AN ANATOMY OF ADAPTATION TO CLIMATE CHANGE AND VARIABILITY

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Abstract. Adaptation to climate variability and change is important both for impact assessment (to estimate adaptations which are likely to occur) and for policy development (to advise on or prescribe adaptations). This paper proposes an "anatomy of adaptation" to systematically specify and differentiate adaptations, based upon three questions: (i) adapt to what? (ii) who or what adapts? and (iii) how does adaptation occur? Climatic stimuli include changes in long-term mean conditions and variability about means, both current and future, and including extremes. Adaptation depends fundamentally on the characteristics of the system of interest, including its sensitivities and vulnerabilities. The nature of adaptation processes and forms can be distinguished by numerous attributes including timing, purposefulness, and effect. The paper notes the contribution of conceptual and numerical models and empirical studies to the understanding of adaptation, and outlines approaches to the normative evaluation of adaptation measures and strategies.

1. Introduction

The role of adaptation to climate change and variability is increasingly considered in academic research, and its significance is being recognized in national and international policy debates on climate change. There are two distinct, but not independent, reasons why adaptation is important when considering climate change and variability. Firstly, the impacts of climate change, and hence its seriousness or dangerousness, can be modified by adaptations of various kinds (e.g., Smit, 1993; Tol et al., 1997). Most impact studies now make assumptions about expected adaptations in the system of interest. Thus, the key question about adaptation is: what adaptations are *likely*? This is mainly a *predictive* exercise, which requires information on how and

Climatic Change **45**: 223–251, 2000.

under what conditions adaptations are expected to occur. Secondly, adaptation is considered as an important policy option or response strategy to concerns about climate change (e.g., Fankhauser, 1996; Smith, J., 1996). Adaptation to climate change and its impacts is receiving increasing attention as an alternative or complementary response strategy to reducing net emissions of greenhouse gases (termed "mitigation" in the climate change community). For this policy application, the key question is: what adaptations are advocated or *recommended*? This is ultimately an advisory or *prescriptive* exercise, which requires information on possible adaptation strategies or measures, as well as principles to evaluate their merit.

As adaptation to climate change and variability has been subjected to more intensive inquiry, analysts have seen the need to distinguish types, to characterize attributes, and to specify applications of adaptation. For example, adaptation can refer to natural or socio-economic systems and be targeted at different climatic variables or weather events. Based on their timing, adaptations can be reactive or anticipatory; and depending on the degree of spontaneity, they can be autonomous or planned. Further, adaptations can take technological, economic, legal and institutional forms.

While the subject of adaptation has been approached from a variety of perspectives, there are some broad consistencies in the use of terms. This paper aims to synthesize and clarify the treatment of climate adaptation in the existing literature. It builds on generally agreed-upon concepts and terms to establish a comprehensive "anatomy" of adaptation. It seeks to facilitate analysis and policy development of adaptation by proposing a conceptual framework within which particular analyses and applications can be set, and a terminology to promote communication and to assist comparisons of findings in the field.

The paper spells out what is meant by "adaptation", and how it has been characterised and classified. The paper begins by summarising the role of adaptation in relation to climate change and variability. The central theme of "what is adaptation?" is addressed by reviewing definitions, then considering in turn three questions: (*i*) adapt to what? (*ii*) who or what adapts? (*iii*) how does adaptation occur? This is followed by a brief critique of approaches to improving our ability to estimate future adaptations. The final section reviews methods to evaluate adaptation options, particularly for prescriptive analyses.

This paper adopts the convention in IPCC and elsewhere that distinguishes adaptation from mitigation. Both represent responses to climate change and variability. "Mitigation", which means abate, moderate or alleviate, could be (and sometimes is, especially in the environmental hazards, engineering and insurance fields) applied to impacts, as in 'mitigate vulnerabilities and effects by adjusting practices or structures'. In this paper, mitigation is considered to be a response to the broad issue of climate change and involves reducing or stabilizing greenhouse gas emissions or levels, in order to mitigate changes in climate. "Adaptation" could be (and sometimes is) applied to altering activities related to greenhouse gases (here called "mitigation"). "Adaptation" is also sometimes used to refer to adjustments, particularly by businesses, to changes in the political-economic environment associated with the climate change issue (notably policies promoting measures to mitigate). In this paper, adaptation refers to adjustments in ecological-social-economic systems in response to actual or expected climatic stimuli, their effects or impacts. These differing applications of the term "adaptation" reinforce the need for users of the term to specify adaptation in what, and to what.

2. Adaptation, Climate Change, Variations and Extremes

A critical document on climate change for both scientists and policy makers is the United Nations Framework Convention on Climate Change (UNFCCC), which was one of the products of the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. The ultimate objective of the UNFCCC, as expressed in Article 2 is:

> ...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 within 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.

The challenges presented to scientists and policy makers alike include the determination of what might be regarded as "dangerous", an essential element of which relates to adaptation. The extent to which natural ecosystems, global food supplies and sustainable development are at risk depends in part upon the magnitude, rate and nature of climate change, but also upon the ability of the impacted systems to adapt. Thus, in order to judge the seriousness of climate change as outlined in Article 2 of the UNFCCC, impact assessments of ecosystems, food production and sustainable development (including systems such as forestry, fisheries, water resources, human settlements and human health) need to address explicitly the capacity for, and the likelihood of, adaptation to potential climatic conditions. Such adaptations are what distinguish "initial impacts" from "residual impacts". Therefore, for *impact assessment*, the main interest is in understanding adaptations, estimating the circumstances under which they can be expected, and forecasting their implications for the systems or regions of interest.

With regard to the *implementation* of adaptation measures as part of a response strategy, the UNFCCC commits parties to:

> Formulate, implement...national and, where appropriate, regional programmes containing measures to mitigate climate change...and measures to facilitate adequate adaptation to climate change (Article 4.1(b)).

More specifically, parties are committed to:

> Cooperate in preparing for adaptation to the impacts of climate change; develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and, for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods (Article 4.1 (e)).

The formulation and implementation of adaptation policies and measures involves one additional analytical step as compared to the analysis of adaptation as part of impact assessment. For both implementation and assessment purposes it is important to know, for example, the forms of adaptation and the conditions under which they are expected to occur. However, analysis for implementation also requires an *evaluation* of measures, strategies or options. It is not sufficient for this implementation role to specify an adaptation and its likelihood; it also requires some judgement as to how appropriate or good it is, such that adaptations be recommended in accordance with the goals of public policy.

Considerable attention has been given to evaluating the need for, and merit of, adaptation measures in the climate change context. The IPCC Technical Guidelines (Carter et al., 1994) outline steps for the evaluation of adaptation strategies, and several other approaches to identifying recommended adaptations have been developed. These methods for advisory applications of adaptation are considered in more detail later in this paper.

The interest in adaptation to climate change, both as an element of impact assessment and as a policy response, is not limited to changes in long-term mean climate variables. Climatic conditions are inherently variable from year to year, decade to decade, century to century and beyond. Hence, variability goes along with, and is an integral part of, climate change: a change in mean climatic conditions is actually experienced through changes in the nature and frequency of particular yearly conditions, including extremes; and it is to this variability that adaptations are made. Thus, adaptation to climate change necessarily includes adaptation to variability.

In addition, and quite apart from the climate change issue, there is an ongoing interest in adaptation to climatic *variations* in their own right. Communities frequently have to deal with extremes or anomalies such as floods, droughts and storms, both individual weather events and patterns of occurrence which may be significant over periods of days, seasons, years, decades, or more. This work on analyzing the processes by which communities or regions cope with such hazards or manage such risks is all about adaptation, and it is an essential element in sustainable development initiatives (Alabala-Bertrand, 1993; Blaikie et al., 1994; Hewitt, 1997. Variability (including extremes) associated with El Niño-Southern Oscillation (ENSO) phenomena represents a particular example. Analysts and policy makers are exploring the ways in which systems have adapted to past ENSO events and the ways in which improved adaptations might be encouraged, particularly given the degree of predictability associated with ENSO conditions (Lagos and Buizer, 1992). Analyses of adaptations to climate variations and extremes have involved scholars both within and beyond the climate change community, and have employed some distinctive terms and interpretations dealing with adaptations. Yet the basic concepts are broadly consistent, and are synthesized in the following development of an anatomy of adaptation to climate change and variability.

3. Definitions and Gross Anatomy of Adaptation

According to dictionaries, "adapt" means to make more suitable (or to fit some purpose) by altering (or modifying). "Adaptation" refers to both the process of adapting and the condition of being adapted. The terms have more specific interpretations in particular disciplines (Smithers and Smit, 1997a). In ecology, for example, adaptation frequently refers to the changes by which an organism or species becomes fitted to its environment (Lawrence, 1995; Abercrombie et al., 1977). In the social sciences, cultural adaptation has referred to adjustments by individuals and to the collective behaviour of socio-economic systems (Denevan, 1983; Hardesty, 1983).

In the climate change literature, numerous definitions have been proposed, some of which refer only to societal adaptation; for example:

> Adaptation to climate is the process through which people reduce the adverse effects of climate on their health and well-being, and take advantage of the opportunities that their climatic environment provides (Burton, 1992);

> Adaptation involves adjustments to enhance the viability of social and economic activities and to reduce their vulnerability to climate, including its current variability and extreme events as well as longer term climate change (Smit, 1993);
>
> The term adaptation means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change (Stakhiv, 1993);
>
> Adaptation to climate change includes all adjustments in behaviour or economic structure that reduce the vulnerability of society to changes in the climate system (Smith *et al.*, 1996);
>
> Adaptability refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of change in conditions (Watson *et al.*, 1996).

These definitions have much in common. They all refer to adjustments in a system in response to (or in light of) climatic stimuli, but they also indicate differences in scope, application and interpretation of the term adaptation. For example, the question "*adaptation to what?*" is answered in different ways. It can refer to climate change, to change and variability, or just to climate. It can be in response to adverse effects or vulnerabilities, but it can also be in response to opportunities. It can be in response to past, actual or anticipated conditions, changes or opportunities.

There are also differences in how the definitions relate to the question *"who or what adapts?"* It can be people, social and economic sectors and activities, managed or unmanaged natural or ecological systems, or practices, processes or structures of systems. The nature of adaptation and its effects will vary not only according to whether the object is natural or socio-economic, small or large scale, single sector/species or complex system, but also according to properties that relate to adaptation propensity such as adaptability, vulnerability, viability, sensitivity, susceptibility, resilience, and flexibility.

The definitions also hint at the ways in which forms or types of adaptation can be distinguished; in other words, "*how does adaptation occur?*" Adaptation refers both to the process of adapting and to the resulting outcome or condition. Most definitions imply a change "to better suit" the new conditions. Adaptations can be passive, reactive or anticipatory; they can be spontaneous or planned; and other typologies and distinctions appear in the literature. For some types of adaptation, there are insights into actual processes by which adaptive measures are adopted or implemented.

As summarized graphically in Figure 1, these three elements together circumscribe the overall question "what is adaptation?". A thorough description of adaptation would specify the system of interest (who or what adapts), the climate-related stimulus (adaptation to what), and the processes and forms involved (how adaptation occurs). The exercise of identifying recommended adaptation options or measures as part of a response strategy involves the additional step of evaluation, in order to judge the merit of potential adaptations (*how good is the adaptation?*) (Figure 1). Evaluations of adaptations can be based on criteria such as costs, benefits, equity, efficiency, urgency and implementability.

The elements of a gross anatomy are distinguished to clarify the concepts and treatments of adaptation; it is not suggested that the elements are independent of each other. For example, certain systems are more adaptable to a given climate stimulus than others. Non-climate forces also affect adaptation types and evaluations. The adaptation process itself can modify systems to alter their sensitivity to climate stimuli. One of the important features of adaptations as part of impact assessment is the estimation of costs and benefits, which is also a common ingredient in the evaluations to recommend adaptations. Development of adaptation policies requires adaptations to be specified — according to the three components of "what is adaptation" — before they can be evaluated. Not all links are shown in the simplified Figure 1. Notwithstanding their interconnectedness, the main components of the anatomy, as shown in Figure 1, can be examined separately, and this is done in subsequent sections.

4. Adaptation to What?

Adaptations can be considered in the context of the various manifestations of climatic stimuli. These have been called "doses", "stresses", "disturbances", "events", "hazards", and "perturbations" (Burton, 1997; Downing *et al.*, 1996). Sometimes the stimuli for adaptations are expressed as climate or weather conditions (*e.g.,* annual average precipitation or experienced hourly or daily precipitation), sometimes as the ecological effects or human impacts of the climatic conditions (*e.g.,* drought, crop failure or income loss), and increasingly as the risks and perceptions of risks associated with climatic stimuli or the opportunities created by changing conditions. Thus, the phenomena to which adaptations are — or might be — made need to be specified according to the

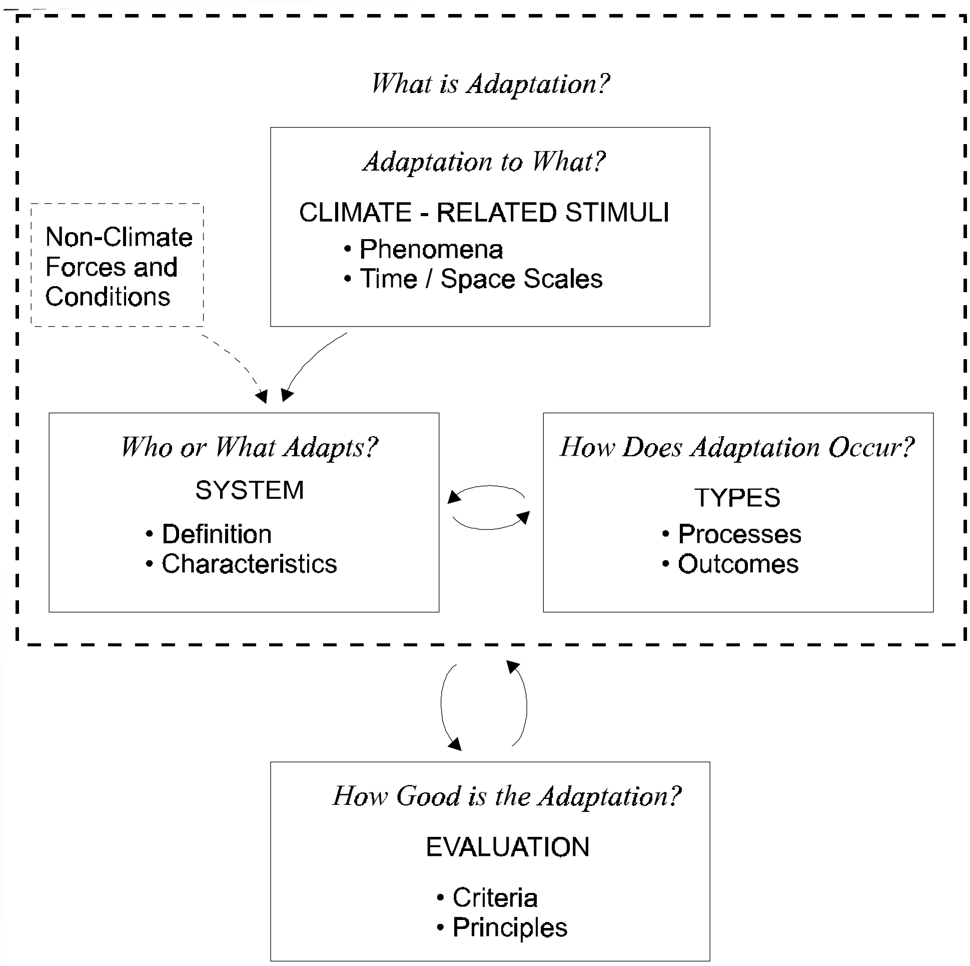

Figure 1. Gross anatomy of adaptation to climate change and variability.

climate characteristics which are relevant (e.g., temperature, precipitation, or some combination such as moisture, over the pertinent time period) *and* their connection to the system which adapts. For example, an adaptation in agriculture may be in response to a sequence such as temperature and precipitation conditions, which result in drought (magnitude and/or frequency) which influences crop yield which has consequences for income. Such distinctions among climate-related stimuli have been suggested elsewhere: direct versus indirect, proximate versus distant, effects versus impacts, and various "levels" of impact (Parry, 1986).

One of the noteworthy developments in recent investigations of adaptation is the search for system-relevant climate-related stimuli, by examining the sensitivity of systems, rather than by considering only the limited array of climate variables provided in scenarios generated by global climate models (Kates, 1985; Kane et al., 1992; Rayner and Malone, 1998; Yohe et al., 1996).

The climatic conditions to which adaptations have been considered (either directly or indirectly) generally fall into three broad *temporal* categories:

global climate change, as reflected in long-term trends in, or scenarios pertaining to, mean temperatures and related climate "norms";

variability about norms over periods ranging from a few years to several decades — this may include shifts or changes in the shape of frequency/probability distributions of climate variables, as well as variations or recurring anomalies associated ENSO or other forces such as volcanic eruptions and sun spots; and

isolated extreme events or catastrophic weather conditions, such as floods, droughts or storms.

In reality, these types of climatic stimuli are not separate or independent. Extreme events are part of variability, which in turn is an inherent feature of climate, including changing climate. The mean conditions which have been the focus of the climate change studies are the summary (central tendencies) of a distribution of (variable) conditions. However, it is useful to distinguish stimuli because adaptations may be (and perhaps should be) quite different when viewed as response to, for example, an isolated extreme event as compared to a recurring anomalous condition or a gradual (or even sudden) change in an overall climate regime as reflected in changes in long-term mean conditions. Furthermore, improved understanding of adaptation to variability may provide insights into adaptation to changes (which will be experienced via variable conditions).

The relationships among extreme events, variability and climate change have been well developed in fields such as natural hazards (Hewitt and Burton, 1971; Kates, 1971), and are illustrated in Figure 2, with clear implications for adaptation. Do systems adapt to a slowly changing mean condition, the cumulative effect of conditions beyond some "coping range" ("critical value", "vulnerability threshold", "band of tolerance" or "damage threshold"), or to a particular extreme event? It is likely that many systems adapt in different ways to all of these time scales of stimuli — and may do so simultaneously. The coping range (Figure 2) may itself change (up, down, expand or contract) reflecting system adaptations (see de Vries, 1985; de Freitas, 1989). In the climate change context, the importance of means, variabilities and extremes is recognized for ecosystems (Sprengers et al., 1994) and for human systems (Parry, 1986; Downing et al., 1996).

Adaptation to climate-related stimuli in each of these time frames is important in its own right. For example, regardless of climate change, there is considerable interest in reducing the vulnerabilities and damages associated with isolated extreme events such as storms, and with variability as reflected in recurring droughts or floods (Smith, K., 1996; Burton 1996).

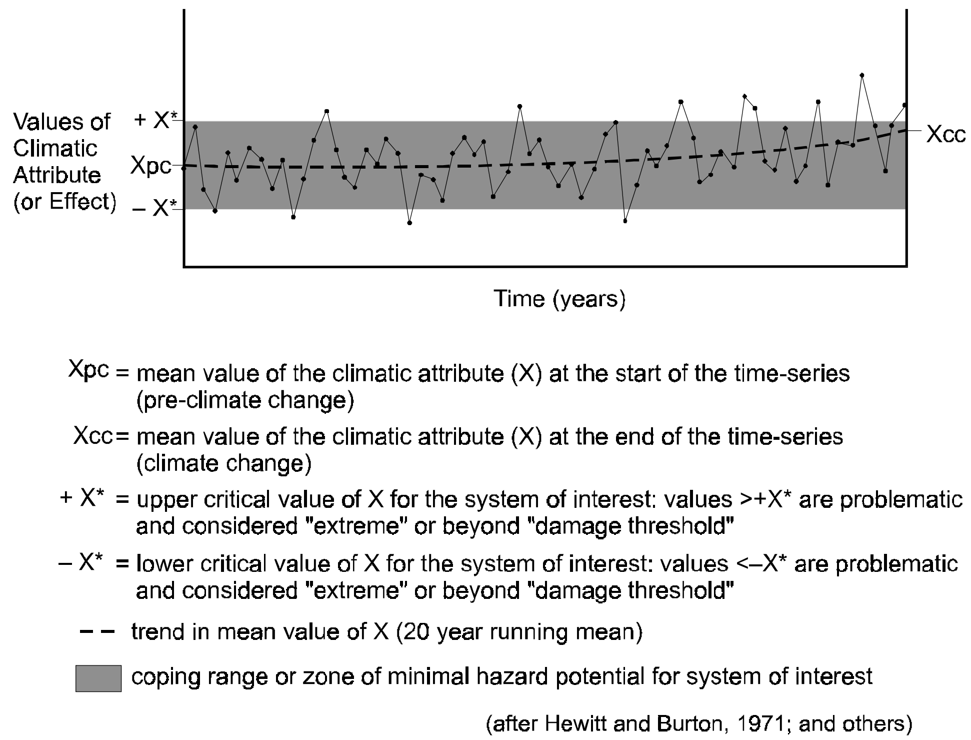

Figure 2. Climate time-series (hypothetical) showing sources of stimuli

When variability and extremes are considered together with climate change, two circumstances are worth distinguishing. An increasingly debated issue is whether climate change will bring with it (or is already bringing) a change in the variability of conditions, i.e., a change in the shape or variance of the frequency distribution. One possibility is that variability increases with climate change, but there is little or no consensus on changing variability (Houghton et al., 1996).

However, even with no change in variability (i.e., no change in shape or variance of the distribution), a shift in the mean (i.e., climate change) will necessarily shift the location of the distribution, as illustrated in Figure 3a. The frequency of occurrence of extreme events can be extremely sensitive to small changes in the mean (Mearns et al., 1984; Wigley, 1985). The implications for impacts and adaptation are fundamental (Heathcote, 1985; Warrick et al., 1986; Parry, 1986). To demonstrate, a condition which is considered extreme or problematic for the system (e.g., values of $X > +X^*$ in Figure 3a) which currently occurs only once every 30 years may, under the changed climate, occur once every four or five years. Such reduced recovery time would alter the feasibility and effectiveness of adaptation options. If there are changes in the mean and the variance of the distribution of a climatic attribute (Figure 3b), then the frequency of extremes can be further increased (or reduced). For adaptation and impact assessment purposes, even without changes in variability, assessments of climate stimuli must consider means, and variations and extremes. Climate change is not just about average temperatures; it is also about such sector-relevant conditions as the frequency of droughts or wet years, changes in diurnal temperature differences, or the intensity of 24 hour precipitation events (Karl and Knight, 1998). The distinction between weather and climate is insufficient to capture the array of climate stimuli and temporal scales pertinent for the analysis of impacts and adaptations.

Other temporal characteristics of climate stimuli have significant implications for adaptation. The speed of onset (or rate of change) is important for adaptations in ecosystems and socio-economic systems, and the duration of a condition may also influence the nature of adaptations (Sonka, 1992; Smithers and Smit, 1997a).

For managed systems, where the opportunity exists for implementing adaptive measures in advance of a stimulus, the degree of certainty or predictability — and the time scale of predictions — is an essential part of understanding and undertaking adaptation. Adaptations may be in response to the anticipation or expectation of a climate-related effect as much as, or in addition to, the climate-related stimulus itself. Most climate stimuli are "predictable" in some sense. There is some confidence about climate change expectations over several decades. Particular extreme events are largely unpredictable (i.e., a storm of certain severity next year), but they are"predictable" in probabilistic terms (i.e., a certain chance next year), and they are "predictable" in an early warning sense (e.g., the storm will arrive in so many hours). The degree of predictability, and the prediction period, is different again for ENSO-related phenomena, for which, upon onset, the probabilistic predictive capability is often quite high and can extend over several months (Hastenrath, 1995).

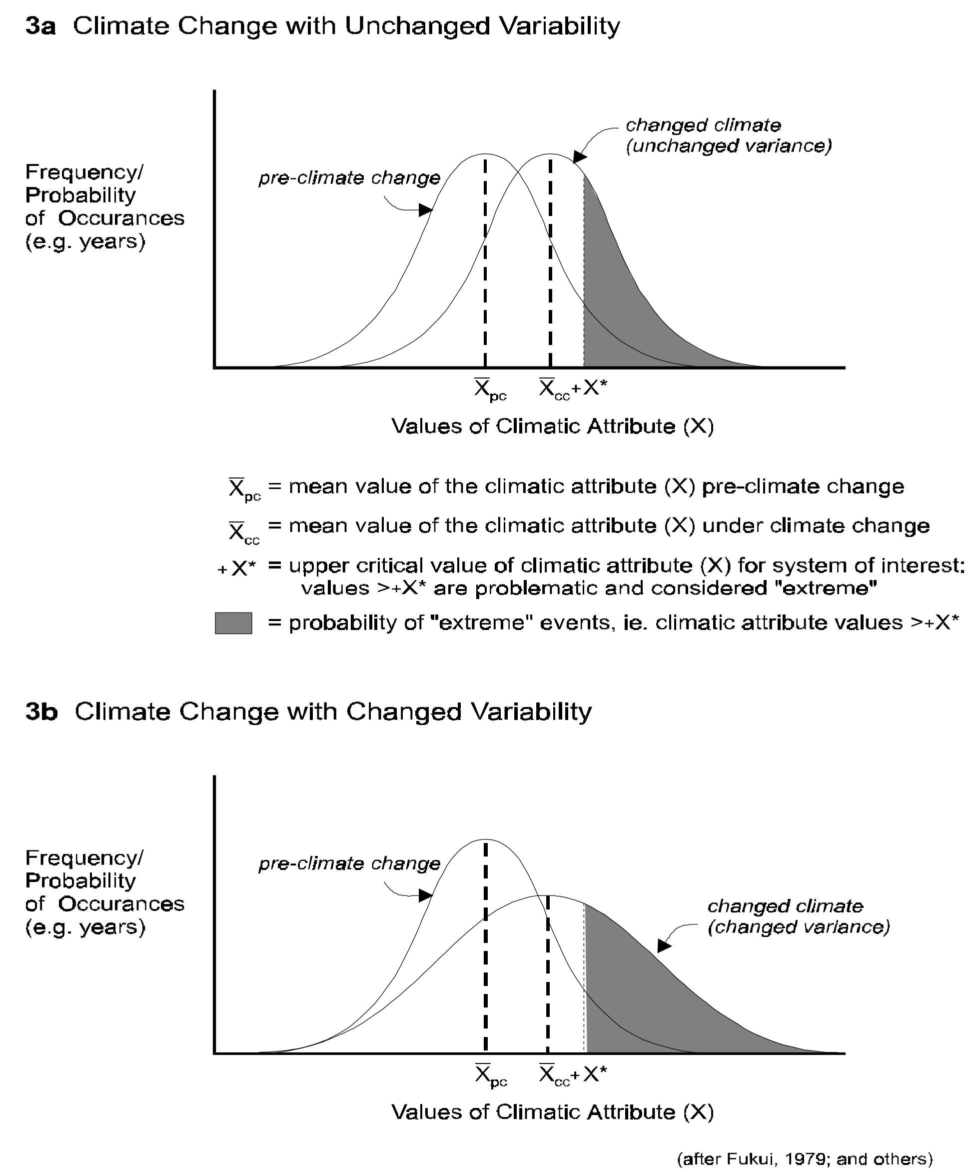

Figure 3. Climate change, variability and extreme events.

Just as climate-related stimuli for adaptation can be differentiated according to their temporal characteristics, so too can they be distinguished according to their spatial characteristics (Smit, 1993; Tol, 1996). Whether a stimulus is experienced locally or over a wide area will influence both the type of adaptation which is likely to occur autonomously and the adaptation measures which might be recommended.

Adaptations vary not only with respect to their climatic stimuli but also with respect to other, non-climate conditions, sometimes called intervening conditions, which serve to influence the sensitivity of systems and the nature of their adjustments. For example, a series of droughts may have similar impacts on crop yields in two regions, but differing economic and institutional arrangements in the two regions may well result in quite different impacts on farmers and hence in quite different adaptive responses, both in the short and long terms. As indicated in Figure 1, systems adapt to a suite of stimuli (climate and other), with climatic effects (either direct or via environmental, social or economic manifestations, and including both risks and opportunities) sometimes being dampened and other times being exacerbated or heightened (Lewandrowski and Brazee, 1992; Sonka, 1992; Smit et al., 1997). Thus, to understand (and predict) adaptations, we need to differentiate and specify what the adaptation is to.

5. Who or What Adapts?

Adaptations represent adjustments in something, sometimes called the "unit of analysis", "exposure unit", "activity of interest", or "sensitive system" (Carteret al., 1994). A necessary step in any analysis or debate on adaptation (whether for impact assessment or for policy evaluation) is to define the system to which the adaptations pertain; this is the point of Figure 1. Are we talking about an individual or a community, a region or a nation, or are we talking about the entire globe? These questions focus attention clearly on the spatial scale of the system, but there is more to it than that. Are we considering adaptation in a species, or in an ecosystem, or in an economic sector, or across a social structure, or across a political entity? This relates to the nature or scope of the system. Are we dealing with instantaneous properties of a system or a system defined to include its variability over years or decades? This relates to the temporal scale of the system.

5.1. SYSTEM DEFINITION

Any consideration of adaptation requires system definition, or delineation of the system's subject and boundaries. Thus, adaptation at the level of a farmer's field might involve planting a new hybrid; at the farm level it might involve diversification or taking out insurance; at the regional or national scales adaptation may relate to changes in the number of farms or modifications to a compensation program; and at a global level, it may involve a shift in patterns of international food trade.

In the ecological field the conventional view is that organisms and species adapt (e.g., by altering genetic structure or moving) but ecosystems do not (Rose and Hurst, 1991; Peters and Lovejoy, 1992; Markham and Malcolm, 1996). However, ecosystems, which include communities and assemblages of species, can and do change (in structure, function, and extent) as a consequence of adaptations by species. Hence, the "ecosystems adapt...naturally" statement in the UNFCCC would refer to adaptations manifest in ecosystem changes. In the ecological field, "adaptation of ecosystems" usually refers to human management practices which influence ecosystem changes. These interpretations are not universal; e.g., Krankina et al. (1997) discuss "natural adaptation of long-lived, complex boreal forests", which are complexes of species or ecosystems. They also refer to management and utilization strategies as means "to assist boreal forests in adaptation to a changing global environment"(197). Pimm (1984) also refers to ecosystem adaptation in reference to reactive adjustments in natural systems to external stresses, including climatic variability and change.

Note that "who" and "what" are not necessarily synonymous. For example, actions by forest managers (who) may result in adaptations in a forest (what). In another forest system, adaptation may occur via a change in species' distribution (what) without any identifiable "who". Adaptations in a coastal zone (what) may reflect actions by authorities (who) which influence actions by individuals (who). Some of these situations can be clarified by distinguishing adaptation as a process from adaptation as a condition. Nonetheless, any systematic treatment of adaptation requires definition of the system of interest.

5.2. System Characteristics

Considerable attention has been given to the characteristics of systems (suitably defined, of course) which influence their propensity to adapt (as part of impact assessment) and/or their priority for adaptation measures (as part of policy development). These characteristics have been called "determinants" of adaptation. Terms such as "sensitivity", "vulnerability", "susceptibility", "coping range", "critical levels", "adaptive capacity", "stability", "robustness", "resilience", and "flexibility" have been used to differentiate systems according to their likelihood of adapting or need for adaptation (Klein and Tol, 1997; Smithers and Smit, 1997a; Sprengers et al., 1994). These characteristics influence (promote, inhibit, stimulate, dampen, or exaggerate) the occurrence and nature of adaptations. In the hazards literature, these characteristics are reflected in "socially constructed" or "endogenous" risks (Hewitt, 1997; Blaikie et al., 1994). Together (in whole or part) they represent the "adaptability" of a system.

Table 1 lists terms commonly used to characterize the adaptive propensity of systems to climate stimuli. Clearly, there is considerable overlap in the basic concepts captured in these terms. Particular terms have been employed to distinguish natural from socio-economic systems, or to differentiate between the pre- and post-adaptation conditions of a system (Klein and Nicholls, 1999). These distinctions are important, but can be captured without narrowing the meaning of widely used terms. Hence, "sensitivity of an ecosystem" is different from "sensitivity of a socio-economic system", and "pre-adaptation vulnerability" is different from "post-adaptation vulnerability".

The terms sensitivity, vulnerability and adaptability capture the broad concepts. To illustrate the distinctions and connections among these central terms, consider a coastal community which is known to be *sensitive* to storms (a recurring climate stimulus, part of variability) in that they significantly change the local environment with effects on living conditions, structures and so on. The community is also expected to be *sensitive* to climate change (a different climate stimulus) in that any change in sea level will alter local land-water relationships, water salinity, and the magnitude of impacts associated with the aforementioned storms (now superimposed on a changed water level).

Many of these *sensitivities* (to storms and climate change) represent detrimental or harmful impacts for the coastal community. Thus, the community is *vulnerable* to storms in that it is susceptible to water contamination, property damage, temporary displacement and loss of life in the event of storms. The reasons for this *vulnerability* relate to the nature of settlement, reflecting population pressure on land resources, benefits of coastal locations in periods without storms, a socio-political system which facilitates settlement in storm-vulnerable sites, together with the relatively infrequent occurrence of severe storms, such that community members perceive little risk, and so on.

In this hypothetical case, the community has some, but limited, *adaptability* to storms. There is knowledge of the risks; there is awareness of structural designs with ability to accommodate storms; there is some preparation for evacuation in time of danger, *et cetera*. However, *adaptability* is limited in this hypothetical case in that risks tend to be underestimated, the storm-adaptive structures are rarely built, and early warning systems are poor at best, so evacuation cannot be initiated early. Again, the reasons underlying this limited level of *adaptability* could be documented, likely relating to similar socio-cultural, political-economic forces underlying sensitivity and vulnerability.

There is a growing literature on the conditions of regions and societies which influence their vulnerability and adaptability (Adger, 1999; Adger and Kelly, 1999; Bohle et al., 1994; Burton, 1997; O'Riordan and Jordon, 1999; Ribot et al.,

Table I

Terms to describe characteristics of systems pertinent to adaptation*

Sensitivity	Degree to which a system is affected by, or responsive to, climate stimuli
Susceptibility	Degree to which a system is open, liable or sensitive to climate stimuli (similar to sensitivity, with some connotations toward damage)
Vulnerability	Degree to which a system is susceptible to injury, damage, or harm (one part — detrimental — of sensitivity)
Impact Potential	Degree to which a system is sensitive or susceptible to climate stimuli
Stability	Degree to which a system is not easily moved or modified
Robustness	Strength; degree to which a system is not given to influence
Resilience	Degree to which a system rebounds, recoups or recovers from a stimulus
Resistance	Degree to which a system opposes or prevents an effect of a stimulus
Flexibility	Degree to which a system is pliable or compliant (similar to adaptability, but more absolute than relative)
Coping Ability	Degree to which a system can successfully grapple with a stimulus (similar to adaptability, but includes more than adaptive means of "grappling")
Responsiveness	Degree to which a system reacts to stimuli (broader than coping ability because responses need not be "successful")
Adaptive Capacity	The potential or capability of a system to adapt to (to alter to better suit) climatic stimuli
Adaptability	The ability, competency or capacity of a system to adapt to (to alter to better suit) climatic stimuli

*These definitions of systems' characteristics are based on widely (but not unanimously) held conventions. They focus on the distinguishing generic properties, and do not include factors which might influence the state of a property or the forms it might take. The terms "climate stimulus" and "system" are used as established earlier.

1996). Drawing from the fields of natural hazards and sustainable development, researchers are attempting to better understand the nature and types of vulnerability, "the capacity to be wounded" (Kates et al., 1985), or the amplification or amelioration of risks (Downing, 1991; Kasperson and Dow, 1991).

Perceptions of risks are known (e.g., from the natural hazards literature) to be important in influencing communities' actions relating to vulnerabilities. In the case of climate-related risks, such perceptions, and the role of information of various kinds in changing perceptions, are problematic because of the difficulty of separating climate change signals (including extremes) from the "normal pulse" of systems. Some of the complexities underlying adaptability of systems, particularly related to uncertainty about climatic risks, are explored in Reilly and Schimmelpfennig (1998).

The concepts of sensitivity, vulnerability and adaptability and the relationships among them are increasingly invoked in both impact assessments and policy recommendations. IPCC (1996) Second Assessment Report (SAR) Summary for Policymakers (p.4) notes: "the most vulnerable systems are those with the greatest sensitivity to climate change and the least adaptability", yet the SAR refers to very little substantive research on vulnerability, sensitivity and adaptability.

6. How Does Adaptation Occur?

Adaptive responses of systems to climate stimuli can occur via a variety of processes and can take many forms. Several useful distinctions and typologies have been proposed. For example, Carter et al. (1994) note the widely (but not universally) acknowledged distinction between "autonomous" (automatic, spontaneous, passive or natural) adaptations which occur in systems as a matter of course, and those that require or result from deliberate "policy decisions", and are called "planned" (strategic or active) adaptations. It is widely accepted that (unmanaged) biophysical systems are limited to autonomous adaptations. In socio-economic systems, autonomous adaptations can be grouped according to their degree of spontaneity (in-built, routine and tactical); and planned adaptations may be distinguished by the intent and timing of the initiative and/or by the actors involved (private individual or governments).

There is also the recognition that modifications (adaptations) to systems in response to non-climatic stimuli may unintentionally or "incidentally" serve as an adaptation to climatic change or variability. For example, wetlands preservation – undertaken for the purpose of preserving wetlands – may also reduce vulnerability to sea-level rise and/or storms.

Most analysts distinguish adaptations according to when they occur relative to the stimulus: anticipatory versus reactive. Burton et al. (1993) apply categories from the environmental hazards field to distinguish adaptation behaviours: prevent loss, tolerate loss, spread loss, change use or activity, change location, restoration. Stakhiv (1993) groups adaptive strategies according to the time frame of the stimulus: long range, tactical, contingency, and/or analytical. Carter et al. (1994) provide a list of adaptive management measures: structural or infrastructural, legal and legislative, institutional, administrative, organizational, regulatory, educational, financial (incentives and/or subsidies on the one hand and taxes, tariffs or user fees on the other), research and development, market mechanisms, and technological change. Bijlsma et al. (1996) classify adaptations by their function: retreat, accommodate or protect. Smithers and Smit (1997a) differentiate adaptations on the basis of intent or purposefulness, the role of government, the spatial and social scale, duration, form and effect.

Clearly, the question "how does adaptation occur?" (Figure 1) can be answered on the basis of numerous attributes relating to processes and to outcomes, and is closely connected to the questions "who or what adapts?" and "adaptation to what?". Condensing attributes into comprehensive, mutually-exclusive categories yields rather non-specific classes like "major, minor" or "Level I, II, III". The approach employed here is to specify the central attributes by which adaptations can be described and differentiated, either discretely or in combination. The following attributes are common elements of typologies of adaptation:

> Based on intent or purposefulness with respect to a climate stimulus, *autonomous* or spontaneous adaptations can be distinguished from consciously *planned* or deliberate intentional adaptive responses to a stimulus (actual or anticipated). Adaptations in unmanaged natural systems are considered to be autonomous. Adaptations initiated by public agencies are usually conscious strategies, but adaptations by private individuals or communities may be autonomous or planned, or some combination of the two, especially when adaptations are considered at different spatial and temporal scales (see Smithers and Smit, 1997b). Impact assessments focus largely, but not exclusively, on autonomous adaptations, whereas adaptation evaluation and prescription necessarily deal with intentionally planned adaptive measures and policies.
>
> Based on timing of the action relative to the climate stimulus, adaptations may be *reactive* (or responsive or *ex post*), *concurrent* (during), or *anticipatory* (proactive or *ex ante*). In unmanaged natural systems adaptations are invariably reactive, and autonomous adaptations in socio-economic systems are usually concurrent or reactive. The greatest interest in planned adaptations, whether in the public or private sectors, is with anticipatory initiatives, in order to avoid or reduce harmful impacts and/or benefit from opportunities.

Based on the temporal scope, adaptations can be short-term or longer-term. This distinction is often considered to be synonymous with tactical versus strategic adjustments (Stakhiv, 1993; Smit et al., 1996); in the natural hazards field it is adjustment versus adaptation (Burton et al., 1993) and is associated with instantaneous versus cumulative and autonomous versus policy (Riebsame, 1991; Easterling, 1996).

Based on their spatial scope or institutional extent, adaptations can be localized or widespread. Based on their intent, adaptations may decrease vulnerability or modify effects (Jepma et al., 1996). Based on the form they take, adaptations can be distinguished according to whether they are primarily technological, behavioural, financial, institutional or informational.

While many types of adaptation have been distinguished, there is less scholarship on actual adaptation processes. Models of how adaptation options (particularly planned ones) should be identified and implemented are now quite common (Klein, 1998; Jodha, 1989; Smith, J., 1996; and see Section 8). Knowledge of the processes by which individuals, communities, sectors or regions adapt, in practice, tends to come mostly from empirical analogue studies (Glantz, 1996; Meyer et al., 1998; Downing et al., 1989; Smit et al., 1997). These studies suggest that adaptation tends to be incremental and ad hoc, to assume multiple forms, to be in response to multiple stimuli (usually involving a particular catalyst) and to be constrained by economic, technological and socio-economic conditions.

Numerous other distinctions exist, based on the type of process or outcome (Burton et al., 1993; Carter et al.., 1994; Darwin et al., 1995; Klein and Tol, 1997; Smithers and Smit, 1997a). It is also possible to categorize adaptations according to their costliness, effectiveness, and implementability. These attributes are important differentiators, and are often considered in analyses of adaptations for impact assessment. For example, the costs of an adaptation and its reduction of impact damages (or enhancement of benefits) need to be calculated to estimate residual impacts. However, these attributes are also central features of evaluation and prescriptions of adaptations, and are addressed in more detail in Section 8. The term "maladaptation" is often considered (Smit, 1993; Burton, 1997). Assuming adaptation implies an adjustment to make more suitable, effectiveness or success can range from large improvement in suitability to no improvement in suitability. In this sense, "maladaptation" is really "no adaptation" where, in addition to there being no improvement in suitability, there is a deterioration in suitability.

The various attributes which permit specifying types of adaptation are often related to each other and to the characteristics of climatic stimuli and the systems of interest (Figure 1). Several models of the interconnectedness among types of stimuli, characteristics of symptoms, and attributes of adaptations provide insights into the process of adaptation, and are considered in the following section.

7. Analysis and Prediction of Adaptation

An understanding of "what is adaptation" — including who or what does it, how it occurs, and in response to what — is necessary for both the estimation of likely adaptations in impact assessment and the evaluation of adaptations in policy development. Analytical approaches to understanding and predicting adaptations — sometimes called the science of adaptation — are numerous, and are not reviewed here in detail. However, within the climate change community especially, the approaches tend to fall into one of three broad and overlapping categories: conceptual models of adaptation processes, numerical models of impacts, and empirical analyses of adaptations.

Conceptual Models of the Adaptation Process specify sequential relationships and feedbacks, such as climatic (and non-climatic) stimuli, sensitivity and vulnerability of systems, short-term or autonomous adaptations, initial impacts, longer-term or strategic adaptations, and net or residual impacts. Such models have been developed both for adaptation processes generally (e.g., Feenstra et al., 1998) and for particular sectors or applications (e.g., Klein and Nicholls, 1999; Sonka and Lamb, 1987; Smit et al.., 1996). These conceptualizations of the processes, sequences, and interconnections commonly provide the framework or structure for empirical analyses and for numerical impact assessment modelling (e.g., Easterling et al., 1993; Rosenzweig and Parry, 1994).

Numerical Impact Assessment Models, whether of particular ecosystems or sectors, or of integrated regional or global systems, now invariably include adaptations via assumptions (Tol et al., 1997). These assumptions about when, how and to what adaptations occur are based on theoretical principles (as in Adams et al., 1993; Hurd et al., 1997; Yohe et al., 1996 and most economic models), inference from observed associations (as in Leemans (1992) and many ecological models), and arbitrary selection, speculation or hypothesis (as in many models assuming technological and behavioural adaptations). Comprehensive integrated assessment models (which specify connections among emission, atmosphere, climate, effects, impacts and responses) also include assumptions about adaptation (*e.g.*, Hulme *et al.*, 1995). The common distinguishing feature of these numerical modelling analyses of impacts is that they use information on adaptations to estimate future impacts of climate stimuli; after the effects of adaptation have been factored in.

The focus of the *Empirical Adaptation Studies* is to better understand the nature and processes of adaptations themselves by observing, documenting and reconstructing current and past adaptations to climate (and other) stimuli. Some ecological and paleoecological studies reconstruct species or community dynamics over hundreds and thousands of years (*e.g.*, MacDonald et al., 1993). Analogue studies (e.g., Glantz, 1988; Olsthoorn et al., 1996), document adaptive responses to climatic stimuli in resource-based economic sectors and communities over periods of several decades. Other empirical analyses have examined the actual adaptive behaviour in key sectors such as agriculture in light of climatic variability and extremes over even shorter time periods (e.g., Smithers and Smit, 1997b; Smit et al., 1997). Analyses of adaptation processes tend to start with the system of interest, then assess its sensitivity and adaptability to climate and other stimuli. This analytical strategy is consistent with the "adjoint approach" (Parry, 1986), and the "shift-in-risk" perspectives (Warrick et al., 1986). These empirical studies have yielded insights — particularly with regard to the relevant climate stimuli and the role of non-climate forces— which provide a basis for modifying some of the assumptions commonly made in modelling exercises.

Clearly, the empirical, conceptual, and numerical modelling analyses are complementary. Impact assessment requires improved specification of adaptations, especially the endogenous, intertemporal, cumulative adaptation of societies and economies to variable and changing climatic stimuli. There is a recognized need in the impact assessment field for more systematic treatment of behavioural and decision-making responses to climatic stresses (e.g., Sonka, 1992) and of the inherent uncertainties (e.g., Viscusi, 1992).

The three broad approaches to the analysis of adaptation contribute primarily to the predictive objective (i.e., "what adaptations are likely?"), which in turn contributes to answering "what impacts are likely?" and hence "how dangerous?" Approaches to evaluative and prescriptive analyses address the question "how good are adaptations?" and hence "what adaptations should be implemented?"

8. Evaluation of Adaptations

Considerable attention has recently been given to the systematic evaluation of climate-related adaptations. Two broad categories of evaluation are apparent, each with distinctive applications.

One body of work, well summarized by Tol et al. (1997), deals with estimating the costs of autonomous, mainly (but not exclusively) reactive, adaptations, undertaken privately (i.e., not adaptation policies of government). As assessments of climate impacts (commonly measured as "costs", which include both damages and benefits) have increasingly incorporated adaptations, and particularly as impact models and "integrated assessment models" have shown the potential of adaptation to offset initial impact costs, interest has grown in calculating the costs of autonomous adaptations. Whether or not climate change or another climate stimulus is expected to have problematic or "dangerous" impacts depends on the adaptations and their costs. A common basis for evaluating impact costs is to sum adaptation costs and residual damage costs (Fankhauser, 1996). Procedures for defining and calculating such adaptation costs are subject to ongoing debate. Tol et al. (1997) note that most approaches consider equilibrium adaptation costs but ignore transition costs. Hurd et al. (1997) include both market and non-market adaptation in their assessment of impact costs. Any comprehensive assessment of adaptation costs (including benefits) would consider not only economic criteria but also social welfare and equity. This cost estimation for autonomous adaptations is not only important for impact assessment, it is also a necessary ingredient in the "base case", "reference scenario" or "do nothing option" for evaluations of policy initiatives, with respect to both adaptation and mitigation.

The second category of adaptation evaluations deals with planned, mainly (but not exclusively) anticipatory adaptations, undertaken or directly influenced by governments as a policy initiative. In this case, the evaluations are essentially of potential policy measures or strategies; the basic questions being asked are: "what are good adaptations?" and "is it worth undertaking these adaptations?" Some very general steps to addressing these questions are offered in Carter et al. (1994), including the selection and weighting of evaluation criteria. Somewhat more detailed procedures for evaluating these "anticipatory adaptation policies" in the climate change context are outlined in Smith and Lenhart (1996). This approach addresses the management of institutional processes and players, and proposes net benefits and implementability as central evaluative criteria. Numerous other considerations are noted, including flexibility, benefits independent of climate change ("no regrets"), local priorities, levels of risk, and time frames of decisions. Stakhiv (1996) and Frederick (1997) consider the need for adaptations to climate change in the U.S. water resources sector, and conclude that existing institutions and planning processes can deal with climate stimuli (i.e., they represent "adaptive management"), but there should be some adaptation in the evaluation criteria. From a disaster management perspective, Tol (1996) argues that policies need to be evaluated with respect to economic viability, environmental sustainability, public acceptability and behavioural flexibility. Klein and Tol (1997) describe methodologies for evaluation, including cost-benefit, cost effectiveness, risk-benefit, and multi-criteria methods.

Fankhauser (1996; 1997) provides an economic efficiency framework in which adaptation actions are considered justified as long as the additional costs of the adaptation are lower than the additional benefits from the associated reduced damages. "Optimal" levels of adaptation (in an economic efficiency sense) are based on minimizing the sum of adaptation costs and residual damage costs. Such studies require the definition of a base case which involves analysis of autonomous adaptations. These, and other normative studies (e.g., Goklany, 1995; Titus, 1990) illustrate the range of principles and methods which have been proposed for identifying, evaluating and recommending adaptation measures.

9. Conclusions

This paper treats adaptation separately from mitigation — as a matter of focus — yet the two main types of policy response to the climate change issue are not independent. They are driven by the same problematique. There is the question of trade-offs or complementarity between the two as policy options (Ausubel, 1991; Fankhauser, 1996). Some adaptations may also have implications for mitigation, such as those that relate to energy use. These interactions and feedbacks are developed elsewhere (e.g., Jepma et al., 1996). The contribution of this anatomy paper is to enhance the understanding of the adaptation component.

Adaptation is an essential ingredient both in assessments of climate impacts and in the development of adaptation policies. The anatomy of adaptation, drawn from a broad consistency in the use of terms across the field, distinguishes three core elements: adaptation to what, who or what adapts, and how does adaptation occur. The evaluation of adaptations addresses the question: how good is the adaptation?

Adaptation to climate stimuli includes adaptive responses to extremes, to variability from year to year, and to changes in long-term mean conditions, both independently and as they relate to each other. Yet the sensitivity and vulnerability of systems and their adaptations are not just to climate, nor do these systems occur in discrete states. Rather, social, economic and ecological systems evolve in a piecemeal, ongoing fashion in response to stimuli of all kinds. Recognition of this milieu is important for analyses of adaptation. It does not mean that adaptation studies necessarily require predictions for sectors and environments. Instead, the comparative-static approaches to adaptation and impact assessment, which begin with specified futures for climate and socio-economic systems, need to be supplemented by sensitivity analyses and investigations of the dynamics of adaptation processes — a transient adaptation approach.

Hence, there is considerable need and opportunity for improving the science of adaptation and its application to policy. The rather *ad hoc* treatment of adaptation in impact assessments (which still tend to rely on assumptions and focus on technological and structural measures) can be improved by specifying adaptations — including those involving institutions and behaviour — which better match observation and theory of system dynamics in response to stresses, including both risks and opportunities.

The identification and evaluation of adaptation policies can also learn from the successes and failures of the past. For example, Magalhaes (1996) shows how the experience in northwest Brazil over several decades illustrates the need for adaptation to be part of regional development planning in order to increase overall societal capacity to handle a suite of stresses.

Adaptation is not just a climate change issue. Improved adaptation to current conditions is likely to enhance prospects for reducing costs of climate change (Burton, 1996; Smith et al., 1996). However, in many parts of the world, more urgent problems are posed by current variability and extreme events in their own right. This is definitely the case in developing countries subject to recurring extremes such as droughts, floods, and tropical storms. However, huge losses associated with extreme climate or weather events have been recently experienced in North America and Europe as well, highlighting the utility of adapting in order to manage risks and benefit from opportunities.

Acknowledgements

This paper benefited from suggestions by anonymous reviewers, Sally Kane, Gary Yohe, and participants at IPCC Workships on Adaptation. The work on which this paper is based was supported by Environment Canada, the U.S. National Oceanic and Atmospheric Administration, and the Social Sciences and Humanities Research Council of Canada.

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(Received 27 May 1998; in revised form 21 December 1999)