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SECTION I

Key Vulnerabilities of the Climate System and Critical Thresholds

INTRODUCTION

As a result of anthropogenic greenhouse gas emissions, key components of the climate system are being increasingly stressed. The primary changes in climate and sea level will be relatively slow and steady (albeit much faster than anything previously experienced by mankind). However, superimposed on these trends, there may well be abrupt and possibly irreversible changes that would have far more serious consequences. The main areas of concern here are the large ice sheets in Greenland and Antarctica, and the ocean's thermohaline circulation. The papers in this chapter focus on these areas.

In their introductory paper, Schneider and Lane present a conceptual overview of 'dangerous' climate change issues, noting the difficulty in defining just what 'dangerous' means. They also highlight the different, but complementary, roles that scientists and policymakers play in this complex arena. In particular, they introduce the notion of Type I errors (exaggerated precautionary action based on ultimately unfounded concerns) and Type II errors (insufficient hedging action, delaying measures while waiting for the advent of overwhelming evidence). Schneider and Lane suggest ways out of these dilemmas using recently developed probabilistic methods.

Rapley focuses on the Antarctic ice sheet and its relationship with sea level. He presents new data-based results on the stability of the West Antarctic Ice Sheet and on the overall mass balance of Antarctica. The melting of the ice shelves, such as Larsen B, which has been continuously present since the last glacial period, may be leading to a speed up of some glaciers, by a factor of 2–6, in a 'cork out of bottle' effect. These processes need to be incorporated in advanced ice-sheet models. The extents to which anthropogenic warming or natural variability are contributing to these changes is unknown but many of the changes are consistent with the expected effects of human activities.

The paper by Lowe and co-authors addresses the Greenland ice sheet. If the Greenland ice sheet melted completely, this would raise global average sea level by around 7 metres – so the probability of such melting and the timescale over which it might occur is an important issue. Lowe and co-authors report on a model ensemble experiment based on the finding that local warming of more than 2.7°C would cause the ice sheet to contract. Using a range of models and emissions scenarios leading to CO_2 stabilisation between 450 ppm and 1000 ppm, the study shows that, even with stabilisation at 450 ppm, 5% of the cases lead to a complete and irreversible melting of the ice sheet. Although complete melting would take place over millennia, there would be an accelerated contribution to sea level rise compared with projections given in the IPCC Third Assessment Report.

A package of three papers is dedicated to the stability of the North Atlantic Thermohaline Circulation (THC). Schlesinger and co-authors present a novel assessment based on probability distributions for crucial system parameters and a spectrum of possible policy interventions. Their results quantify both the probability of a THC collapse in the absence of policy, and the effects of different policies on this probability. Challenor and co-authors present similar results for the probability of a THC collapse, based on a large ensemble study using a statistically-based representation of a medium-complexity climate model. Both of these papers suggest that the likelihood of a THC collapse before 2100 could be higher than suggested by previous studies. However, both papers employ simple models so their quantitative results must be treated cautiously – their main contributions are in demonstrating methods for producing probabilistic results. Wood and co-authors show from a model simulation that the cooling effect of a hypothetical rapid THC shutdown in 2049 would more than outweigh global warming in and around the North Atlantic. They demonstrate the feasibility of using ensembles of AOGCMs to quantify the likelihood of THC collapse, noting that no AOGCM in the IPCC TAR or since has shown a shutdown by 2100. They note that further modelling experiments and observational data are essential for more robust answers.

Turley and co-authors review data showing the marked acidification (pH reduction) of the oceans due to the build up of atmospheric carbon dioxide. As atmospheric concentrations continue to increase, so too will acidification, and this in turn may result in drastic changes in marine ecosystems and biogeochemical cycling. Thus, even in the absence of substantial climate change, the oceans may suffer serious damage, providing yet another reason to be concerned about continuing increases in CO_2 emissions.

The papers presented in this section illustrate why the term 'global warming' is inadequate to describe the changes we can expect in the Earth System. We should focus not only on temperature, but also on anticipated shifts (perhaps rapid) in the full range of climate variables,

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their variability and their extremes; and also on the direct oceanic consequences of atmospheric CO_2 concentration increases. Further, we need to quantify uncertainties arising from uncertainties in future emissions and in climate models, as far as possible, in probabilistic terms. Some of the papers in this section make initial attempts to do this. Addressing climate change will involve balancing uncertainties in both future change and the consequences of policy actions, and understanding the dangers associated with delayed action.

Our understanding of the Earth System is still incomplete and models of the climate system clearly need to be improved. For example, while we have a good sense of how much sea level would rise if the Greenland ice sheet were to disappear, we do not fully understand the thresholds that might lead to such a dramatic effect, nor the time frame over which this might happen. Similarly, while our most physically detailed and realistic models, AOGCMs, indicate that a shutdown of the THC is unlikely, at least by 2100, new analyses presented here using simpler models give somewhat greater cause for concern. A better understanding of the probability of dangerous interference with the climate system requires improved understanding of and quantitative estimates of the thresholds and ‘tipping points’ explored by the papers in this section.

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CHAPTER 1

Avoiding Dangerous Climate Change

Rajendra Pachauri
Presentation given to the Exeter Conference, February 2005

This conference comes at a time when both scientific research in the field of climate change and public policy are waiting for vital inputs. There is a pressing need to provide objective scientific information to assist the process of decision-making in the field.

I am going to talk about the kind of framework within which we need to look at the whole issue of what constitutes dangerous interference with the climate system. This is not a trivial question. The Framework Convention on Climate Change, which was negotiated with a great deal of effort, highlighted the provisions of Article-2 which raises the issue of dangerous levels of anthropogenic emissions and the impacts of human actions on climate change. What I would like to submit is that this is no doubt a question that must be decided on the basis of a value judgment. What is dangerous is essentially a matter of what society decides. It is not something that science alone can decide. But, science certainly can provide the inputs for facilitating that decision. I would like to highlight some cardinal principles which I suggest are important in arriving at a framework and in arriving at what constitutes dangerous. The first, of course, is universal human rights. We need to be concerned with the rights of every society. Every community on this Earth should be able to exist in a manner that they have full rights to decide on. So, therefore, what I would like to highlight is the importance of looking at the impacts of climate change on every corner of the globe and on every community, because we cannot ignore some as being irrelevant to this decision and they certainly have to be part of the larger human rights question that we or most societies today subscribe to.

The next issue that I would like to highlight is the needs of future generations and sustainable development. Climate change is at the heart of sustainable development. If we are going to leave a legacy that essentially creates a negative force for future generations and their ability to be able to meet their own needs then we are certainly not moving on the path of sustainable development. Now, science can provide a basis for this perspective by assessing the impacts and the damage that climate change at different levels can create and, more particularly, the socio-economic dimensions of these impacts. This is an area where I must say that the scientific community has not done enough. And, that is largely because we generally find that social scientists have not really got adequately involved in researching on issues of climate change.

There are several questions which I am sure will come up for discussion in this conference. Setting an explicit threshold for a dangerous level of climate change – how valid is that? You have to start somewhere and I am sure there is no perfect measure, there is no perfect datum on the basis of which you could decide what is dangerous. But this is a question that needs to be answered. Of course, we must also understand that if we fix a certain threshold then reaching that threshold depends to a significant extent on initial conditions. You could have a place that is severely stressed as a result of a variety of factors, where even a slight change in the climate could take you over the threshold. These baseline or initial conditions are extremely important to define and understand. Then we need to look at the marginal impacts and the damage that climate change causes. This requires an assessment of the extent of climate change that is likely to take place and the marginal impacts associated with it. At the same time, we need to determine the costs of the impacts. Of course, when we are dealing with human lives, the classical models of economics will not apply. We need to have some other basis by which we can value the kind of human dimensions that would be involved in assessing impacts. We need to look at irreversibility and the feasibility of appropriate adaptation measures; where is it that you can adapt to a certain level of climate change and thereby tolerate it without really making any stark or major difference to the way we live?

And where is it that we need to seriously consider irreversibility? When we talk about irreversibility, it is not merely issues related to our day-to-day business. It has to do with slow processes that could damage coral reefs; it has to do with various ecosystems across the globe, which may not have an immediate and obvious implication or significance for our day-to-day living but would certainly prove significant over a period of time. And we necessarily have to look at mitigation options; we cannot isolate the impacts question from what is possible from the mitigation point of view. For example, in the UK we have seen a drastic reduction in emissions accompanied by an extremely robust and healthy rate of growth, which gives us an indication of the economic dimensions of mitigation measures. We need to assess these under different conditions and define what the mitigation options would be in the future. Therefore, to sum up what I have said – we need to assess the issue of danger in terms of dangerous for whom (because there is an equity dimension involved), and dangerous by when.

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Even if we were to bring about very deep cuts in emissions today, we know that there is an enormous inertia in the system which will result in continuation of climate change for a long time to come. There are intergenerational issues too. We also have to look at plausible adaptation scenarios. Some measures of adaptation can be implemented immediately, others would take a substantial period of time and they would also take a substantial expenditure of effort, finance and other inputs. And, similarly, we need plausible mitigation scenarios. On the basis of these, perhaps we may be able to define in a balanced way actions that would be required.

Now, some practical questions that I am sure will be discussed in the conference. Can a target of increase in temperature capture the limit of what is dangerous? Undoubtedly, that is just one indicator; there are several dimensions to what is dangerous. Of course, we need some measures by which we can decide on a course of action. Is a temperature target the best way to define it? That is the question that I think needs to be answered. Do we have a scientific rationale for setting this target? And, if so, how can we provide its underlying basis? This is where the scientific community really has an enormous responsibility to understand the framework within which this decision would have to be taken and then try to fill in the gaps with adequate and objective scientific knowledge that would assist the politician and the decision maker.

This is where I would like to highlight the character of the IPCC. The IPCC is required to review and assess policy relevant research; i.e. not be policy prescriptive, but policy relevant! And, relevance has to be based on our perception of the decision-making framework and the kinds of issues that become part of policy. Then we can perhaps address in an objective and scientific manner what would assist that system of decision-making. Can a global-mean temperature target, for example, represent danger at the local level? I would mention the importance of looking across the globe and seeing what the impacts would be for different communities and different locations. And, how do we determine a concentration level for GHGs? Where is it that we draw the limit? And what is the trajectory that we require to achieve stabilization because we are not dealing with a static concept, we are not talking about reaching a certain level at a particular point of time. The path by which you reach that particular level is critically important and that necessarily needs to be defined.

Now some issues of initial conditions. Here I will pick out a combination of results from the Third Assessment Report and a few other assessments available in the literature. We know that the global-mean surface temperature has increased by about 0.7°C over the last century. We know that there has been a decrease in Arctic sea ice extent by 10 to 15% and in thickness by 40%; and a decrease in Arctic snow cover area by some 10% since satellite observations started in 1960. We know about the damage to the coral reefs and that the 1990s was likely the warmest decade of the millennium.

In assessing what is dangerous we have to look at every aspect of the impacts on health, agriculture, water resources, coastal areas, species and natural assets. Of course, in coastal areas, natural disasters will take place. We can certainly warn communities against them if we have adequate and effective warning systems. But we must also understand that natural disasters are going to take place no matter what. If climate change is going to exacerbate conditions, which would enhance the severity of the impacts, then that adds another responsibility that the global community has to accept. In Mauritius, a couple of weeks ago, there was the major UN conference involving the small island developing states. In discussions with several people there, I heard an expression of fear based on the question: suppose a tsunami such as that of December 26 were to take place in 2080 and suppose the sea level was a foot higher, can you estimate what the extent of damage would be under those circumstances? Hence, I think when we talk about dangerous it is not merely dangers that are posed by climate change *per se*, but the overlay of climate change impacts on the possibility of natural disasters that could take place in any event.

Another issue that I would like to highlight is the issue of dangerous for whom. There are several studies none of which I am going to endorse, but I just want to put these forward as examples – the work of Norman Myers, for instance. He wrote about the possibility of 150 million environmental refugees by the year 2050. Numbers are not important, but I would like to highlight the issue that we need to look at. What is likely to happen as a result of sea level rise and agricultural changes to human society in different parts of the globe, for instance, in the form of refugees? Bangladesh, which as you know is a low-lying country is particularly vulnerable to sea level rise and the impacts that this would bring. Egypt is another country that would lose 12–15% of its alluvial land, and so on. Consequently, we really need a cataloging of all the impacts that are likely to take place. Science should be able to at least attempt the quantification of what these impacts are likely to be for different levels of climate change. This might help decision makers focus on how to deal with the whole issue.

When we discuss dangerous for whom, then there is also the question of extreme events. The IPCC Third Assessment Report clearly identified that the number of disasters of hydro-meteorological origin have increased significantly, along with an increase in precipitation in the mountains accompanied by melting of glaciers, increased incidence of floods, mud slides, and severe land slides. There is a fair amount of data now available on this, particularly in parts of Asia; large areas with high population densities are susceptible to floods, droughts and cyclones as in Bangladesh and India.

I would now like to highlight some of the social implications of the impacts that are likely to happen related to extreme weather or climatic events. Here I would like to underline the fact that demographic and socio-economic

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factors can amplify the dangers. There has been an upward trend in weather related losses over the last 50 years linked to socio-economic factors; population growth, increased wealth, urbanization in vulnerable areas, etc. These are trends that are going to continue. If we have to define dangerous then this changing baseline must be considered. Dangerous must be assessed on the basis of scenarios that are consistent with the changes that we already see, for instance, in migration, demographics, and in incomes. All of these in essence define the initial conditions that I mentioned earlier on. We also need to understand the operation of financial services such as insurance in defining the behaviour of societies, in defining where people are likely to settle, because these things are intimately linked with perceptions of the damages – climate-related damages – that might occur over a period of time.

Now the question is, can we adapt to irreversible changes? Can science give us some answers on this? You certainly can adapt to changes like deforestation because we have the means by which we can carry out aforestation, by which we can plant trees in areas wherever deforestation is taking place. But can we bring back the loss of biodiversity which is taking place? Issues of this nature need to be defined because all of this becomes an important part of the package on what is dangerous. In fact, we know that in the 20th century especially during an El Niño event there has been a major impact on coral reef bleaching. Worldwide increase in coral reef bleaching in 1997–98 was coincidental with high water temperatures associated with El Niño. Will future such occurrences be irreversible?

Other examples include the frequency and severity of drought, now fairly well documented in different parts of Africa and Asia. Duration of ice cover of rivers and lakes has decreased by about 2 weeks over the 20th century in mid and high latitudes of the northern hemisphere. Arctic sea ice extent, as I mentioned earlier, decreased by 40% in recent decades in late summer to early autumn and decreased by 10 to 15% since the 1950s in spring and summer. And temperate glaciers are receding rapidly in different parts of the globe.

We also need to look at climate change and its relationship to possible singular events; such as a shutdown of the ocean's thermohaline circulation or rapid ice losses in Greenland or Antarctica. Here, of course, science has a long way to go, but it is a challenge for the scientific community to be able to establish if there is likely to be a relationship between these possible singular events and the process of climate change that we are witnessing. Such events could lead to very high magnitude impacts that could overwhelm our response strategies.

We need to put some of these possible impacts into a framework with an economic perspective where they are translated into the impacts on numbers of people in specific geographical areas. This is a challenge that requires scientists not only to look at the geophysical impacts of climate change, but also start looking at the socio-economic implications. The inertia of the climate system must also be taken into account. Even if we were to stabilize the concentrations of CO_2 and other greenhouse gases today, the inertia in the system can carry the impacts of climate change, particularly sea level rise, through centuries if not a millennium. Indeed, sea level rise could continue for centuries after global-mean temperature was effectively stabilized, complicating the issue of choosing a single metric to defining a dangerous interference threshold.

Even if we are going to think in terms of a temperature target, this necessarily requires that we look at the relationship between emissions, concentrations, and the temperature response. Related to this would be all the other issues that I have put before you in terms of the impacts of climate change as they relate to the global-mean temperature response, particularly adaptation issues. Adaptation strategies can be planned or anticipatory. I highlight the importance of looking at adaptation measures because they need to be considered in defining what is dangerous. If you cannot adapt to a particular change and yet it is likely to have a very harmful impact, then clearly it could be dangerous; but if you can adapt to it without serious consequences then it certainly is not dangerous. We need to define, therefore, adaptation measures within choices including planned and anticipatory as well as autonomous and reactive.

On the mitigation side, we often take a very narrow view of costs and economics of mitigation. We must look at a holistic assessment of mitigation measures and identify measures where there are several co-benefits including those related to goals for sustainable development (in economic, equity, and environmental terms). Then, of course, there is a whole range of so-called no regrets measures that also need to be identified. And the key linkages between mitigation and development are numerous. So, in assessing mitigation costs and options it is absolutely essential that we look at the whole gamut of associated benefits and costs as well.

In addressing the need for assessing the issue of value judgments we must try to see that we create value in terms of scientific information and analysis. But, once again, I would like to emphasize that the decision itself has to be based on a collective assessment by the global community on what they are willing to accept. However, let me repeat that decisions would have to be guided by certain principles, principles that must look at the rights of every community on this globe and at some of the intergenerational implications of climate change (because what may not be dangerous today could very well turn out to be dangerous fifty years from now). It would be totally irresponsible if, as a species, we ignore that reality. So, there is before us a huge agenda for the scientific community. In this context we need to understand the framework within which decisions have to be made. It is my hope that in the Fourth Assessment Report of the IPCC we will be able to provide information through which some of the holes, in the form of uncertainties or unknowns that affect decision-making, can be filled up effectively.

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CHAPTER 2

An Overview of 'Dangerous' Climate Change

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ABSTRACT: This paper briefly outlines the basic science of climate change, as well as the IPCC assessments on emissions scenarios and climate impacts, to provide a context for the topic of key vulnerabilities to climate change. A conceptual overview of 'dangerous' climate change issues and the roles of scientists and policy makers in this complex scientific and policy arena is presented, based on literature and recent IPCC work. Literature on assessments of 'dangerous anthropogenic interference' with the climate system is summarized, with emphasis on recent probabilistic analyses. Presenting climate modeling results and arguing for the benefits of climate policy should be framed for decision makers in terms of the potential for climate policy to reduce the likelihood of exceeding 'dangerous' thresholds.

2.1 Introduction

Europe's summers to get hotter… The Arctic's ominous thaw… Study shows warming trend in Alaskan Streams… Lake Tahoe Warming Twice as Fast as Oceans. Global Warming Seen as Security Threat… Global warming a bigger threat to poor… Tibet's glacier's heading for meltdown… Climate change affects deep sea life… UK: Climate change is costing millions. These are just a few of the many headlines related to climate change that crossed the wires in 2004 and they have elicited widespread concern even in the business community. 2004 is thought to have been the fourth warmest year on record and the worst year thus far for weather-related disaster claims – though the devastation in the US Gulf Coast from intense hurricanes in the summer of 2005 could well set a new record for disaster spending. Munich Re, the largest reinsurer in the world, recently stated that it expects natural-disaster-related damages to increase 'exponentially' in the near future and it attributes much of these damages to anthropogenic climate change. Thomas Loster, a climate expert at Munich Re, says: 'We need to stop this dangerous experiment humankind is conducting on the Earth's atmosphere'.

'Dangerous' has become something of a cliché when discussing climate change, but what exactly does it mean in that context? This paper will explore some basic concepts in climate change, how they relate to what might be 'dangerous', and various approaches to characterizing and quantifying 'dangerous anthropogenic interference [DAI] with the climate system' [70]. It will also outline and differentiate the roles of scientists and policymakers in dealing with dangerous climate change by discussing current scientific attempts at assessing elements of dangerous climate change and suggesting ways in which decision makers can translate such science into policy. It will state explicitly that determination of 'acceptable' levels of impacts or what constitutes 'danger' are deeply normative decisions, involving value judgments that must be made by decision makers, though scientists and policy analysts have a major role in providing analysis and context.

2.2 Climate Change: A Brief Primer

We will begin by stressing the well-established principles in the climate debate before turning to the uncertainties and more speculative, cutting-edge scientific debates. First, the greenhouse effect is empirically and theoretically well-established. The gases that make up Earth's atmosphere are semi-transparent to solar energy, allowing about half of the incident sunlight to penetrate the atmosphere and reach Earth's surface. The surface absorbs the heat, heats up and/or evaporates liquid water into water vapor, and also re-emits energy upward as infrared radiation. Certain naturally-occurring gases and particles – particularly clouds – absorb most of the infrared radiation. The infrared energy that is absorbed in the atmosphere is re-emitted, both up to space and back down towards the Earth's surface. The energy channeled towards the Earth causes its surface to warm further and emit infrared radiation at a still greater rate, until the emitted radiation is in balance with the absorbed portion of incident sunlight and the other forms of energy coming and going from the surface. The heat-trapping 'greenhouse effect' is what accounts for the ~33°C difference between the Earth's actual surface air temperature and that which is measured in space as the Earth's radiative temperature. Nothing so far is controversial. More controversial is the extent to which non-natural (i.e. human) emissions of greenhouse gases have contributed to climate change, how much we will enhance future disturbance, and what the consequences of such disturbance could be for social, environmental, economic, and other systems – in short, the extent to which human alterations could risk DAI.

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It is also well-known that humans have caused an increase in radiative forcing. In the past few centuries, atmospheric carbon dioxide has increased by more than 30%. The reality of this increase is undeniable, and virtually all climatologists agree that the cause is human activity, predominantly the burning of fossil fuels. To a lesser extent, deforestation and other land-use changes and industrial and agricultural activities like cement production and animal husbandry have also contributed to greenhouse gas buildups since 1800. [One controversial hypothesis ([58]) asserts that atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) were first altered by humans thousands of years ago, resulting from the discovery of agriculture and subsequent technological innovations in farming. These early anthropogenic CO_2 and CH_4 emissions, it is claimed, offset natural cooling that otherwise would have occurred.]

Most mainstream climate scientists agree that there has been an anomalous rise in global average surface temperatures since the time of the Industrial Revolution. Earth's temperature is highly variable, with year-to-year changes often masking the overall rise of approximately 0.7°C that has occurred since 1860, but the 20th century upward trend is obvious, as shown in Figure 2.1. Especially noticeable is the rapid rise at the end of the 20th century.

For further evidence of this, Mann and Jones, 2003 [33]; Mann, Bradley and Hughes, 1998 [32]; and Mann, Bradley and Hughes, 1999 [31] have attempted to push the Northern Hemisphere temperature record back 1,000 years or more by performing a complex statistical analysis involving some 112 separate indicators related to temperature. Although there is considerable uncertainty in their millennial temperature reconstruction, the overall trend shows a gradual temperature decrease over the first 900 years, followed by a sharp upturn in the 20th century. That upturn is a compressed representation of the 'real' (thermometer-based) surface temperature record of the last 150 years. Though there is some ongoing dispute about temperature details in the medieval period (e.g. [72]), many independent studies confirm the basic picture of unusual warming in the past three decades compared to the past millennium [73].

It is likely that human activities have caused a discernible impact on observed warming trends. There is a high correlation between increases in global temperature and increases in carbon dioxide and other greenhouse gas

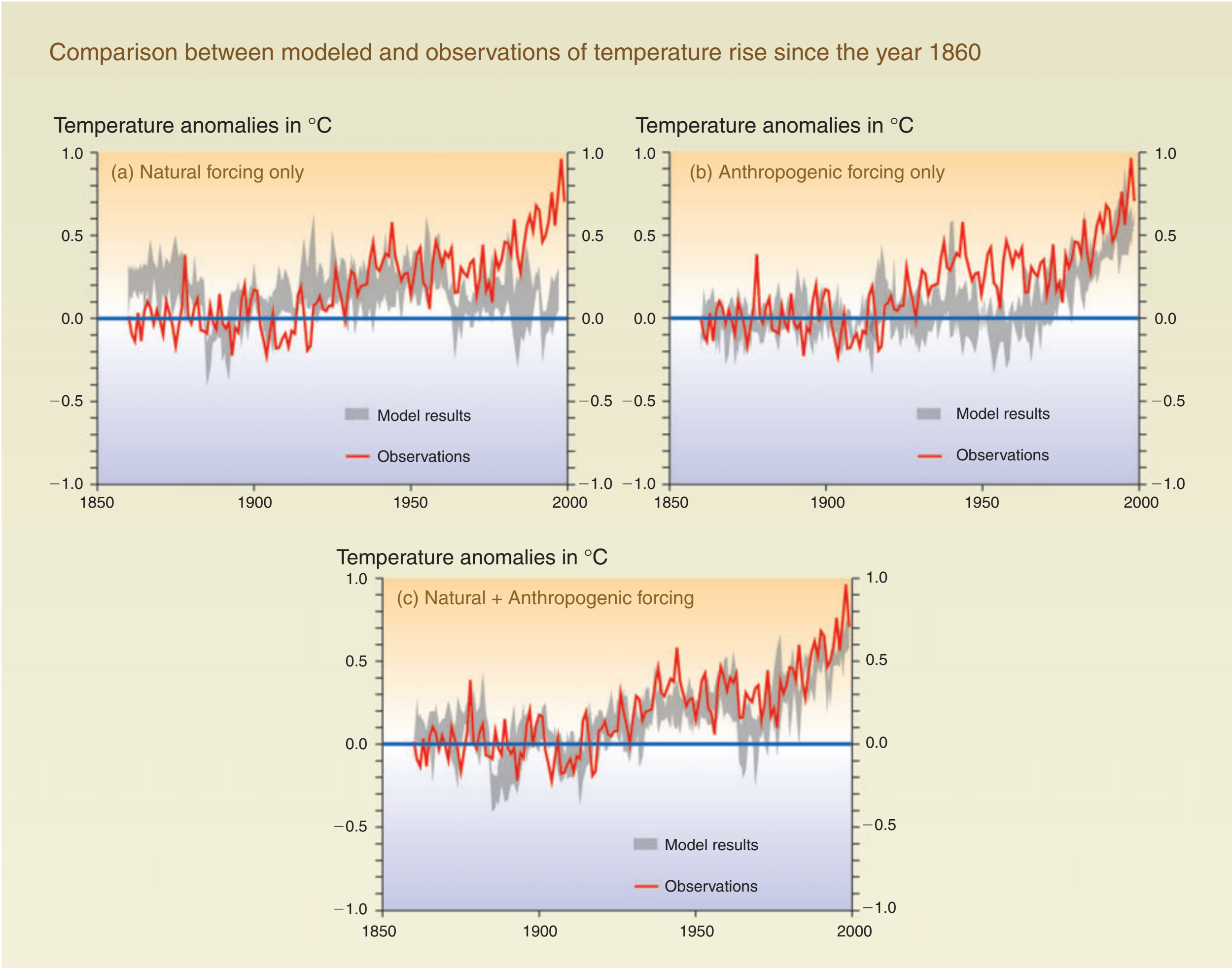

Figure 2.1 Explaining temperature trends using natural and anthropogenic forcing.
Source: IPCC, 2001d.

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concentrations during the era, from 1860 to present, of rapid industrialization and population growth. As correlation is not necessarily causation, what other evidence is there about anthropogenic CO_2 emissions as a direct cause of recent warming? Hansen et al. (2005) [18] offer considerable data to suggest that there is currently an imbalance of some $0.85 \pm 0.15\,W/m^2$ of extra heating in the Earth-atmosphere system owing to the heat-trapping effects of greenhouse gas build-ups over the past century. If accepted, this new finding would imply that not only has an anthropogenic heat-trapping signal been detected in observational records, but that the imbalance in the radiative heating of the Earth-atmosphere system implies that there is still considerable warming "in the bank", and that another 0.6°C or so of warming could be inevitable even in the unlikely event that greenhouse gas concentrations were frozen at today's levels [76].

Other evidence can be brought to bear to show human influences on recent temperatures from a variety of sources, such as the data summarized in Figure 2.1. The Figure suggests that the best explanation for the global rise in temperature seen thus far is obtained from a combination of natural and anthropogenic forcings. Although substantial, this is still circumstantial evidence. However, many recent 'fingerprint analyses' have reinforced these conclusions (i.e. [60], [20], [48], [55], and [59]). Most recently, Root et al. (2005) [54] have shown that the timing of biological events like the flowering of trees or egg-laying of birds in the spring are significantly correlated with anthropogenically-forced climate, but only weakly associated with simulations incorporating only natural forcings. This same causal separation is illustrated in Figure 2.1 comparing observed thermometer data and modeled temperature results for natural, anthropogenic, and combined forcings. (Root et al. came to these results using the HadCM3 model, the same model used to obtain the results depicted in Figure 2.1.) Since plants and animals can serve as independent 'proxy thermometers', these findings put into doubt suggestions that errors in instrumental temperature records due to urban heat island effects as well as claims that satellite-derived temperatures do not support surface warming – the satellite-derived temperature trend dispute apparently has been largely resolved in mid-2005 by a series of reports reconciling lower atmospheric warming in models, balloons and satellite temperature reconstructions. These and other anthropogenic fingerprints in global climate system variables and temperature trends represent an overwhelming preponderance of evidence. In our opinion, results from 30 years of research by the scientific community now convincingly suggest it is fair to call the detection and attribution of human impacts on climate a well-established conclusion.

2.3 Climate Change Scenarios

Since the climate science and historical temperature trends show highly likely direct cause-and-effect relationships, we must now ask how climate may change in the future. Scientists, technologists, and policy analysts have invested considerable effort in constructing 'storylines' of plausible human demographic, economic, political, and technological futures from which a range of emissions scenarios can be described, the most well-known being the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES), published in 2000 [38]. One grouping is the A1 storyline and scenario family, which describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter and, in several variations of it, the rapid introduction of new and more efficient technologies. Major underlying themes are convergence between regions, capacity-building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A1 is subdivided into A1FI (fossil-fuel intensive), A1T (high-technology), and A1B (balanced), with A1FI generating the most CO_2 emissions and A1T the least (of the A1 storyline, and the second lowest emissions of all six marker scenarios). But even in the A1T world, atmospheric concentrations of CO_2 still near a doubling of preindustrial levels by 2100.

For a contrasting vision of the world's social and technological future, SRES offers the B1 storyline, which is (marginally) the lowest-emissions case of all the IPCC's scenarios. The storyline and scenario family is one of a converging world with the same global population as A1, peaking in mid-century and declining thereafter, but with more rapid change in economic structures towards service and information economies, which is assumed to cause a significant decrease in energy intensity. The B1 world finds efficient ways of increasing economic output with less material, cleaner resources, and more efficient technologies. Many scientists and policymakers have doubted whether a transition to a B1 world is realistic and whether it can be considered equally likely when compared to the scenarios in the A1 family. The IPCC did not discuss probabilities of each scenario, making a risk-management framework for climate policy problematic since risk is probability times consequences (e.g. see the debate summarized by [14]). Figure 2.2 is illustrative of the SRES scenarios.

2.4 Climate Change Impacts

After producing the SRES scenarios, the IPCC released its Third Assessment Report (TAR) in 2001, in which it estimated that by 2100, global average surface temperatures would rise by 1.4 to 5.8°C relative to the 1990 level. While warming at the low end of this range would likely be relatively less stressful, it would still be significant for some 'unique and valuable systems' [25] – sea level rise of concern to some low-lying coastal and island communities and impacts to Arctic regions, for example. Warming at the high end of the range could have widespread catastrophic consequences, as a temperature change of 5–7°C on a globally-averaged basis is about the difference between an ice age and an interglacial – and over a period

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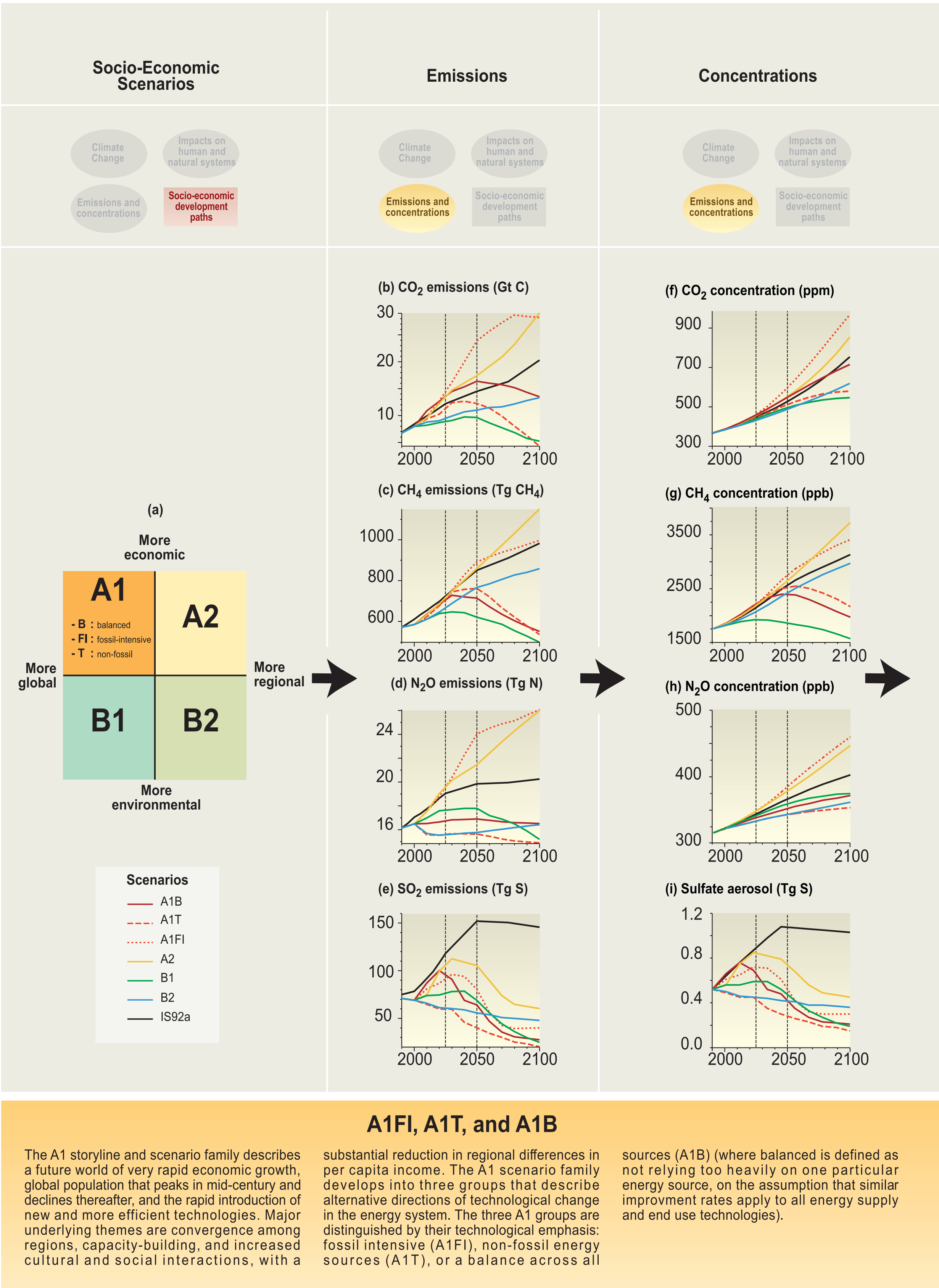

Figure 2.2 SRES emissions scenarios.
Source: IPCC, 2001d.

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