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Vulnerability to Climate Change and Reasons for Concern: A Synthesis

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EXECUTIVE SUMMARY

This chapter synthesizes the results of Work Group II of the Third Assessment Report (TAR) and assesses the state of knowledge concerning Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). The TAR's task is to define what is known about the effects of climate change: how sensitive systems are, what adaptive capacity they have, and what their vulnerability is. It is not the goal of this assessment to determine whether these effects are tolerable or are considered dangerous.

The goal of this chapter is to synthesize information on climate change impacts in a manner that will enable readers to evaluate the relationship between increases in global mean temperature and impacts. The chapter focuses on certain "reasons for concern" that may aid readers in making their own determination about what is a "dangerous" climate change. Each reason for concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concern are:

1) The relationship between global mean temperature increase and damage to or irreparable loss of unique and threatened systems
2) The relationship between global mean temperature increase and the distribution of impacts
3) The relationship between global mean temperature increase and global aggregate damages
4) The relationship between global mean temperature increase and the probability of extreme weather events
5) The relationship between global mean temperature increase and the probability of large-scale singular events such as the breakup of the West Antarctic Ice Sheet or the collapse of the North Atlantic thermohaline circulation.

In addition, we examine what observed effects of climate change tell us with regard to Article 2 of the UNFCCC. Increase in global mean temperature since 1900 (i.e., mean global warming) is used as the common metric against which impacts are measured. This metric is closely related to greenhouse gas (GHG) concentrations but is more relevant for impact assessments.

Some general caveats apply to all of the reasons for concern:

- In spite of many studies on climate change impacts, there still is substantial uncertainty about how effective adaptation will be (and could be) in ameliorating negative effects of climate change and taking advantage of positive effects.
- The effect of changes in baseline conditions, such as population and economic growth and development of new technologies that could change vulnerability, has not been adequately considered in most impact studies.
- Most impact studies assess the effects of a stable climate, so our understanding of what rates of change may be dangerous is limited.

It does not appear to be possible to combine the different reasons for concern into a unified reason for concern that has meaning and is credible. However, we can review the relationship between impacts and temperature for each reason for concern and draw some preliminary conclusions about the potential severity and risk of impacts for the individual reasons for concern. Note that the following findings do not incorporate the costs of limiting GHG emissions to levels that are sufficient to avoid changes that may be considered dangerous. Also note that there is substantial uncertainty regarding the impacts of climate change at the temperatures mentioned. These temperatures should be taken as approximate indications of impacts, not as absolute thresholds. In addition, change in global mean temperature does not describe all relevant aspects of climate change impacts, such as rate and pattern of change and changes in precipitation, extreme climate events, or lagged (or latent) effects such as rising sea levels. For simplification, we group different levels of temperature increase into "small," "medium," and "large." "Small" denotes a global mean temperature increase of as much as approximately 2°C; "medium" denotes a global mean temperature increase of approximately 2–3°C; and "large" denotes a global mean temperature increase of more than approximately 3°C.

Based on a review of the literature of observations of climate change impacts, as reflected in other chapters in the TAR, we conclude the following:

- *Observations:* Statistically significant associations between trends in regional climate and impacts have been documented in ~100 physical processes and ~450 biological species or communities in terrestrial and polar environments. Although the presence of multiple factors (e.g., land-use change, pollution, biotic invasion) makes attribution of observed impacts to regional climate change difficult, more than 90% (~99% physical, ~80% biophysical) of the changes documented worldwide are consistent with how physical and biological processes are known to respond to climate. Based on expert judgment, we have high confidence that the overall patterns and processes of observations reveal a widespread and coherent impact of 20th-century climate changes on many physical and biological systems. Signals of regional climate change impacts may be clearer in physical and biological systems than in socioeconomic systems, which also are simultaneously undergoing many complex changes that are not related to climate change, such as population growth and urbanization. Socioeconomic systems have complex and varying mechanisms for adapting to climate change. There are preliminary indications that some social and economic systems have been affected in part by 20th-century regional climate changes (e.g., increased damages from flooding and droughts in some locations). It generally is difficult to separate climate change effects from coincident or alternative explanations for such observed regional impacts.

- *Unique and Threatened Systems:* Tropical glaciers, coral reefs, mangroves, ecotones, and biodiversity "hot spots" are examples of unique and threatened entities that are confined to narrow geographical ranges and are very sensitive to climate change. However, their degradation or loss could affect regions outside their range. There is medium confidence that several of these systems will be affected by a small temperature increase; for example, coral reefs will bleach and glaciers will recede. At higher magnitudes of temperature increase, other and more numerous unique and threatened systems would be adversely affected.
- *Distribution of Impacts:* The impacts of climate change will not be evenly distributed among the peoples of the world. There is high confidence that developing countries will be more vulnerable to climate change than developed countries, and there is medium confidence that climate change would exacerbate income inequalities between and within countries. There also is medium confidence that a small temperature increase would have net negative impacts on market sectors in many developing countries and net positive impacts on market sectors in many developed countries. However, there is high confidence that with medium to high increases in temperature, net positive impacts would start to decline and eventually would turn negative, and negative impacts would be exacerbated. Estimates of distributional effects are uncertain because of aggregation and comparison methods, assumptions about climate variability, adaptation, levels of development, and other factors.
- *Aggregate Impacts:* With a small temperature increase, there is medium confidence that aggregate market sector impacts would amount to plus or minus a few percent of world gross domestic product (GDP), and there is low confidence that aggregate nonmarket impacts would be negative. Most people in the world would be negatively affected by a small to medium temperature increase. Most studies of aggregate impacts find that there are net damages at the global scale beyond a medium temperature increase and that damages increase from there with further temperature increases. The important qualifications raised with regard to distributional analysis (previous bullet item) also apply to aggregate analysis. By its nature, aggregate analysis masks potentially serious equity differences. Estimates of aggregate impacts are controversial because they treat gains for some as canceling out losses for others and because the weights that are used to aggregate over individuals are necessarily subjective.
- *Extreme Climate Effects:* The frequency and magnitude of many extreme climate events increase even with a small temperature increase and will become greater at higher temperatures (high confidence). Extreme events include, for example, floods, soil moisture deficits, tropical and other storms, anomalous temperatures, and fires. The impacts of extreme events often are large locally and could strongly affect specific sectors and regions. Increases in extreme events can cause critical design or natural thresholds to be exceeded, beyond which the magnitude of impacts increases rapidly (high confidence).
- *Large-Scale Singularities:* Large-scale singularities in the response of the climate system to external forcing, such as shutdown of the North Atlantic thermohaline circulation or collapse of the West Antarctic ice sheet, have occurred in the past as a result of complex forcings. Similar events in the future could have substantial impacts on natural and socioeconomic systems, but the implications have not been well studied. Determining the timing and probability of occurrence of large-scale singularities is difficult because these events are triggered by complex interactions between components of the climate system. The actual impact could lag the climate change cause (involving the magnitude and the rate of climate change) by decades to millenia. There is low to medium confidence that rapid and large temperature increases would exceed thresholds that would lead to large-scale singularities in the climate system.

19.1. Introduction

This chapter draws on the results of the entire TAR to assess the state of knowledge concerning Article 2 of the UNFCCC. Article 2 of the UNFCCC states that:

> "...the ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved with a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (UNEP/WMO, 1992).

The ultimate goal for stabilizing GHG concentrations is to avoid "dangerous anthropogenic interference with the climate system." The question of what is dangerous is one that the authors of this chapter cannot answer. Danger is a function of the degree to which effects are negative and the degree to which those effects are unacceptable. The latter is a value judgment. The TAR's task is to define what is known about the effects of climate change—to identify their character and their implications and whether they are negative or positive. It is not about determining whether these effects are acceptable.

The preceding chapters review the literature about vulnerability to climate change in regions and sectors. The goal of this chapter is to draw on very disparate reasons for concern regarding climate change impacts in a manner that will enable readers to evaluate the relationship between increases in global mean temperature and impacts (for an explanation of why change in global mean temperature is used as an indicator, see Section 19.1.2). It attempts to enable readers to understand the risks of higher magnitudes of increased global mean temperature.

19.1.1. Reasons for Concern

To provide information to readers in a manner that will enable them to make judgments about what level of climate change may be dangerous, this chapter addresses "reasons for concern," which represent a way for readers to think about the seriousness of climate change impacts. These reasons for concern are taken from debates and literature about the risks of climate change. The authors of this chapter make no judgment regarding whether one or several reasons for concern are more important than others. Nor do we attempt to combine the reasons for concern to produce a single "bottom line."

The reasons for concern are as follows:

1) *The relationship between global mean temperature increase and damage to or irreparable loss of unique and threatened systems:* Some unique and threatened systems may be irreparably harmed by changes in climate beyond certain thresholds.
2) *The relationship between global mean temperature increase and the distribution of impacts:* Some regions, countries, islands, and cultures may be adversely affected by climate change, whereas others could benefit, at least up to a point. For example, in some sectors, adverse effects may be experienced in some parts of the world while other parts may have net gains. Within countries, some regions or groups of people could be harmed while others benefit or experience less harm.
3) *The relationship between global mean temperature increase and global aggregated impacts:* Using a consistent method of measurement and aggregation of climate change impacts, we address how aggregate impacts change as global mean temperature increases, whether aggregate impacts are positive at some levels of temperature increase and negative at others, whether change will occur smoothly or in a more complex dynamic pattern, and whether aggregate impacts mask unequal distribution of impacts.
4) *The relationship between global mean temperature increase and the probability of extreme weather events:* As mean climate changes, so too will the probability of extreme weather events such as days with very high or very low temperatures, extreme floods, droughts, tropical cyclones, and storms. This chapter addresses how the probability and consequences of such events may change as global mean temperature increases.
5) *The relationship between global mean temperature increase and the probability of large-scale singular events, such as collapse of the West Antarctic ice sheet (WAIS) or shutdown of the North Atlantic thermohaline circulation (THC):* This chapter addresses what is known about how the probabilities of such events change as the magnitude of climate change increases.

In addition, this chapter addresses whether changes in climate during the 20th century have resulted in observed impacts. The IPCC has documented these changes, and an important question is whether these changes have resulted in measurable impacts on nature or society. Important questions include the following:

- Are the observed effects of climate change consistent with model predictions, particularly those that estimate more serious impacts at larger GHG concentrations?
- Even if it is not clear whether observed effects are caused primarily by climate change, do these effects give us information about the potential vulnerability of systems to climate change?

Observations are not a reason for concern. Instead, they help us determine whether impacts that are relevant to any of the five reasons for concern have occurred.

19.1.2. Choice of Indicator

A critical issue is the indicator of climate change against which we measure impacts. A common measure allows consistent discussion about the relationship between climate change and impacts. Several indicators could be used:

1) GHG emission levels
2) Atmospheric GHG concentration levels
3) Changes in global mean temperature and sea-level rise
4) Changes in regional climate variables
5) Changes in the intensity or frequency of extreme events.

Several considerations must be taken into account in selecting an indicator. Using GHG emission levels (1) or even concentration levels (2) implies examining impacts beyond the 21st century. Published estimates of time frames for stabilizing GHG atmospheric concentration levels tend to assume such levels will not be stabilized until after the end of the 21st century (Enting *et al.*, 1994; Wigley *et al.*, 1996; Schimel *et al.*, 1997).

The problem with using such levels as an indicator is that most of the impact literature examines potential impacts only as far as 2100. In addition, most studies are based on scenarios of specific changes in global mean or, more typically, regional climate variables such as temperature or precipitation.[1] It is difficult to relate a specific level of GHG concentration to a specific change in global average climate or regional climate. For each GHG concentration level, there is a range of potential changes in global mean temperature (see Box 19-1). And for each change in global mean temperature, there is a range of potential changes in average regional temperature, precipitation, and extreme events.

The problem with indicators 3, 4, and 5 is the inverse of the foregoing problem. For each change in global or regional climate or extreme events, there is a range of levels of GHG concentrations that could cause such a change in climate. Thus, using these indicators makes it more difficult to work back to defining atmospheric concentrations of GHGs, as required by Article 2 of the UNFCCC. In addition, as one gets to finer levels of spatial and temporal resolution, such as changes in regional climates and extreme events, it becomes more difficult to attribute such changes to changes in GHG concentrations.

Thus, whatever the indicator selected, there will be problems in using it to relate impacts to the level of GHG concentrations. The choice of indicator depends on two factors:

1) What does the literature on climate change impacts allow us to consider?
2) What indicator can be most directly related to GHG concentrations?

We selected change in global mean temperature as our indicator for two reasons. The first is that the impact literature can be directly related to a change in global mean temperature. Many studies are based on specific results from general circulation models (GCMs), which estimate a change in global mean temperature. Other studies can be related to a change in global mean temperature by inversely using the scaling method from Chapter 4. The second reason is that, as discussed in Box 19-1, it is most feasible to relate changes in global mean temperature to GHG concentrations. It is harder to relate the other indicators directly to GHG concentrations. Thus, global mean temperature increase is the indicator that can be used most readily to relate GHG emissions (and emissions control) to changes in climate and impacts.

For any change in global mean temperature, there are many possible changes in regional climate and climate variability, which could have quite different results. Thus, a 2°C increase in global mean temperature may result in a particular region being much wetter or drier or having more or fewer extreme climate events. Whether the region gets wetter or drier or has more severe climate is likely to have much greater bearing on impacts than a change in mean temperature. Hence, although the use of global mean temperature as an indicator is preferable to the other options because it has fewer problems in implementation, it has its own limitations.

This chapter does not address the effect of different rates of change in climate on vulnerability. There is no doubt that a 3°C increase in global mean temperature realized in 50 years could be far worse than the same amount of warming realized in 100 or 200 years. In addition, changes in extreme events such as more intense El Niño-Southern Oscillation (ENSO) events (see, e.g., Timmermann *et al.*, 1999) could lead to more adverse impacts than a monotonic and gradual change in climate. Thus, rate of change is an important factor affecting what climate change is considered to be dangerous. Unfortunately, most of the impact literature has addressed only static or equilibrium changes in climate. These studies have not examined what rates of change various sensitive systems can adapt to. Future research should address this matter.

19.1.3. Role of Adaptation

Successful adaptation reduces vulnerability to an extent that depends greatly on adaptive capacity—the ability of an affected system, region, or community to cope with the impacts and risks of climate change (see Chapter 18). Enhancement of adaptive capacity can reduce vulnerability and promote sustainable development across many dimensions.

Adaptive capacity in human systems varies considerably among regions, countries, and socioeconomic groups. The ability to adapt to and cope with climate change impacts is a function of wealth, technology, information, skills, infrastructure, institutions, equity, empowerment, and ability to spread risk. Groups and regions with adaptive capacity that is limited along any of these dimensions are more vulnerable to climate change damages, just as they are more vulnerable to other stresses. Enhancement of adaptive capacity is a necessary condition for reducing vulnerability, particularly for the most vulnerable regions, nations,

[1] One recent exception is DETR (1999), which examines changes in global impacts at different CO_2 stabilization levels.

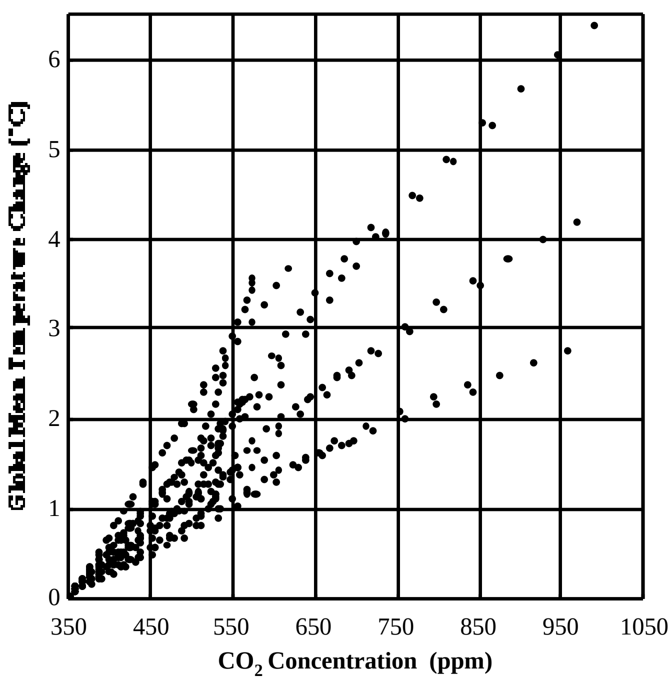
Box 19-1. Uncertainties in Future Warming

Does a given atmospheric concentration of GHGs cause a specific change in global mean temperature (or other climate variables, for that matter)? To answer this question, we quantify uncertainties in the change in global mean temperature for a given CO_2 concentration level. This is accomplished by using the same simple models that are used in the TAR Working Group I report (TAR WGI Chapter 9). These models are updated versions of models used previously by the IPCC in the Second Assessment Report (SAR) (Kattenberg *et al.*, 1996; see also Raper *et al.*, 1996). We consider the effects of uncertainties in future emissions of *all* radiatively important gases (particularly the relative importance of CO_2 to other forcing factors) and climate sensitivity, but not uncertainties in translating emissions to concentrations.

These uncertainty issues are addressed by comparing CO_2 concentrations (not other GHGs) and the corresponding temperature projections for 5-year time steps from 1990 to 2100 (i.e., using results for 1995, 2000, 2005, etc.) for the six illustrative emissions scenarios from the IPCC *Special Report on Emissions Scenarios* (SRES) (Nakicenovic *et al*., 2000) under a range of climate sensitivity assumptions. The six emissions scenarios provide a sampling of the space of the relative effects of CO_2 compared with other GHGs and sulfur dioxide (SO_2)-derived sulfate aerosols. Climate sensitivity (ΔT_{2x}) values of 1.5, 2.5, and 4.5°C are used.

The results are plotted as a simple scatter diagram of temperature change against CO_2 concentration (see Figure 19-1). The scatter plot has 22 5-year values (1990 values are zero in each case) by six scenarios by three sensitivities (396 points). The diagram is meant only to illustrate a range of possibilities. One cannot associate any specific confidence intervals with the ranges shown; however, simultaneous use of realistic values in several input parameters with the judgment that the climate sensitivity range of 1.5–4.5°C represents approximately the 90% confidence interval (see, e.g., Morgan and Keith, 1995) suggests that the probability of a result *outside* the ranges shown, during the interval 1990–2100, is less than 10%.

The results are shown in Figure 19-1. For example, for a future CO_2 level of 550 ppmv, the global mean warming range is 1–3°C relative to 1990. Thus, a specific CO_2 concentration could lead to a range of increases in global mean temperature. Note that this is a transient result; in other words, *if CO_2 concentrations were stabilized at 550 ppmv, substantial additional warming would occur beyond this range* as the climate system slowly relaxed toward a new equilibrium state. The levels of increase in global mean temperature displayed in the diagram are less than what would eventually happen if CO_2 concentrations were stabilized at a particular level. Note also that there is no time (or date) associated with any particular concentration level. For, example, in the SRES scenarios, 550 ppmv is reached at a range of dates from about 2050 onward.



➤ **Figure 19-1**: Global mean temperature change (from 1990) as a function of CO_2 concentration for SRES scenarios. For any given CO_2 level, uncertainties in temperature arise through several factors. The three most important are accounted for here: First, different temperatures for a given future CO_2 level may arise because each emissions scenario has different levels of other GHGs and different levels of SO_2 emissions—factors that lead to a range of possible non-CO_2 forcings (results here consider all six SRES illustrative scenarios); second, different temperatures arise because of uncertainties in climate sensitivity (three values—1.5, 2.5, and 4.5ºC equilibrium warming for a CO_2 doubling—are used here); and third, different temperatures arise because different rates of radiative forcing change and different climate sensitivities lead to different levels of damping of the instantaneous equilibrium response.

and socioeconomic groups. To be sure, some development paths can increase some types of vulnerabilities, whereas others can reduce those vulnerabilities.

Adaptive capacity in natural systems tends to be more limited than adaptive capacity in human systems. Many species have limited ability to migrate or change behavior in response to climate change. What may be of greater concern is the harm that already has been done to natural systems by societal development. Habitat fragmentation and destruction, as well as creation of barriers to migration, will make it much more difficult for species to cope with climate change than if natural systems were undisturbed.

We do not address adaptation explicitly in this chapter, except to the extent that the literature cited here considers adaptation. Adaptation may have the potential to reduce vulnerability and, in many cases, shift the threshold for negative impacts to higher magnitudes of climate change. The degree to which adaptation can do so is not addressed here; it should be the subject of future research.

19.1.4. Chapter Organization

The chapter is organized into the following sections:

- Section 19.2 addresses the insights we can gain by examining observed effects of climate change. Are we seeing impacts of climate change on nature and society?
- Section 19.3 addresses what changes in global mean temperature may cause harm to threatened and unique systems. For example, are threatened and unique systems at risk from even low levels of increase in global mean temperature? Are some societies at particular risk at low levels of temperature increase?
- Section 19.4 addresses the evidence regarding the relationship between change in global mean temperature and distribution of impacts. Are adverse or positive impacts from climate change distributed equally around the world and within countries? Are some regions harmed at certain levels of climate change while others benefit? Are some subgroups or cultures at greater risk than the population as a whole?
- Section 19.5 addresses what insights we gain from aggregate or comprehensive approaches to measuring impacts. What do approaches such as monetization or looking at the number of people who are harmed or benefited tell us about the relationship between aggregate impacts and higher temperatures? This section also addresses insights gained from integrated assessment models (IAMs).
- Section 19.6 addresses the potential for increases in extreme climate events and large-scale singular effects. As temperatures increase or the rate of temperature rise increases, does the potential for extreme climate events and singular effects such as a change in ocean circulation patterns or the collapse of ice sheets increase? Can thresholds of change in terms of magnitudes or rates of change be identified?
- Section 19.7 addresses the limitations of the information used in this chapter to address observations and the reasons for concern. It also addresses future research that is needed to narrow these uncertainties.
- Section 19.8 summarizes the findings on observations and the reasons for concern.

Sections 19.2 and 19.3 draw most heavily on the TAR. Examples can be found in the region and sector chapters of this report; the sections in this chapter do not introduce new information. Instead, they synthesize that information in ways that the other chapters are unable to because they do not examine all regions and sectors. Sections 19.4, 19.5, and 19.6 draw on information that is not found in the regional and sectoral chapters. They do so because they address issues that those chapters cannot:

- Comparison of impacts across regions (Section 19.4). The sectoral chapters do this for each sector, but this can be done comprehensively only in this chapter.
- Aggregation of impacts (Section 19.5). This requires use of common metrics to aggregate impacts across sectors and regions. None of the other chapters can do this.
- Examination of changes in extreme events and large-scale discontinuities (Section 19.6). This generally is not addressed in the region and sector chapters because the climate change scenarios that are used most commonly in impacts studies examine only changes in average conditions, not changes in extreme events or large-scale discontinuities (see Chapter 4).

Thus, this chapter contains much new information in a framework that can help readers judge what may considered to be a dangerous level of climate change.

19.2. Observations of Climate Change Impacts

It is well established from physical, ecological, and physiological studies that climate strongly influences physical and biological systems. This section addresses whether changes in regional climate during the 20th century, documented by WGI, have resulted in measurable impacts on physical and biological systems. We also consider the potential for detecting observed impacts of regional climate change in socioeconomic systems. The objective here is to evaluate the accumulating body of evidence with regard to the following questions:

1) Is there a coherent signal in patterns of observed impacts?
2) Are observed effects of regional climate changes consistent with functional understanding and modeled predictions of impacts?
3) Do observed effects provide information about the potential vulnerability of systems to climate change?
4) How do impacts observed over the past century relate to the five reasons for concern brought forward by this chapter?

In relation to the five reasons for concern, the accumulating body of studies documenting observed impacts of regional climate changes may contribute to understanding of:

- Actual and potential climate change effects on *unique and threatened systems*
- Relationships of impacts to changes in *extreme events*
- Functional and geographical *distribution* of current and future climate change effects
- *Aggregation of impacts*
- Potential effects of *large-scale singularities*.

In this section, we focus on observed impacts that have been associated with regional climate changes over the past 100 years. We examine evidence in physical and biological systems in terrestrial, coastal and marine, and freshwater environments, as well as in socioeconomic systems, including agriculture, commercial fisheries, human settlements, insurance and financial services, and human health (see also other chapters in this report).

The studies reviewed document an observed impact in a physical, biological, or socioeconomic system associated with changes in one or more regional climate variables (most often temperature rise). The effects are examined with regard to the range and geographical extent of processes and species involved, their consistency with functional understanding of mechanisms or processes involved in climate-impact relationships, and the possibility of alternative explanations and confounding factors. Expected directions of change relating to regional climate warming for physical systems include shrinkage of glaciers, decrease in snow cover, shortening of duration of lake and river ice cover, declines in sea-ice extent and thickness, lengthening of frost-free seasons, and intensification of the hydrological cycle. Expected directions of change relating to regional climate warming for biological systems include poleward and elevational shifts in distribution and earlier phenology (i.e., earlier breeding, emergence, flowering) in plant and animal species.

We follow the WGI definition of climate change as a statistically significant variation in the mean state of the climate or its variability, persisting for an extended period (typically decades or longer). Climate change, as defined here, may be caused by natural internal processes or external forcings or by persistent anthropogenic changes in the composition of the atmosphere or land use.

Since 1860, the global mean temperature has warmed 0.6± 0.2°C; regional temperature changes have varied, ranging from greater than 0.6°C to cooling in some regions (TAR WGI Chapter 2). Annual land-surface precipitation has increased (0.5–1% per decade) in most middle and high latitudes of the northern hemisphere, except over eastern Asia. In contrast, over much of the subtropical land areas, rainfall has decreased during the 20th century (0.3% per decade), although it has been recovering in recent years (TAR WGI Chapter 2). The recent warming period began in 1976, with pronounced warming observed in northwestern North America, central northern Asia, and the southern Pacific Ocean. Detection of climate change and attribution of causes are discussed in TAR WGI Chapter 12.

19.2.1. Methods of Analysis

Accumulation of evidence over time and space, based on numerous individual studies, is needed to detect and characterize patterns and processes of observed climate change impacts on a global basis (see Chapter 2). In many studies, changes in impact systems are compared with trends in climate variables over the same period and location. Many studies establish statistically significant trends in the observed impact and the climate variable, as well as a statistically significant association between the two (e.g., Beebee, 1995; Brown *et al.*, 1999; Barber *et al.*, 2000). Others refer to trends in climate documented elsewhere (e.g., Menzel and Fabian, 1999; Thomas and Lennon, 1999). When multiple species or locations are examined, cases are reported that exhibit no change, change that is consistent with understanding of climate-impact relationships, and change that is inconsistent with understanding of climate-impact relationships. This allows for assessment of whether observed changes are significantly different from random chance and are consistent with functional understanding of climate responses (e.g., Ellis, 1997; Ellis *et al.*, 1997; Bradley *et al.*, 1999; Pounds *et al.*, 1999).

Individual studies that link observed impacts to regional climate change may be hampered by methodological problems such as length of time-series data of observed impacts; number of replications of populations, census sites, or species; availability of climate data to which to compare observed changes; and uncertainty about whether observed impacts and regional climate variables are measured at appropriate spatial scales (Chapter 2). In some regions, several individual studies have focused on differing aspects of a common ecosystem, providing evidence for associations between climate change and multiple responses in a given geographical area (e.g., Smith *et al.*, 1999); in other regions, however, studies examine more isolated responses.

Because changing climate and ecological responses are linked over a range of temporal scales, long periods of study allow more accurate conclusions regarding the significance of observed ecosystem changes. Large-amplitude temporal changes usually involve large spatial dimensions, so broad-scale spatial/temporal ecosystem studies tend to be more robust. The majority of studies document trends for periods of more than 20 years (e.g., Post *et al.*, 1997; Winkel and Hudde, 1997; Post and Stenseth, 1999); a few studies document trends for 10–19 years (e.g., Jarvinen, 1994; Forchhammer *et al.*, 1998); and several studies analyze data from two periods with a gap between them (Bradley *et al.*, 1999; Sagarin *et al.*, 1999).

Climate Trends: The various studies of observed impacts of recorded regional temperature change over the past century, which include the recent warm decades of the 1980s and 1990s, often differentiate responses to mean, minimum, and maximum temperatures. Regional precipitation changes and periods of droughts and floods are much more variable in observed records and more uncertain with regard to future predictions and are not the primary focus here. Studies also have considered possible observed responses to the rising atmospheric concentrations of CO_2 over the past century, but these studies are not included in this review.

To the extent that periodicities or trends are found in the climate record, nonzero autocorrelations are to be expected on the interannual time scale. Their importance depends on the percentage of variance associated with the periodicities and the magnitude of the trend relative to interannual noise. Often the periodicities represent only a small proportion of the total variance; this is especially true on a local level, where the noise is likely to be higher than at broader spatial scales. A nonzero autocorrelation does not automatically mean the year-to-year ecological impact is not meaningful because if year-to-year climate variability is associated with a periodic or steadily increasing climate forcing, so too would be the ecological response.

Processes and Mechanisms: Beyond statistical association, an important aspect of many studies is comparison of documented changes to known relationships between climate and impact systems. For example, under regional warming, retreat of glaciers is expected because of shifts in the energy balance of glaciers, as is poleward expansion of species' ranges when temperatures exceed physiological thresholds. If documented changes are consistent with known processes that link climate and the impact system, confidence in the associations between changes in regional climate and observed changes is enhanced.

Multiple Causal Factors: The presence of multiple causal factors (e.g., land-use change, pollution, biotic invasion) makes attribution of many observed impacts to regional climate change a complex challenge at the individual study and meta-analysis levels (e.g., Prop *et al.*, 1998; Körner, 1999). Some of the competing explanations for observed impacts themselves could have a common driver that would make them strongly correlated; identifying these drivers is a methodological challenge. Studies seek to document observed climate change impacts by ruling out other possible contributing causative factors, ecological or anthropogenic, through study design and sampling techniques (e.g., Parmesan, 1996; Menzel and Fabian, 1999; Parmesan *et al.*, 1999), statistical analyses (e.g., Prop *et al.*, 1998; Reading, 1998), or expert judgment (De Jong and Brakefield, 1998; Brown *et al.*, 1999). Sometimes, different studies offer alternative explanations for observed impacts (e.g., Körner, 1999).

Signals of regional climate change impacts may be clearer in physical systems than in biological systems, which are simultaneously undergoing many complex changes that are not related to climate, including land-use change and pollution processes such as eutrophication and acidification. Observed impacts in high-latitude and high-altitude physical systems, such as melting of glaciers, may be more straightforward to detect, whereas biological responses to climate tend to be more complex and may be masked by the presence of the aforementioned multiple causal factors. To deal with these ecological complexities, confounding factors often are minimized by conducting studies away from large urban or agricultural areas, in large natural areas (e.g., northern Canada, Australia), or in preserved areas.

Signals of regional climate change impacts probably are most difficult to detect in socioeconomic systems because such systems are strongly affected by simultaneous trends in population and income growth and urbanization and because of the presence of adaptive capacity (see Chapter 18). Observed climate change impacts in socioecosystems may be adaptations in many cases, such as farmers sowing crops earlier in response to warmer spring temperatures.

An example of these methodological complexities in climate change impact detection may be drawn from the human health sector. Although climate is known to influence many disease vectors (such as the range of anopheline mosquitos that carry malaria), the presence or absence of sanitation systems, vaccination programs, adequate nutritional conditions, animal husbandry, irrigation, and land-use management also influences whether the presence of a disease in wild vectors leads to disease outbreaks in human populations (see Chapter 9).

Evaluating Patterns of Change: Grouping individual studies to evaluate patterns and processes of change on larger spatial scales reduces the influences of study-specific biases and local nonclimatic factors. Comparing expected geographical patterns of responses to regional climate changes and to changes that are not related to climate helps distinguish among multiple possible causations. For example, regional warming would be expected to skew the distribution of insect extinctions to be greater at the southern boundaries rather than at the northern boundaries; land-use change, in contrast, would be expected to cause approximately equal extinctions at both range boundaries (Parmesan, 1996; Parmesan *et al.*, 1999). Care must be taken to ensure that the sample of studies is representative across time and space, is not biased in reporting, and uses appropriate statistical tests. Spottiness of evidence in other regions may indicate that observed impacts of regional climate change are not occurring, have not yet been detected, or are being masked by other changes, such as urbanization.

Some studies of observed impacts have used a "fingerprint" approach, based on the definition of expected biological changes arising from regional climate change (e.g., Epstein *et al.*, 1998). This approach is similar to that used in detection of climate changes (see TAR WGI Chapter 12) but differs in that fingerprint studies of ecosystem impacts use selected data and that long-term monitoring of changes in ecosystems generally is lacking at regional or global scales.

19.2.2. Synthesis of Observed Impacts

There is an accumulating body of evidence of observed impacts relating to regional climate changes—primarily rising temperature across a broad range of affected physical processes and biological taxa—and widespread geographical distribution of reported effects (see Figure 19-2 and accompanying notes). In many cases, reported changes are consistent with functional understanding of the climate-impact processes involved. Cases of no change or change in unexpected direction are noted, as are possible alternative explanations and confounding factors, where available.

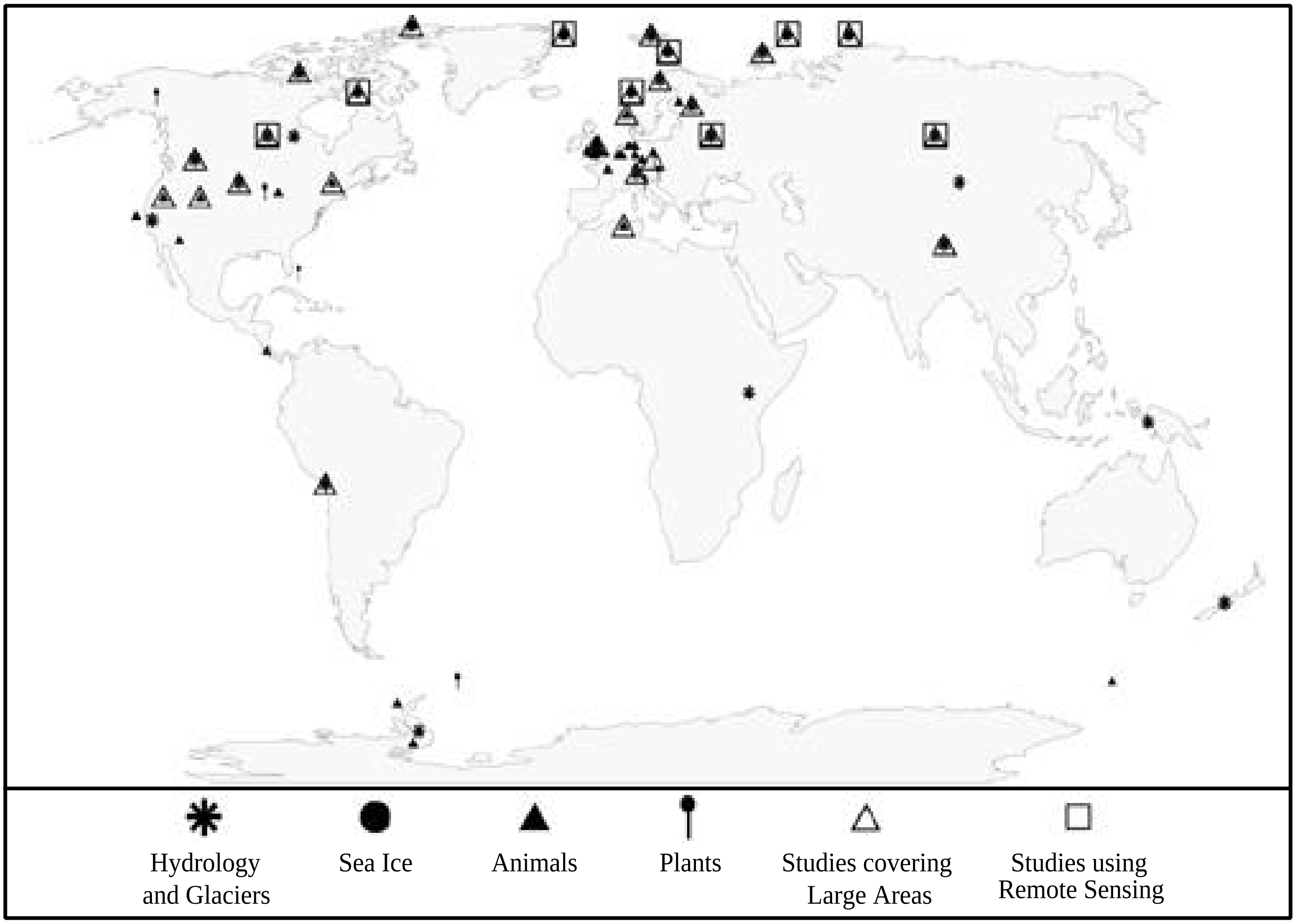


Figure 19-2: Observed impacts of temperature-related regional climate change in the 20th century:

- *Hydrology and Glaciers*—Glacier retreat, decrease in snow-cover extent/earlier snowmelt, reduction in annual duration of lake and river ice
- *Sea Ice*—Decline in sea-ice extent and thickness
- *Animals*—Poleward and elevational shifts in range, alteration in species abundance, changes in phenology (including earlier reproduction and migration), physiological and morphological adaptation
- *Plants*—Change in abundance and diversity, change in phenology (including earlier flowering), change in growth.

Studies that cover large areas and use remote-sensing methods are indicated. About 50 studies were selected, according to the following criteria: (1) hydrology/sea-ice studies that report long-term trends in observed variables (time periods of studies range from ~20 to 150 years), and (2) terrestrial and marine ecosystem studies that associate trends in observed change(s) with trends in regional climate data for ≥20 years (time periods of studies range from ~20 to 50 years). Of the ~100 physical processes and ~450 biophysical species that exhibited change, more than 90% (~99% physical, ~80% biophysical) are consistent with well-known mechanisms of system responses to climate.

Sources: *Hydrology and Glaciers, and Sea Ice*—Ames and Hastenrath (1996), Cavalieri *et al*. (1997), Dettinger and Cayan (1995), Dowdeswell *et al*. (1997), Dyurgerov and Meier (1997), Greene *et al*. (1999), Groisman *et al*. (1994), Haeberli and Beniston (1998), Hastenrath (1995), Johannessen *et al*. (1999), Kaser (1999), Kratz *et al*. (2001), Magnuson *et al*. (2000), Maslanik *et al*. (1996), Rothrock *et al.* (1999), Schindler *et al*. (1990), and Vinnikov *et al.* (1999); *Animals and Plants*—Barber *et al*. (2000), Bergmann (1999), Bezzel and Jetz (1995), Bradley *et al*. (1999), Brown *et al*. (1999), Crick and Sparks (1999), Crick *et al*. (1997), Cunningham and Moors (1994), Dunn and Winkler (1999), Ellis (1997), Ellis *et al*. (1997), Fleming and Tatchell (1995), Forchhammer *et al*. (1998), Fraser *et al*. (1992), Gatter (1992), Grabherr *et al.* (1994), Hasenauer *et al*. (1999), Jarvinen (1994), Loeb *et al.* (1997), Ludwichowski (1997), Mason (1995), McCleery and Perrins (1998), Menzel and Fabian (1999), Pauli *et al.* (1996), Parmesan (1996, 2001), Parmesan *et al.* (1999), Post and Stenseth (1999), Post *et al.* (1997), Pounds *et al*. (1999), Ross *et al.* (1994), Sagarin *et al*. (1999), Slater (1999), Smith (1994), Smith *et al*. (1999), Sparks (1999), Thomas and Lennon (1999), Visser *et al*. (1998), Winkel and Hudde (1996, 1997), Zhou *et al*. (1995).

19.2.2.1. Hydrology

The hydrological cycle is expected to respond to regional climate warming through changes in the energy balance of glaciers and the depth and extent of snow cover, earlier snowmelt runoff, seasonal changes in freezing and thawing of lakes and rivers, and intensification of precipitation and evaporative processes. For the most part, evidence of regional climate change impacts on elements of the hydrological cycle is consistent with expected responses to warming temperatures and intensification of hydrological regimes (see Chapters 4 and 5, and TAR WGI).

Evidence for such changes in the 20th century includes recession of glaciers on all continents (e.g., Hastenrath, 1995; Ames and Hastenrath, 1996; Dowdeswell *et al.*, 1997; Dyurgerov and Meier, 1997; Haeberli and Beniston, 1998; Greene *et al.*, 1999; Kaser, 1999; Krabill *et al.*, 1999; Serreze *et al.*, 2001). There have been decreases in the extent of snow cover (10% since the late 1960s and 1970s) in the northern hemisphere (e.g., Groisman *et al*., 1994; Serreze *et al*., 2001). Since the late 1940s, snowmelt and runoff have occurred increasingly earlier in northern and central California (Dettinger and Cayan, 1995). Annual duration of lake- and river-ice cover in the middle and high latitudes of the northern hemisphere has been reduced by about 2 weeks and is more variable (Schindler *et al.*, 1990; Magnuson *et al.*, 2000; Kratz *et al.*, 2001).

Also reported is increased frequency of extreme rainfall in the middle and high latitudes of the northern hemisphere, including the United States (Karl and Knight, 1998), the UK (Osborn *et al.*, 2000), and most extratropical land areas except China (Groisman *et al.*, 1999).

19.2.2.2. Terrestrial Ecosystems

Ecological theory predicts several types of species and community responses to changing regional climate in plants and animals: changes in ecosystem structure and dynamics, including shifts in ranges and distributions; altered phenology; effects on physiology; and genetic evolutionary responses (see Chapters 2 and 5). Changes in disturbance (e.g., fires, wind damage) also may be occurring but are not included in this review (see Chapters 5 and 6). Evidence from plants and animals documents all of these types of ecological responses to regional warming, especially poleward and elevational shifts in species ranges and earlier timing of reproduction. Reviews of recent changes in biological systems also have documented examples of these different types of responses, consistent with process-level understanding (Hughes, 2000).

19.2.2.2.1. Vegetation

Much of the evidence of vegetation change relating to regional climate change comes from responses to warming at high-latitude and high-altitude environments, where confounding factors such as land-use change may be minimized and where climate signals may be strongest (see TAR WGI Chapter 12). Increases in species richness were found at 21 of 30 high summits in the Alps; remaining summits exhibited stagnation or a slight decrease (Grabherr *et al.*, 1994; Pauli *et al.*, 1996). However, Körner (1999) suggests that grazing, tourism, and nitrogen deposition may be contributing to such observed migrations. Hasenauer *et al.* (1999) found significant increases in diameter increments of Norway spruce across Austria related to increased temperatures from 1961 to 1990. In North America, Barber *et al.* (2000) linked reduced growth of Alaskan white spruce to temperature-induced drought stress, and Hamburg and Cogbill (1988) propose that historical declines in red spruce in the northeastern United States are related to climatic warming, possibly aggravated by pollution and pathogen factors.

In more temperate ecosystems, Bradley *et al.* (1999) documented phenological advances in flowering date in 10 herbaceous and tree species and no change in 26 such species related to local warming in southern Wisconsin over the periods 1936–1947 and 1976–1998. Menzel and Fabian (1999) document extension of the growing season for 12 tree and shrub species at a network of sites throughout Europe, which they attribute to warming temperature. Alward and Detling (1999) found reorganization of a shortgrass steppe ecosystem in a semi-arid site in Colorado related to increased spring minimum temperatures, although the responses of C_3 and C_4 species did not occur as expected.

Regarding regional changes in precipitation—which are much more uncertain with regard to future climate—reorganization of a semi-arid ecosystem in Arizona, including increases in woody shrubs, has been associated with increases in winter precipitation (Brown *et al.*, 1997); retraction of mesic species to areas of higher rainfall and lower temperature has been attributed to a long-term decline in rainfall in the West African Sahel (Gonzalez, 2001).

19.2.2.2.2. Animals

Temperature change-related effects in animals have been documented within all major taxonomic groups (amphibians, birds, insects, mammals, reptiles, and invertebrates) and on all continents (see Chapter 5). Terrestrial evidence in animals that follows process-level understanding of responses to warming includes poleward and elevational changes in spatial distribution, alterations in species abundance and diversity, earlier phenology (including advances in timing of reproduction), and physiological and genetic adaptations.

Poleward and elevational shifts associated with regional warming have been documented in the ranges of North American, British, and European butterfly species (Parmesan, 1996; Ellis, 1997; Ellis *et al.*, 1997; Parmesan *et al.*, 1999), birds (Thomas and Lennon, 1999), and insects (Fleming and Tatchell, 1995). Prop *et al.* (1998) found that increasing spring temperatures and changes in agricultural practices in Norway have allowed barnacle geese (*Branta leucopsis*) to move northward and invade active agricultural areas. Changes in species distribution and abundance of amphibians, birds, and reptiles in Costa Rica have been associated with changing patterns of dry-season mist frequency and Pacific sea-surface temperatures (SST) (Pounds *et al.*, 1999; Still *et al.*, 1999).

Earlier timing of reproduction has been found for many bird species (Mason, 1995; Crick *et al.*, 1997; McCleery and Perrins, 1998; Crick and Sparks, 1999; Slater, 1999) and amphibians (Beebee, 1995; Reading, 1998) in the UK and Europe (Winkel and Hudde, 1996, 1997; Ludwichowski, 1997; Forchhammer *et al.*, 1998; Visser *et al.*, 1998; Bergmann, 1999). Zhou *et al.* (1995) found a warming trend in the spring to be associated with earlier aphid flights in the UK. Also in the UK, Sparks (1999) has associated arrival times of bird migration to warmer spring temperature. Bezzel and Jetz (1995) and Gatter (1992) document delays in the autumn migratory period in the Alps and Germany, respectively.

In North America, Brown *et al.* (1999) document earlier egg-laying in Mexican jays (*Aphelocoma ultramarina*) associated with significant trends toward increased monthly minimum temperatures in Arizona. Dunn and Winkler (1999) found that the egg-laying date of North American tree swallows advanced by as much as 9 days, associated with increasing air temperatures at the time of breeding. Bradley *et al.* (1999) document phenological advances in arrival dates for migratory birds in southern Wisconsin, associated with earlier icemelt of a local lake and higher spring temperature.

Post *et al.* (1997) and Post and Stenseth (1999) document differential selection of body size in red deer throughout Norway from 1965 to 1995. Male red deer have been getting larger and females smaller, correlated with warming trends and variations in the North Atlantic Oscillation (NAO). Post and Stenseth (1999) also report on the interactions of plant phenology, northern ungulates (red deer, reindeer, moose, white-tailed deer, musk oxen, caribou, and Soay sheep), and the NAO. Jarvinen (1994) found that increased mean spring temperatures in Finnish Lapland are associated with mean egg volume of the pied flycatcher. De Jong and Brakefield (1998) found shifts in color patterns (black with red spots versus red with black spots), most likely related to thermal budgets of ladybird beetles (*Adalia bipunctata*) in The Netherlands, coinciding with an increase in local ambient spring temperatures. The potential for rapid adaptive responses and their genetic costs to populations has been studied by Rodriguez-Trelles and Rodriguez (1998), who found microevolution and loss of chromosomal diversity in *Drosophila* in northwestern Spain as the local climate warmed.

19.2.2.3. Coastal Zones and Marine Ecosystems

In coastal zones and marine ecosystems, there is evidence of changes in physical and biological systems associated with regional trends in climate, especially warming of air temperatures and SST (see Chapters 4, 5, and 6). However, separating out responses of marine ecosystems to variability caused by large-scale ocean-atmosphere phenomena, such as ENSO and NAO, from regional climate changes is a challenge (e.g., Southward *et al.*, 1995; McGowan *et al.*, 1998, 1999; Sagarin *et al.*, 1999). Variations caused by ENSO and NAO *per se* are not considered climate change, but multi-decadal trends of change in ENSO or NAO frequency and intensity are climate changes, according to the IPCC definition.

19.2.2.3.1. Physical processes

Changes in the physical systems of coastal zones related to regional warming trends include trends in sea ice and coastal erosion. Since the 1950s, Arctic sea-ice extent has declined by about 10–15%; in recent decades, there has been about a 40% decline in Arctic sea-ice thickness during late summer to early autumn and a considerably slower decline in winter (e.g., Maslanik *et al*., 1996; Cavalieri *et al*., 1997; Johannessen *et al*., 1999; Rothrock *et al.*, 1999; Vinnikov *et al.*, 1999; Serreze *et al.*, 2001). No significant trends in Antarctic sea-ice extent are apparent (see TAR WGI).

19.2.2.3.2. Marine ecosystems

Evidence from marine ecosystems documents changes in species abundance and diversity and spatial distributions associated with air and ocean temperature rises (Chapters 5 and 6). Several studies document changes from the Antarctic region: Increases in chinstrap (*Pygoscelis antarctica*) penguins, stability or slow declines in Adelie (*Pygoscelis adeliae*) penguins, and declines in rockhopper penguins in recent decades are attributed in part to differential responses to warming climate conditions that are altering bird habitats (Fraser *et al*., 1992; Cunningham and Moors, 1994; Smith *et al.*, 1999). Loeb *et al.* (1997) report effects on the Antarctic food web resulting from decreased frequency of winters with extensive sea-ice development; krill abundance is positively correlated with sea-ice extent, and salp abundance is negatively correlated. Smith (1994) reports a significant and relatively rapid increase in the numbers of individuals and populations of the only two native Antarctic vascular plant species at two widely separated localities in the maritime Antarctic.

Increases in abundance of southern macroinvertebrate species and declines in northern species in a rocky intertidal community on the California coast are consistent with recent climate warming (Sagarin *et al.*, 1999). Warming annual temperature has been suggested as a possible cause of increases in abundance of plankton in the German Bight, but numerous factors, including regional eutrophication, also have been noted (Greve *et al.*, 1996). Lehman (2000) found that the distribution of phytoplankton biomass in northern San Francisco Bay Estuary was influenced by environmental conditions resulting from an interdecadal climate regime shift between 1975 and 1993; precipitation regimes were primarily implicated, with water temperatures also playing an important role. Ross *et al.* (1994) document the loss of low-elevation pine forests in the Florida Keys because of rising sea level.

19.2.2.4. Socioeconomic Systems

Evidence of observed impacts of regional climate changes from socioeconomic systems is much sparser than from physical and biological systems, and methodologically it is much more difficult to separate climate effects from other factors such as technological change and economic development, given the complexities of these systems. Vulnerability to climate change and climate variability is a function of exposure and adaptive capacity (see Chapter 18). Exposure varies from region to region, sector to sector, and community to community, and adaptive capacity may be even more variable. The adaptive capacity of socioeconomic systems also contributes to the difficulty of documenting effects of regional climate changes; observable effects may be adaptations to a climate change rather than direct impacts. Evidence of observed adaptation of many of these systems to multiple stresses, including climate variability, suggests that complexities inherent in socioeconomic systems could be a source of resilience, with potential for beneficial adaptations in some cases. Studies that have explored some of these complex relationships are briefly reviewed in the following subsections, but they are not included in the summary tabulation or figure.

19.2.2.4.1. Agriculture and commercial fisheries

It has been proposed that observed impacts of changes in regional climate warming that are relevant to agriculture are related to increasing yield trends in Australia, lengthening growing seasons at high latitudes, improved wine quality in California, and expansion and advanced phenologies of agricultural pests. However, links between changes in regional climate variables and such changes are hard to prove because agriculture is a multifactored biophysical and socioeconomic system (see Chapter 5).

Nicholls (1997) analyzed Australian wheat yields from 1952 to 1992 and concluded that climate trends appear to be responsible for 30–50% of observed increases, with increases in minimum temperatures (decreases in frosts) the dominant influence (Nicholls, 1997); this conclusion has been questioned, however, by Godden *et al.* (1998) and Gifford *et al.* (1998). Possible confounding socioeconomic factors in identifying the effects of climate change on crop yields are responses of farmers to growing conditions (e.g., farmers may increase fertilizer application in good years, thereby exaggerating the impact of climate variables on yield), technological progress, changes in market structure, and changes in agricultural subsidies. Crop responses to increasing atmospheric CO_2 concentrations also may affect yield trends.

Carter (1998) found that the growing season in the Nordic region (Iceland, Denmark, Norway, Sweden, and Finland) lengthened between 1890 and 1995 at all sites except Iceland, with likely but undocumented impacts on crop phenologies and timing of farm operations.

Nemani *et al.* (2001) relate warming at night and during spring in California over the period 1951–1997 (especially since 1976) to improved vintage quantity and quality.

Recent expansion and advances in insect phenologies may be associated with regional increases in mean or minimum temperatures (e.g., advances in flight phenology of aphid species in Britain) (Fleming and Tatchell, 1995; Zhou *et al.*, 1995). Such increases in insect pests may be contributing to agricultural losses at least partially related to recent climate trends, but these effects have not been examined analytically.

Some changes in marine and coastal ecosystems have links to commercial fisheries, but it is difficult to separate regional climate effects from human use of fish stocks (see Chapter 6). Recent warming trends and coincident overfishing and eutrophication have been noted in the English Channel and North Sea, with potential future consequences for fish of high mass-market value (e.g., haddock, cod, plaice, lemon-sole cod—Southward *et al.*, 1995; O'Brien *et al.*, 2000). Diminished krill supplies in the Antarctic associated with decreases in annual sea-ice cover and warmer air temperature documented by Loeb *et al.* (1997) between 1976 and 1996 may have long-term negative effects on upper tropic levels, affecting commercial harvests. These observations, in part, have prompted the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) to request updated krill data currently used in krill management. CCAMLR manages and sets limits on the international harvest of Antarctic krill (Loeb *et al.*, 1997).

19.2.2.4.2. Energy, industry, human settlements, and financial and insurance services

Associations between regional climate trends and impacts related to energy, industry, and human settlements are sparse. One documented example is rapid coastal retreat along ice-rich coasts of the Beaufort Sea in northwestern Canada (Dallimore *et al.*, 1996). Where communities are located in ice-rich terrain along the shore, warmer temperatures combined with increased shoreline erosion can have a very severe impact (see Chapter 6).

Determining the relationship between regional climate trends and impacts relating to financial and insurance services is difficult because of concurrent changes in population growth, economic development, and urbanization. Trends have been analyzed regarding increased damages by flooding and droughts in some locations. Global direct losses resulting from large weather-related disasters have increased in recent decades (see Chapter 8). Socioeconomic factors such as increased coverage against losses account for part of these trends; in some regions, increases in floods, hailstorms, droughts, subsidence, and wind-related events also may be partly responsible (see Chapter 8). Attribution is still unclear, however, and there are regional differences in the balance of these two causes. Hurricane and flood damages in the United States have been studied by Changnon *et al.* (1997), Changnon (1998), and Pielke and Downton (2001). Pielke and Downton (2001) found that increases in recent decades in total flooding damage in the United States are related to climate factors and societal factors: increased precipitation and increasing population and wealth. Hurricane damages, on the other hand, are unaffected by observed climate change (Changnon *et al.*, 1997; Changnon, 1998).

19.2.2.4.3. Human health

There is little evidence that recent trends in regional climates have affected health outcomes in human populations (see Chapter 9). This could reflect a lack of such effects to date or difficulty in detecting them against a noisy background containing other more potent influences on health (Kovats *et al.*, 1999). The causation of most human health disorders is multifactorial, and the socioeconomic, demographic, and environmental context varies constantly. With respect to infectious diseases, for example, no single epidemiological study has clearly related recent climate trends to a particular disease.

Various studies of the correlation between interannual fluctuations in climatic conditions and the occurrence of malaria, dengue, cholera, and several other infectious diseases have been reported. Pascual *et al.* (2000) report a relationship between cholera and El Niño events. Such studies confirm the climate sensitivity of many infectious diseases, but they do not provide quantitative information about the impact of decadal-level climate change. Fingerprint studies examine the patterns of collocated change in infectious diseases and their vectors (if applicable) in simpler physical and ecological systems. This is an exercise in pattern recognition across qualitatively different systems.

One example is the set of competing explanations for recent increases in malaria in the highlands (see Chapter 9). A fingerprint study has hypothesized possible connections of plant and insect data, glacier observations, and temperature records to global climate change in high-altitude locations, with implications for patterns of mosquito-borne diseases (Epstein *et al.*, 1998). Loevinsohn (1994) notes a connection between climate warming and increased rainfall with increased malaria incidence in Rwanda, whereas Mouchet *et al.* (1998) emphasizes the importance of nonwarming factors (e.g., land-use change in response to population growth, climate variability related to ENSO) in explaining variations in malaria in Africa.

Changes in disease vectors (e.g., mosquitoes, ticks) are likely to be detected before changes in human disease outcomes. Furthermore, a change in vector does not necessarily entail an increase in health impacts because of simultaneous processes related to the disease itself and the human population at risk. For example, the presence or absence of sanitation systems, vaccination programs, adequate nutritional conditions, animal husbandry, irrigation, and land-use management influences whether the presence of a disease in wild vectors leads to disease outbreaks in human populations. The effects of changes in frequency of extreme events may entail changes in health impacts, but these have not been documented to date.

19.2.3. Conclusions

Statistically significant associations between trends in regional climate and impacts have been documented in ~100 physical processes and ~450 biological species or communities in terrestrial and polar environments. More than 90% of the changes (~99% physical, ~80% biophysical) documented worldwide are consistent with how physical and biological processes are known to respond to climate. There are systematic trends of ecological change across major taxonomic groups (amphibians, birds, insects, mammals, reptiles, and invertebrates) inhabiting diverse climatic zones and habitats. The overall processes and patterns of observations reveal a widespread and coherent impact of 20th-century climate changes on many physical and biological systems (see Figure 19-2).

Expected directions of change relating to regional climate warming for physical systems have been reported in studies documenting shrinkage of glaciers, decreases in snow cover, shortening of duration of lake- and river-ice cover, declines in sea-ice extent and thickness, lengthening of frost-free seasons, and intensification of the hydrological cycle. Expected directions of change relating to regional climate warming for biological systems have been reported in studies documenting poleward and elevational shifts in distribution and earlier phenology (i.e., earlier breeding, emergence, flowering) in plant and animal species.

In general, geographic patterns of responses also conform to expectations relating to regional climate change, as opposed to alternative explanations. Reported cases of observed impacts are concentrated in high-latitude and high-altitude physical and biological systems and tend to be in regions where observed regional warming has been greatest and confounding factors often are at least partially minimized. Although land-use change, pollution, and biotic invasions are widespread anthropogenic influences, they are unlikely to cause the spatial patterns (e.g., skewed poleward and elevational range shifts) and temporal patterns (e.g., earlier breeding and flowering) that are documented over the set of reported studies.

The sample of studies shown in Figure 19-2 was drawn from a literature survey with keywords relating to climate trends and observed trends in impacts. The time period of most of the studies includes the recent warm period beginning in the late 1970s. The geographical distribution of studies to date is biased toward Europe and North America but does include evidence of observed impacts of regional climate change relating to physical processes from all continents. The spottiness of biological evidence in other regions may indicate that observed impacts of regional climate change are not occurring, have not yet been detected, or are being masked by other changes, such as urbanization. Many studies include multiple species and report on the number of species that responded to regional climate changes as expected, not as expected, or exhibited no change. Most of the biophysical studies included in Figure 19-2 report on statistical tests of trends in climate variable, trends in observed impacts, and relationships between the two (see Chapter 5).

In Figure 19-2, ~16 studies examining glaciers, sea ice, snow-cover extent/snowmelt, or ice on lakes or streams at more than 150 sites were selected. Of these ~150 sites, 67% (~100) show change in one or more variable(s) over time. Of these ~100 sites, about 99% exhibit trends in a direction that is expected, given scientific understanding of known mechanisms that relate temperatures to physical processes that affect change in that variable. The probability that this proportion of sites would show directional changes by chance is much less than 0.00001.

There are preliminary indications that some social and economic systems have been affected in part by 20th-century regional climate changes (e.g., increased damages from flooding and droughts in some locations). It generally is difficult to separate climate change effects from coincident or alternative explanations for such observed regional impacts. Evidence from studies relating regional climate change impacts on socioeconomic systems has been reviewed but is not included in the summary figure because of the complexities inherent in those systems.

The effects of regional climate change observed to date provide information about the potential vulnerability of physical, biological, and socioeconomic systems to climate change in terms of exposure, sensitivity, and adaptive capacity. Some of the observed effects are adaptations. In some cases, observed impacts are large relative to the levels of regional climate changes (e.g., large changes in ecosystem dynamics with small changes in regional climate). In general, observations of impacts agree with predictions that estimate more serious impacts at higher GHG concentrations because the greater regional climate changes are associated with stronger impacts.

Relating the observed impacts summarized here to the reasons for concern analyzed in this chapter, we find the following:

1) There is preliminary evidence that *unique and threatened systems* are beginning to be affected by regional climate change (e.g., glaciers, polar environments, rare species).
2) With regard to the *distributional effects* of observed impacts relating to regional climate changes, most evidence to date comes from high-latitude and high-altitude environments, where regional warming has been and is expected to be more pronounced.
3) *Aggregate impacts* of regional climate changes at the global level are difficult to define, except in sectors in which there is a common metric, as in market sectors. The many simultaneous factors and varying adaptive capacities make extracting aggregate effects attributable to observed climate change difficult. What can be stated in summary regarding the diverse set of impacts reported to date is that there are cases of observed impacts in many diverse environments; that they occur in a wide array of processes, species, and ecosystems; and that the overall patterns and processes reveal a coherent impact of 20th-century climate changes on many physical and biological systems.
4) Impacts of *extreme events* have been implicated in many of the observations summarized in this section, including increases in extreme precipitation events in some locations.
5) There is no current evidence in observed impacts that *large-scale abrupt changes* already are occurring. Yet, paleoclimate evidence (see TAR WGI Chapter 2) shows that such changes have occurred in physical and biological systems in the past and therefore may occur with a continuation of the current warming trend.

19.3. Impacts on Unique and Threatened Systems

19.3.1. What are Unique and Threatened Systems?

Unique systems are restricted to a relatively narrow geographical range but can affect other entities beyond their range. Indeed, many unique systems have global significance. The fact that these unique entities are restricted geographically points to their sensitivity to environmental variables, including climate, and therefore attests to their potential vulnerability to climate change.

Identification of these unique entities provides the first reason for concern regarding vulnerability to climate change. In this section, we provide examples of unique entities that are likely to be threatened by future changes in climate. From those treated by WGII, we address physical, biological, and human systems. We offer a few examples in each system: tropical glaciers, coral reefs, mangrove ecosystems, biodiversity “hot spots,” ecotones, and indigenous communities. These are meant only as illustrative examples; there are many unique and threatened entities. Table 19-1 lists some unique and potentially threatened systems in relation to climate change thresholds that may cause adverse effects. Table 19-2 lists some of the unique and threatened systems that are discussed elsewhere in the TAR.

19.3.2. Physical Systems

Anumber of physical systems are threatened by climate change. Among the most prominent are those in regions dominated by cold temperatures, such as glaciers. Many glaciers already are receding, and many are threatened by climate change. Other physical systems, such as small lakes in areas that will become drier (see Chapter 4), also are threatened by climate change. Changes in unique physical systems can have serious consequences for unique biological and human systems.

19.3.2.1. Tropical Glaciers

Tropical glaciers are present on several mountains in Asia, Africa, and Latin America. These glaciers are valuable because, among other reasons, they are a major source of water for people living below them. For example, through a network of mountain streams, meltwater of the Himalayan glaciers contributes a sizeable portion of river flows to the Ganges, Brahmaputra, Indus, and other river systems in south Asia.

Table 19-1*: Vulnerability of wildlife to climate change (compiled from Chapter 5).*

Geographic Area	Impact	Vulnerable to
Most continents, marine, polar regions	– Poleward/elevational shifts in ranges	– Already observed in many species in response to regional climate change
Most continents, marine, polar regions	– Shifts in phenology (e.g., breeding, arrival dates, flowering)	– Already observed in response to regional climate change
Sunderbans, Bangladesh	– Loss of only remaining habitat of Royal Bengal tiger	– Sea-level rise
Caribbean, South Pacific Islands	– Habitat loss, direct mortality of birds	– Hurricanes
Marine	– Reproductive failure in seabirds	– Increased sea-surface temperature (ENSO)
Galapagos, Ecuador, Latin America	– Reduced survival of iguanas	– ENSO
Africa	– Reduced overwinter survival of palearctic migratory birds	– Extreme drought in the Sahel
Monteverde Reserve, Costa Rica	– Extirpation of some cloud forest reptiles and amphibians (already has occurred), elevational shift in some birds	– ENSO, warming, increased frequency of dry season mist
Norway	– Poleward shift of spring range of barnacles geese	– Increase in number of April and May days with temperatures above 6°C
Australia	– Susceptibility of quokka to salmonella infections	– Environmental conditions
United Kingdom	– Earlier hatching of spittlebugs	– Winter-warmed (3°C) grassland plots (experimental)
Scotland	– Faster growth in juvenile red deer, leading to increased body size	– Warmer springs
Isle Royale National Park, United States	– Increased wolf pack size, increased moose mortality, greater growth of understory balsam fir	– Reduction in winter snow cover
Western Antarctic Peninsula	– Reductions in Adelie penguin populations, increases in chinstrap penguin populations	– Increased midwinter surface air temperature, reductions in pack ice, increased snowfall
Northern Hemisphere	– Increased winter survival of some boreal insect pests	– Increased nighttime winter temperatures
Great Plains, USA, and Canada	– Reductions in waterfowl breeding populations as a result of wetland loss	– Increased drought
Africa and Australia	– Wetland loss	– Increased drought
Africa and Australia	– Reduced populations of some mammals	– Increased drought

Table 19-1 (continued)

Geographic Area	Impact	Vulnerable to
Canada	– Loss of 60% of available habitat (habitat migration blocked by Arctic Ocean)	– Climate change
USA and Canada	– Reductions in populations of caribou	– Increased temperatures, snowfall, shifts in precipitation timing
Mexico	– Loss of wintering habitat for eastern population of monarch butterfly	– Climate change leading to habitat change
USA	– Loss of migratory shorebird habitat	– Sea-level rise tied to 2°C temperature increase
Arctic	– Reduced habitat availability and accessibility hampering migration and survival of polar bears, muskox, caribou, and some birds	– Increased temperatures, changing sea-ice regimes
United Kingdom	– Loss of habitat in 10% of designated nature reserves within 30–40 years	– Climate change

Similarly, snow accumulates in winter in the high parts of the cordillera in Peru and melts during summer, becoming the main source of water for many rivers in Latin America (see Section 14.1.3.1.1). In addition, glaciers act as buffers that regulate runoff water supply from mountains to plains during dry and wet spells. Thus, tropical glaciers are instrumental in securing agricultural productivity and livelihoods and provide cultural inspiration for millions of people who live remote from their sources.

Because of the narrow range of ambient temperatures in the tropics, tropical glaciers are more sensitive to climate change than glaciers elsewhere (see Section 4.3.11). Indeed, records spanning several decades show accelerated retreat of several Himalayan and other tropical glaciers (see Section 11.2.1.2).

In the transient phase of melting, increasing discharge will generate floods in the mountains and immediate vicinity, increased siltation of rivers, and larger sediment load in dams and reservoirs. Riparian mountain ecosystems will be impacted during their dry seasons—in the transient phase by a significant increment of downstream flow, as well as following the transient phase—by significant reduction of this flow. These changes will have tangible economic and cultural implications (see Section 11.2.1.2). This example of a tropical unique entity provides an “early warning” for nontropical glaciers and their potential impacts.

19.3.3. Biological Systems

As discussed in Section 19.2, change in climate already appears to be affecting many biological systems. Continued climate changes can threaten a large number of unique biological systems. This section identifies specific characteristics of some of the most unique and threatened systems, which explain why many are at risk from climate change. In addition, some specific examples of unique and threatened biological systems are presented. Many others also are threatened by climate change; these are discussed in detail in other chapters of this report. Examples of natural systems that may be threatened include montane ecosystems that are restricted to upper 200–300 m of mountainous areas, prairie wetlands, remnant native grasslands, coldwater and some coolwater fish habitat, ecosystems that overlie permafrost, and ice-edge ecosystems that provide habitat for polar bears and penguins. Examples of species that may be threatened by changes in climate include forest birds in Tanzania, the resplendent quetzal in Central America, the mountain gorilla in Africa, amphibians that are endemic to the cloud forests of the neotropics, and the spectacled bear of the Andes.

19.3.3.1. Risks to Species and Ecosystems

Laboratory and field studies have demonstrated that climate plays a strong role in limiting the ranges of species and ecosystems. Species already are responding to changes in regional climate, with altered population sizes and breeding times or flowering dates that occur earlier in the season (see Chapter 5). These responses suggest that many unique species will undergo complex changes with a few degrees of warming, which could lead to extinction in many locations. Such species can be found across various regions (see Table 19-1). Other chapters in this report list many examples (see Table 19-2). However, projecting possible responses of wild animal and plant species is extremely difficult for most species because there are many possible biological interactions and confounding factors, such as habitat destruction and invasive species.

***Table 19-2**: Threatened and unique entities identified in WGII TAR.*

Chapter	**Entity**
4. Water Resources	– Endorheic lakes: Caspian and Aral Seas, Lake Balkash, Lake Chad, Lake Titicaca, Great Salt Lake – Glaciers (in general, no particular reference)
5. Ecosystems and Their Services	– Some butterfly species in United States and Europe – Leadbetters's possum in Australia – Cape Floral Kingdom, South Africa
6. Coastal Zones and Marine Ecosystems	– Coral reefs
7. Human Settlements	– Coastal settlements along North Sea coast in northwest Europe, the Seychelles, parts of Micronesia, Gulf Coast of United States and Mexico, Nile delta, and Bay of Bengal
10. Africa	– Cape Floral Kingdom and Succulent Karoo
11. Asia	– Biodiversity of Lake Baikal – Glaciers in the Tianshan, Hindukush Himalayas; permafrost in Tibet – Mangroves
12. Australasia	– Alpine ecosystems, snow and glaciers in New Zealand, wetlands in Kakadu National Park, Queensland fruit fly – Indigenous communities
13. Europe	– Snowpack and permafrost in the mountains
14. Latin America	– Mountain glaciers
15. North America	– Mountain glaciers – Sardine population – Indigenous communities
16. Polar Regions (Arctic and Antarctic)	– Indigenous communities
17. Small Island States	– Mangroves and seagrass beds – Coral reefs

Species that make up a natural community, however, most likely will not shift together (Davis, 1986; Overpeck *et al*., 1994; Root, 2000). This could break apart established natural communities and create newly evolving assemblages. Depending on the magnitude and duration of the environmental disturbance, some or all individuals of a given species may shift out of an area. This, in turn, can cause a local (or even the overall) population size to decline. Superimposed on these potential changes are those caused by land-use change, which frequently fragments populations into patches throughout their ranges.

Species with wide nonpatchy ranges, rapid dispersal mechanisms, and a large population normally are not in danger of extinction [e.g., European house sparrow (*Passer domesticus)* and many weedy plant species]. Those with narrow patchy ranges and small populations frequently are endangered and may require management for survival [e.g., most crane species (*Gruidea spp.*)]. In summary, species tend to become rarer when ranges shift from wide to narrow, available habitat becomes patchier, and population size declines (Huntley *et al*., 1997). Indeed, a species is likely to become extinct if it is forced into a narrow patchy range and its population declines—a probability that is enhanced when environmental disturbances such as climate change, along with companion transient changes, occur.

Even when conservation management of rare species is effective, survival still may be problematic because in a small population, genetically similar individuals may breed, which decreases genetic variability. This, in turn, may reduce adaptability to stresses, thereby further lowering population size and decreasing the types of habitat within which the species could survive. Environmental catastrophes such as hurricanes, oil spills, extreme temperatures, and drought can trigger the extinction of even well-managed rare species. The only way to reduce the risk of extinction brought about by catastrophes is to increase population sizes and maintain corridors between isolated populations.

19.3.3.2. Biodiversity Hot Spots

Biodiversity "hot spots" are areas that feature exceptional concentrations of species, including many endemic species. Unfortunately, many such hot spots also experience large habitat losses. In addition to a hot spot's economic, social, and cultural significance to local people, the uniqueness of its biodiversity and its high share of global biodiversity give the hot spot a global value. Thus, biodiversity hot spots qualify as unique and threatened entities.

Myers *et al.* (2000) define a hot spot as an area featuring a biogeographic unit that contains at least 0.5% of the world's 300,000 vascular plant species as endemics and has lost 70% or more of its primary vegetation. Table 19-3 shows that two-thirds of the hot spots listed in Myers *et al.* (2000) are in the tropics, some of which have the highest percentage of global plants (6.7%) and as much as 28% of area of habitat with primary vegetation. Arctic and boreal biomes, however—which are devoid of hot spots—will have the greatest changes in temperature and precipitation by 2100, whereas the exposure of nearly all hot spots to a global change of 4°C and/or 30% of precipitation is ranked only 3 (on a 1 to 5 scale proposed by Sala *et al.*, 2000). With respect to biome-specific exposure, climate is expected to warm most dramatically at high latitudes, change least in the tropics, and show intermediate changes in other biomes. Indeed, Table 19-3 shows that the tropical hot spots are least vulnerable to climate change and elevated CO_2 (0.12 and 0.10, respectively, on a scale of 0 to 1), whereas the eight Mediterranean and savanna hot spots are at least twice as vulnerable (0.24 and 0.30 for climate change and elevated CO_2, respectively—Sala *et al.*, 2000).

The Cape Floral Kingdom (also called the Cape Floristic Province) and the adjacent succulent Karoo in South Africa are examples of Mediterranean and savanna biodiversity hot spots that very much qualify as unique and threatened entities. The Cape Floral Kingdom is sixth in the world in plant richness of species (5,682 endemic species—Cowling and Hilton-Taylor, 1997). These hotspots are vulnerable for the following reasons:

- Their mountains have no permanent snow cover to which high montane species can retreat as climate warms.
- Montane endemic plants already are concentrated near the peaks, with little or no possibility for altitudinal expansion.
- Endemics are concentrated in the southwestern corner of Africa, with no possibility for latitudinal shifts farther south (except for the extreme southern tip of the continent, which is intensively farmed).
- Increased frequency of fires and drought will affect many short-lived and fire-sensitive species; seedlings that germinate after fires will be exposed to successively more extreme climate conditions.

The succulent Karoo flora may be effectively lost with a mean annual temperature increase of 3–4°C (Rutherford *et al.*, 1999), owing to changing fire regimes, loss of specialist pollinators, and increased frequency of drought. Tropic hot spots that are not as sensitive as the Cape Floral Kingdom also will be seriously affected if other anthropogenic drivers act synergistically (Sala *et al.*, 2000). Thus, although the hot spot analysis (Myers *et al.*, 2000) indicates that much of the problem of current and projected mass extinction could be countered by protection of the 25 hot spots, the ability of these hot spots to be sources of biodiversity is threatened by climate change.

19.3.3.3. Ecotones

Ecotones are transition areas between adjacent but different environments: habitats, ecosystems, landscapes, biomes, or ecoclimatic regions (Risser, 1993). Ecotones that are unique

Table 19-3*: Sensitivity of biodiversity hot spots (Myers et al., 2000; Sala et al., 2000).*

Biome	Number of Hotspots Biome	% of Global Plants (range)	% of Remaining Habitats with Primary Vegetation (range)	Impact by 2100 (of a large change in driver, scale 1–5)		Effect by 2100 (expected change in driver x impact, scale 0–1)	
				of climate change	of elevated CO_2	of climate change	of elevated CO_2
Tropical forests	15	0.5–6.7	3–28	3	1	0.12	0.10
Mediterranean	5	0.7–4.3	5–30	3	2	0.24	0.20
Savanna, grassland	3	0.6–1.5	20–27	3	3	0.23	0.30
North temperate forest	2	0.5–1.2	8–10	2	1.5	0.17	0.15

entities in the context of climate change are transition zones between ecoclimatic regions. Ecotones have narrow spatial extent, a steep ecological gradient and hence high species richness (Risser, 1993), a unique species combination, genetically unique populations (Lesica and Allendorf, 1994), and high intra-species genetic diversity (Safriel *et al.*, 1994).

Ecotones affect distant and larger areas: They regulate interactions between biomes by modifying flows between them (Johnston, 1993; Risser, 1993); they generate evolutionary diversity (Lesica and Allendorf, 1994); and they serve as repositories of genetic diversity to be used for rehabilitation of ecosystems in adjacent ecoclimatic regions if and when these ecosystems lose species because of climate change (see Section 11.3.2.2.2; Volis *et al*., 1998; Kark *et al.*, 1999). Conservation of ecotone biodiversity therefore is an adaptation. Finally, although ecological changes in response to climate change will occur everywhere, the signals will be detectable first in ecotones (Neilson, 1993). This sensitivity makes them indicators that provide early warning for other regions (Risser, 1993).

Although ecotones are unique in provision of climate change-related services, they are threatened. Conservation traditionally is aimed at "prime" core areas of biomes rather than ecotones. Even conservation efforts that are directed at ecotones may not suffice, however: 47–77% of the areas of biosphere reserves are predicted to experience change in ecosystem types, compared to only 39–55% of the total global terrestrial area that will undergo such changes (Leemans and Halpin, 1992; Halpin, 1997).

An example of a threatened ecotone is the desert/nondesert ecoclimatic transition zone—the semi-arid drylands sandwiched between arid and the dry subhumid drylands (Middleton and Thomas, 1997). Semi-arid drylands are prone to desertification, expressed as irreversible loss of soil productivity because of topsoil erosion (see Section 11.2.1.4). Already affected by extreme soil degradation are 67 Mha of semi-arid drylands (2.9% of global semi-arid area)—nearly as much as affected dry-subhumid drylands (28 Mha, 2.2%) and arid drylands (43 Mha, 2.7%—Middleton and Thomas, 1997). This degradation is destroying the habitats of the biodiversity assets of these ecotones, including those to be conserved as an adaptation to climate change (Safriel, 1999a,b).

Climate change is expected to exacerbate desertification (see Section 11.2.1.4; Schlesinger *et al*., 1990; Middleton and Thomas, 1997). Reduced precipitation and increased evapotranspiration will change ecotones' spatial features (e.g., coalescence of patches at one side and increased fragmentation at the other—Neilson, 1993). Furthermore, overexploitation of vegetation that is typical in semi-arid drylands (UNDP, 1998; ICCD, 1999), in synergy with climate change, will further increase habitat loss and hence loss of biodiversity, ecosystem services, and the potential for adaptation. Similar synergies between climate change effects and other anthropogenic impacts are projected for alpine ecotones (Rusek, 1993). To conclude, ecotones between biomes and within climatic transition areas are unique entities; they are important for monitoring climate change and for adapting to climate change, yet they are highly threatened by climate change interacting with other anthropogenic stresses.

19.3.3.4. Coral Reefs

Coral reefs are restricted to narrow latitudinal, horizontal, and vertical ranges along the tropical continental shelves. Their contribution to global coastal biodiversity is disproportionate to their spatial extent: Although they cover less than 1% of the world's oceans, they are inhabited by one-third of globally known marine species (Reaka-Kudla, 1996). Coral reefs have far-reaching effects; they are nurseries for many ocean fish species, and they protect coastlines from wave impact and erosion (see Section 11.2.4.3). Thus, fisheries, tourism, infrastructures, societies, and cultures depend on the well-being of this unique entity that is impacted by increased temperature, atmospheric CO_2, and sea level, synergistically combined with anthropogenic stresses that are independent of climate change.

Many reef-building coral species already live close to their upper thermal limit (see Section 6.4.5). If they are exposed to moderate increases (1–2°C) in water temperature, they become stressed and experience bleaching (Goreau *et al*., 1998; Hoegh-Guldberg, 1999). The increasing frequency of coral bleaching events during the past decade provides a reason for concern for this warming-induced impact (see Section 12.4.2.3). For example, 50–90% bleaching-induced mortality in the Indian Ocean reefs was associated with a 2–6°C above-normal sea-surface maximum triggered by El Niño during 1997–1998; several other severe bleaching events occurred in the 1982–1983 and 1987 El Niño years (Glynn, 1991; Wilkinson *et al*., 1999; see Figure 19-3).

Defining the upper thermal thresholds of corals and using global warming scenarios, Hoegh-Guldberg (1999) found that the frequency of bleaching is expected to rise until they become annual events in most oceans (at about a 1°C warming). In some areas, bleaching events would happen more frequently as early as 2020 (with less than 0.5°C warming); within the next 30–50 years, bleaching could be triggered by normal seasonal changes in seawater temperature, and most regions may experience severe bleaching conditions every year. This trend exceeds the frequency at which corals can effectively recover from bleaching-related mortality (Hoegh-Guldberg, 1999).

Besides the detrimental effect of temperature rise, increased atmospheric CO_2 concentrations reduce coral calcification rates (Gattuso *et al.*, 1999; Kleypas *et al.*, 1999; see Sections 6.4.5 and 12.4.1.6), which already might have decreased and could decrease an additional 10–30% by 2100 (see Chapter 6). A 10–20% decrease in calcium carbonate production may impair expansion of coral reefs into higher latitudes as a response to predicted increasing SST (Kleypas *et al.*, 1999). Healthy reef flats may benefit from projected increased sea level because they would be able to keep up with the projected rise in sea level. However, any increase in the frequency of El Niño and

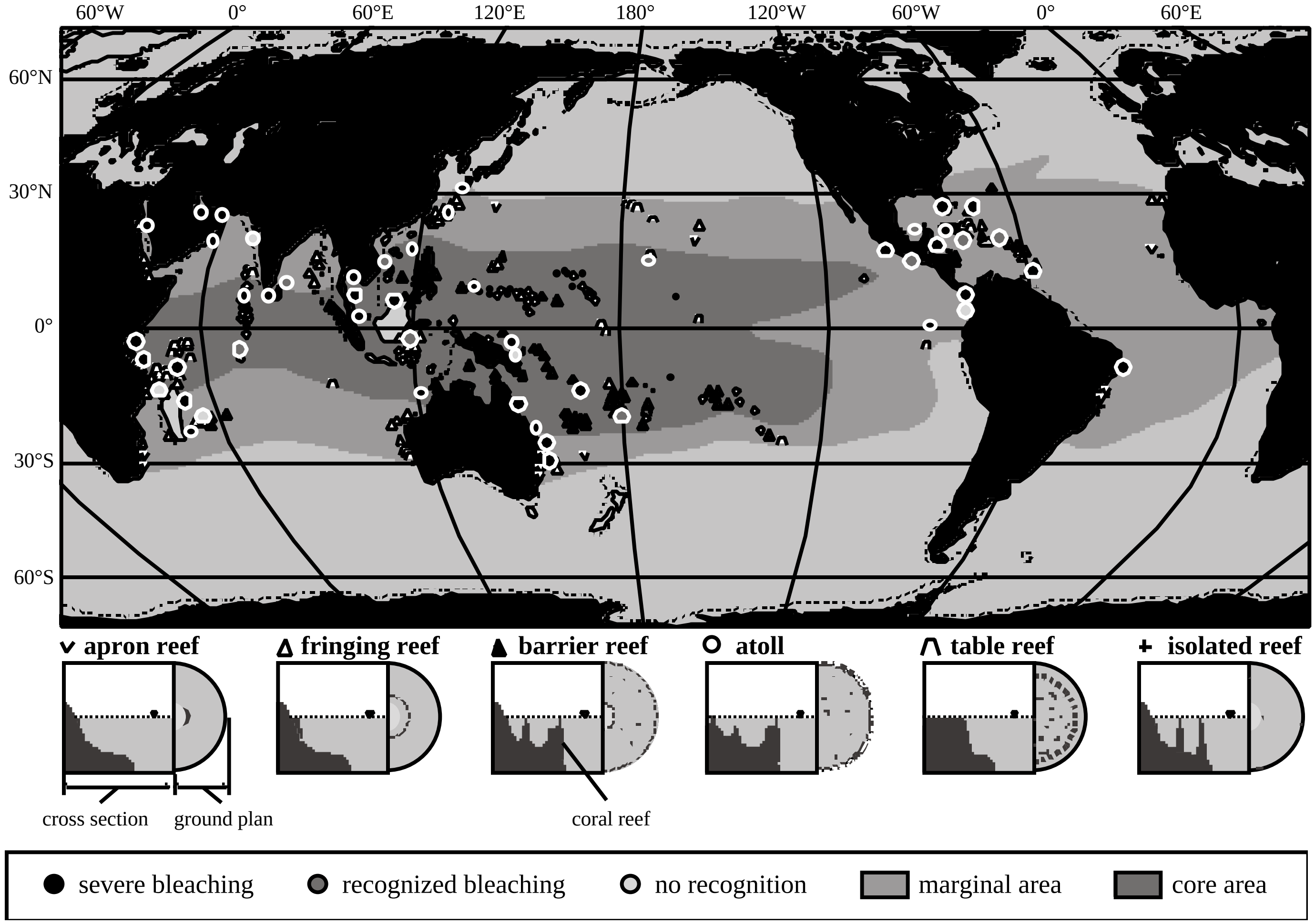


Figure 19-3: Bleaching of coral reefs reported from 1997 to 1998 (Mimura and Harasawa, 2000).

other ocean-atmosphere interactions, such as Indian Ocean dipole events, will lead to regular and prolonged sea-level depressions (10–40 cm) in the western Pacific and eastern Indian Ocean, with adverse effects on shallow reefs in their regions (see Chapter 6).

19.3.3.5. Mangrove Ecosystems

Mangrove ecosystems resemble coral reefs in that they have a narrow global distribution: They cover 11,500 km² in all of Australia, and the largest mangrove forest in the world—the Sundarbans of Bangladesh and India—covers 6,000 km² (see Section 11.2.4.1). Yet they have a rich biodiversity and a significant effect on adjacent and distant systems. Mangroves are made up of salt-adapted, intertidal evergreen trees on low-energy, sedimentary tropical shorelines, extending landward in lagoons, estuary margins, and tidal rivers (see Sections 6.4.4 and 11.2.4.1).

Mangrove ecosystems are highly vulnerable to sea-level rise induced by climate change, which will change the salinity distribution and inundate mangroves. For example, a 45-cm rise could inundate 75% of the Sundarbans (see Section11.4.1); a 1-m rise will completely inundate the Sundarbans (see Section 11.2.1.6). In addition, redistribution of species whose habitats will be affected by inundation may be impaired because migration, especially to the north, will be blocked by human settlements. Loss of productivity, species, and ecosystem goods and services therefore is expected. Climate change effects will be further exacerbated, and vulnerability to climate change will increase human-induced damage. For example, between 56 and 75% of different Asian mangrove forests have been lost during the 20th century because of overexploitation and replacement by aquaculture installations (see Section 11.1.3.1). Like the Sundarbans, the Port Royal mangrove wetland in Jamaica may completely collapse with a 1-m sea-level rise (see Section 17.2.4.2).

On the other hand, although mangroves are vulnerable, some may be adaptable to climate change (see Section 12.4.1.6) because they could survive in areas where vertical accretion equals sea-level rise. Because sediment flux determines mangrove response to sea-level rise and fluxes vary between regions and locations, the fate of the world's mangrove ecosystems will not be uniform (see Section 6.4.4). Yet even where accretion will offset sea-level rise, any infrastructure will limit the potential for landward migration of coastal mangrove species and habitats (see Section 6.2). Thus, at least some if not many of the world's mangrove ecosystems are unique and threatened entities.

19.3.4. Human Systems

Some human systems also are unique and threatened by climate change. These tend to be poor and isolated communities that are tied to specific locations or ecosystems. Among the unique and threatened human systems are some small island states and indigenous communities.

19.3.4.1. Threatened Small Island States

Because of their low elevation and small size, many small island states are threatened with partial or virtually total inundation by future rises in sea level. In addition, increased intensity or frequency of cyclones could harm many of these islands. The existence or well-being of many small island states is threatened by climate change and sea-level rise over the next century and beyond.

Many small island states—especially the atoll nations of the Pacific and Indian Oceans—are among the most vulnerable to climate change, seasonal-to-interannual climate variability, and sea-level rise. Much of their critical infrastructure and many socioeconomic activities tend to be located along the coastline—in many cases at or close to present sea level (Nurse, 1992; Pernetta, 1992; Hay and Kaluwin, 1993). Coastal erosion, saline intrusion, sea flooding, and land-based pollution already are serious problems in many of these islands. Among these factors, sea-level rise will pose a serious threat to the ecosystems, economy, and, in some cases, existence of many small island states. It is estimated that 30% of known threatened plant species are endemic to such islands, and 23% of bird species found on these islands are threatened (Nurse *et al.*, 1998). Projected future climate change and sea-level rise will lead to shifts in species composition (see Chapter 17).

Many small island nations are only a few meters above present sea level. These states may face serious threat of permanent inundation from sea-level rise. Among the most vulnerable of these island states are the Marshall Islands, Kiribati, Tuvalu, Tonga, the Federated States of Micronesia, and the Cook Islands (in the Pacific Ocean); Antigua and Nevis (in the Caribbean Sea); and the Maldives (in the Indian Ocean). Small island states may face the following types of impacts from sea-level rise and climate change (Gaffin, 1997; Nurse *et al.*, 1998):

- Increased coastal erosion
- Changes in aquifer volume and water quality with increased saline intrusion
- Coral reef deterioration resulting from sea-level rise and thermal stress
- Outmigration caused by permanent inundation
- Social instability related to inter-island migration
- Loss of income resulting from negative effects on tourist industry
- Increased vulnerability of human settlement due to decrease in land area
- Loss of agriculture and vegetation.

Gaffin (1997) concludes that without planned adaptation, the vulnerabilities of small island states are as follows:

- An 80-cm sea-level rise could inundate two-thirds of the Marshall Islands and Kiribati.[2]
- A 90-cm sea-level rise could cause 85% of Male, the capital of the Maldives, to be inundated (Pernetta, 1989).

19.3.4.2. Indigenous Communities

Indigenous people often live in harsh climatic environments to which their culture and traditions are well adapted. Indigenous people generally have low incomes and inhabit isolated rural environments and low-lying margins of large towns and cities. Therefore, they are more exposed to social problems of economic insecurity, inadequate water supplies, and lower health standards (see Sections 12.2.5 and 15.3.2.8). These inadequacies in social safety nets indeed put them at greater risk of climate-related disasters and their effects (see Section 12.7.2.4).

For many reasons, indigenous communities are unique and threatened by climate change. First, they are more vulnerable to climate-related disasters such as storms, floods, and droughts because of inadequate structural protection measures and services, as well as to any increase in the prevalence of pests and diseases—especially vector-borne, respiratory, or otherwise infectious diseases (Woodward *et al.*, 1998; Braaf, 1999). Second, their lifestyles are tied to current climate and vegetation and wildlife. Third, changes in current climate could threaten these lifestyles and would present these peoples with difficult choices concerning their future.

Native peoples in the Mackenzie basin in Canada are an example of an indigenous community that is threatened by climate change (Cohen 1994, 1996, 1997a,b,c). The Mackenzie basin is a watershed that extends from the mid-latitudes to the subarctic in northwest Canada. Over the past 35 years, the area has been experiencing a rapid temperature increase of about 1°C per decade. The changes in temperature also are changing the landscape of the basin as permafrost melts, landslides and forest fires increase, and water levels are lowered.

For the native people in the basin, wildlife is the important natural resource; it is harvested by hunting, fishing, and trapping. It is critically important in economic terms—primarily as a source of food, income, and traditional clothing—but inseparable from the cultural importance for maintaining traditional systems

[2]The estimate of land loss based on a 1-m sea-level rise, resulting in 80% island losses (IPCC, 1996).

of knowledge and identity (Pinter, 1997). As noted, changes in the climate in the basin would have substantial impacts on water resources and vegetation. Changes in forest fire frequencies would lead to cumulative impacts on wildlife, including terrestrial, aquatic, and bird species. For example, because of a decrease in water availability, muskrats already have disappeared from the Peace Athabasca delta (Pinter, 1997). In this area, trapping once was a major industry, but this economic activity has now disappeared. Thus, changes in ecosystem resource bases will have direct impacts on native lifestyles in the Mackenzie basin (Cohen *et al*., 1997a).

Some important changes are expected in native lifestyles in the Mackenzie Basin regardless of climate change. For example, an increasing number of people will seek their livelihoods in the wage economy, and migration to other areas will intensify. These changes could result in a decline in cultural values and heritage that are thousands of years old. If climate change adversely affects the lifestyle of the indigenous community, this decline could be accelerated.

19.3.5. Conclusions

There are many unique and threatened systems distributed over various regions of the world. Although they are restricted to relatively narrow geographical ranges, they can affect other entities beyond their range. The existence or functioning of some of these systems is threatened by a small temperature change; the existence or functioning of many others will be threatened by a medium to large temperature change. These effects include impacts such as loss of many species and ecosystems, disappearance of tropical glaciers, damage to coral reefs, inundation of some low-lying islands, loss of coastal wetlands, and potential harm to aboriginal societies and their cultures.

Many of these systems already are stressed by development, including pollution, habitat destruction, encroachment for expansion of human habitation, and overextraction of natural resources. The combination of climate change and societal development puts these systems at greater risk. In some cases, climate change hastens the destruction of these systems; in other cases it may result in the destruction of systems that could survive societal stresses alone (e.g., small island states and some mangrove ecosystems such as the Sundarbans).

Removing societal stresses and managing resources in a sustainable manner may help some unique and threatened systems cope better with climate change.

19.4. Distribution of Impacts

Asecond reason for concern is the distribution of impacts among people and across regions. The impacts of climate change will not be distributed equally. Some individuals, sectors, systems, and regions will be less affected—or may even benefit; other individuals, sectors, systems, and regions may suffer significant losses. This pattern of relative benefits or losses is not likely to remain constant over time. It will be different with different magnitudes of climate change. Some regions may have gains only for certain changes in temperature and precipitation and not for others. As a result, some regions that may first see net benefits eventually may face losses as well as the climate continues to warm.

19.4.1. Analysis of Distributional Incidence: State of the Art

Research into the distribution of impacts of climate change is in its infancy, in large measure because this research poses several methodological challenges.

A first difficulty is synthesis—the need to reduce the complex pattern of individual impacts to a more tractable set of regional or sectoral indicators. The challenge is to identify a set of indicators that can summarize and make comparable the impacts in different regions, sectors, or systems in a meaningful way. A range of indicators and methods have been put forward. Many models use physical measures such as the number of people affected (e.g., Hoozemans *et al.*, 1993), change in net primary productivity (NPP) (White *et al*., 1999), or the number of systems undergoing change (e.g., Alcamo *et al*., 1995).

The most widespread numeraire, however, is economic cost (Nordhaus, 1991, 1994a; Cline, 1992; Hohmeyer and Gaertner, 1992; Titus, 1992; Downing *et al*., 1995, 1996; Fankhauser, 1995; Tol, 1995; Mendelsohn and Neumann, 1999). This numeraire is particularly well-suited to measure market impacts—that is, impacts that are linked to market transactions and directly affect GDP (i.e., a country's national accounts). The costs of sea-level rise, for example, can be expressed as the capital cost of protection plus the economic value of land and structures at loss or at risk; agricultural impacts can be expressed as costs or benefits to producers and consumers, including the incremental costs of adaptation. Using a monetary numeraire to express nonmarket impacts such as effects on ecosystems or human health is more difficult. It is possible in principle, however. There is a broad and established literature on valuation theory and its application, including studies (mostly in a nonclimate change context) on the monetary value of lower mortality risk, ecosystems, quality of life, and so forth. However, economic valuation can be controversial and requires sophisticated analysis, which still is mostly lacking in a climate change context.

Physical metrics—such as NPP or percentage of systems affected—on the other hand, are best suited for natural systems. When they are applied to systems under human management, they suffer from being poorly linked to human welfare, the ultimate indicator of concern. Some researchers therefore recommend different numeraires for market impacts, mortality, ecosystems, quality of life, and equity (Schneider *et al*., 2000b). They recognize, however, that final comparisons across different numeraires nonetheless are required; they regard this as the job of policymakers, however.

Persistent knowledge gaps is a second source of difficulty. Distributional analysis depends heavily on the geographical details of climate change, but these details are one of the major uncertainties in the outputs of climate change models. This is particularly true for estimates of precipitation; for example, estimates of water-sector impact can vary widely depending on the choice of GCM.[3] Uncertainties continue at the level of impact analysis. Despite a growing number of country-level case studies, our knowledge of local impacts is still too uneven and incomplete for a careful, detailed comparison across regions. Furthermore, differences in assumptions often make it difficult to compare case studies across countries. Only a few studies try to provide a coherent global picture on the basis of a uniform set of assumptions. The basis of most such global impact assessments tends to be studies undertaken in developed countries—often the United States—which are then extrapolated to other regions. Such extrapolation is difficult and will be successful only if regional circumstances are carefully taken into account, including differences in geography, level of development, value systems, and adaptive capacity. Not all analyses are equally careful in undertaking this task.

There are other shortcomings that affect the quality of analysis. Although our understanding of the vulnerability of developed countries is improving—at least with respect to market impacts—information about developing countries is quite limited. Nonmarket damages, indirect effects (e.g.,the effect of changed agricultural output on the food-processing industry), the link between market and nonmarket effects (e.g., how the loss of ecosystem functions will affect GDP), and the sociopolitical implications of change also are still poorly understood. Uncertainty, transient effects (the impact of a changing rather than a changed and static climate), and the influence of climate variability are other factors that deserve more attention. Because of these knowledge gaps, distributional analysis has to rely on (difficult) expert judgment and extrapolation if it is to provide a comprehensive picture.

Athird problem is adaptation. There has been substantial progress in the treatment of adaptation since the SAR, but adaptation is difficult to capture adequately in an impact assessment. Adaptation will entail complex behavioral, technological, and institutional adjustments at all levels of society, and the capacity to undertake them will vary considerably (see Chapter 18). Various approaches are used to model adaptation (e.g., spatial analogs, microeconomic modeling), but they are prone to systematic errors about its effectiveness. The standard approach used in coastal impact assessment and in many agricultural models is to include in the analysis a limited number of "prominent" but ultimately arbitrary adaptations. This underestimates adaptive capacity because many potentially effective adaptations are excluded (Tol *et al*., 1998). On the other hand, approaches that are based on analogs—such as the Ricardian approach used by, for example, Mendelsohn *et al.* (1994), Mendelsohn and Dinar (1998), and Darwin (1999)—probably overestimate adaptive capacity because they neglect the cost of transition and learning. This is especially true for cases in which adaptation in developed countries today is used as a proxy for worldwide adaptation to an uncertain future climate. Only a very few studies model adaptation as an optimization process in which agents trade off the costs and benefits of different adaptation options (Fankhauser, 1995; Yohe *et al.*, 1995, 1996).

Box 19-2. The Impact of Climate Change on Coastal Zones

The impact of sea-level rise has been widely studied for many parts of the world. Although uncertainties remain, several generic conclusions can be drawn. First, impacts will not be distributed evenly. Islands and deltas are particularly vulnerable. Second, forward-looking and sustainable economic development, coupled with efficient adaptation (mostly protection of vulnerable shores), can significantly reduce the economic impact of sea-level rise. Some analysts have even found that coastal vulnerability may decrease if the rate of economic development is sufficiently high and climate change sufficiently slow. However, not all countries will be able to undertake the necessary adaptation investments without outside financial assistance, and uncertainty about sea levels (e.g., as a result of storm surges) may make it difficult to identify efficient policies. Third, coastal wetlands can cope with a relatively modest rate of sea-level rise, but not with a fast one. Additional wetlands could be lost if their migration is blocked by hard structures built to protect developed coastal areas. Fourth, most of the impact will not be through gradual sea-level rise but through extreme events such as floods and storms. This makes people without insurance or a strong social network especially vulnerable. Thus, as a whole, sea-level rise is likely to have strong negative effects on some people, even if the aggregate impact is limited. Fifth, the aggregate impact of sea-level rise could be roughly proportional to the observed rise. At a local scale, however, sea-level rise is more likely to be felt through successive crossings of thresholds.

The analysis is further complicated by the strong link between adaptation and other socioeconomic trends. The world will change substantially in the future, and this will affect vulnerability to climate change. For example, a successful effort to roll back malaria (as promoted by the development community) could reduce the negative health effects of climate change. On the other hand, growing pressure on natural resources from unsustainable economic development is likely to exacerbate the impacts of

[3]For example, Frederick and Schwarz (1999) found that climate changes estimated in the southeastern United States in the 2030s under the Canadian Climate Centre scenario result in an estimated US$100 billion yr^{-1} in damages. This estimate may be the result of internal model variability and does not fully account for adaptive responses or lower damages from reduced flood risks. Nonetheless, it demonstrates the high sensitivity of water resources to extreme changes in climate.

climate change on natural systems. Even without explicit adaptation, impact assessments therefore depend on the "type" of socioeconomic development expected in the future. The sensitivity of estimates to such baseline trends can be strong enough in some cases to reverse the sign (i.e., a potentially negative impact can become positive under a suitable development path, or vice versa) (Mendelsohn and Neumann, 1999).

Despite the limits in knowledge, a few general patterns emerge with regard to the distribution of climate change impacts. These patterns are derived from general principles, observations of past vulnerabilities, and limited modeling studies.

19.4.2. Distribution of Impacts by Sector

Susceptibility to climate change differs across sectors and regions. A clear example is sea-level rise, which mostly affects coastal zones (see Box 19-2). People living in the coastal zone generally will be negatively affected by sea-level rise, but the numbers of people differ by region. For example, Nicholls *et al.* (1999) found that under a sea-level rise of about 40 cm by the 2080s, assuming increased coastal protection, 55 million people would be flooded annually in south Asia; 21 million in southeast Asia, the Philippines, Indonesia, and New Guinea; 14 million in Africa; and 3 million in the rest of the world. The relative impacts in small island states also are significant (see Section 19.3). In addition, the Atlantic coast of North and Central America, the Mediterranean, and the Baltic are projected to have the greatest loss of wetlands. Inland areas face only secondary effects—which, unlike the negative primary effects, may be either negative or positive (Yohe *et al.*, 1996; Darwin and Tol, 2001).

Agriculture, to turn to another example, is a major economic sector in some countries and a small one in others. Agriculture is one of the sectors that is most susceptible to climate change, so countries with a large portion of the economy in agriculture face a larger exposure to climate change than countries with a lower share, and these shares vary widely. Whereas countries of the Organisation for Economic Cooperation and Development (OECD) generate about 2–3% of their GDP from agriculture, African countries generate 5–58% (WRI, 1998).

Activities at the margin of climatic suitability have the most to lose from climate change, if local conditions worsen, and the most to win if conditions improve. One example is subsistence farming under severe water stress—for instance, in semi-arid regions of Africa or south Asia. A decrease of precipitation, an increase in evapotranspiration, or higher interannual variability (particularly longer droughts) could tip the balance from a meager livelihood to no livelihood at all, and the unique cultures often found in marginal areas could be lost. An increase in precipitation, on the other hand, could reduce pressure on marginal areas. Numerous modeling studies of shifts in production of global agriculture—including Kane *et al.* (1992), Rosenzweig and Parry (1994), Darwin *et al.* (1995), Leemans (1997), Parry *et al.* (1999), and Darwin (1999)—have estimated that production in high-latitude countries is likely to increase and production in low-latitude countries is likely to decrease, even though changes in total global output of agriculture could be small. Results in the temperate zone are mixed. Low-latitude countries tend to be least developed and depend heavily on subsistence farming. Under current development trends they will continue to have a relatively high share of GDP in agriculture. Thus, the impacts of declines in agricultural output on low-latitude countries are likely to be proportionately greater than any gains in high-latitude countries (see Box 19-3).

Box 19-3. The Impact of Climate Change on Agriculture

The pressures of climate change on the world's food system are better understood than most other impacts. Research has focused on crop yields; on the basis of those insights, many studies also look at farm productivity, and a smaller number look at national and international agricultural markets.

Climate change is expected to increase yields at higher latitudes and decrease yields at lower latitudes. Changes in precipitation, however, also can affect yields and alter this general pattern locally and regionally. Studies of the economic impact of this change (in all cases, climate change associated with $2xCO_2$) conclude that the aggregated global impact on the agricultural sector may be slightly negative to moderately positive, depending on underlying assumptions (e.g., Rosenzweig and Parry, 1994; Darwin, 1999; Parry *et al.*, 1999; Mendelsohn *et al.*, 2000). Most studies on which these findings are based include the positive effect of carbon fertilization but exclude the negative impact of pests, diseases, and other disturbances related to climate change (e.g., droughts, water availability). The aggregate also hides substantial regional differences. Beneficial effects are expected predominantly in the developed world; strongly negative effects are expected for populations that are poorly connected to regional and global trading systems. Regions that will get drier or already are quite hot for agriculture also will suffer, as will countries that are less well prepared to adapt (e.g., because of lack of infrastructure, capital, or education). Losses may occur even if adaptive capacity is only comparatively weak because trade patterns will shift in favor of those adapting best. Overall, climate change is likely to tip agriculture production in favor of well-to-do and well-fed regions—which either benefit, under moderate warming, or suffer less severe losses—at the expense of less-well-to-do and less well-fed regions. Some studies indicate that the number of hungry and malnourished people in the world may increase, because of climate change, by about 10% relative to the baseline (i.e., an additional 80–90 million people) later in the 21st century (e.g., Parry *et al.*, 1999).

Vulnerability to the health effects of climate change also differs across regions and within countries, and differences in adaptive capacity again are important. Box 19-4 notes that wealthier countries will be better able to cope with risks to human health than less wealthy countries. Risks also vary within countries, however. In a country such as the United States, the very young and the very old are most sensitive to heat waves and cold spells, so regions with a rapidly growing or rapidly aging population would have relatively large exposure to potential health impacts. In addition, poor people in wealthy countries may be more vulnerable to health impacts than those with average incomes in the same countries. For example, Kalkstein and Greene (1997) found that in the United States, residents of inner cities, which have a higher proportion of low-income people, are at greater risk of heat-stress mortality than others. Differences among income groups may be more pronounced in developing and transition countries because of the absence of the elaborate safety nets that developed countries have constructed in response to other, nonclimate stresses.

These observations underscore one of the critical insights in Chapter 18: Adaptive capacity differs considerably between sectors and systems. The ability to adapt to and cope with climate change impacts is a function of wealth, technology, information, skills, infrastructure, institutions, equity, empowerment, and ability to spread risk. The poorest segments of societies are most vulnerable to climate change. Poverty determines vulnerability via several mechanisms, principally in access to resources to allow coping with extreme weather events and through marginalization from decisionmaking and social security (Kelly and Adger, 2000). Vulnerability is likely to be differentiated by gender—for example, through the "feminization of poverty" brought about by differential gender roles in natural resource management (Agarwal, 1991). If climate change increases water scarcity, women are likely to bear the labor and nutritional impacts.

The suggested distribution of vulnerability to climate change can be observed clearly in the pattern of vulnerability to natural disasters (e.g., Burton *et al*., 1993). The poor are more vulnerable to natural disasters than the rich because they live in more hazardous places, have less protection, and have less reserves, insurance, and alternatives. Adger (1999), for instance, shows that marginalized populations within coastal communities in northern Vietnam are more susceptible to the impacts of present-day weather hazards and that, importantly, the wider policy context can exacerbate this vulnerability. In the Vietnamese case, the transition to market-based agriculture has decreased

Box 19-4. The Health Impacts of Climate Change

Global climate change will have diverse impacts on human health—some positive, most negative. Changes in the frequency and intensity of extreme heat and cold, floods and droughts, and the profile of local air pollution and aeroallergens will directly affect population health. Other effects on population health will result from the impacts of climate change on ecological and social systems. These impacts include changes in infectious disease occurrence, local food production and nutritional adequacy, and the various health consequences of population displacement and economic disruption. Health impacts will occur very unevenly around the world. In general, rich populations will be better protected against physical damage, changes in patterns of heat and cold, introduction or spread of infectious diseases, and any adverse changes in world food supplies.

The geographic range and seasonality of various vector-borne infectious diseases (spread via organisms such as mosquitoes and ticks) will change, affecting some populations that currently are at the margins of disease distribution. The proportion of the world's population living in regions of potential transmission of malaria and dengue fever, for example, will increase. In areas where the disease currently is present, the seasonal duration of transmission will increase. Decreases in transmission may occur where precipitation decreases reduce vector survival, for example.

An increased frequency of heat waves will increase the risk of death and serious illness, principally in older age groups and the urban poor. The greatest increases in thermal stress are forecast for mid- to high-latitude (temperate) cities, especially in populations with limited air conditioning. Warmer winters and fewer cold spells, because of climate change, will decrease cold-related mortality in many temperate countries. Basic research to estimate the aggregate impact of these changes has yet been limited largely to the United States and parts of Europe. Recent modeling of heat-wave impacts in 44 U.S. urban populations, allowing for acclimatization, suggests that large U.S. cities may experience, on average, several hundred extra deaths per summer. Although the impact of climate change on thermal stress-related mortality in developing country cities may be significant, there has been little research in such populations.

For each anticipated adverse health impact, there is a range of social, institutional, technological, and behavioral adaptation options that could lessen that impact. The extent to which health care systems will have the capacity to adopt them is unclear, however, particularly in developing countries. There is a basic and general need for public health infrastructure (programs, services, surveillance systems) to be strengthened and maintained. The ability of affected communities to adapt to risks to health also depends on social, political, and economic circumstances.

the access of the poor to social safety nets and facilitated the ability of rich households to overexploit mangroves, which previously provided protection from storms. Similarly, Mustafa (1998) demonstrates differentiation of flood hazards in lowland Pakistan by social group: Insecure tenure leads to greater impacts on poorer communities. See Chapter 18 for further examples. The natural disaster literature also concludes that organization, information, and preparation can help mitigate large damages at a moderate cost (e.g., Burton *et al.*, 1993). This underscores the need for adaptation, particularly in poor countries.

19.4.3. Distribution of Total Impacts

Several studies have estimated the total impact (aggregated across sectors) in different regions of the world. Table 19-4 shows aggregate, monetized impact estimates for a doubling of atmospheric CO_2 on the current economy and population from four studies. Clearly, in all of these studies there are substantial uncertainties about the total impacts to regions and whether some regions will have net benefits or net damages at certain changes in global average temperature. Most studies, however, show the following:

- Developing countries, on the whole, are more vulnerable to climate change than developed countries.
- At low magnitudes of temperature change, damages are more likely to be mixed across regions, but at higher magnitudes virtually all regions have net damages.
- The distribution of risk may change at different changes in temperature.

Developing countries tend to be more vulnerable to climate change because their economies rely more heavily on climate-sensitive activities (particularly agriculture), and many already

Table 19-4*: Indicative world impacts, by region (% of current GDP). Estimates are incomplete, and confidence in individual numbers is very low. See list of caveats in Section 19.4.1. There is a considerable range of uncertainty around estimates. Tol's (1999a) estimated standard deviations are lower bounds to real uncertainty. Figures are expressed as impacts on a society with today's economic structure, population, laws, etc. Mendelsohn et al. (2000) estimates denote impact on a future economy. Positive numbers denote benefits; negative numbers denote costs (Pearce et al., 1996; Tol, 1999a; Mendelsohn et al., 2000; Nordhaus and Boyer, 2000).*

	IPCC SAR	**Mendelsohn *et al*.**		**Nordhaus and Boyer**	**Tol**
	2.5°C Warming	1.5°C Warming	2.5°C Warming	2.5°C Warming	1°C Warming[a]
North America					3.4 (1.2)
– United States			0.3	-0.5	
OECD Europe					3.7 (2.2)
– EU				-2.8	
OECD Pacific					1.0 (1.1)
– Japan			-0.1	-0.5	
Eastern Europe/FSU					2.0 (3.8)
– Eastern Europe				-0.7	
– Russia			11.1	0.7	
Middle East				-2.0[b]	1.1 (2.2)
Latin America					-0.1 (0.6)
– Brazil			-1.4		
South, Southeast Asia					-1.7 (1.1)
– India			-2.0	-4.9	
China			1.8	-0.2	2.1 (5.0)[c]
Africa				-3.9	-4.1 (2.2)
Developed countries	-1.0 to -1.5	0.12	0.03		
Developing countries	-2.0 to -9.0	0.05	-0.17		
World					
– Output weighted	-1.5 to -2.0	0.09	0.1	-1.5	2.3 (1.0)
– Population weighted				-1.9	
– At world average prices					-2.7 (0.8)
– Equity weighted					0.2 (1.3)

[a] Figures in brackets denote standard deviations.
[b] High-income countries in Organization of Petroleum Exporting countries (OPEC).
[c] China, Laos, North Korea, Vietnam.

operate close to environmental and climatic tolerance levels (e.g., with respect to coastal and water resources). If current development trends continue, few developing countries will have the financial, technical, and institutional capacity and knowledge base for efficient adaptation (a key reason for higher health impacts). For temperature increases of less than 2–3°C, some regions may have net benefits and some may have net damages. If temperature increases more than 2–3°C, most regions have net damages, and damages for all regions increase at higher changes in global average temperature.

19.5. Aggregate Impacts

The third reason for concern relates to the overall (i.e., worldwide or aggregate) economic and ecological implications of climate change. Numerous studies have addressed aggregate impacts, particularly in the context of integrated assessment.

19.5.1. Aggregate Analysis: An Assessment

Estimating the aggregate impact of climate change is an intricate task that requires careful professional judgment and skills. Aggregate analysis is based on the same tools as most distributional analysis and uses regional data as inputs. Consequently, it shares with distributional analysis the methodological difficulties and shortcomings discussed more fully in Section 19.4:

- Choice of an appropriate (set of) numeraire(s) in which to express impacts
- Need to overcome knowledge gaps and scientific uncertainties to provide a comprehensive picture
- Difficulties in modeling the effects of adaptation
- Difficulties in forecasting baseline developments (such as economic and population growth, technical progress).

In addition, analysts have to grapple with some issues that are generic to aggregate analysis. The most important issue is spatial and temporal comparison of impacts. Aggregating impacts requires an understanding of (or assumptions about) the relative importance of impacts in different sectors, in different regions, and at different times. Developing this understanding implicitly involves value judgments. The task is simplified if impacts can be expressed in a common metric, but even then aggregation is not possible without value judgments. The value judgments that underlie regional aggregation are discussed and made explicit in Azar and Sterner (1996), Fankhauser *et al*. (1997, 1998), and Azar (1999). Aggregation across time and the issue of discounting are discussed in more detail in TAR WGIII Chapter 7. Aggregate impact estimates can be very sensitive to the aggregation method and the choice of numeraire (see Chapter 1).

All of these factors make aggregate analysis difficult to carry out and reduce our overall confidence in aggregate results. Nevertheless, aggregate studies provide important and policy-relevant information.

19.5.2. Insights and Lessons: The Static Picture

Most impact studies assess the consequences of climate change at a particular concentration level or a particular point in time, thereby providing a static "snapshot" of an evolving, dynamic process. The SAR suggested that the aggregate impact of 2xCO_2—expressed in monetary terms—might be equivalent to 1.5–2.0% of world GDP. Estimated damages are slightly lower (relative to GDP) in developed countries but significantly higher in developing countries—particularly in small island states and other highly vulnerable countries, where impacts could be catastrophic (Pearce *et al.*, 1996). The SAR was careful, however, to point out the low quality of these numbers and the many shortcomings of the underlying studies.

Since publication of the SAR, our understanding of aggregate impacts has improved, but it remains limited. Some sectors and impacts have received more analytical attention than others and as a result are better understood. Agricultural and coastal impacts in particular are now well studied (see Boxes 19-2 and 19-3). Knowledge about the health impacts of climate change also is growing (see Box 19-4). Several attempts have been made to identify other nonmarket impacts, such as changes in aquatic and terrestrial ecological systems and ecosystem services, but a clear and consistent quantification has not yet emerged.

Table 19-4 contains a summary of results from aggregate studies that use money as their numeraire. The numerical results as such remain speculative, but they can provide insights on signs, orders of magnitude, and patterns of vulnerability. Results are difficult to compare because different studies assume different climate scenarios, make different assumptions about adaptation, use different regional disaggregation, and include different impacts. The estimates by Nordhaus and Boyer (2000), for example, are more negative than others because they factor in the possibility of catastrophic impact. The estimates by Mendelsohn *et al.* (2000), on the other hand, are driven by optimistic assumptions about adaptive capacity and baseline development trends, which result in mostly beneficial impacts.

Standard deviations rarely are reported, but they are likely to be several times larger than the "best guess." They are larger for developing countries, where results generally are derived through extrapolation rather than direct estimation. This is illustrated by the standard deviations estimated by Tol (2001b), also reproduced in Table 19-4. These estimates probably still underestimate the true uncertainty—for example, because they exclude omitted impacts and severe climate change scenarios. Note that the aggregation can mask large standard deviations in estimates of damages to individual sectors (Rothman, 2000).

An alternative indicator of climate change impact (excluding ecosystems) is the number of people affected. Few studies directly calculate this figure, but it is possible to compare the population of regions experiencing negative impacts with that of positively affected regions. Such calculations suggest that a majority of people may be negatively affected already at average global warming of 1–2°C. This may be true even if the net aggregate monetary impact is positive because developed economies, many of which could have positive impacts, contribute the majority of global production but account for a smaller fraction of world population. The quality of estimates of affected population is still poor, however. They are essentially "back-of-the envelope" extensions of monetary models, and the qualifications outlined in that context also apply here. In addition, they do not consider the distribution of positive and negative effects within countries.

On the whole, our confidence in the numerical results of aggregate studies remains low. Nevertheless, a few generic patterns and trends are emerging in which we have more confidence:

- Market impacts are estimated to be lower than initially thought and in some cases are estimated to be positive, at least in developed countries. The downward adjustment is largely a result of the effect of adaptation, which is more fully (although far from perfectly) captured in the latest estimates. Efficient adaptation reduces the net costs of climate change because the cost of such measures is lower than the concomitant reduction in impacts. However, impact uncertainty and lack of capacity may make efficient and error-free adaptation difficult.
- Nonmarket impacts are likely to be pronounced, and many (but not all) of the effects that have not yet been quantified could be negative. In particular, there is concern about the impact on human health and mortality. Although few studies have taken adequate account of adaptation, the literature suggests substantial negative health impacts in developing countries, mainly because of insufficient basic health care (e.g., Martens *et al*., 1997). There also is concern about the impact on water resources (e.g., Arnell, 1999; Frederick and Schwarz, 1999) and ecosystems (e.g., Markham, 1996; White *et al*., 1999).
- "Horizontal" interlinkages such as the interplay between different impact categories (e.g., water supply and agriculture), the effect of stress factors that are not related to climate, adaptation, and exogenous development trends are crucial determinants of impact but have not been fully considered in many studies.
- Estimates of global impact are sensitive to the way numbers are aggregated. Because the most severe impacts are expected in developing countries, aggregate impacts are more severe and thus more weight is assigned to developing countries. Using a simple summing of impacts, some studies estimate small net positive impacts at a few degrees of warming; others estimate small net negative impacts. Net aggregate benefits do not preclude the possibility that a majority of people will be negatively affected—some of them severely so.

Overall, the current generation of aggregate estimates may understate the true cost of climate change because they tend to ignore extreme weather events, underestimate the compounding effect of multiple stresses, and ignore the costs of transition and learning. However, studies also may have overlooked positive impacts of climate change. Our current understanding of (future) adaptive capacity, particularly in developing countries, is too limited, and the treatment of adaptation in current studies is too varied, to allow a firm conclusion about the direction of the estimation bias.

19.5.3. Insights and Lessons: Vulnerability over Time

One of the main challenges of impact assessments is to move from the static analysis of certain benchmarks to a dynamic representation of impacts as a function of shifting climatic parameters, adaptation measures, and exogenous trends such as economic and population growth. Little progress has been made in this respect, and our understanding of the time path that aggregate impacts will follow under different warming and development scenarios still is extremely limited. Among the few explicitly dynamic analyses are Sohngen and Mendelsohn (1999) and Yohe *et al.* (1996).

Some information about impacts over time is available for individual sectors. Scenarios derived from IAMs can provide comprehensive emissions, concentrations, and climate change estimates that can be linked to impact models. Table 19-5 summarizes estimates of global ecosystem impacts that were derived from such a model (IMAGE 2.1—Leemans *et al*., 1998; Swart *et al*., 1998). The metric used is percentage change. The example illustrates the clearly nonlinear dynamics of nonmarket impacts with different pathways for positive (escalating) and negative (saturating) impacts. The impact levels in this model evolve gradually, and there are impacts even at low levels of climate change. Although this finding is consistent with observed change (see Section 19.2), it is sensitive to the choice of metric. White *et al.* (1999), for example, found that carbon storage in terrestrial vegetation would expand under moderate warming because increases in productivity are enough to offset reductions elsewhere. They show that as higher GHG concentrations and magnitudes of climate change are reached, carbon storage eventually will decline.

Little is known about the shape of the aggregate impact function. Dynamic functions remain highly speculative at this point because the underlying models provide only a very rough reflection of real-world complexities. Figure 19-4 provides examples from three studies. Although some analysts still work with relatively smooth impact functions (e.g., Nordhaus and Boyer, 2000), there is growing recognition (e.g., Mendelsohn and Schlesinger, 1997; Tol, 2001c) that climate change dynamics in fact might be more complex and may not follow a monotonic path. Generic patterns that are emerging include the following:

- Moderate climate change may have positive and negative effects, with most positive effects occurring in the market sector of developed countries. For higher levels of warming, impacts are likely to become predominantly negative. However, the overall pattern is complex, estimates remain uncertain, and the possibility of highly deleterious outcomes cannot be excluded (medium confidence).

Table 19-5*: Aggregate impact of climate change on ecosystems (Swart et al., 1998). See also list of caveats in Section 19.4.1.*

	Scenario					
Impact Indicator	0.5°C	1.0°C	1.5°C	2.0°C	2.5°C	3.0°C
Temperate cereals, area experiencing						
– Yield decrease[a]	12	16	18	20	20	22
– Yield increase[a]	2	3	4	8	12	15
Maize, land area experiencing						
– Yield decrease[a]	13	18	22	26	29	33
– Yield increase[a]	2	4	6	9	13	17
Change in natural vegetation[b]	11	19	26	32	37	43
Endangered nature reserves[c]	9	17	24	32	37	42

[a] Yield decrease and increase are percentage area with at least 10% change in potential rainfed yield. Reference area is current crop area.
[b] Change in natural vegetation is percentage of land area that shifts from one vegetation type to another. Reference area is global land area.
[c] Endangered nature reserves are percentage of reserves, where original vegetation disappears, so that conservation objectives cannot be met. Reference is total reserve number.

- Impacts in different sectors may unfold along different paths. Coastal impacts, for example, are expected to grow continuously over time, more or less in proportion to the rise in sea level. The prospects for agriculture, by contrast, are more complex. Whereas some models predict aggregate damages already for moderate warming, many studies suggest that under some (but not all) scenarios the impact curve might be hump-shaped, with short-term (aggregate) benefits under modest climate change turning into losses under more substantial change (e.g., Mendelsohn and Schlesinger, 1997) (low confidence).

Aggregating intertemporal impacts into a single indicator is extremely difficult, perhaps elusive. The marginal damages caused by 1 t of CO_2 emissions in the near future were estimated in the SAR at US$5–125 t^{-1} C. Most estimates are in the lower part of that range; higher estimates occur only through the combination of high vulnerability with a low discount rate (see Pearce *et al*., 1996). Plambeck and Hope (1996), Eyre *et al.* (1997), and Tol (1999a) have since reassessed the marginal costs of GHG emissions. Performing extensive sensitivity and uncertainty analyses, they arrive at essentially the same range of numbers as Pearce *et al.* (1996). In the complex dynamics that determine marginal damage costs, the more optimistic estimates of market damages used in recent studies are balanced out by other factors such as higher nonmarket impacts and a better capture of uncertainties. Overall, the SAR assessment still is a good reflection of our understanding of marginal damage costs; our confidence in marginal damage numbers remains very low.

19.5.4. Sensitivity of Aggregate Estimates

At a time when the quality of numerical results still is low, a key benefit of aggregate impact analysis lies in the insights it provides regarding the sensitivity of impacts. Sensitivity analysis offers critical information about attributes of the damage function that are likely to be most influential for the

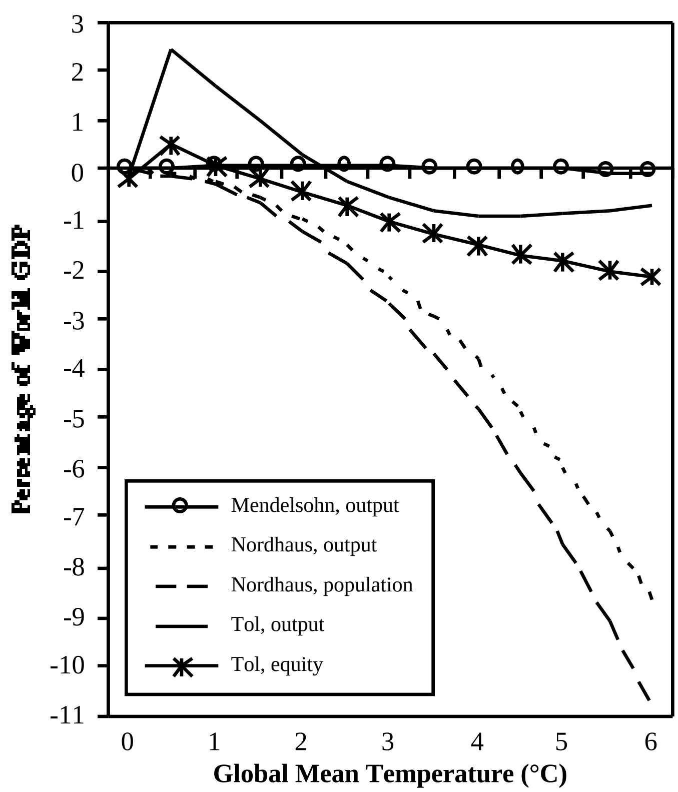


Figure 19-4: Monetary impacts as a function of level of climate change (measured as percentage of global GDP). Although there is confidence that higher magnitudes and rates of increase in global mean temperature will lead to increasing damages, there is uncertainty about whether aggregate damages are positive or negative at relatively low increases in global mean temperature.

choice of policy and, by implication, where additional climate change impacts research is most needed.

19.5.4.1. Composition of Impact Function

Most aggregate analysis is based on IAMs (see Chapter 2). Impact functions used in IAMs vary greatly with respect to the level of modeling sophistication, the degree of regional aggregation, the choice of numeraire, and other characteristics (see Tol and Fankhauser, 1998). Many models have used monetary terms (e.g., U.S. dollars) to measure impacts. Spatially detailed models (e.g., Alcamo *et al.*, 1998) pay some attention to unique ecosystems. Disruptive climate changes have received little attention, except for a survey of expert opinions (Nordhaus, 1994b) and analytical work (e.g., Gjerde *et al.*, 1999). Some climate change impact studies restrict themselves to sectors and countries that are relatively well studied (e.g., Mendelsohn and Neumann, 1999). Others try to be comprehensive, despite the additional uncertainties (e.g., Hohmeyer and Gaertner, 1992). Some studies rely on an aggregate description of all climate change impacts for the world as a whole (e.g., Nordhaus, 1994a). Other studies disaggregate impacts with substantial spatial and regional detail (e.g., Alcamo *et al.*, 1998). The aggregate approaches tend to point out implications for efficiency and in practice often ignore equity (see Tol, 2001a, for an exception). The detailed approaches tend to identify distributional issues, but working out the equity implications typically is left to the reader.

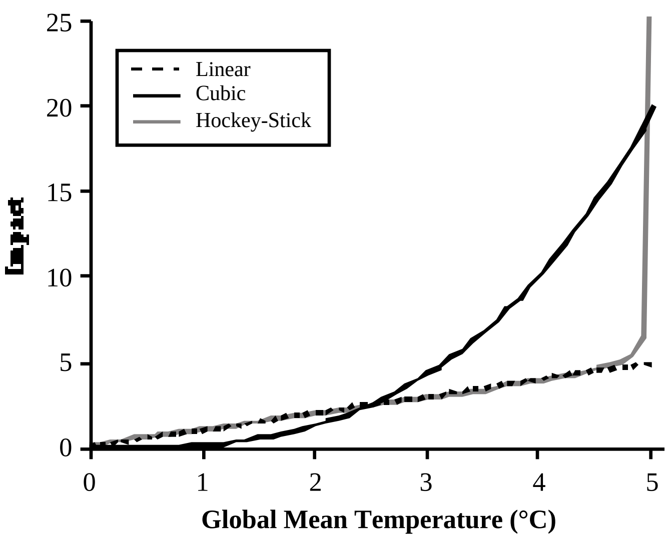


Figure 19-5: Aggregate impact of climate change as a function of global mean temperature. Displayed are hypothetical examples of a linear function, which assumes that impacts are proportional to temperature change since preindustrial times; a cubic function, which assumes that impacts are proportional to temperature change to the power of three; and a hockey-stick function, which assumes that impacts are approximately proportional to temperature change until a critical threshold is approached. Aggregate damage functions used in integrated assessments are mostly illustrative. They should be regarded as "placeholders" that will be replaced by more accurate functional forms as our knowledge of impact dynamics improves.

19.5.4.2. Shape of Damage Function

Most impact studies still look at the equilibrium effect of one particular level of GHG concentration, usually $2xCO_2$. Full analysis, however, requires impacts to be expressed as a function of change in GHG concentrations. With so little information to estimate this function, studies have to rely on sensitivity analyses. Different damage functions can lead to profoundly different policy recommendations. Compare, for example, the profile of impacts under a linear and a cubic damage function (see Figure 19-5). Relative to the linear specification, a cubic function implies low near-term impacts but rapidly increasing impacts further in the future. Using conventional discounting, this means that early emissions under a cubic damage function will cause less damage over their atmospheric lifetime, compared to a scenario with linear damages. The marginal damage caused by emissions further in the future, on the other hand, is much higher if we assume a cubic damage function (Peck and Teisberg, 1994).

Some studies explore the implications of more nonlinear impact functions. For instance, Manne and Richels (1995) use a "hockey-stick" function that suddenly turns upward at arbitrarily chosen thresholds. Such studies are designed to reflect relatively small impacts before $2xCO_2$ and rapidly worsening impacts beyond $2xCO_2$. In this analysis, it is economically efficient to stabilize CO_2 concentrations, but the desired level of stabilization depends on the shape of the hockey stick and the location of its kink. Other analyses, which rely on more linear impact functions, have difficulty justifying concentration stabilization at any level.

19.5.4.3. Rate of Change

Although most impact studies focus on the level of climate change, the rate of climate change generally is believed to be an important determinant, in many instances because it affects the time that is available for adaptation. Again, the paucity of underlying impact studies forces integrated assessors to use exploratory modeling. Under most "business-as-usual" scenarios, the rate of climate change is greater in the short run than in the long run because emissions increase faster in the short run; this is even more pronounced in emission reduction policy scenarios. Indeed, in considering the rate of change, tolerable window and safe-landing analyses (Alcamo and Kreileman, 1996; Toth *et al*., 1997; Petschel-Held *et al.*, 1999) often find the rate of change to be the binding constraint in the first half of the 21st century.

19.5.4.4. Discount Rate and Time Horizon

Aggregate models suggest that the most severe impacts of climate change will occur further in the future. The chance of large-scale discontinuities (thermohaline circulation, West Antarctic ice sheet) also is higher in the future. The outcome of policy analysis therefore is sensitive to the weight afforded to events occurring in the remote future. In other words, estimates are sensitive to the choice of time horizon (Cline, 1992; Azar and Sterner, 1996; Hasselmann *et al.*, 1997) and the discount rate (i.e., the value of future consumption relative to today's value). The literature on discounting is reviewed in Portney and Weyant (1999) and in TAR WGIII Chapter 7. Numerical analysis (e.g., Tol, 1999a) has shown that estimates of marginal damage (i.e., the additional damage caused by an extra ton of emissions) can vary by as much as a factor of 10 for different (and reasonable) assumptions about the discount rate. This makes the discount rate the second-most important parameter for marginal damage. The most important parameter is the degree of cooperation in reducing emissions (Nordhaus and Yang, 1996; Tol, 1999b).

19.5.4.5. Welfare Criteria

Comparison of impacts (i.e., the relative weight assigned to impacts in different regions and at different times) is one of the most sensitive aspects of aggregate analysis. With the exception of the discount rate, little explicit attention is paid to this aspect of climate change impacts, although studies differ considerably in their implicit assumptions. Fankhauser *et al.* (1997) and Azar (1999) are among the few studies that make their aggregation assumptions explicit. They find that, in general, the higher the concerns about the distribution of the impacts of climate change, the more severe the aggregate impacts. Fankhauser's (1995) estimate of the annual global damage of $2xCO_2$, for instance, is based on the implicit assumption that people are neutral with respect to distribution (that is, losses to the poor can be compensated by equal gains to the rich) and risk (that is, a 1:1,000,000 chance of losing $1 million is equivalent to losing $1 with certainty). Replacing these assumptions with standard risk aversion or mild inequity aversion, the global damage estimate increases by about one-third (Fankhauser *et al.*, 1997). Marginal impacts are more sensitive. For the same changes in assumptions, Tol (1999a) finds a three-fold increase in the marginal damage estimate. The sensitivity of aggregate impact estimates is further illustrated in Figure 19-4.

19.5.4.6. The Treatment of Uncertainty

Sensitivity analysis is the standard approach to deal with impact uncertainty. Some studies, however, have gone one step further and explicitly model uncertainty as a hedging problem. The premise underlying these models is that today's policymakers are not required to make once-and-for-all decisions binding their successors over the next century. There will be opportunities for mid-course adjustments. Climate negotiations are best viewed as an ongoing process of "act, then learn." Today's decisionmakers, in this view, must aim at evolving an acceptable hedging strategy that balances the risks of premature actions against those of waiting too long.

The first step, then, is to determine the sensitivity of *today's* decisions to major uncertainties in the greenhouse debate. How important is it to be able to predict impacts for the second half of this century? Or to know what energy demands will be in 30 years and identify the technologies that will be in place to meet those demands? An exhaustive analysis of these questions has yet to be undertaken, but considerable insight can be gleaned from an Energy Modeling Forum study conducted several years ago (EMF, 1997). In the study, seven modeling teams addressed a key consideration in climate policymaking: concerns about events with low probability but high consequences.

The study assumed uncertainty would not be resolved until 2020. Two parameters were varied: the mean temperature sensitivity factor and the cost of damages associated with climate change and variability. The unfavorable high-consequence scenario was defined as the top 5% of each of these two distributions. Two surveys of expert opinion were used for choosing the distribution of these variables (for climate sensitivity, see Morgan and Keith, 1995; for damages, see Nordhaus, 1994a).

The analysis showed that the degree of hedging depends on the stakes, the odds, and nonimpact parameters such as society's attitude toward risk and the cost of greenhouse insurance. Also critical is the timing of the resolution of key uncertainties. This underscores the importance of scientific research.

19.6. Extreme and Irreversible Effects

19.6.1. The Irregular Face of Climate Change

Natura non facit saltus—nature does not take jumps. Modern science has thoroughly shattered this tenet of the Aristotelian school of thought. Long-term observations and experimental insights have demonstrated convincingly that smooth, or *regular*, behavior is an exception rather than a rule. Available records of climate variability, for example, reveal sudden fluctuations of key variables at all time scales. Large, abrupt climate changes evident in Greenland ice-core records (known as Dansgaard-Oeschger oscillations—Dansgaard *et al.*, 1993) and episodic, massive discharges of icebergs into the North Atlantic (known as Heinrich events—Bond *et al*., 1992) are obvious examples of *irregular* behavior as a result of weak external forcing. Ecosystems also display discontinuous responses to changing ambient conditions, such as changes in disturbance regimes (Holling, 1992a; Peterson *et al*., 1998) and species extinctions (Pounds *et al*., 1999). Irreversible changes in ecosystems are triggered by disturbances (e.g., Gill, 1998), pests (e.g., Holling, 1992b), and shifts in species distributions (Huntley *et al.*, 1997). Irregular behavior is accepted as a major aspect of the dynamics of complex systems (Berry, 1978; Schuster, 1988; Wiggins, 1996; Badii and Politi, 1997).

A quantitative entity behaves "irregularly" when its dynamics are discontinuous, nondifferentiable, unbounded, wildly varying, or otherwise ill-defined. Such behavior often is termed *singular*, particularly in catastrophe theory (Saunders, 1982), and illustrates how smooth variations of driving forces can cause abrupt and drastic system responses. The occurrence, magnitude, and timing of singularities are relatively difficult to predict, which is why they often are called “surprises” in the literature.

It is important to emphasize that singular behavior is not restricted to natural systems. There has been speculation, for example, about possible destabilization of food markets, public health systems, and multilateral political agreements on resource use, but solid evidence rarely has been provided (e.g., Döös, 1994; Hsu, 1998). Rigorous scientific analysis of certain classes of singular socioeconomic phenomena is emerging (Bunde and Schellnhuber, 2000), but huge cognitive gaps remain in this field.

Singularities have large consequences for climate change vulnerability assessments. Unfortunately, most of the vulnerability assessment literature still is focusing on a smooth transition from what is assumed to be an equilibrium climate toward another equilibrium climate (often $1xCO_2$ to $2xCO_2$). This means that most impact assessments still implicitly assume that climate change basically is a “well-behaved” process. Until recently, only a few authors have emphasized the importance of discontinuous, irreversible, and extreme events to the climate problem (e.g., Lempert *et al*., 1994; Nordhaus, 1994a; Schellnhuber, 1997); concerns about the impacts of these events and their consequences for society now are becoming much more common. Singularities could lead to rapid, large, and unexpected impacts on local, regional, and global scales. Anticipating and adapting to such events and their impacts would be much more difficult than responding to smooth change, even if these responses must be made in the face of uncertainty. Furthermore, singularities considerably complicate the search for optimal emissions reduction strategies that are based on, for example, benefit-cost analysis or tolerable emissions strategies that are based on, as another example, the precautionary principle.

This section reviews and synthesizes relevant available information on the impacts of singular behavior of (components of) the climate system or singular impacts of climate change and draws conclusions about the consequences for vulnerability assessments. Because no generally accepted framework to assess singularities of climate change exists, an illustrative typology of singularities is discussed first. The different characteristics of each class in this typology justify why insights from this section contribute to two separate reasons for concern: extreme weather events and large-scale singularities.

19.6.2. Characteristics of Singularities

The causes of singularities are diverse, but most can be grouped in the categories of *nonlinearity*, *complexity*, and *stochasticity*. Choices about how to assess singular climate impacts depend strongly on the factors generating such behavior. The first two categories arise in a largely *deterministic* context, so their incidence can be assessed with proper models. The latter is probabilistic, however, rendering its incidence basically unpredictable. Only statistical properties can be analyzed. Predictability (and consequently adaptability) is directly related to the *stochastic* nature of the underlying dynamics.

The first, and most obvious, class of singularities is caused by strongly nonlinear or discontinuous functional relationships. A conspicuous case is the critical threshold, where responses to a continuous change in a driving variable bring about sudden and severe impacts, such as extinction events. Changes in mean climate can increase the likelihood of crossing these thresholds. Even one of the simplest physical thresholds in the climate system—the melting point of ice—could induce singular impacts. For example, thawing of permafrost regions would be induced by only a few degrees of warming (Pavlov, 1997) and would severely affect soil and slope stability, with disastrous effects on Arctic infrastructure such as oil pipelines (see Section 16.2.5 and SAR WGII Section 11.5.3). Section 19.3 extensively illustrates the occurrence of critical thresholds that are relevant for bleaching of coral reefs (a temperature threshold) and coastal mangroves (a sea-level rise threshold).

Complexity itself is a second potential cause for singular behavior in many systems. Complex systems, of course, are composed of many elements that interact in many different ways. Anomalies in driving forces of these systems generally distort interactions between constituents of the system. Positive feedback loops then can easily push the systems into a singular response. (Note that complexity is by no means synonymous with nonlinearity!)

Complex interactions and feedbacks gradually have become a focal point of global and climate change investigations: Several illustrative studies, for example, deal with the interplay between atmosphere, oceans, cryosphere, and vegetation cover that brought about the rapid transition in the mid-Holocene from a “green” Sahara to a desert (Brovkin *et al.*, 1998; Ganopolski *et al.*, 1998; Claussen *et al.*, 1999), with the mutual amplification of regional climate modification and unsustainable use of tropical forests as mediated by fire (Cochrane, 1999; Goldammer, 1999; Nepstad *et al*., 1999) and with the dramatic disruptions possibly inflicted on Southern Ocean food webs and ecological services by krill depletion resulting from dwindling sea-ice cover (see Brierly and Reid, 1999; see also Section 16.2.3).

The third category, stochasticity, captures a class of singularities that are triggered by exceptional events. In the climate context, these are, by definition, extreme weather events such as cyclones and heavy rains (see Table 3-10). Their occurrence is governed by a generally well-behaved statistical distribution. The irregular character of extreme events stems mainly from the fact that, although they reside in the far tails of this distribution, they nonetheless occur from time to time. Therefore, they could affect downstream systems by surprise and trigger effects that are vastly disproportional to their strength. Climate change also could lead, however, to changes in probability distributions for extreme events. Such changes actually could cause serious problems because the risk and consequences of these transitions are difficult to quantify and identify in advance. The impacts caused by these events have not yet been explored, although they should constitute an essential aspect of any impact and adaptation assessment.

The impacts of extreme event consequences of stochastic climate variability, however, have begun to attract researchers' attention in a related context. As noted in Chapter 18, changes in mean climate can increase the likelihood that distributed weather will cross thresholds where the consequences and impacts are severe and extreme. This variant of stochastic singularity therefore can change in frequency even if the probability of extreme weather events, measured against the mean, is unaffected by long-term trends.

There also is a fourth type that generally arises from a combination of all other singularity categories. This type—sometimes referred to as "imaginable surprises" (Schneider *et al*., 1998; see also Chapter 1)—represents conceivable global or regional disruptions of the operational mode of the Earth system. Such *macro-discontinuities* may cause damages to natural and human systems that exceed the negative impacts of "ordinary" disasters by several orders of magnitudes.

Responses to climate change can alter their character from singular to regular—and vice versa—as they cascade down the causal chain: *geophysical perturbations*, *environmental impacts*, *sectoral and socioeconomic impacts,* and *societal responses*. Only the last three are climate change effects in the proper sense, but the first is important because it translates highly averaged indicators of climate change into the actual trigger acting at the relevant scale. Most singular geophysical perturbations create singular impacts—which may, in turn, activate singular responses. One therefore might assume that singularities tend to be preserved down such a cascade. Singular events also can arise further down the causal chain. Purely regular geophysical forcing, for example, can cause singular impacts, and singular socioeconomic responses may result from regular impacts.

Harmful impacts of climate change generally can be alleviated by adaptation or exacerbated by mismanagement (see, e.g., West and Dowlatabadi, 1999; Schneider *et al.*, 2000a; see also Chapter 18). Climate-triggered singular phenomena can generate substantial impacts because their predictability and manageability are low. Such impacts would be considerably reduced if they could be "regularized" by appropriate measures. For example, an ingenious array of seawalls and dikes could transform an extreme storm surge into a mundane inundation that could be controlled by routine contingency procedures. So too could a long-term policy of retreat from the sea. However, inappropriate flood control structures could wreak havoc, particularly because they foster a false sense of security and actually inspire further coastal development.

In summary, singularities tend to produce singularities, as a rule; regularities may turn into singularities under specific conditions, and singularities can be regularized by autonomous ecological processes or judicious societal measures. Defining the propagation of singular events in the causal cascade or opportunities to convert them into regular events remains a major research challenge.

19.6.3. Impacts of Climate Change Singularities

This subsection sketches the most evident singularities discussed in the context of climate change and reviews the pertinent literature on their potential impacts.

19.6.3.1. Extreme Weather Events

That the occurrence of weather events is essentially stochastic is a well-established fact (e.g., Lorenz, 1982; Somerville, 1987). Most climatic impacts arise from extreme weather events or from climatic variables exceeding some critical level and thereby affecting the performance or behavior of a biological or physical system (e.g., Downing *et al.*, 1999). The same holds for the impacts of climate change (see Chapters 1, 2, and 3, especially Table 3-9; Pittock and Jones, 2000).

For many important climate impacts, we are interested in the effects of specific extreme events or threshold magnitudes that have design or performance implications. To help in zoning and locating developments or in developing design criteria for the capacities of spillways and drainage structures, the heights of levee banks, and/or the strengths of buildings, for example, planners and engineers routinely use estimated "return periods" (the average time between events) at particular locations for events of particular magnitudes. Such event magnitudes include flood levels (Hansen, 1987; Handmer *et al.*, 1999) and storm-surge heights (Middleton and Thompson, 1986; Hubbert and McInnes, 1999). Return period estimates normally are based on recent instrumental records, sometimes augmented by estimates from other locations, or statistical or physically based modeling (Middleton and Thompson, 1986; Hansen, 1987; Beer *et al.*, 1993; National Research Council, 1994; Pearce and Kennedy, 1994; Zhao *et al.*, 1997; Abbs, 1999). The assumption usually is made that these statistics, based on past events, are applicable to the future—but climate change means that this often will not be the case.

Thus, a central problem in planning for or adapting to climate change and estimating the impacts of climate change is how these statistics of extreme events are likely to change. Similar problems arise in nonengineering applications such as assessing the economic performance or viability of particular enterprises that are affected by weather—for example, farming (Hall *et al.*, 1998; Kenny *et al.*, 1999; Jones, 2000)—or health effects (Patz *et al.*, 1998; McMichael and Kovats, 2000; see also Chapter 9).

Relatively rapid changes in the magnitude and frequency of specified extreme events arise because extremes lie in the low-frequency tails of frequency distributions, which change rapidly with shifts in the means. Moreover, there also can be changes in the shape of frequency distributions, which may add to or subtract from the rate of change of extremes in particular circumstances (Mearns *et al.*, 1984; Wigley, 1985, 1988; Hennessy and Pittock, 1995; Schreider *et al.*, 1997). Such changes in the shape of frequency distributions require special attention. Evidence suggests that they are particularly important for changes in extreme rainfall (Fowler and Hennessy, 1995; Gregory and Mitchell, 1995; Walsh and Pittock, 1998), possibly in the intensities of tropical cyclones (Knutson *et al.*, 1998; Walsh and Ryan, 2000), and in ENSO behavior (Dilley and Heyman, 1995; Bouma *et al*., 1997; Bouma, 1999; Timmermann *et al.*, 1999; Fedorov and Philander, 2000). Return periods can shorten, however, even if none of these higher moment effects emerge; simply moving mean precipitation higher, for example, could make the 100-year flood a 25-year flood.

It is noteworthy that the central role in impact assessments of the occurrence of extreme weather events gives rise to multiple sources of uncertainty in relation to climate change. The stochastic nature of the occurrence of extremes and the limited historical record on which to base the frequency distribution for such events give rise, even in a stationary climate, to a major uncertainty. Beyond that, any estimate of a change in the frequency distribution under a changing climate introduces new uncertainties. Additional uncertainties relate to our limited understanding of the impacted systems and their relevant thresholds, as well as the possible effects of adaptation, or societal change, in changing these thresholds. If this were not complicated enough, many impacts of weather extremes arise from sequences of extremes of the same or opposite sign—such as sequences of droughts and floods affecting agriculture, settlements, pests, and pathogens (e.g., Epstein, 2000) or multiple droughts affecting the economic viability of farmers (e.g., Voortman, 1998).

Planned adaptation to climate change therefore faces particular difficulty in this environment because projections of changes in the frequency of extreme events and threshold exceedence require a multi-decadal to century-long projected (or "recent" observed) data series, or multiple ensemble predictions (which is one way of generating improved statistics). Thus, it is difficult to base planned adaptation on the record of the recent past, even if there is evidence of a climate change trend in the average data. Planned adaptation therefore must rely on model predictions of changes in the occurrence of extreme and threshold events (e.g., see Pittock *et al.*, 1999), with all their attendant uncertainties. Real-life adaptation therefore will most likely be less optimal (more costly or less effective) than if more precise information on future changes in such thresholds and extremes were available.

Nonetheless, planned adaptation will most likely proceed in response to changes in the perceived relative frequency of extreme events. Properly done, it can have immediate benefit by reducing vulnerability to current climate as well as future benefit in reducing exposure to future climate change. As suggested above, however, there are many ways to respond inappropriately if care is not taken. In short, changes in extremes and in the frequency of exceeding impacts thresholds are a vital feature of vulnerability to climate change that is likely to increase rapidly in importance because the frequency and magnitude of such events will increase as global mean temperature rises.

19.6.3.2. Large-Scale Singularities

Singularities that occur in complex systems with multiple thresholds can be assessed with appropriate models. In real systems, however, there always are stochastic elements that influence the behavior of these systems, which are difficult to model. The runaway greenhouse effect, for example, consists of a series of positive feedback loops that result from systemic interactions or can be triggered by stochastic events (Woodwell *et al.*, 1998). Table 19-6 lists examples of such singularities that are triggered by different causes. All of these examples have regional or global consequences. The systemic insights in their behavior generally are based on different simulation approaches. Although local examples (e.g., species extinction) also are abundant in the scientific literature, they are ignored here because climate change does not (yet) seem to be the sole cause, and the processes involved generally are not modeled systematically.

19.6.3.2.1. Nonlinear response of North Atlantic thermohaline circulation

Many model studies (reviewed in Weaver *et al*., 1993; Rahmstorf *et al*., 1996) have analyzed the nonlinear response of the worldwide ocean circulation—the so-called conveyor belt. This system transports heat and influences regional climate patterns. One component of this system is the current in the Atlantic Ocean. Warm surface currents flow northward. Heat release and evaporation from the ocean surface lowers the temperature and increases the density and salinity of the water. In the North Atlantic, this denser water sinks at the Labrador and Greenland convection sites and flows back south as deepwater. This so-called North Atlantic THC could slow down or even shut down under climate change (see TAR WGI Chapters 7 and 9).

The paleoclimatic record shows clear evidence of rapid climatic fluctuations in the North Atlantic region (with possible connections to other regions) during the last glaciation and in the early Holocene (see TAR WGI Section 2.4.3). At least some of these events—notably the Younger Dryas event, when postglacial warming was interrupted by a sudden return to colder conditions within a few decades about 11,000 years ago—are thought to be caused by changes in the stability of North Atlantic waters. These changes, which are recorded in the central Greenland ice cores and elsewhere, were accompanied by large changes in pollen and other records of flora and fauna in western Europe, indicating that they had widespread effects on European regional climate and ecosystems (Ammann, 2000; Ammann *et al*., 2000). The likely cause for these fluctuations is changes in the stability of the THC brought about by an influx of freshwater from melting icebergs and/or ice caps (see TAR WGI Section 7.3.7). As discussed in WGI, enhanced greenhouse

***Table 19-6**: Examples of different singular events and their impacts.*

Singularity	Causal Process	Impacts	Reference
Nonlinear response of thermohaline circulation (THC)	– Changes in thermal and freshwater forcing could result in complete shutdown of North Atlantic THC or regional shutdown in the Labrador and Greenland Seas. In the Southern Ocean, formation of Antarctic bottomwater could shut down. Such events are found in the paleoclimatic record, so they are plausible.	– Consequences for marine ecosystems and fisheries could be severe. Complete shutdown would lead to a stagnant deep ocean, with reducing deepwater oxygen levels and carbon uptake, affecting marine ecosystems. Such a shutdown also would represent a major change in heat budget and climate of northwestern Europe.	WGI TAR Chapters 2.4, 7, and 9; see Section 19.6.4.2.1
Disintegration of West Antarctic Ice Sheet (WAIS), with subsequent large sea-level rise	– WAIS may be vulnerable to climate change because it is grounded below sea level. Its disintegration could raise global sea level by 4–6 m. Disintegration could be initiated irreversibly in the 21st century, although it may take much longer to complete.	– Considerable and historically rapid sea-level rise would widely exceed adaptive capacity of most coastal structures and ecosystems.	WGI TAR Chapters 7 and 11; see Section 19.6.4.2.2; Oppenheimer, 1998
Runaway carbon dynamics	– Climate change could reduce the efficiency of current oceanic and biospheric carbon sinks. Under some conditions, the biosphere could even become a source. – Gas hydrate reservoirs also may be destabilized, releasing large amounts of methane to the atmosphere. – These processes would generate a positive feedback, accelerating buildup of atmospheric GHG concentrations.	– Rapid, largely uncontrollable increases in atmospheric carbon concentrations and subsequent climate change would increase all impact levels and strongly limit adaptation possibilities.	WGI TAR Chapter 3; Smith and Shugart, 1993; Sarmiento *et al*., 1998; Woodwell *et al*., 1998; Bains *et al*., 1999; Joos *et al*., 1999; Katz *et al*., 1999; Norris and Rohl, 1999; Walker *et al*. 1999; White *et al*., 1999
Transformation of continental monsoons	– Increased GHGs could intensify Asian summer monsoon. Sulfate aerosols partially compensate this effect, although dampening is dependent on regional patterns of aerosol forcing. Some studies find intensification of the monsoon to be accompanied by increase in interseasonal precipitation variability.	– Major changes in intensity and spatial and temporal variability would have severe impacts on food production and flood and drought occurrences in Asia.	TAR WGI Sections 9.3.6.2 and 9.3.5.2.2; TAR WGII Section 11.5.1; Lal *et al*., 1995; Mudur, 1995; Meehl and Washington, 1996; Bhaskaran and Mitchell, 1998
Qualitative modification of crucial climate-system patterns such as ENSO, NAO, AAO, and AO	– ENSO could shift toward a more El Niño-like mean state under increased GHGs, with eastward shift of precipitation. Also, ENSO's variability could increase. – There is a growing attempt to investigate changes in other major atmospheric regimes [NAO, Arctic Oscillation (AO), and Antarctic Oscillation (AAO)]. Several studies show positive trend in NAO and AO indices with increasing GHGs.	– Changing ENSO-related precipitation patterns could lead to changed drought and flood patterns and changed distribution of tropical cyclones. – A positive NAO/AO phase is thought to be correlated with increased storminess over western Europe.	TAR WGI Sections 7.7.3 and 9.3.5.2; Corti *et al*., 1999; Fyfe *et al*., 1999; Shindell *et al*., 1999; Timmermann *et al*., 1999

Table 19-6 (continued)

Singularity	Causal Process	Impacts	Reference
Rearrangement of biome distribution as a result of rising CO_2 concentrations and climate change	– Many studies show large redistribution of vegetation patterns. Some simulate rapid dieback of tropical forests and other biomes; others depict more gradual shifts. More frequent fire could accelerate ecosystem changes.	– All models initially simulate an increase in biospheric carbon uptake, which levels out later. Only a few models simulate carbon release.	White *et al*., 1999; Cramer *et al*., 2000
Destabilization of international order by environmental refugees and emergence of conflicts as a result of multiple climate change impacts	– Climate change—alone or in combination with other environmental pressures—may exacerbate resource scarcities in developing countries. These effects are thought to be highly nonlinear, with potential to exceed critical thresholds along each branch of the causal chain.	– This could have severe social effects, which, in turn, may cause several types of conflict, including scarcity disputes between countries, clashes between ethnic groups, and civil strife and insurgency, each with potentially serious repercussions for the security interests of the developed world.	Homer-Dixon, 1991; Myers, 1993; Schellnhuber and Sprinz, 1995; Biermann *et al*., 1998; Homer-Dixon and Blitt, 1998

warming could produce similar changes in stability in the North Atlantic because of warming and freshening of North Atlantic surface waters.

The current operation of THC is self-sustaining within limits that are defined by specific thresholds. If these thresholds were exceeded, two responses would be possible: shutdown of a regional component of the system or complete shutdown of the THC. Both responses have been simulated. A complete shutdown was simulated by Manabe and Stouffer (1993) for a quadrupling of atmospheric CO_2 and by Rahmstorf and Ganopolski (1999) for a transient peak in CO_2 content. These studies suggest that the threat of such complete shutdown increases beyond a global mean annual warming of 4–5°C, but this is still speculative. It took several centuries until the circulation was shut down completely in both studies. A regional shutdown in the Labrador Sea (while the second major Atlantic convection site in the Greenland Sea continued to operate) was simulated by Wood *et al*. (1999). Simulated regional shutdown can occur early in the 21st century and can happen rapidly—in less than a decade. Simulations by Manabe and Stouffer (1993) and Hirst (1999) show further the possibility of a shutdown of the formation of Antarctic bottomwater, which is the second major deepwater source of the world ocean.

These simulations clearly identify possible instability for the THC. Determining appropriate threshold values, however, requires analysis of many scenarios with different forcings and sensitivity studies of important model parameters. Stocker and Schmittner (1997), for example, have shown that the THC is sensitive not only to the final level of atmospheric CO_2 concentration but also to the rate of change. Rahmstorf and Ganopolski (1999) show that uncertainties in the hydrological cycle are a prime reason for uncertainty in forecasting, whether a threshold is crossed or not (see Figure 19-6). Further parameters are climate sensitivity (high values increase the likelihood of a circulation change) and the preindustrial rate of Atlantic overturning (an already weak circulation is more liable to break down) (e.g., Schneider and Thompson, 2000). These simulations suggest that global warming over the next 100 years could lead to a sudden breakdown of the THC decades to centuries later, which would lead irrevocably to major effects on future generations.

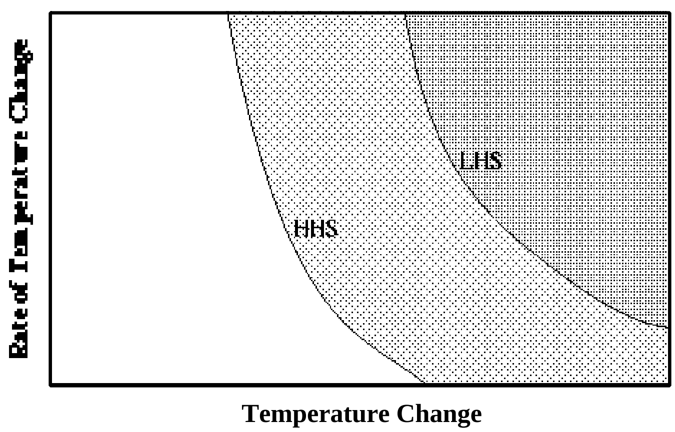


Figure 19-6: Stability of North Atlantic thermohaline circulation (THC) computed with the CLIMBER model (Petoukhov *et al*., 2000). Degree of shading indicates probability of THC collapse. Light shading denotes low probability; dark shading denotes high probability. The higher the hydrological sensitivity (HHS = high hydrological sensitivity, LHS = low hydrological sensitivity), the faster the rate of temperature increase, or the greater the magnitude of temperature increase, the more likely that the North Atlantic THC becomes unstable.

The possible impacts of these circulation changes have not yet been studied systematically. Complete shutdown of the THC would represent a major change in the heat budget of the northern hemisphere because this circulation currently warms northwestern Europe by 5–10°C (Manabe and Stouffer, 1988; Rahmstorf and Ganopolski, 1999). Consequently, shutdown would lead to sudden reversal of the warming trend in this region. The impacts of a regional shutdown would be much smaller but probably still serious. For the European climate, loss of the Greenland Sea branch probably would have a much stronger effect than loss of the Labrador Sea branch because the northward extent of the warm North Atlantic current depends mainly on the former. In either case, the consequences of circulation changes for marine ecosystems and fisheries could be severe (see Section 6.3). Shutdown of the major deepwater sources in the North Atlantic and Southern Ocean would lead to an almost stagnant deep ocean, with as-yet unexplored consequences (e.g., for deepwater oxygen levels, carbon uptake, and marine ecosystems).

Neither the probability and timing of a major ocean circulation change nor its impacts can be predicted with confidence yet, but such an event presents a plausible, non-negligible risk. The change would be largely irreversible on a time scale of centuries, the onset could be relatively sudden, and the damage potential could be very high.

19.6.3.2.2. Disintegration of West Antarctic ice sheet

The WAIS contains 3.8 million km^3 of ice, which, if released to the ocean, would raise global sea level by 4–6 m. The WAIS has been the subject of attention since analysis of paleodata (Hughes, 1973) and ice sheet models (Weertman, 1974) predicted that such a marine-grounded ice sheet is inherently unstable.

Analysis of ice sediments indicates that in the past 1.3 million years, the WAIS has collapsed at least once (Scherer *et al.*, 1998). It was inferred from marine sediments that the WAIS is still dynamic. Since the last glacial maximum, the grounding line (i.e., the boundary between the floating ice shelves and the grounded ice) has retreated considerably (Hughes, 1998), and this process continues. It probably reflects dynamics that were set in motion in the early Holocene (Conway *et al.*, 1999). This has important implications because it points toward the long equilibration time scales involved in WAIS dynamics.

Fast-flowing ice streams, which feed the shelves from the interior, dominate the discharge of the WAIS (see TAR WGI Section 11.5). These ice flows are constrained at various boundaries. Whereas early studies emphasized the role of ice-shelf boundaries in such ice flow, more recent work points to the importance of different boundaries (i.e., the ice-stream bed, the lateral margins, and the inland end—Anandakrishnan *et al.*, 1998; Bell *et al.*, 1998; Joughin *et al.*, 1999; Payne, 1999). With respect to the time scales of an eventual WAIS disintegration, this distinction is crucial because the ice shelves respond to changes in climate within centuries, whereas the conditions at the ice-stream margins and beds have response times on the order of millennia (e.g., McAyeal, 1992). Whether proper incorporation of ice-stream dynamics into ice-sheet models generally eliminates the presumed instability cannot be conclusively resolved. McAyeal (1992), for example, incorporated ice-stream dynamics and deformable bed conditions explicitly into his ice-sheet model and showed that under periodic climate and sea-level forcing (100,000-year cycles), the WAIS collapsed and regrew sporadically throughout a period of 1 million years.

Even if accelerated loss of grounded ice were unlikely to occur over the 21st century, changes in ice dynamics could result in increased outflow of ice into the ice shelves and trigger a grounding-line retreat. An in-water temperature of a few degrees Celsius could cause the demise of the WAIS ice shelves in a few centuries and float its marine-based parts over a period of 1,000–2,000 years (Warner and Budd, 1998). This would produce a sea-level rise of 2–3 m. Huybrechts and de Wolde (1999) evaluate a climate change scenario that stabilizes GHG concentrations at four times the present value in 2150. They show that melting of the WAIS would contribute to 1-m sea-level rise by 2500—a rate of rise that would be sustained at 2 mm yr^{-1} for centuries thereafter. The response of the Greenland ice sheet contributed to several meters of sea-level rise by 3000. Even under this stabilization scenario, melting of the Greenland ice sheet would be irreversible. Both studies, however, simply assume no change in ocean circulation and an immediate warming of water in the sub-ice-shelf cavity with a warming climate. Both assumptions still await full validation.

Global warming projected for the 21st century could set in motion an irreversible melting of the West Antarctic and Greenland ice sheets, implying sustained sea-level rise and irreversible losses. The impacts of complete disintegration of the WAIS and subsequent sea-level rise by 4–6 m, however, have not been fully explored. As summarized by Oppenheimer (1998), the disintegration time scales predicted by models vary widely, between 400–500 years (Thomas *et al.*, 1979) and 1,600–2,400 years (McAyeal, 1992). These time scales correspond to a mean contribution to sea level of 10–15 and 2.5 mm yr^{-1}, respectively. Whereas an estimate in the lower range is approximately equal to the present-day rate of sea-level rise, a value in the middle to high range lies outside human experience and would widely exceed the adaptive capacity of most coastal structures and ecosystems (see Sections 19.3 and 6.5).

19.6.4. Climate Protection in an Irregular World

The predictability and manageability of singular phenomena is low. Their impacts can be sudden, large, and irreversible on a time scale of centuries. Regularizing such impacts would be an appropriate response, but this would require much better understanding of the statistics and characteristics of the complex processes involved. The presence of singularities therefore makes analytic and political treatment of the climate change problem particularly difficult.

Little is known, in quantitative terms, about the potential damages that could be inflicted by singularities on ecosystems and market sectors across the globe. This deficit has two main reasons (see also Moss and Schneider, 2000). First, extensive research on the causes, mechanisms, and impacts of singular events in the context of climate change is just getting started. Second, mechanistic and probabilistic analysis of complex nonlinear systems is more demanding—by orders of magnitude—than investigation of simple linear ones.

The knowledge base for assessing consequences of singularities will probably be broadened considerably over the next 5–10 years. Further advances in simulation modeling soon will allow better projections of future climate variability down to modified extreme events statistics (CLIVAR, 1998), as well as better translations of those projections into impacts on natural and societal systems (e.g., Weyant *et al.*, 1996; Alcamo *et al.*, 1998; Rotmans and Dowlatabadi, 1998). Earth system analysis, as supported by the big international research programs—World Climate Research Programme (WCRP), International Geosphere-Biosphere Programme (IGBP), and International Human Dimensions Programme (IHDP)—will bring about more complete understanding of macro-singularities within the responses of the Earth system under pertinent forcing (Schellnhuber, 1999). A major source of information and comprehension, in this context, will be evidence provided by paleorecords (IGBP, 1998). These scientific efforts should assist the decisionmaking process by creating a clearer picture of the future. Unfortunately, creating plausible projections is always tricky in practice (Sarewitz *et al*., 2000).

A major challenge is to make responsible use of available information regarding the likelihood and the consequences of conceivable singular events. Responsibility here means the obligation of decisionmakers to make the "right" decision, taking into account the diverse societal values and wide ranges of individual interests that are at stake and that may be mutually contradictory. Thus, the standard challenge is to develop proper policies under uncertainty (i.e., neither ignorance nor omniscience) to achieve the objectives of the UNFCCC and to satisfy affected stakeholders as well as possible.

Abroad and intensive discourse on the ethical aspects of singular responses to climate change (e.g., Markandya and Halsnaes, 2000; Munasinghe, 2000; Toth, 2000) is rediscovering many of the arguments put forward in traditional moral philosophy and risk policy. Ethical and procedural aspects of this type have been examined in various other contexts before, where certain concepts (such as human rights) act as a constraint on economic activity (emphasizing utilitarian goals), even when the cost-benefit ratio is unfavorable (e.g., the review of the agricultural situation by Aiken, 1986).

One of the crucial questions is how to deal with high-consequence impacts that *may* wipe out entire systems or cultures. Such non-implausible "nightmare" or "doomsday" scenarios could result from the speculative but consistent concatenation of individually possible causal relationships (e.g., Schellnhuber and Yohe, 1997). A vexing question is whether the lack of credible scientific evidence for such a scenario provides justification to ignore its possibility completely. Some argue that such effects have to be avoided by all means, irrespective of the economic burdens involved. Others argue that the uncertainties involved do not provide enough support for extensive measures and their economic costs. Within the climate-change framework, however, many incalculable risks could be reduced considerably by more sensible measures. The debate on the "legitimacy" of the different perspectives is impossible to resolve, however (Jasanoff, 1990).

The vague evidence provided by the present state of research supports the notion that even relatively small changes in mean climate could lead to large changes in the occurrence of stochastic extreme events. Furthermore, it suggests that large-scale discontinuities are unlikely below a 2°C warming but relatively plausible for a sustained warming of 8–10°C. The relatively small set of investigations discussed above lead to the conclusion that a warming range of 4–5°C seems to represent a critical disturbance regime where macro-discontinuities may start to emerge. This temperature threshold appears to be sensitive to the rate of change at which this level is reached.

19.7. Limitations of Methods and Directions for Future Research

This section discusses the strengths and limitations of the analytic approaches used to address the reasons for concern, mainly with regard to whether they can, with the confidence levels given, indicate the severity of impact or risk as a function of increase in global mean temperature. This discussion identifies key uncertainties inherent in each method and offers directions for future research that could improve our confidence in the results produced with each approach.

The organization of this section parallels that of the previous sections of this chapter. The strengths, limitations, uncertainties, and directions for each approach are discussed in the same order in which they were discussed in the preceding sections. However, integrated assessment frameworks are considered separately from aggregate approaches. Last is a discussion of integration across methods and reasons for concern.

19.7.1. Observations

Advantages: Because observations are based on observed effects rather than models, they can be used to indicate whether climate change is causing impacts and whether impacts lead to positive, negative, or indeterminate outcomes. They also can be used to validate hypotheses and models that formalize hypotheses on cause and effect.

Disadvantages: The problem with relying on observations to determine the severity of impacts or risk from climate change is that there has been only 0.7°C of mean global warming over the past century (although some regions have experienced much more warming). Because many impact thresholds may not be crossed until greater magnitudes or rates of warming are reached, it is not clear how to interpret an observed effect of warming or a group of such observations. Such observed impacts to date often will be of only minor consequence, even though they may tend to confirm our understanding of impact processes. Moreover, lack of observed impacts may be simply because climate change has not yet reached critical thresholds for such effects. Finally, attribution of causality is very difficult with observed effects or groups of effects. One must be able to demonstrate that a regional change in climate is a significant cause of an observed effect and that the regional change in climate is linked to global climate change.

Uncertainties: Uncertainties include the magnitude of climate change that has occurred, the extent to which impacts can be attributed to climate change that has occurred, and whether the relationship between climate change and possible impacts is linear or nonlinear and continuous or discontinuous.

Research Needs: For climate change impact detection to advance, there is a need for continued, improved, and augmented data collection and further development of analytical techniques. Geographical diversity is needed to balance the current bias of study locations in North America and Europe; more observation studies are needed in developing countries, with emphasis on those where physical, biological, and socioeconomic systems have higher vulnerability to climate change (see Chapter 18).

Because climate and impact systems are linked over a range of temporal scales, longer time series of data allow better understanding of the relative magnitudes of short- and long-term responses (Duarte *et al*., 1992; McGowan *et al*., 1999). Large-amplitude temporal changes usually involve large spatial dimensions, so broad-scale spatial/temporal studies are necessary as well. Satellite measurements of the Earth's surface provide a very useful monitoring capability for ocean, ecosystem, and land-cover changes. For example, satellite measurements of the Earth's surface offer the potential for aggregation of observed impacts with regard to broad-scale ecological responses such as vegetative responses to increasing lengths of growing seasons (e.g., Myneni *et al*., 1997), complemented by meteorological and vegetation data (e.g., Schwartz, 1998).

For ecosystem impacts, continuing observations are needed at sites where studies already have been conducted, at long-term ecological research sites (e.g., Chapin *et al.,* 1995), and in protected areas. Programs that provide continued long-term monitoring of marine and terrestrial environments also are important (Duarte *et al.,* 1992; Southward *et al.,* 1995). Large-scale spatial/temporal ecosystem studies are necessary because effects from local changes cannot be extrapolated to large areas without evidence (McGowan *et al.,* 1999; Parmesan *et al.,* 1999).

Definition of indicator species or systems is a useful element of detection studies (e.g., Beebee, 1995; Nehring, 1998; Cannell *et al.,* 1999). Coupled with monitoring programs, such data may then provide a consistent set of evidence with which to study past, present, and future impacts of climate changes.

A further critical research need is to strengthen analytical tools for understanding and evaluating observed climate change impacts. Robust meta-analyses of studies that present good quality, multivariate data from a diversity of settings around the world will help to define further the global coherence among impacts now observed. Care also must be taken to ensure that the sample of studies is representative across time and space, is not biased in its reporting, and uses appropriate statistical tests. Also needed is development of methods to analyze differential effects of climate across a range or sector. Individual and grouped studies need to address possible correlations with competing explanations in a methodologically rigorous manner.

Also needed are refinements in the fingerprint approach (e.g., Epstein *et al.*, 1998), including more precise definition of expected changes and quantitative measurement techniques, similar to that used in detection of climate changes (see TAR WGI Chapter 12). For climate, fingerprint elements include warming in the mid-troposphere in the southern hemisphere, a disproportionate rise in nighttime and winter temperatures, and statistical increases in extreme weather events in many locations. These aspects of climate change and climate variability have implications for ecological, hydrological, and human systems that may be used to define a clear and robust multidimensional "expected impact signal" to be tested in a range of observations. A more refined and robust fingerprint approach may aid in the study of difficult-to-detect, partially causal climate effects on socioeconomic systems such as agriculture and health.

19.7.2. Studies of Unique and Threatened Systems

Assessments of unique and threatened systems tend to be based on studies of particular exposure units such as coral reefs, small islands, and individual species.

Advantages: These studies contain richness of detail and involve many researchers, often from developing and transition countries. In contrast to aggregate studies, studies of exposure units can be used, at least in principle, to analyze distributional effects by focusing on impacts on particular systems, species, regions, or demographic groups.

Disadvantages: One of the main disadvantages is that exposure-unit studies often are not carried out in a consistent manner. Exposure-unit studies often examine related sectors in isolation and do not examine linkages or integration among sectors and regions; for example, studies of the effects of climate change on ecosystems or individual species often are conducted without examining the potential effects of societal development on such systems. Local processes and forces (e.g., urbanization, local air pollution) often can be more important than global ones at the local scale, complicating the task of measuring the influence of global climate change at the local scale.

Another key disadvantage is incompleteness of coverage. For example, in spite of many and extensive country studies, there still are many gaps in coverage in terms of countries, regions within countries, and unique and important potential impacts that have not been assessed. The choice of exposure units may not necessarily cover the most vulnerable systems. Topics such as impacts on biodiversity or unique ecosystems often are not covered. There also has been little attention to impacts on poor and disadvantaged members of society. Even where particular critical exposure units have been covered, there may be just a single study. Drawing conclusions with high confidence on the basis of one study may be inappropriate.

Uncertainties: Uncertainties include the likely magnitude of climate change at the spatial resolution required by the study of the particular unique and threatened system, masking of global change effects by nonclimate factors, the degree of linearity/nonlinearity in the relationship between stimulus and response, and the degree to which results from individual studies can be extrapolated or aggregated.

Research Needs: It would be desirable to have more studies of individual systems, according to some set of priorities concerning the likely immediacy of the impacts. Additional work on standardizing methods and reporting of results also would be extremely useful. It also would be useful to devote more effort to integration of results from existing studies. Again, it would be especially useful to increase monitoring of changes in organisms, species, and systems that have limited range now or are near their limits and to try to separate out or consider other causal mechanisms such as local air pollution, loss of habitat, and competition from invading pests and weeds.

19.7.3. Distributional Impacts

Advantages: Distributional impact studies draw attention to likely heterogeneity in impacts among different regions and social and economic groups. They also help to identify and assess the situation of the "most vulnerable" people and systems. Thus, such studies bring equity considerations to center stage.

Disadvantages: Distributional impact studies require regional climate change projections and impact projections at the regional to local scale, where GCMs may not be very accurate. They also require projections of demographics and socioeconomic structure over a long time horizon.

Uncertainties: Research into the distribution of impacts of climate change is recent (see Section 19.4). There are some findings on which there is virtual unanimity. Some findings are broad conclusions—such as that more resource-constrained regions are likely to suffer more negative impacts, as are people whose geographic location exposes them to the greatest hazards from climate change. (Such people often live in regions with marginal climate for food growing or in highly exposed coastal zones.) Others are more specific but to date have been more conclusive with regard to the direction of different impacts among regions, rather than the magnitudes. For example, we know that impacts in developing low-latitude countries are more negative—in part because those countries tend to be operating at or above optimum temperatures already—and, in some cases, in regions where rainfall will decrease, leading to water stress. There also is limited capacity for adaptation in these areas. In some mid-latitude developed countries, agriculture would benefit initially from warmer conditions and longer growing seasons. Beyond such sweeping statements, uncertainties are vast. Resource constraints and (climatic) marginality are multidimensional and complex phenomena. Currently, it is not known which components of resource constraints or climatic marginality are more important or which components may compensate for others or may have synergistic effects. There are suggestions in other literature, but these have not been systematically applied to the impacts of climate change, conceptually or empirically.

In sum, there is virtual consensus about the broad patterns. There is much less knowledge about the details, although that situation is slowly improving.

Research Needs: Development of appropriate indicators of differences in regional impacts and ways of comparing them across regions and socioeconomic groups would be extremely useful. Improved methods for characterizing baseline demographics and socioeconomic conditions in the absence of climate change or climate change-motivated policies also would be useful. There is a need to quantify regional differences and to develop estimates of the cost of inequity in monetary or other terms (e.g., effect on poverty rates and trade, social and political instability, and conflict). More accurate projections of regional climate change would increase confidence in predictions of regional climate change impacts.

19.7.4. Aggregate Approaches

Advantages: Aggregate analyses synthesize climate change impacts in an internally consistent manner, using relatively comprehensive global indicators or metrics. These often are expressed in U.S. dollars (e.g., Tol, 2001b) or other common metrics such as changes in vegetation cover (Alcamo *et al*., 1998). This enables direct comparisons of impacts among sector systems and regions and with other environmental problems and emission control costs. Some aggregate analyses have assessed differences in relative impacts in developed and developing regions of the world and have shown that regional differences in impacts may be substantial.

Disadvantages: Aggregate analyses lack richness of detail. Partly this is inherent because aggregation explicitly seeks to synthesize complex information. Partly this is because aggregate analyses tend to rely on reduced-form models. Condensing the diverse pattern of impacts into a small number of damage indicators is difficult. Some metrics may not accurately capture the value of certain impacts; for example, nonmarket impacts such as mortality and loss of species diversity or cultural heritage often are not well captured in monetization approaches, and change in vegetation cover may not clearly indicate threats to biodiversity. Other complicating issues concern comparison of impacts across time (impact today and several generations from now) and between regions (e.g., impact in developing and developed countries), as well as how much importance to assign to different effects. In addition, many aggregate studies examine a static world rather than a dynamic one and do not consider the effects of changes in extreme events or large-scale discontinuities. The aggregation process is not possible without value judgments, and different ethical views imply different aggregate measures across socioeconomic groupings and generations (see Azar and Sterner, 1996; Fankhauser *et al.*, 1997). Choice of discount rates can affect valuation of damages. In addition, general shortcomings that affect all reasons for concern are particularly prominent in aggregate analysis (e.g., accounting for baseline development, changes in variability and extreme events, and costs and benefits of adaptation).

Uncertainties: Uncertainties include whether all climate change impacts (positive and negative) are included, the implications of various aggregation and valuation methods, and implicit or explicit assumptions of methods, including possible mis-specifications of nonlinearities and interaction effects.

Research Needs: The next generation of aggregate estimates will have to account better for baseline developments, transient effects, climate variations, and multiple stresses. Further progress also is still needed in the treatment of adaptation. A broader set of primary studies on impacts in developing countries and nonmarket sectors would reduce the need for difficult extrapolation. More work also is needed on the ethical underpinnings of aggregation and on alternative aggregation schemes. Work on reflecting information from the other reasons for concern into the aggregate approach is underway, but proceeding slowly.

19.7.5. Integrated Assessment Frameworks

Advantages: Integrated assessment frameworks or models provide a means of structuring the enormous amount of and often conflicting data available from disaggregated studies. They offer internally consistent and globally comprehensive analysis of impacts; provide "vertical integration" (i.e., cover the entire "causal chain" from socioeconomic activities giving rise to GHG emissions to concentration, climate, impacts, and adaptations); provide "horizontal integration" (i.e., account for interlinkages between different impact categories, adaptations, and exogenous factors such as economic development and population growth); and allow for consistent treatment of uncertainties. IAMs have been used primarily for benefit-cost and inverse (or threshold) analyses. The latter have the advantage of being directly related to Article 2 because they define impacts that may be considered "dangerous" (through specification of thresholds related to, e.g., harm to unique and threatened systems or the probability of large-scale discontinuities).

Disadvantages: The main disadvantages with most IAMs are those associated with aggregate approaches: reliance on a single or a limited number of universal measures of impacts. These may not adequately measure impacts in meaningful ways. This is partly because IAMs rely on reduced-form equations to represent the complexities of more detailed models. Their usefulness is highly dependent on how well they are able to capture the complexities of more disaggregated approaches. Some of the IAMs used for benefit-cost analyses have considered large-scale irregularities (e.g., Gjerde *et al.*, 1999), but inclusion of such outcomes is preliminary. Few have accounted for loss of or substantial harm to unique and threatened systems. Although inverse (or threshold) approaches allow researchers to overcome these problems, the disadvantages of this kind of analysis include the difficulty of explicitly specifying thresholds and combining them within and across sectors and regions.

Uncertainties: Uncertainties are the same as those for the aggregate approach or for unique and threatened systems, depending on the structure and objectives of the model. This also would include the effects of different assumptions, methods, and value choices.

Research Needs: Among the biggest challenges facing integrated assessment modelers (see Weyant *et al.*, 1996) are developing a credible way to represent and value the impacts of climate change; a credible way to handle low-probability but potentially catastrophic events; a credible way to incorporate changes in extreme weather events; and realistic representations of changes in socioeconomic and institutional conditions, particularly in developing countries. In addition, they must decide how to allow explicitly for effects of different value choices, systems, and assumptions; how to quantify uncertainties; and how to credibly incorporate planned adaptation, including costs and limitations.

19.7.6. Extreme Events

Advantages: Extreme events are recognized as major contributors to the impacts of climate variability now and to potential impacts of climate change in the future. Thus, realistic climate change impact assessments must take them into account even though they may change in complex ways—such as in frequency, magnitude, location, and sequences (e.g., increased variability may lead to more frequent floods and droughts). Better understanding of changes in extreme events and adaptation measures for coping with them also will help in coping with present variability.

Disadvantages: Extreme events are more difficult to model and characterize than average climates. Changes in extreme events will be complex and uncertain, in part because extremes occur in a chaotic manner even in the present climate. Large data series are needed to characterize their occurrence because, by definition, they are rare events. This means that long time scale model simulations are needed to develop relevant statistics from long time slices or multiple realizations. Extreme events need to be considered in terms of probabilities or risks of occurrence rather than predictions. This chaotic element adds to other sources of uncertainty. It means that engineering or other design standards based on climatology that normally use long data series of observations will need a synthetic data set that simulates potential changes in future climate. It also makes adaptation to changes in extremes more difficult because planned adaptation must rely on necessarily uncertain projections into the future from theory and thus requires greater faith in the science before the information will be acted on.

Uncertainties and Research Needs: Better knowledge of the behavior of extremes will require long or multiple simulations at finer spatial and temporal scales, to capture the scale, intensity, and frequency of the events. Some types of extreme events (e.g., hail and extreme wind bursts) are poorly simulated at present; others, such as ENSO and tropical cyclones, are extremely complex and only now are beginning to be better simulated. Arguments for changes in their behavior are still often largely theoretical, qualitative, or circumstantial, rather than well based in verified models. Moreover, much more work is needed on how they will affect natural and human systems and how much of the recent trend to greater damages from extreme events is related to changes in exposure (e.g., greater populations, larger investments, more insurance cover, or greater reporting) rather than changes in the number and intensity of those extremes. More work is needed on how best to adapt to changes in extreme events, especially on how planners and decisionmakers can best take information on projected changes in extremes into consideration. This may be done best by focusing on projected change in the risk of exceeding prescribed natural, engineering, or socioeconomic impacts thresholds.

19.7.7. Large-Scale Singular Events

Advantages: Consideration of strongly nonlinear or even disruptive effects accompanying climate change is a critical component of the "dangerous interference" debate. The basic idea is to corroborate any non-negligible probability for high-consequence impacts that may be triggered by human climate perturbations. The political process to avoid high-consequence impacts may be facilitated by the global scope of such effects (e.g., disintegration of the WAIS generating a planetary sea-level rise of approximately 5 m). Inclusion of extreme events in the analysis helps, in general, to pursue all other reasons for concern in a realistic way because irregular impacts may dominate impacts on unique and threatened systems, distributional impacts, and aggregate impacts.

Disadvantages: This is an emerging area of research, facing several serious challenges because of the complexity of nonlinear interactions to be considered. The prevailing lack of knowledge is reflected in use of the term "surprises" for disruptive events. The potentials for climate change-induced transformations of extreme events regimes and for large-scale discontinuities in the Earth system are still highly uncertain. The search for irregularities might turn out to be futile and distract scientific resources from other important topics, such as the distributional aspects of regular climate change impacts.

Uncertainties and Research Needs: By definition, uncertainties are most severe in this realm of impact research. At present, there is no way of estimating the probabilities of certain disruptive events or assigning confidence levels to those probabilities. As a consequence, a strong research program should be launched that combines the best paleoclimate observations with the strongest simulation models representing full and intermediate complexity.

19.7.8. Looking across Analytic Approaches

Looking across the different analytic approaches (implicitly, the different reasons for concern), it is clear that to a great extent they complement and in many respects do not overlap each other. Combining these approaches into an integrated framework is the ambition of IAMs, at least in principle. However, this process is just starting. Because observed evidence has not been incorporated in the other analytic approaches, impacts to unique and threatened systems have not been accounted for in aggregate and IAM approaches, they are difficult to sum, and large-scale irregular impacts have only begun to be addressed, it does not appear to be feasible yet to combine these approaches into a comprehensive analytic approach. Thus, those who are seeking to implement climate policies must currently do their own integration of information from the alternative lines of inquiry.

19.8. Conclusions

This chapter focuses on certain reasons for concern with regard to what might be considered a "dangerous" climate change (reported as increases in global mean temperature; see Section 19.1.2). Each reason for concern can be used by itself or in combination with other reasons for concern to examine different aspects of vulnerability to climate change. We offer no judgment about how to use some or all of these reasons for concern to determine what is a dangerous level of climate change. The reasons for concern are as follows:

1) The relationship between global mean temperature increase and damage to or irreparable loss of unique and threatened systems
2) The relationship between global mean temperature increase and the distribution of impacts
3) The relationship between global mean temperature increase and globally aggregated impacts
4) The relationship between global mean temperature increase and the probability of extreme weather events
5) The relationship between greenhouse concentrations and the probability of large-scale singular events.

In addition, we address what observed effects of climate change tell us with regard to Article 2 of the UNFCCC. We review the state of knowledge with regard to what observations and each reason for concern tell us about climate change impacts.

19.8.1. Observations

Based on a review of the literature of observations of climate change impacts, as reflected in other TAR chapters, we conclude:

- Statistically significant associations between trends in regional climate and impacts have been documented in ~10 physical processes and ~450 biological species, in terrestrial and marine environments on all continents. Although the presence of multiple factors (e.g., land-use change, pollution, biotic invasion) makes attribution of observed impacts to regional climate change difficult, more than 90% (~99% physical, ~80% biophysical) of the changes documented worldwide are consistent with how physical and biological processes are known to respond to climate. Based on expert judgment, we have high confidence that the overall patterns and processes of observations reveal a widespread and coherent impact of 20th-century climate changes on many physical and biological systems.
- Signals of regional climate change impacts may be clearer in physical and biological systems than in socioeconomic systems, which also are simultaneously undergoing many complex changes that are not related to climate, such as population growth and urbanization. There are preliminary indications that some social and economic systems have been affected in part by 20th-century regional climate changes (e.g., increased damages from flooding and droughts in some locations). It generally is difficult to separate climate change effects from coincident or alternative explanations for such observed regional impacts.

There is preliminary evidence that unique and threatened systems are beginning to be affected by regional climate change and that some systems have been affected by recent increases in extreme climate events in some areas. Many high-latitude and high-altitude systems are displaying the effects of regional climate change. It is difficult to define observed impacts at aggregate levels, and evidence of large-scale singular events occurring as a result of recent climate change is lacking.

19.8.2. What does Each Reason for Concern Indicate?

Looking across these different reasons for concern, what can we conclude about what change in global average temperature is "dangerous"? Afew general caveats apply:

- In spite of many studies on climate change impacts, there is still substantial uncertainty about how effective adaptation will be (and could be) in ameliorating negative effects of climate change and taking advantage of positive effects.
- The effect of changes in baseline conditions, such as economic growth and development of new technologies, that could reduce vulnerability has not been adequately considered in most impact studies.
- Most impact studies assess the effects of a stable climate, so our understanding of what rates of change may be dangerous is limited.

It does not appear to be possible—or perhaps even appropriate—to combine the different reasons for concern into a unified reason for concern that has meaning and is credible. However, we can review the relationship between impacts and temperature over the 21st century for each reason for concern and draw some preliminary conclusions about what change may be dangerous for each reason for concern. *Note that the following findings do not incorporate the costs of limiting climate change to these levels. Also note that there is substantial uncertainty regarding the temperatures mentioned below.These magnitudes of change in global mean temperature should be taken as an approximate indicator of when various categories of impacts might happen; they are not intended to define absolute thresholds.*

For simplification, we group different levels of global mean temperature increase into "small," "medium," and "large." "Small" denotes a global mean temperature increase of up to approximately 2°C;[4] "medium" denotes a global mean temperature increase of approximately 2–3°C; and "large" denotes a global mean temperature increase of more than approximately 3°C. In addition, changes in global mean temperature do not describe all relevant aspects of climate-change impacts, such as rates and patterns of change and changes in precipitation, extreme climate events, or lagged (or latent) effects such as rising sea levels.

19.8.2.1. Unique and Threatened Systems

Tropical glaciers, coral reefs, mangroves, biodiversity "hot spots," and ecotones are examples of unique and threatened entities that are confined to narrow geographical ranges and are very sensitive to climate change. However, their degradation or loss could affect regions outside their range. There is medium confidence that many of these unique and threatened systems will be affected by a small temperature increase. For example, coral reefs will bleach and glaciers will recede; at higher magnitudes of temperature increase, other and more numerous unique and threatened systems would become adversely affected.

19.8.2.2. Distributional Impacts

The impact of climate change will not be evenly distributed among the peoples of the world. There is high confidence that

[4] A 2°C warming from 1990 to 2100 would be a magnitude of warming greater than any that human civilization has ever experienced. Thus, "small" does not necessarily mean negligible.

developing countries tend to be more vulnerable to climate change than developed countries, and there is medium confidence that climate change would exacerbate income inequalities between and within countries. There also is medium confidence that a small temperature increase would have net negative impacts on market sectors in many developing countries and net positive impacts on market sectors in many developed countries. However, there is high confidence that with medium to high increases in temperature, net positive impacts would start to decline and eventually turn negative, and negative impacts would be exacerbated. Estimates of distributional effects are uncertain because of aggregation and comparison methods, assumptions about climate variability, adaptation, levels of development, and other factors. In addition, impacts are likely to vary between and within countries. Thus, not all developing or developed countries will necessarily have benefits or damages in unison.

19.8.2.3. Aggregate Impacts

With a small temperature increase, there is medium confidence that aggregate market sector impacts would amount to plus or minus a few percent of world GDP; there is low confidence that aggregate nonmarket impacts would be negative. Some studies find a potential for small net positive market impacts under a small to medium temperature increase. However, given the uncertainties about aggregate estimates, the possibility of negative effects cannot be excluded. In addition, most people in the world would be negatively affected by a small to medium temperature increase. Most studies of aggregate impacts find that there are net damages at the global scale beyond a medium temperature increase and that damages increase from there with further temperature increases. The important qualifications raised regarding distributional analysis also apply to aggregate analysis. By its nature, aggregate analysis masks potentially serious equity differences. Estimates of aggregate impacts are controversial because they treat gains for some as cancelling out losses for others and because weights that are used to aggregate over individuals are necessarily subjective.

19.8.2.4. Extreme Climate Effects

The frequency and magnitude of many extreme climate events increase even with a small temperature increase and will become greater at higher temperatures (high confidence). Extreme events include, for example, floods, soil moisture deficits, tropical and other storms, anomalous temperatures, and fires. The impacts of extreme events often are large locally and

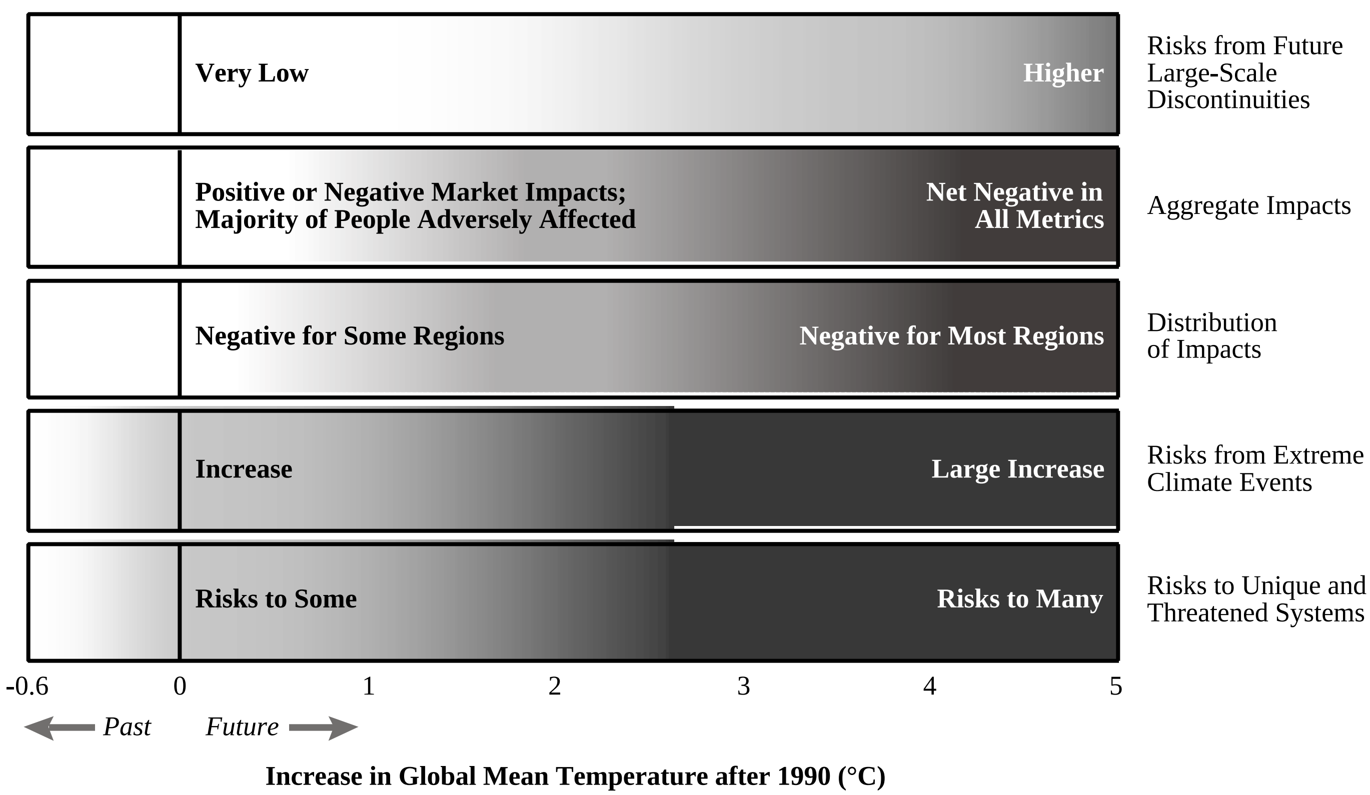


Figure 19-7: Impacts of or risks from climate change, by reason for concern. Each row corresponds to a reason for concern; shades correspond to severity of impact or risk. White means no or virtually neutral impact or risk, light gray means somewhat negative impacts or low risks, and dark gray means more negative impacts or higher risks. Global average temperatures in the 20th century increased by 0.6°C and led to some impacts. Impacts are plotted against increases in global mean temperature after 1990. This figure addresses only how impacts or risks change as thresholds of increase in global mean temperature are crossed, not how impacts or risks change at different rates of change in climate. Temperatures should be taken as approximate indications of impacts, not as absolute thresholds.

could strongly affect specific sectors and regions. Increases in extreme events can cause critical design or natural thresholds to be exceeded, beyond which the magnitude of impacts increases rapidly (high confidence).

19.8.2.5. Large-Scale Singularities

Large-scale singularities in the response of the climate system to external forcing, such as shutdown of the North Atlantic THC or collapse of the WAIS, have occurred in the past as a result of complex forcings. Similar events in the future could have substantial impacts on natural and socioeconomic systems, but the implications have not been well studied. Determining the timing and probability of occurrence of large-scale singularities is difficult because these events are triggered by complex interactions between components of the climate system. The actual impact could lag the climate change cause (involving the magnitude and the rate of climate change) by decades to millenia. There is low to medium confidence that rapid and large temperature increases would exceed thresholds that would lead to large-scale singularities in the climate system.

Figure 19-7 sums up the reasons for concern regarding impacts relative to change in temperature. Each row corresponds to a reason for concern, and the shades correspond to the severity of impact or risk. White means no or virtually neutral impact or risk, light gray means somewhat negative impacts or low risks, and dark gray means more negative impacts or higher risks. The period 1850–1990 warmed by 0.6°C and led to some impacts. Unique and threatened systems were affected, and the magnitude and frequency of some extreme events have changed. Future impacts are plotted against increases in global mean temperature after 1990.

Adverse impacts are estimated to occur in three reasons for concern even at a small increase in temperature: unique and threatened systems, extreme weather events, and distributional impacts. For the other two reasons for concern—adverse impacts and large-scale discontinuities—adverse impacts begin at the medium level of temperature increase for the former and a large temperature increase for the latter.

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