess' deaths per year in the UK and 1 million per year globally.[16] Meanwhile, climate change produced by human activities may also affect the magnitude and frequency of atmospheric and oceanic hazard events.[10]

Having learnt about the progress of environmental science, modern societies now expect to be informed about scientifically based predictions and forecasts of all kinds of natural and artificial environmental hazards. Indeed, they also expect warnings about other kinds of societal hazards such as conflict, disease, financial problems, and so on.[17,18] In general, demand for environmental forecasts is growing because they are becoming more reliable and more closely related to the impacts of hazards on society. Paradoxically, they are found to be more useful as their fundamental limitations are explained and become better appreciated. For example, current guidance on flood risk requires consideration of both infrastructure failure[19,20] and social impacts. The similarities between one kind of disaster and another[21] should make for more coordinated policies and better predictions of risk consequences.[22–24] Following the international community's adoption of this strategy, the UN[3] now encourages countries to form national committees for coordinating response to natural disasters, through working closely with national agencies and task forces, and also to work with civil society and research to make longer term improvements.[25] Different countries can contribute their experience in dealing with the effects of climatic extremes and play a role in coordinating data, especially about societal aspects such as the differing responses of communities and organisations for different kinds of hazard.[4]

The greatest advances in forecasting environmental hazards (e.g. European Union framework 6 research)[26] have been made where they focus on physical effects, especially where they occur separately (e.g. floods, cyclones, earthquakes). However, hazards often come together or one hazard causes another (e.g. floods and landslides).[27] Complex systems analysis is now able to show where there are common features of the physics and prediction methods for different hazards, as well as how they are dealt with by organisations.[28]

Depending on the particular environment, real-time forecasts for imminent hazards are a practical possibility over limited periods, from minutes up to a few months. They are only useful if they are made with sufficient detail and accuracy for practical action and if they are communicated soon enough. The shortest timescale forecasts have been developed in Japan for earthquake warnings. Following sudden, rapid and localised jerking movements of tectonic plates, elastic waves propagating in the Earth's crust at about 3000 m/s can be predicted usefully for periods of a few seconds. With fast enough and prioritised communication systems, the new Japanese system of

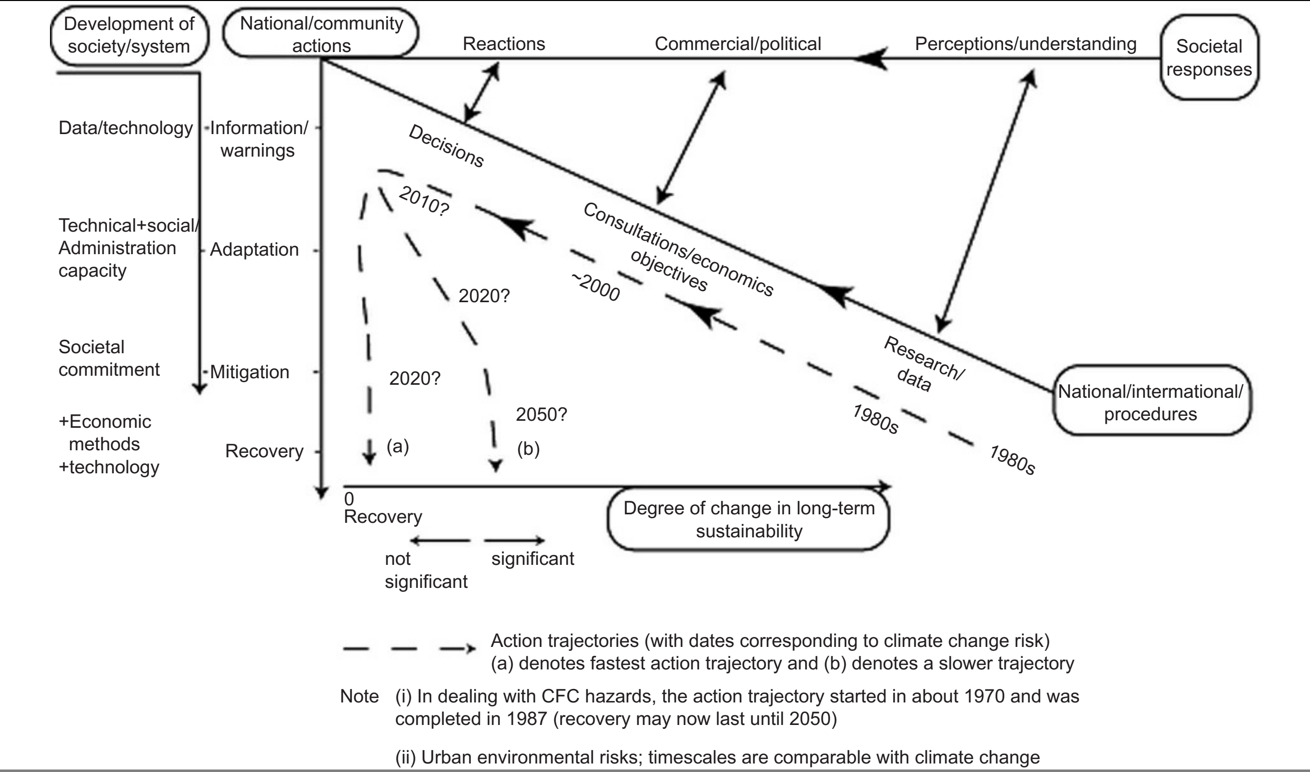

Fig. 2. Typical sequence of responses by societies and governments to new environmental risks

very short period warnings of earthquakes could be used worldwide to save many lives in transportation systems, hospitals and buildings.[23]

For short periods, the most reliable forecasts (in terms of accuracy and estimates of possible error) for the atmosphere, ocean and rivers are based on computing mathematical models with thousands of computers operating 'in parallel'.[29] The useful 'skill' of such forecasts, depending on meteorological conditions, can sometimes extend to ten days. For example, the track of tropical cyclones or major storms can now be predicted with an error of less than 130 km for 24 h (double that for two days, and so on).[30]

For longer periods, the errors in these deterministic grid-based methods become too great to provide reliable forecasts. However, statistically based forecasts are possible over periods of weeks and months by combining data at the time leading up to the forecasts with previous measurements of correlations between weather at different times and locations.[31,32] Recently, in Europe, combinations of deterministic and statistical methods have provided a more reliable basis for seasonal forecasts.[33] An important application are predictions (with an accuracy of about 20%) made by a number of research centres for the likely number and intensity of hurricanes to impact on a coastline in a given year.[34]

However, many environmental hazards have to be assessed over periods much longer than any of the natural phenomena causing the hazards. A statistical method based on past data is the only technique available for estimating the risks, as for example in the design of engineering structures to withstand earthquakes over their lifetime.[35] But where the environment is changing over these long periods, as for example owing to climate change, again it is necessary to combine modelling of these geophysical changes with statistical estimates of risk based on previous data.

For predicting long-term changes in the climate over the next few hundred years and the effects of human activities, the combined effects of atmospheric, ocean and land surface processes have to be considered. However, because some important aspects of these processes will be changing, they cannot be simply predicted based on statistical extrapolation from past climates. Rather, as in planetary science, the computations have to be based on the laws of physics and chemistry and other scientific concepts that will be valid even as the phenomena and the applications change.[31,36] The aim broadly is to predict how the main elements of the Earth system that affect the climate will interact with each other as less long-wave radiation escapes to space because of the expected doubling or even trebling of concentrations of carbon dioxide and other GHGs in the atmosphere by the end of this century. Similar processes occur, but even more strongly, in the climates of other planets such as Venus. When research first showed how the Earth's atmosphere developed, it led some scientists to suggest that the 'Earth system' might be so stable that human influences were unlikely to be significant.[37,38]

Models must also represent the large natural variations of the global climate as well as those produced by artificial causes. Progressive developments in research have also reduced the differences in the predictions between the various models; they now indicate that by the year 2050 the global temperature rise caused by human effects will be about 2°C. When these models were first tried in the 1980s, the computational grids were about 300 km and the atmospheric physics was oversimplified. So, for example, the British Isles was continuous with the Continent, most European mountain ranges were hardly represented and the substantial cooling effects of atmospheric aerosols were neglected (thus overestimating global warming by 1–2°C over 50 years).

Current models using faster computers with greater capacity now represent orography and the processes more faithfully, extending from the ocean bottom and the layers of rock and soil below the land surface up to the top of the atmosphere. The models meet the basic statistical test that the fluctuations in climate simulations have the full range of timescales (for periods longer than decades) that are observed in the atmosphere.[39] Significant global temperature fluctuations are also caused by volcanic eruptions and changing ocean circulations, which can be as much as 0·2°C over a year and about 0·15°C over decades.

Important global phenomena are still not adequately modelled,[40] for example decadal oscillations in the ocean and the contribution to the greenhouse effect from the emission of methane into the atmosphere where the permafrost is rapidly melting in arctic regions. Uncertainty in the predictions of global temperature rise over the next 50 years, which is currently estimated at ± 1°C (over decadal periods), should continue to diminish as research in natural and social science progresses and computers become faster and have larger memories.[41]

Over certain regions, global emissions of GHGs and local atmosphere and ocean circulations can cause rapid variations in the annual temperature. On the Antarctic peninsula,[42] the rise has been about twice the average trend over the past 30 years, causing unexpectedly fast melting of sea ice. There may be decades when natural fluctuations will add to or cancel out the global temperature rise. In fact, in the 1990s the global surface temperature rose by nearly 0·35°C, faster than the predicted average rise of 0·25°C. This was mistakenly regarded by some climate scientists as a clear demonstration of increased global warming. By contrast, in the present decade, when there has been prolonged cooling of the eastern equatorial Pacific, there has been no rise at all. This caused some environmentalists,[43] followed up by parliamentarians,[44,45] to ask whether global warming can effectively be ignored. However, over the whole land area (where the temperature is less affected by fluctuations of the ocean temperature and where people live) the surface temperature has continued its remorseless rise, by about 0·15°C between 2000 and 2006 (see Hansen *et al.*,[46,47] Figure 3 and the recent UK government statement).[48]

In many areas of the world, regional and global changes to the environment are likely to cause increases in the frequency and intensity of natural hazards, such as higher temperatures lasting for longer periods,[49] more flash floods and perhaps greater winds in hurricanes.[50,51] These and other environmental forecasts and models depend on having accurate and comprehensive measurements, which should also be available to all forecasting groups, as well as to those applying the results. But despite general agreement about the need for openness, environmental (including topographical) data from research and observations are still difficult and costly to obtain by industry and even government agencies, both within the originating country and internationally.[24,52,53] Improved data availability is also an important way of improving the reliability of forecasts. The expansion of environmental monitoring by Earth-observing satellites[54,55] is providing more openly available data.[56]

For predicting the impacts of changing environmental risks associated with global warming on society and on the economy over periods of decades and even centuries, even more complex and controversial assumptions are needed. These assumptions, which depend on how the economy and society responds to these and other serious impacts, may or may not be related (such as shortage of resources, disease, etc.) (see Section 4).[57]

3. REDUCING THE IMPACTS OF HAZARDS AND OF CLIMATE CHANGE

Turning to policies for reducing the impacts of environmental hazards, societies and organisations are addressing this challenge in several ways. In some regions, policies for dealing with hazards and the adverse effects of changing climate are integrated in the framework of sustainable development.[58]

First protective measures are taken long before the hazards arrive, based on information and warnings about the probability of future events, which, as already mentioned, may not be the same as in the past. As forecasts and warnings for specific events improve, short-term measures of avoidance or protection can also be very effective. Industries and communities are following the well-established example of mariners, farmers, etc., and taking measures that are more focussed with regard to the hazard and location and are therefore less costly.

International/national media are used for warnings about hazards, even over very short periods of a few minutes (Figure 2). But for information that is specific to certain areas, specific warnings about local natural hazards and secondary effects (including, for example, risks of infrastructure failures) have to be communicated. Hong Kong, for example, has trained its citizens to understand and respond to such warnings without fail.[27,59] In some earthquake-prone countries (including the USA) school children are regularly trained in emergency response. This has prevented the numerous casualties experienced in other countries where these exercises are neglected. Research is significantly improving the reliability and comprehensiveness of forecasts underlying warning systems, as, for example, with tsunamis.[60]

For longer term and repeated hazards, the experience of weather services is that only through repetition is information taken seriously. Annual statistics of hazards, such as rising global temperatures and GHG concentration,[61] and the occurrence of natural disasters are regularly publicised. However, where critical hazard data and/or forecasts are uncertain, information is not publicised so widely or as frequently, as, for example, data on the long-term rise in global average sea level or desertification.

Technology is ensuring more effective dissemination of hazard data. Mobile phones in India carry warnings automatically translated into 14 languages.[62] Street-scale air pollution warnings to the mobile phones of individuals suffering from breathing difficulties are now provided through local government agencies in London.[63] Cosmar is a network of agencies in the coastal zones of Africa that provided vital warnings of the tsunami in 2004.[64] However, despite improvements in communication systems, warnings are not always communicated effectively or taken seriously. The deadly tornados in USA in February 2008 were forecast five days ahead, but still people did not take sufficient precautions.[65]

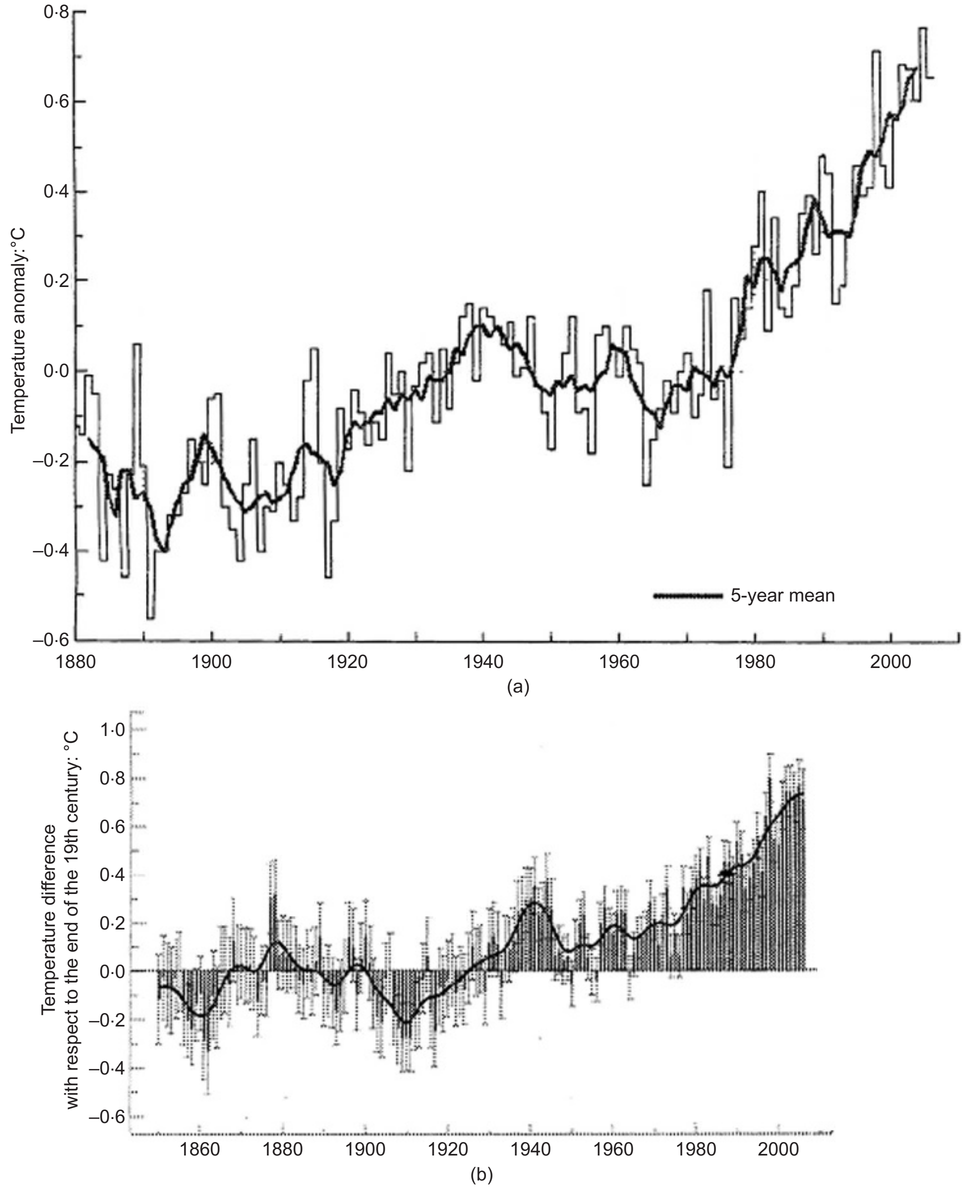

Fig. 3. Comparison of global near-surface temperatures (a) over land[47] and (b) over the whole land/sea/ice surface.[10] Note the difference in the trend over the years 1999–2006 because of the cooling of surface waters of the oceans during this period

After major hazard events, policies are needed for minimising both immediate and long-term impacts on the affected communities, including protection against secondary hazards that often follow.[20] Planning for future events should begin immediately, for example by improving resilience[66,67] or, in extreme cases, deciding to steer communities to areas with lower environmental risks.

The effects of improving resilience to the impact of a single hazard event are sketched in Figure 4 to show how the timescale of the response depends on resilience and the strength of the hazard. Figure 5 shows how the effect of climate change on increasing frequency and severity of certain hazards causes short and longer term impacts, whose severity greatly depends on the resilience and timescale of response.

One can differentiate between 'technical' policies that are directed towards specific responses and 'sustainable' policies that are directed towards integrated, longer term and often indirect responses. Sustainable solutions need to contribute towards the mitigation of global effects and also ensure that social objectives are included in the response to impacts of hazards and climate change (Figure 1).

Systems and economic analysis, together with political judgement, are all necessary to balance sustainability with the demands for short-term investments in resilience. The optimum solutions have been found to involve industries and communities changing their habits. They may even involve redistributing environmental risks, for example in flood management schemes, by a wider exposure of more people to smaller risks.[68]

Where hazards are exacerbated by global warming,[69] a combination of technical and sustainable policies is even more necessary, for example for dealing with artificially high temperatures and high levels of air pollution that now occur in most of the largest urban areas. 'Technical' solutions such as new reflective materials on buildings and roads are being introduced. Although air conditioning is a direct way of lowering the temperature within buildings and vehicles, it also

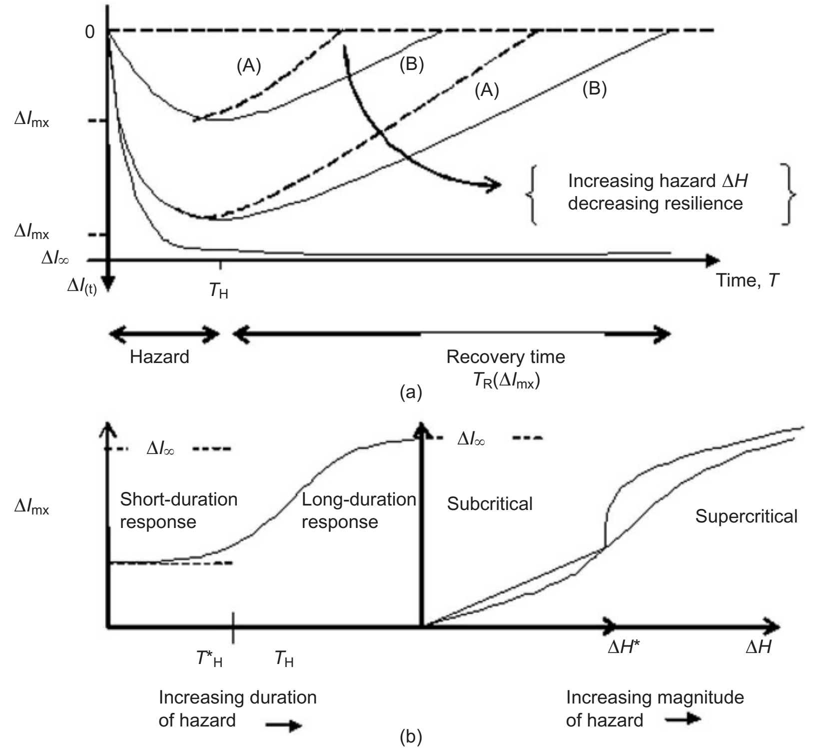

Fig. 4. The connections between impact, hazard and resilience. (a) Impact ΔI over time, showing the maximum impact ΔI_{mx}, hazard timescale T_H and response/recovery over time T_R, depending on the severity of the hazard and the resilience of the communities and systems affected. (b) Variation of maximum impact or damage ΔI_{mx} depending on its duration T_H and magnitude ΔH. ΔI_{mx} can increase more rapidly with T_H and ΔH when they exceed critical values, T^*_H and ΔH^* (which in turn depend on the system and type of hazard). Note that 'shock-like' transitions occur in some systems. ΔI_∞ is the upper limit of ΔI_{mx} (when the entire community/region can effectively not be restored)

leads to high energy use and raises temperatures in the streets. It is needed less in sustainable 'green' buildings, which may generate power from photovoltaic panels on roofs or car parks. Such buildings also cool their local environment and can even be used for food production.[58]

Japan has shown how expectations and habits can be changed by urging building managers to reduce air conditioning so that temperatures are typically about 28°C in the summer months and by encouraging the wearing of cooler clothes appropriate to the higher temperature. With less energy used for the cooling of public buildings,[70] Japan's GHG emissions have been significantly reduced.

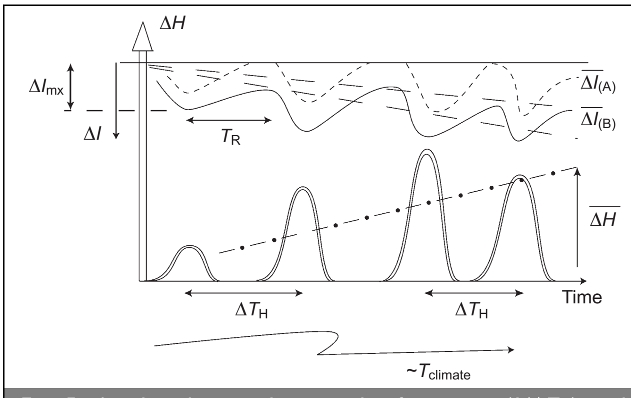

Fig. 5. As the climate changes, the frequency ($1/\Delta T_H$) and magnitude ΔH of hazard events increase. The long-term impact $\overline{\Delta I}$ increases more in low-resilience systems (B) (where there are higher maximum impacts ΔI_{mx} and where the recovery time T_R is less than the time between events ΔT_H) than in high-resilience systems (A) (where $T_R < \Delta T_H$)

Policies for resilience to floods are also being transformed (see Crichton[4] for a trenchant analysis of non-resilience). Remarkable technical progress has been made with temporary structures that can protect cities against floods with only 24 hours warning (as in Prague).[71] But for the longer term, buildings in flood plains may have to withstand flooding—a radical and uncomfortable departure in urban organisations[72] but one that China has addressed for many years.

In developing countries, government and community organisations have limited resources for providing information and for dealing with environmental risks or even local hazards. Many communities along the coasts of Africa and Asia have become more vulnerable to hazards and are often unaware of the reasons. For example, cutting down mangrove trees for fuel exposes nearby villages to infestation from insects that formerly inhabited the mangrove forests;[73] it also exposes the communities to damage from tsunami waves.[74] Following the tsunami in December 2004, lives were lost in areas where coastal protection had been damaged by the removal of coral reefs and sand dunes to provide cheap building materials.

Different types of policy and public campaigns are needed to deal with longer term environmental hazards—from seasonal periods to decadal climate change.[11] Intergovernmental and commercial organisations (e.g. those dealing in food and other resources) are taking precautionary actions for these time periods based on detailed data from across the world and on long-range forecasts.

4. HAZARD REDUCTION AND MITIGATION

Can natural hazards be reduced directly? Over the short periods of weather systems, increasing or decreasing precipitation by artificially seeding clouds has been shown to be successful, even very successful on occasion (when forest fires in Mongolia in 1996 were suppressed by artificial snowfall induced by cloud seeding). Although generally there is a low probability of success, weather modification continues to be part of the official programme of the World Meteorological Organisation.[61] However, United Nations bodies have expressed concern that if these methods became more successful, it might change the relative amounts of precipitation in neighbouring countries and seriously affect their mutual relations. For the much longer periods of vegetation growth and decay, there have been proposals for reducing drought and desertification hazards through altering the albedo or stimulating the hydrological cycle, for example, by desalination.[75]

On a global scale, 'geo-engineering' solutions to reduce major environmental hazards are theoretically possible.[76,77] Such 'global solutions' might involve reducing solar radiation by putting aerosols into the upper atmosphere[78] or space reflectors/deflectors in space, or changing the biochemistry of carbon absorption in the upper ocean. But the general view is still that direct methods are so risky that they are not politically or socially acceptable unless global hazards begin to threaten large populations. Precautionary measures, with low risks of adverse effects, are the basis of current policies.

International efforts to reduce the causes of environmental risks are mainly focused on the hazards associated with the contribution to global warming caused by the emission of GHGs from industry, agriculture and naturally. Preventing the rise in global average temperature by more than 2–2·5°C will require a very substantial decrease in GHG emissions. Action will have to be taken in each country; in total, emissions must be reduced by more than 50% below present levels over the next 50 years and not grow any further. Because of the dynamics of the climate–human system, earlier cuts in emissions will avoid having to make more drastic cuts later.[10,57] Much greater proportional cuts are needed by industrialised countries (between 60 and 80%) to allow for the predicted growth of energy use and carbon emissions in developing countries (see Figure 1).

Some technologies are already demonstrating how energy use in buildings can be greatly reduced (by more than 50% on average), which in the UK is responsible for about 50% of carbon emissions. Indeed, some buildings and their ancillary support systems (e.g. cleaning, drinking and drainage water) have become carbon neutral, that is they do not increase net carbon emissions (as in the Bedzed development in London[79]). Surface transport could also move to being carbon neutral through the use of certain biofuels (provided the production processes of such fuels do not cause worse effects).[80] Zero GHG emissions are possible through hydrogen and electrically driven fuel cells.[81] However, these changes will require both local technological and planning initiatives, for example, in mass-produced systems with lower carbon footprints and in the design of cities.

Economic and technological analysis has shown that these goals can only be achieved by using the full range of existing energy technologies and new technologies still being researched,[82] which may require considerable social, political and economic reorganisation. Although this 'portfolio solution' is now accepted in India, China and the USA (and by all the main political parties in the UK), it is regarded as controversial in other G8 countries.

Advances in electricity generation are now materially reducing GHG emissions through improved efficiency—up to 57% from 38% in some fossil fuel power stations (using combined cycle gas turbine plant). Nuclear power stations have effectively zero GHG emissions; the next generation will produce a fraction of the radioactive waste of current stations, but are currently taking a minimum of 5 years to be constructed. Renewable systems have the advantage of flexibility in size, speed of construction and availability on regional and local scales, and GHG emissions can thus be reduced faster than by other technologies. All solutions have some adverse impacts on the environment that have to be minimised (e.g. nuclear waste, construction materials, aesthetic impact of wind turbines). Buildings will increasingly reduce their energy needs with embedded generation systems ranging from heat pumps to wind and solar; micro-fission systems are even being considered.

To ensure that these technologies contribute most cost effectively to environmental sustainability, they need to be integrated with each other and with other measures of adaptation and mitigation. While power companies find that large corporate users are taking up initiatives such as combined central and local power systems, they need more long-term commitment from governments, for example, to utilise waste heat in domestic heating/cooling and by local industries.

There is now a search for policies to minimise the economic and social disruption associated with programmes of mitigation and more sustainable use of energy resources. Can these be integrated with programmes of adaptation and with the general reduction of environmental risk as Figure 4 illustrates? Local communities are already showing the benefits of integration by linking schemes for carbon reduction, reduced energy use, healthier buildings, and harmonising urban and rural environments.[83] For political sustainability, these initiatives also have to be consistent with policies for the use of limited resources, including land, and for strengthening local economies and employment.

Policies on environmental resilience and sustainability have geopolitical impacts through countries affecting each others' environments and resources, and consequently other countries' share of global impacts.[84] Some interactions are physical, as with regional and global transport of pollution and disease, whether on the timescales of hazards or global environmental changes. But they can be equally influential and complex when they are embedded in the products or services exchanged between countries.

Since, in either case, greater sustainability in one country can benefit or threaten that in another, global and regional policies have to be internationally agreed. For example, embedded or 'virtual water' is contained in wheat exported from, say, Canada to the Middle East or other countries with great water shortages; embedded 'virtual' carbon-saving is provided by African fruit/flower growers whose exports save carbon emissions from heated greenhouses in Europe (even allowing for aviation emissions).[85] Tourism can also contribute—subtropical countries who receive elderly European tourists in winter in fact lessen these people's carbon emissions from heating their homes. However, sometimes 'embedded' environmental benefits gained through importation lead to risks for the exporting country. For example, embedded adaptation is provided by tropical forest wood exported to Japan—this means (as Japanese colleagues explain) that Japan does not have to cut trees on steeply sloping hills and thus the dangers of mud slides and flooding are reduced. This policy could lessen its impact on tropical rain forests through the use of sustainably managed forests, which are now being developed world wide. Similarly, pollution and carbon emissions are reduced in countries importing manufactured goods from low-cost countries employing limited pollution controls and in countries importing food based on the intensive use of agrochemicals in another. China's consumption of US meat from cattle fed on maize grown with artificial fertilisers has led to serious water pollution in the Mississippi and the Gulf of Mexico[86] (a point made by the US ambassador for oceans and fisheries). As environmental risks and their secondary effects (Figure 2) differ greatly across the world (as demonstrated by these examples), optimum policies are possible provided they are based on identifying and minimising the varying types of risks wherever they occur.

5. CONCEPTS FOR INTEGRATED POLICIES

Because of their importance for the health and wellbeing of the entire population of a country, environmental risks are the responsibility of national government as well as of industry and local communities. Governments have a unique role in coordinating and integrating policies for reduced risks. As recent cyclone-flood events in America and Asia have shown, governments that attempt to deny responsibility have had to reverse their position. Whether the risks are regional or global, they have to be tackled through intergovernmental cooperation and a multitude of specific agreements for every aspect of the environment. This effective but piecemeal approach began in the 1970s and 1980s when Europe and North America dealt with acid rain; in the 1980s the UN introduced the Montreal protocol for eliminating chlorine/fluorine based refrigerants that were damaging stratospheric ozone. Increasingly, the international media and the internet are publicising the preparations leading up to international agreements. Perhaps, as the whole world realises how and why countries differ about policies on the urgent issue of climate change, the compromises that will be necessary to reach international agreements might well be reached sooner—as recent gatherings of experts and legislators are indicating.[13,87]

Governments need to work with a few key sectors of society—research, industry, political organisations and civil society—when policies and international agreements on new types of environmental risk are being established. This process is depicted schematically as a set of influence lines in Figure 2. Since politicians and governments generally want to hear about solutions when they are faced with problems, advice has to focus on how to reduce the impacts of the hazard and what can be done to eliminate or lessen the hazard itself. Introducing policies to tackle all the relevant aspects of climate change is proving difficult for governments as they are already having difficulty in dealing with other more immediate types of environmental risk such as air pollution from vehicles or aircraft noise. Although governments and legislators have broadly accepted that the climate is changing and that this holds many dangers for their countries, and although they have also accepted the need to reduce GHG emissions, not all countries have accepted the need to have targets for global GHG concentrations or the necessity of making substantial cuts in their own emissions. They fear that that this could be damaging to their economies.[87]

The Stern report[57] on the economics of climate change reviewed this hypothesis in detail by examining, with the aid of climate models, the economic consequences of different policies for mitigating emissions over various timescales. The calculations included the costs of adapting to worsening climate conditions. The UK government agrees with its conclusions, which go well beyond the limited range of the Kyoto protocol, namely that investments are indeed required to reduce emissions and to reduce the impacts of environmental change (i.e. adaptation). This will cost of the order of 1–2% of gross domestic product (GDP) (for the whole world) over the next 20–30 years—money that might otherwise be used for public programmes (e.g. health and education) or private consumption. However, Dasgupta[88] has argued that this expenditure should be delayed and passed on to later and richer generations and concludes that, over the next decade or two, governments should not attempt artificially to limit GHGs. But this would probably lead to the steady elimination of animal and plant species (which are under threat) and would cause the world's climate systems to move towards a new equilibrium that differs significantly from its present state. Furthermore, governments would be breaking their commitments to the UN climate change and biodiversity treaties of 1992. These UN treaties provide a coherent framework within which governments can effectively integrate their policies.

To settle these arguments about differing economic and environmental strategies, there first needs to be better, and more open predictions about all aspects of their consequences. This is essential before the major countries of the world can agree about how to replace the Kyoto protocol by 2012. The decisions reached will affect the state of the global environment extending beyond the end of this century (as the action trajectories in Figure 2 demonstrate).

The debate has to go beyond economic and environmental issues if the conclusions are to be effective politically, institutionally and socially. Organisations like national health services and large industries faced with strategic choices for their future planning make use of various forms of data gathering, analysis and computational simulation. This methodology of complex systems modelling is not just for research, but should lead to relevant concepts and guidance for making decisions.[89] The European Union has supported this systematic approach because of its value to multinational organisations with different organisational and cultural traditions.[90]

The development of policies by government agencies about reducing hazards illustrates this point. They cannot rely simply on economics, but have to consult widely with, for example, industry, local communities and research institutions,[91] particularly when they are experiencing serious practical and political difficulties in meeting their objectives. This is now happening in countries that have accepted the need to make large (by more than 50%) reductions in emissions. For example, despite the achievement in Singapore and London[92] in limiting the overall use of cars powered by fossil fuels, other cities in Europe have baulked at this proposal, not with standing the additional benefits of reduced air pollution. Architects and planners[93] are recommending that there should be a higher density of housing in city centres with less use of private cars and clean public transport systems.

Practical policies for mitigation and adaptation have often been initiated by local leaders through innovative pilot projects. This helps national politicians make their environmental decisions through the loop process of information–consultation–pilot-stage–policy–action (see Figures 1 and 2). The reactions of people and industry can lead to considerable changes, even at the end of the process (e.g. as in the UK fuel strike in 2000 against the rising environmental fuel tax). Systems analysis may in future guide governments about the likely consequences and timescales for the introduction of policies over spatial and organisational networks.[18] New visualisation and simulation technology now enables complex environmental risks and policy options to be explored by communities[94] and in 'decision theatres'.[95] For example, users can now explore the 'future' with interactive and overlapping displays based on data, maps and back-up computations in real time; decisions can now be better informed about planning and security[96] against possible effects of flooding or water shortage in large urban areas.

6. PUBLICISING AND EXPLAINING INTEGRATED POLICIES

Politicians have to rely on ideas to explain and promote new policies that affect the patterns of people's lives and even their ways of thinking. Climate change is forcing this kind of revolution on society. Politicians, commentators and academics engaged in public debate on this topic draw on various themes. Gore's[97] educational film alarms the audience, without offering many solutions. In 1979, Lovelock[37] introduced the idea of the Earth as a self-correcting system, but has now accepted that this notion is invalidated by current levels of human interference with the system, as species are eliminated and ice sheets and forest areas disappear. The ideas about sustainability in the Brundtland report[7] had a great impact on the UN, governments, communities and industries around the world. The principles were accepted as central for environmental policy and even legislation in Europe from the 1990s and in the USA when US Congress passed the Energy Act in 2005.

However, a more philosophical and conceptual guide is also needed to help unify and explain policies for reducing environmental risks while ensuring economic development and environmental sustainability. Integration causes some Orwellian nervousness in politicians and officials who recall the clumsy use of power by states and monopoly industries in Europe, America and Asia, and the dangers of erroneous central policies following a particular party line. Innovation can also suffer. In the UK's new Climate Change Act of 2008, mitigation and adaptation policy are organised and budgeted separately, in two separate government departments. However, within local and regional government, integrated initiatives are increasingly accepted and argued for by environmental groups such as Environmental Protection UK and the Environment Agency. In the Netherlands, the long tradition of building windmills on dykes has been brought up to date with tall wind turbines using the concrete coastal defence structures as their foundation, with huge cost savings.

Perhaps in countries like India and China whose rapid economic development has benefited from centralised planning and self-sufficiency, the adoption of integrated solutions involving industry and environment may be more straightforward. It is significant that for the economically least developed countries, the UN Development Programme[98] and the World Bank are now promoting integration of their sustainable development projects.

As integration becomes a theme that politicians and engineers are re-visiting, their thinking is now more drawn from natural systems and less from the engineering paradigm of steam engines, circuits and feedback.[99] This softer, self-organising, organic approach resonates more with most people's experience about how effective social organisations actually operate, as well as with their intuitive and religious convictions about the holistic nature of physical and living systems. Indeed, looking for holistic solutions and policies is becoming the new political and administrative orthodoxy (the word was invented by Smuts,[100] Prime Minister of South Africa, in his remarkable 1926 book *Holism and Evolution*). Such an approach can be supported by modern scientific understanding of the adaptive, protective and creative strengths of complex systems and societies, and how, paradoxically, such systems are reinforced by internal tensions between competition, cooperation and self-interest (Bertalanffy[101] incidentally quotes another Premier, E. C. Manning of Alberta, Canada). The internet reinforces the gradual trend to these more integrated policies;[94] governments now prefer to provide frameworks providing information and facilitation for encouraging optimum forms of integration to emerge 'bottom-up' Environmental regulation and financial incentives aim to steer and energise new developments. But central planning and large financial investments over decades are essential for engineering solutions to ensure sustainable infrastructure and energy systems such as power generation, transportation, barrages, and so on.

As political leaders in countries all over the world deal with environmental risks and long-term sustainability, they recognise both the complexity and the urgency of the task. As in previous international crises, they realise the advantages of integrated policies despite well-known and long-standing political difficulties. There is some survey evidence that this approach, if well explained, is well supported in communities where climate-related policies are being implemented.

7. DEVELOPING, PRIORITISING AND COMMUNICATING RESEARCH ON RESILIENCE AND SUSTAINABILITY

Ever since science began, it has been applied to studying natural and artificial hazards. Over the past two centuries, scientists have identified many of the most serious environmental risks before the worst effects become apparent (the dashed line in Figure 1). This role becomes even more important as society faces greater technical and social challenges associated with global environmental change and the likely occurrence of more severe local hazards.

Equally, many of the developments in science, technology and policy have come from collaboration between research and practice. There have been calls in many countries to strengthen this collaboration (e.g. in the UK from witnesses to parliamentary committees)[84] from those dealing with the urgent problems of short- and long-term environmental hazards. There is a particular need for research to provide more long-term databases (such as Keeling's record of carbon dioxide at Hawaii) and to bring new insights to the study of innovative practical projects, such as those improving urban sustainability around the world.[58] In the UK, the Natural Environmental Research Council is now directing more funds in this direction.

Unfortunately, in most countries, investment in research into extreme hazards is still small in relation to the economic benefits that such research could bring in terms of improved warnings and resilience, including insurance cover.[53] Japan has led in terms of research and technological investment into all kinds of hazards over many years;[22] the international response to the disastrous Asian tsunami in 2004 has led to new scientific understanding[102] and an extended warning system in south and southeast Asia.[60]

Climate change research, which has had a higher level of political, scientific and financial support, is well coordinated nationally and internationally. It is a unique programme in the scale of its collaboration between scientists in almost all branches of natural and social sciences—from meteorology, oceanography and earth sciences to chemistry, botany and economics. Regrettably, in developing countries, some of the important climatic measurements being taken (e.g. in critical locations) are not actually being disseminated through lack of funds and exchange arrangements.[103] Engineers are also involved in advanced projects both in mitigating climate change through the design of sustainable energy systems and in adaptation through new designs in infrastructure and sustainable construction projects such as multi-purpose tidal barrages. At the same time, research into new energy technologies is growing, although not yet back to the levels of the 1970s. The aim is to increase efficiency within the critical timescale needed to limit global warming. The generation and distribution of hydrogen is, in principle, sustainable, but will it be practical and economic?[104] Nuclear systems have the capability of lasting thousands of years into the future (when future climate trends may differ considerably from the present) hence the importance of research into new and sustainable systems such as fusion[105] and hybrid fusion–fission technology.[106]

Connections are clearly growing between the scientific disciplines focused on atmospheric, oceanic, hydrological and land surface phenomena as they become more extensively engaged in the 'applied' problems of research on natural hazards and on the variability of climate change, whether natural or artificial. This has resulted in improved measures for the resilience of communities and for policies of adaptation, mitigation and sustainability. The scientific problems and appropriate measures are different all over the world depending on the natural conditions and the societies involved, so capabilities must be geographically distributed throughout countries and regions. In China, India and South Africa, environmental information services connected to universities are growing fast.[107–109]

Academic research and teaching is responding to these developments, moving from individual scholarship- and discipline-based organisation to the development of multidisciplinary centres.[110,111] Such centres are capable of studying the merits of integrated solutions, using previous research on integrated assessments of climate change policies.[112]

These research centres, however, can only dimly foresee how future environmental hazards and longer term climate change will affect society. They need to be responsive as societal and environmental events occur, such as unexpected outbreaks of internationally contagious disease, the sudden disappearance of polar ice-fields (e.g. the Larsen field in 2002) or unprecedented drought (as, for example, in one of the rainiest places in the world in India).[113–115] New policies became necessary after the damaging tsunami on the Asian and African coasts in 2004 affected the communities there enormously.

Even if they are tentative, background explanations of such environmental events are expected by both the public and the media.[116] Without an understandable commentary on the evolving global environment, the public and politicians find it difficult to understand and accept environmental policies.[45,117]

Environmental centres are also expected to respond to the quite reasonable questions and varied opinions of different groups of the public, politicians and professionals.[110] Recently, 90% of actuaries who were polled in London said they accept the reality of climate change (perhaps because they are familiar with uncertainty). By contrast, a rough sample of the opinions of civil engineers at a large meeting in London in October 2007 indicated that more than 50% remain sceptical; many of them quoted the uncertainty of climate models.

Clearly there is still much work to do in establishing better understanding between scientists, engineers and leaders of society concerning the complex but vital issues of resilience and sustainability.[118]

ACKNOWLEDGEMENTS

This paper is based on a keynote speech given at the *G8–United Nations Educational, Scientific and Cultural Organization (UNESCO) World Forum on Education, Research and Innovation; New Partnership for Sustainable Development*, held in Trieste, Italy on 10–12 May 2007. I am grateful to Professor Sreenivasan for his invitation to the forum, and for many conversations with colleagues at Arizona, London, Cambridge, Brussels, Toulouse and Delhi. I acknowledge the referees' constructive comments. Support came from Natural Environment Research Council (NERC) at University College London (UCL) through the grant to Centre for Polar Observation and Modelling, from Arizona State University as a visiting professor from Cornell, as a Mary B. Upson visiting professor and from Midi-Pyrenees Innovation during my stay in Toulouse as a Pierre Fermat visiting professor.

REFERENCES

1. Ban K.-M. Opening address. *Proceedings of UN FCC*

Conference, Bali, 2007. See www.unfccc.int/ for further details. Accessed 22/02/2009.
2. Bush G. W. *State of the Union Address*, 2007. See http://www.whitehouse.gov/news/releases/2007/01/20070123-2.html for further details. Accessed 01/02/2008.
3. See www.unisdr.org
4. Crichton D. What can cities do to increase resilience? *Philosophical Transactions of the Royal Society A*, 2007, **365**, No. 1860, 2731–2740.
5. Pielke R. Jr. Climate change and coastal development. *Philosophical Transactions of the Royal Society A*, 2007, **365**, No. 1860, 2717–2730.
6. King R. O. *Hurricane Katrina: Insurance Losses*. CRS report for congress RL33086.
7. Brundtland G. H. *Our Common Future*. Oxford University Press, Oxford, 1987.
8. Walker B., Carpenter S. R. and Kinzig A. Resilience, adaptability and transformability in social–ecological systems. *Ecology & Society*, 2004, **9**, 5, http://www.ecologyandsociety.org/vol9/iss2/art5/
9. See www.oakfnd.org
10. Intergovernmental Panel on Climate Change. *Fourth Assessment Report*, 2007. See www.ipcc.ch for further details. Accessed 01/12/2007.
11. Corfee-Morlot, J., Maslin, M. and Burgess, J. (2007). Global warming in the public sphere. *Philosophical Transactions of the Royal Society A*, 2007, **365**, No. 1860, 22741–776.
12. Schellenhuber H. J., Cramer W., Nakicenovic N., Wigley T. and Yohe G. *Dangerous Climate Change*. Cambridge University Press, Cambridge, 2006.
13. United Nations Framework Convention on Climate Change. *Bali Conference of the Parties* 13, 2007. See www.unfccc.int/meeting/cop_13 for further details. Accessed 01/02/2008.
14. See http://www.defra.gov.uk/
15. See www.em-dat.net
16. See www.who.int
17. Hunt J. C. R. Mathematical model could clarify arms race. *Nature*, 2001, **411**, 737.
18. Bishop S. R. and Hunt J. C. R. General systems dynamics applied to policy. *Proceedings of European Conference on Mathematics in Industry*. (Ed. Norbury J.) Springer, Berlin, 2009.
19. Centre for Ecology and Hydrology. *Flood Estimation Handbook*. CEH, Wallingford, 2005.
20. Xu Y. P., Booij M. T. and Mynett A. E. An appropriate framework for the Dutch Meuse decision support system. *Environmental Modelling*, 2007, **22**, 1667–1678.
21. Parker D. J. and Penning Rowsell E. C. Dealing with disasters. In *London's Environment* (Hunt J. (ed.)). Imperial College Press, London, 2005, pp. 175–202.
22. See www.dpri.kyoto-u.ac.jp
23. See www.jma.go.jp
24. Adger W. N. Vulnerability. *Global Environmental Change*, 2006, **16**, No. 3, 268–281.
25. Troop P. *Anticipating the Demands of Future Emergencies*. Health Protection Agency, 2007. See www.ijocc.eu for further details. Accessed 01/02/2008.
26. See http://ec.europa.eu
27. Hunt J. C. R. Forecasts and warnings of natural disasters and the roles of national and international agencies. *Meteorological Applications*, 1995, **2**, No. 1, 53–63.
28. Sellnow T., Seeger M. W. and Ulmer R. R. Chaos theory, informational needs, and natural disasters. *J. App. Comm. Res.*, 2002, **30**, 269–292.
29. Hunt J. C. R., Maslin M., Killeen T., Backlund P. and Schellnhuber H. J. Introduction. Climate change and urban areas; research dialogue in a policy framework. *Philosophical Transactions of the Royal Society*, 2007, **365**, No. 1860, 2615–2630.
30. Cullen M. J. 'New mathematical developments in atmosphere and ocean dynamics, and their application to computer simulations' in *Large Scale Atmosphere Ocean Dynamics* (Norbury J. and Roulstone I. (eds)). Cambridge University Press, Cambridge, 2003, pp. 202–287.
31. Hunt J. C. R. Environmental forecasting and modelling turbulence. *Physica D*, 1999, **133**, No. 1, 270–295.
32. Carson D. J. Seasonal forecasting. *Quarterly Journal of the Royal Meteorological Society*, 1998, **124**, No. 1, 1–26.
33. See www.metoffice.gov.uk/weather/seasonal/....
34. Saunders M. A. and Lea A. S. Seasonal prediction of hurricane activity reaching the coast of the U.S. *Nature*, 2005, **434**, 21 April, 1005–1008.
35. Woo G. *The Mathematics of Natural Disasters*. Imperial College Press, London, 1999.
36. Houghton J. *Global Warming. Complete Briefing*. Oxford University Press, Oxford, 1994.
37. Lovelock J. E. *Gaia: A New Look at Life on Earth*. Oxford University Press, Oxford, 1979.
38. Budyko M. I. *Global Ecology*. Progress Publishers, Moscow, 1980.
39. Hunt J. C. R., Mitchell J. and Tett S. (1996). Mathematical and physical basis of general circulation models of climate. *Zeitschrift für Angewandte Mathematik und Mechanik*, 1996, **76**, No. S4, 501–508.
40. Enfield D. B., Mestas-Nuñez A. M. and Trimble P. J. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysics Research and Letters*, 2001, **28**, No. 10, 2077–2080.
41. Stott P. A. and Kettlebrough J. A. Origins and estimates of uncertainty in predictions of 21st century temperature rise. *Nature*, 2002, **416**, No. 6882, 723–726.
42. Orr A., Cresswell D., Marshall G. J., Hunt J. C. R., Sommaria J., Wang C. G. and Light M. A low level explanation for the recent large warming trend over the western Antarctic peninsular involving blocked winds and changes in zonal circulation *Geophysics Research and Letters*, 2004, **31**, No. 6, L06204.
43. Bellamy D. and Barnett J. Climate stability; an inconvenient proof. *Proceedings of the Institution of Civil Engineers, Civil Engineering*, 2007, **160**, May, 66–72.
44. Hansard, 2007, November 27, col. 696. Question by Lord Hamilton of Epsom.
45. Lawson N. *An Appeal to Reason—A Cool Look at Global Warming*. Duckworth, London, 2008.
46. Hansen J. E., Sato M., Ruedy R., Lo K. and Medina-Elizade M. Global temperature change, *Proc. Natl. Acad. Sci.* 2006, **103**, 14288–14293.
47. See http://cdiac.ornl.gov/trends/temp/hansen/graphics/gl_la
48. Hansard, 2008, July 15, col. 1093. Response by Lord Rooker.
49. Cassou C. and Guilyardi E. Modes de variabilité et changement climatique. *La Météorologie*, 2007, **59**, November, 22–30.
50. World Meteorological Organisation. *Tropical Cyclone Report*. WMO, Geneva, 2006.

51. HOLLAND G. J. and WEBSTER P. J. Heightened tropical cyclone activity in the north Atlantic: natural variability or climate trend. *Philosophical Transactions of the Royal Society*, 2007, **365**, No. 1860, 2613–2776.
52. MCGLADE J. E. European Environment Agency, Copenhagen, 2006.
53. WOOD R. Science and finance. *Foundation of Science and Technology Journal*, 2008, **19**, No. 8, 17–18.
54. HUNT J. C. R. and COATES A. Developments in space engineering and space science. *Philosophical Transactions of the Royal Society*, 2003, **361**, No. 1802, 205–218.
55. HUNT J. C. R. and COATES A. Joint efforts needed to forecast space weather. *Nature*, 2004, **427**, No. Jan, 13.
56. www.gmes.info
57. STERN N. *The Economics of Climate Change*, 2006. See www.sternreview.org.uk for further details. Accessed 01/02/2008.
58. HEAD P. *Entering an Ecological Age*. Brunel International Lecture, Institution of Civil Engineers, London, 2007.
59. LEE B. J. and DAVIS I. *Forecasts & Warnings*. Programme Overview. UK Coordination Committee for IDNDR, 1999, Thomas Telford, London.
60. See www.ioc-tsunami.org
61. See www.wmo.ch
62. See www.vodafone.com
63. see www.cerc.co.uk/yourair
64. See www.nepadcosmar.org
65. BROOKS H. E. Tornado warning performance in the past and future. *Bulletin of the American Meteorological Society*, 2004, **84**, No. 6, 837–843.
66. MOSER S. Is California preparing for sea level rise? *California Coast & Ocean*, 2007, **22**, No. 4, 24–30.
67. KINTISCH E. Levees came up short, researchers tell Congress. *Science*, 2005, **310**, No. 5750, 953–955.
68. COMMISSION FOR ARCHITECTURE AND THE BUILT ENVIRONMENT AND CONSTRUCTION INDUSTRY COUNCIL. *Adapting to Climate Change*. Cabe/CIC, London, 2007.
69. POPE V. *et al.* The Met Office Hadley Centre climate modelling capability: the competing requirements for improved resolution, complexity, and dealing with uncertainty. *Philosophical Transactions of the Royal Society A*, 2007, **365**, No. 1860, 2635–2658.
70. MIKI T. (2006). "Energy Efficiency and Conservation Policy in Japan", Energy Efficiency and Conservation Division Energy Division. http://www.nedo.go.jp/kokusai/kouhou/181206/session02/2-1.pdf. Accessed 23/02/2009.
71. See www.envis.praha-mesto.cz
72. See www.cabe.org.uk
73. See www.Acops.org
74. FERNANDO J., BRAUN A., GALAPATTI R., RUWANPURA J. and WIRASINGHE S. C. Tsunamis. In *Large Scale Disasters* (GAD EL HAK M. (ed.)). Cambridge University Press, Cambridge, 2007, pp. 258–292.
75. MITSUBISHI HEAVY INDUSTRY. *Technical Note on Geoengineering in Saudi Arabia*. MHI, Tokyo, 2007.
76. SCHRAG D. Geo-engineering. *Science*, 2007, **318**, No. 5853, 1054–1055.
77. LAUNDER B. E. and THOMPSON M. Special issue on geoengineering. *Philosophical Transactions of the Royal Society*, 2008, **366**, No. 1882, Nov, 3845–4056.
78. TELLER E., HYDE R. and WOOD W. Active climate stabilization; practical physics-based approaches to prevention of climate change. Preprint University of California Lawrence Livermore Report, *UCRL–JC-148012*, 2002.
79. see www.peabody.org.uk/bedzed
80. SEARCHINGER T., HEIMLICH R., HOUGHTON R. A., DONG F., ELOBEID A., FABIOSA J., TOKGOZ S., HAYES D. AND YU T. H. Use of US croplands for biofuels increases green house gases through emissions from land use change. *Science*, 2008, Feb 7, 1238–1240.
81. INTERNATIONAL UNION OF AIR POLLUTION PREVENTION AND ENVIRONMENTAL PROTECTION ASSOCIATIONS. *Proceedings of International Conference on Air Pollution*, Brighton, 2004.
82. PACALA S. and SOCOLOW R. Stabilizing wedges: solving the climate problem for the next 50 years with current technologies. *Science*, 2004, **305**, August, 968–972.
83. JONES A. *Sustainable Policies in Woking UK. Evidence to House of Lords Committee on EU Policy on Climate Change*. The Stationery Office, London, 2004.
84. BYRNE, J., GLOVER L., ALLENG G., INNISS V., MAN Y.-M. AND WANG W.-D. The postmodern greenhouse: creating virtual carbon reductions from business-as-usual energy politics. *Bulletin of Science, Technology and Society*, 2001, **21**, No. 6, 443–455.
85. GHANA HIGH COMMISSIONER. *Speech to Acops Meeting on Climate Change in Africa*, 2007.
86. MOFFAT A. S. Nitrogen effects in oceans and rivers. *Science*, 1998, **279**, No. 5353, 988–989.
87. See www.globeinternational.org
88. See www.econ.cam.ac.uk
89. ALMEIDA C. and BASCOLO E. Use of research results in policy decision-making, formulation, and implementation: a review of the literature. *Cadernos de Saúde Pública*, 2006, **22**, S7–S33.
90. See www.cordis.europa.eu
91. WALKER L. and SIMMONS M. Towards a sustainable environment for London. In *London's Environment* (HUNT J. (ed.)). Imperial College Press, London, 2005, pp. 241–254
92. HUNT J. C. R. (ed.) *London's Environment*. Imperial College Press, London, 2005.
93. ROGERS R. London's urban renaissance. In *London's Environment* (HUNT J. (ed.)). Imperial College Press, London, 2005, pp. 23–31.
94. HUDSON SMITH A., EVANS S., BATTY M. and BATTY S. Community participation in urban regeneration using internet technologies. In *London's Environment* (HUNT J. (ed.)). Imperial College Press, London, 2005, pp. 221–240.
95. See www.asu.edu/stardust
96. ANGELOUDIS P. and FISK D. Large subway systems as complex networks, *Physica A*. 367, 553–558.
97. GORE A. *An Inconvenient Truth*, 2006. Bloomsbury, London.
98. See www.undp.org
99. GIDDENS A. *Beyond Left and Right*. Polity Press, Cambridge, 1994.
100. SMUTS J. C. *Holism and Evolution*. Macmillan, London, 1926.
101. BERTALANFFY L. V. *General Systems Theory*. George Braziller, New York, 1968.
102. KLEITNER C. A. EAMES I., HUNT J. C. R. AND FERNANDO H. Evolution and runup of tsunami waves. *Proceedings of European Conference on Mathematics in Industry*. (Ed. Wilson, E.) Springer, Berlin, 2009.
103. HUNT J. C. R. Expand free journal project so that poor countries can share their valuable climate data. *Nature*, 2007, **447**, May 259.

104. See www.nrel.gov/hydrogen
105. See www.mofa.go.jp/iter
106. International Atomic Energy Agency. *Potential of Fusion–Fission Sub-critical Neutron Systems for Energy Production and Transmutation*. IAEA, Vienna, 2006.
107. See www.hku.hk
108. See www.iitb.in
109. See www.ukzn.ac.za
110. Lorenzoni I., Pidgeon F. and O'Connor R. E. Dangerous climate change; the role of risk research. *Risk Analysis*, 2005, **25**, No. 6, 1387–1398.
111. Holmes J. Geography's emerging cross disciplinary links. *Australian Geographical Studies*, 2002, **40**, No. 1, 2–20.
112. Dawson R. *et al. A Blue Print for the Integrated Assessment of Climate Change in Cities*. Tyndall Centre, Norwich, 2006, working paper 104.
113. See www.imd.ernet.in
114. Goswami B. N., Venugopal V., Sengupta D., Madhusoodanan M. and Xavier P. K. Increasing trend of extreme rain events over India in 2006. *Science*, 2006, **314**, 1442–1445.
115. Dash S. and Hunt J. C. R. Variability of climate change in India. *Current Science*, 2007, **93**, No. 6, 782–788.
116. See www.benfieldhrc.org
117. Hunt J. C. R. Sound science is not enough. *New Statesman*, April 3 2006, pp. 14–15.
118. Hunt J. C. R. Climate change and civil engineering challenges. *Proceedings of the Institution of Civil Engineers, Civil Engineering*, 2007, **160**, No. 4, 170–175.