ADAPTING TO CLIMATE CHANGE IN AFRICA

THOMAS E. DOWNING[1], LASSE RINGIUS[2], MIKE HULME[3] and DOMINIC WAUGHRAY[4]
[1]*Environmental Change Unit, University of Oxford, U.K. (corresponding author)*
[2]*CICERO, Oslo, Norway*
[3]*Climatic Research Unit, University of East Anglia, Norwich, U.K.*
[4]*Institute of Hydrology, Wallingford, U.K.*

(Received: 10 December 1996; accepted in final form 28 April 1997)

Abstract. The intersection of present vulnerability and the prospect of climate change in Africa warrants proactive action now to reduce the risk of large-scale, adverse impacts. The process of planning adaptive strategies requires a systematic evaluation of priorities and constraints, and the involvement of stakeholders. An overview of climate change in Africa and case studies of impacts for agriculture and water underlie discussion of a typology of adaptive responses that may be most effective for different stakeholders. The most effective strategies are likely to be to reduce present vulnerability and to enhance a broad spectrum of capacity in responding to environmental, resource and economic perturbations. In some cases, such as design of water systems, an added risk factor should be considered.

Key words: adaptation, Africa, agriculture, climate change, vulnerability, water

1. Introduction

The prospect of adverse climate change is not going to diminish in the near future. Publication of the Second Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1996) marks a shift in policy issues from 'What is the likelihood of climate change?' to 'What are the most appropriate responses to climate change?' The IPCC report is the largest scientific review of an international environmental threat ever undertaken, encompassing the work of several thousand scientists.

Responding to climate change will encompass two strategies: (i) abatement: controlling greenhouse gases (GHGs) to stabilize climate change at an acceptable level and (ii) adaptation: preparing for the impact of climate change that we are committed to given existing GHG concentrations and projections of emissions over the next few decades.* This article focuses on the second strategy in Africa, perhaps the continent most vulnerable to adverse climate change.

We argue that:

1. The intersection of present vulnerability and risk of adverse climate change warrants proactive action now, especially in Africa, to reduce the threat of large-scale, adverse impacts of climate change.

* The terms abatement and adaptation are commonly defined in this sense of upstream prevention and downstream coping, although many other definitions and other terms may also be appropriate.

2. The process of planning adaptive strategies requires an inventory of potential options, based on a systematic typology and evaluation of priorities and constraints.
3. Implementing adaptation strategies requires an understanding of the stakeholders and their management of resources.

We begin by asking the question, Why invest now in adaptation? The answer depends on the balance of present resource management in Africa and the potential risk of adverse climate change. (A brief review of climate scenarios for Africa is presented as an appendix.) This sets the stage to ask What is the range of potential adaptive strategies? And, Who should adapt? Throughout we focus on two sectors, agriculture and water. The conclusion suggests that enhancing present resource management and reducing vulnerability to climatic hazards are essential to prepare for the potential impacts of climate change. This initial review needs to be followed by more thorough assessments by African governments, public organizations and businesses toward defining their futures. *

2. Why Invest Now in Adaptation?

The argument for adaptation is related to the extent of present vulnerability and the potential impact of climate change (see Henderson–Sellers, 1996). Compared to industrialized countries, developing countries are more dependent on climatic resources and have a lower adaptive capacity at present (Hernes *et al.* 1995; Schelling, 1992:6). The impacts on global climate of GHGs already in the atmosphere could be felt for several generations, regardless of present abatement measures. The IPCC estimates that an increase in global mean temperature from 0.1 to 0.7°C will occur after 1990 because of carbon dioxide emissions prior to 1990 (Houghton *et al.*, 1995:10). Situations where it is clearly preferable to anticipate climate change are discussed in the next section.

However, some have concluded that it is better to delay adaptation to climate change (e.g., Ausubel, 1991). Many key factors in climate change predictions are uncertain, better and cheaper technology will be available in the future, and future generations will have greater wealth that can be used for adaptive purposes. However, it is doubtful that market-based approaches to adaptation will be sufficient or optimal on their own in Africa. The timing of specific strategies needs to be clarified; planning adaptation to climate and other global changes should be an ongoing component of resource management.

* We are grateful for the many collaborators over the past decade of our research in resource management, climatic hazards and climate change in Africa. Two projects contributed directly to this paper: preparation of guidelines for adaptation to climate change for the African Technical Division of the World Bank and Norwegian Government (Ringius *et al.*, 1996) and a review of the impacts of climate change in southern Africa funded by the World Wide Fund for Nature (Hulme, 1996).

Table I
Regional distribution of water resources in Africa

Region	Population 1994 1000	Area $1000km^2$	Rainfall km^3/yr	Water resources km^3/yr	Withdrawals km^3/yr	Withdrawals % of water resources
Northern	123,697	5,753	411	50	76.3	152.6
Sudano-Sahelian	83,350	8,591	2,878	170	24.1	14.2
Gulf of Guinea	172,804	2,106	2,965	952	6.1	0.6
Central	71,473	5,329	7,621	1,946	1.4	0.1
Eastern	142,531	2,916	2,364	259	6.5	2.5
Indian Ocean Islands	15,048	591	1,005	340	16.6	4.9
Southern	92,205	4,739	2,967	271	18.9	6.9
Total	701,108	30,024	20,210	3,988	149.9	3.8

Notes: **Northern:** Algeria, Egypt, Libya, Morocco, Tunisia; **Sudano-Sahelian:** Burkina Faso, Cape Verde, Chad, Djibouti, Eritrea, Gambia, Mali, Mauritania, Niger, Senegal, Somalia, Sudan; **Gulf of Guinea**: Benin, Cote d'Ivoire, Ghana, Guinea, Guinea Bissau, Liberia, Nigeria, Sierra Leone, Togo; **Central:** Angola, Cameroon, Central African Republic, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Zaire; **Eastern:** Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda; **Indian Ocean Islands:** Comoros, Madagascar, Mauritius, Seychelles; **Southern:** Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe.
Source: World Bank (1993), World Resources Institute (1994)

Another argument for postponing adaptation is that climate change is likely to happen gradually, at the same pace as societal adaptation. However, future climate change is likely to be more rapid than has occurred within recent human history, and in any case we have little knowledge of how quickly societies can adapt to climate change (both long term trends in mean conditions and changing risks of climatic hazards). The IPCC emphasised the occurrence of non-gradual changes (Houghton *et al.,* 1996: 7) and evidence from the distant past (more than 5,000 years ago) suggests that climate has changed considerably within decades (Dansgaard *et al.*, 1993; Overpeck, 1996).

Exposure to climatic hazards and vulnerability to climate change varies enormously between regions and sectors in Africa. Only Central Africa has a widespread abundance of water, although most of Africa uses less than 10% of its water resources (Table I). Factors that contribute to vulnerability in African water systems include high seasonal and inter-annual variations, river basins that span political boundaries, and poorly developed national and regional institutions. For example, northern Africa imports half of its consumption.

Most of Africa's water (85%) is used in agriculture, which is highly sensitive to climatic fluctuations, with a low intensity of cultivation, little irrigation, low yields and stagnant or declining food production (Table IIa). While GNP per capita is low, and dependent on agriculture, African economies have been growing. Investment in agriculture, however, is low (Table IIb). Most importantly, household expenditure

Table II

Agricultural sensitivity, capacity and vulnerability in Africa

(a) Sensitivity to agricultural impacts of climate change

Region	Population Density per km^2	Population Growth % per yr	Crop Land % of total	Irrigated Land % of total	Average Yield of Cereals kg/ha	Food Production Index 1970 = 100
Northern	226	2.25	5%	27	1,973	115
Sudano-Sahelian	106	2.72	4%	7	727	90
Gulf of Guinea	891	2.83	21%	2	892	100
Central	145	2.70	4%	1	923	87
Eastern	541	2.88	10%	2	1,363	92
Indian Ocean	262	1.96	5%	23	1,988	98
Southern	208	2.56	6%	7	929	76
Total	253	2.65	6%	8	1,098	92
Bangladesh	9,853	2.18	72%	31	2,572	96
Thailand	1141	0.92	45%	19	2,052	109
Mexico	491	1.55	13%	21	2,430	100
Greece	795	0.07	30%	31	3,700	101
United Kingdom	2404	0.19	28%	2	6,332	112

(b) Capacity to adopt to agricultural impacts of climate change

Region	GNP per capita $	GDP in agricultural %	GDP Growth Rate %/yr	Fertiliser use kg/ha	Public agricultural investment $million
Northern	1,285	17	3.60	94	25
Sudano-Sahelian	860	34	2.36	5	7
Gulf of Guinea	760	39	1.87	6	15
Central	760	22	2.15	2	5
Eastern	593	47	3.05	12	13
Indian Ocean	280	22	3.85	140	6
Southern	333	21	3.38	27	7
Total	355	30	2.75	25	11
Bangladesh	205	37	4.20	101	68
Thailand	1,697	13	7.80	39	78
Mexico	2,971	8	1.50	69	129
Greece	6,530	17	1.60	172	25
United Kingdom	33,850	2	2.80	350	347

(c) Vulnerability to food crises

Region	Expenditure on food % of H/hold exp	Food aid kg per cap	Refugees No.	Female literacy %	Infant mortality per 1000
Northern	42	18	221,450	45	59
Sudano-Sahelian	42	13	974,800	17	119
Gulf of Guinea	39	6	819,750	28	109
Central	39	3	480,500	41	97
Eastern	37	4	1,408,150	43	102
Indian Ocean	57	12	0	73	66
Southern	57	15	1,793,800	53	85
Total	57	10	5,698,450	35	97
Bangladesh	59	12	245,300	22	108
Thailand	30	2	255,000	90	26
Mexico	35	3	47,300	85	35
Greece	30	−1	1,900	89	8
United Kingdom	12	−3	24,600	0	7

Note: Regions as for Table 1.
Source: World Resources Institute (1994)

on food is high (on average) and human development is inadequate (high infant mortality and low female literacy), both being indicators of high socioeconomic vulnerability (Table IIc). Dependence on food aid and high numbers of refugees highlight potential economic and political instability. For example, Eastern Africa has a population density comparable to Mexico, but higher population growth, a lower percentage of cropped land, little irrigation, cereals yields that are a third lower, and food production that has declined in the past two decades. GDP is less than a fourth of Mexico's and almost half of GDP is in agriculture. Modest fluctuations in climatic resources would have immediate impacts on the national food balance and economy, perhaps exacerbating present vulnerability as indicated by high expenditure on food, significant receipts of food aid, the burden of refugees, and low nutritional status.

How great is the threat of climate change in Africa? The most important elements of climate change for Africa are CO_2 enrichment, changes in precipitation and changes in extreme events. Unfortunately, only projected changes in CO_2 concentrations are reasonably sure. Although impacts are contingent on scenarios of climate change (see the appendix), recent research highlights many of the issues that need to be addressed (see Table III). *

The effect of a combination of CO_2 enrichment, warmer temperatures and altered precipitation are contingent on the balance of evapotranspiration and precipitation. The direct effect of carbon dioxide enrichment on plants tends to increase

* See Hulme (1996) and Hulme *et al.* (1995) for more detailed examples of impacts in Africa.

the rate of photosynthesis (and yields) and reduce water use. According to the IPCC (Watson *et al.*, 1996), the effect of a doubling in CO_2 concentrations (from the present) varies from a 10% to almost three-fold increase in biomass. This effect is likely to be more significant for crops than for river basins where perennial vegetation may attenuate the CO_2 responses.

Warmer temperatures increase plant demand for water and alter the distribution of agroecological zones. Highlands may become more suitable for annual cropping due to increased temperatures (and radiation) and reduced frost hazards. In some lowlands high temperature events may affect some crops. Warming tends to accelerate plant growth, reducing the length of the growing season. If growth is accelerated during the period in which the grain is filling, the quality of yields may decrease.

Since thermal suitability is not a major constraint in Africa, the dominant effect of climate change will be in altered water balances, especially in tropical and subtropical regions. Higher temperatures increase the atmospheric demand for moisture, or potential evapotranspiration (PET). Changes in monthly PET per degree of warming are on the order of 100 mm in climates typical of semi-arid Africa. Where soils are deep and changes are modest, some amelioration of the impacts can be expected. In shallow, sandy soils reduced precipitation will have immediate consequences for agriculture. Effects on water resources are clear: changes in runoff and groundwater recharge.

In general, the impacts of average changes in CO_2, temperature and precipitation are relatively modest over the next few decades in most of Africa. More worrisome are spatial shifts in resources and the potential for dramatic shifts in climatic hazards. Spatial patterns of temperature and precipitation will shift, resulting in different configurations of cropping zones and hydrological regions. If this leads to differences in investment, some regions may become less suitable and sources of out-migration. For example, as the highlands of Kenya become more productive and the lowland semi-arid regions less suitable for agriculture (see Fischer *et al.* 1996), large-scale internal displacement of populations could threaten political stability.

Changes in climatic variability and climatic hazards alter the risk distribution of agricultural or water system yields. Prolonged drought would have the greatest impact. If the 1991-92 drought in southern Africa, for example, became more frequent, perhaps occurring every decade instead of every century, the consequences for rural agriculture and settlement would be enormous. However, the present state of knowledge of climate change prediction precludes any definitive (or even approximate) estimate of potential shifts in extreme events such as drought. Climate change will have mixed impacts. Sectors in some regions may benefit, while the same sector in other regions or other sectors in the same region may suffer. Within specific sectors, the impacts (positive and negative) will not be evenly distributed among stakeholders or populations at-risk. Even without climate change, agriculture and water resources in Africa are likely to be severely stressed during

Table III
Effects of climate change on agriculture and water resources

Climate change	Effect	Impact
CO_2 enrichment	Increased photosynthesis; Reduced transpiration	Increased water use efficiency
Increased temperature	Faster plant growth, increased transpiration but over shorter growing season; Reduced runnoff and reduced groundwater recharge; Higher demand for water for irrigation, bathing and cooling	Reduced economic agricultural yields; Changes in water yields; Higher stress and peak loads for water delivery systems
Rise in sea level	Land loss; Saline intrusion into coastal aquifers; Movement of salt-front estuaries affecting freshwater abstraction points	Reduced coastal agriculture; Reduced water quality in coastal areas; Reduced groundwater abstraction
Change in seasonal precipitation	Change in soil moisture; Change in river runoff and groundwater recharge	Changes in agricultural yields; Changes in projected yields of reservoir systems; Changes in water quality
Change in spatial patterns of temperature and precipitation	Shift in agroclimatic suitability; Shift in basin hydrology (surplus and deficit regions)	Changes in cropping systems; Changes in infrastructure to supply water
Change in variability of precipitation (daily and inter-annual)	Changes in water stress between rainfall events; Changes in peak runoff	Increased requirement for storage, in marketed produce, subsistence crops and water supply systems
Change in drought hazard	Change in seasonal water stress or off-season water replenishment	Altered risk for agricultural production and water resources
Change in flood hazard	Change in risk in flood plain; Change in area affected	Altered risk, especially for water resources; Change in reservoir operations

the next half century. For example, using the World Bank benchmark for water scarcity of $500m^3$/cap/year (Falkenmark and Widstrand, 1992), Table IV indicates the extent of the future crisis in water availability in selected African countries. Global warming adds further pressure on the adaptability of the water system. Similarly, a dramatic reversal of the decline in African agricultural productivity is required to keep pace with population growth and economic demand.

Example of impacts on agriculture in southern Africa

Three levels of impacts—the field, region and continent—illustrate varying approaches to climate change impact assessment in Africa.

Table IV
Water availability (m^3 per capita per year) in 2050 under a range of climate scenarios

Country	Present (1990)	Present Climate (2050)	Climate change (2050) (range of scenarios)
Egypt	1005	452	300-600
Kenya	640	150	210-250
Madagascar	3330	710	480-730
South Africa	1320	540	150-500
Togo	3400	900	550-880

Source: Watson *et al.* (1996)

At the field scale, the Ceres-Maize crop model (Tsuji *et al.*, 1994) was run for four sites in Zimbabwe as part of the US Country Studies project (Makadho, 1996, Matarira *et al.* 1996), following earlier work reported by Muchena (1994, see also Downing, 1992). The Ceres model simulates crop development and yield using specialized functions to calculate photosynthesis, phenological stage, evapotranspiration, and partitioning of biomass. Simulations were discrete, with the default initial soil water moisture set at the field capacity of the soils. Nitrogen stress and pests were not simulated. The cultivar was R201, common in communal farming regions in Zimbabwe.

Average potential yields, as simulated with 40 years of climate data, range from over 3.5 t/ha in the high veld to barely 1 t/ha in the semi-arid lowlands. There is a considerable gap between these potential yields and the yields realized by farmers in the region. In the semi-arid zones, 500 kg/ha would be an above-average yield. Average commercial farm yields in the high veld are closer to the potential due to application of fertilizer.

For the two equilibrium scenarios of climate change, yields decrease in the high veld and semi-arid region, but increase in the middle zones. If the season start is adjusted, the yield decreases in the high veld and semi-arid zones become sizable increases. For example, planting on 15 October at Karoi in the high veld results in 3.7 t/ha (simulated) at present. With climate change and delaying planting to 1 November, yields would be 4.6 t/ha, a 25% increase over the present. In the lowlands, the season would shift toward earlier planting to avoid the warmer temperatures at the height of the summer.

The most authoritative national assessments are the South African studies using the ACRU/Ceres hybrid model (see Schulze *et al.*, 1993, 1996). The diverse geography of South Africa is divided into 712 relatively homogeneous zones, each associated with vegetation, soil and climate data. Daily values of temperature (minimum and maximum), rainfall, wind speed, and solar radiation are used in the crop evaluation. Recent scenario analysis (see Hulme, 1996) shows a wide range of potential maize yields in South Africa. Western South Africa is not suitable for rain-fed agriculture and much of the central area experiences mean yields that are less than 2.5 t/ha. The higher elevations in the east are the core agricultural zones, with potential mean yields over 10 t/ha.

For three scenarios of climate change, corresponding to the middle of the next century, yields decrease in the semi-arid west. However, for most of the country potential yields would increase, generally by up to 5 t/ha. The CO_2 enrichment effect counter-acts the relatively modest scenarios of changes in temperature and precipitation. In parts of the eastern highlands, particularly in Lesotho, the dramatic increases in yields are due to reductions in temperature constraints.

Ultimately, climate change is a global issue, even more so for traded commodities such as agriculture (in contrast to water resources). Some regions, for example, may be less competitive in national and global agricultural markets, with corresponding impacts on exports and imports. Africa in particular may be sensitive to changes in world prices and stocks since many countries rely on food imports.

Example of impacts on water resources in the Nile and Zambesi

The Nile is one of the most sensitive river basins to climate change (Strzepek *et al.*, 1995; Conway *et al.*, 1996). Equilibrium GCM scenarios of temperature increases of 3.1°C–4.7°C and precipitation increases of 5-31%, result in an impact on Nile river flow at Aswan varying from a 30% increase to a 75% decrease, with the Sudd swamps acting as significant evaporation pans. Almost the entire population of Egypt lives in the Nile river valley and delta, dependent on the water resources and riverine economy of the Nile. An increase in evaporation would lead to significant reductions in water availability. Lake basin managers in Egypt state that they can adapt to a 10% reduction in water availability, while reductions greater than 25% would cause major water resource management problems. While that may be true at present, it may not be the case in 2050.

Strzepek *et al.* (1995) estimate that infrastructure development, improved agricultural technology and irrigation might mitigate 7-8% of the agricultural impacts of climate change. Completion of the Jonglei canal scheme, which will divert Nile water from the Sudd swamps, could provide an additional 20% in total water availability. Thus, water resource managers in the Nile river basin will also have to improve irrigation efficiency and manage water demand if adverse scenarios of climate change are realized.

Salewicz (1995), using scenarios based on equilibrium GCMs, illustrates the vulnerability to climate change of African water management systems which rely on a large reservoirs. In the upper Zambezi river basin, the Barotse Plain and Chobe swamps function as significant evaporation pans and sediment traps, to the extent that two thirds of the region's 2400 mm annual precipitation is lost to evaporation before it passes over Victoria Falls. This water system faces high demand and operational uncertainty under climate change. Climate change scenarios indicate a shift in the seasonal reliability of discharges for the lower Zambezi. The probability of a hydropower station receiving $1000m^3/s$ in 2060 changes by ±50% for different scenarios. An additional hydropower system at Batoka is useful, although its net value is reduced by climate change. Power output at Kariba would decrease by 10%, while output at Batoka in the dry season would be half of the potential.

3. What is the range of potential adaptive strategies?

Adaptation may be warranted in situations where changes in mean climate and climatic hazards may be rapid and where the consequences would be significant, especially for vulnerable populations. The incremental cost of preparedness and anticipatory adaptation may be less than suffering the consequences or undertaking remedial relief. At the least, evaluation of adaptive options should proceed and identify actions that are warranted given present vulnerability and the threat of future disruptions to climatic resources.

Our typology of adaptive strategies distinguishes between four generic types of adaptation:*

- Anticipatory adaptation. Anticipating climate change is warranted for projects with long life spans (e.g., reservoirs), where the marginal cost of adaptation is small or brings benefits regardless of climate change, for protection against extreme events, and to prevent irreversible impacts (e.g., preservation of biodiversity).
- Institutional and regulatory adaptation. Where development increases vulnerability (e.g., coastal development) or fails to protect the vulnerable (e.g., economic restructuring), then institutional and regulatory reform may be warranted.
- Research and education. If the present scope for adaptation is limited, investment in research and education are warranted to develop new solutions and stimulate behavioral changes to accommodate climate change.
- Development assistance for capacity building. Institutional development is required to enhance the productivity of natural resources, strengthen capacity to respond to developmental pressures and resource crises, and to improve environmental quality.

Implementing adaptive policies requires screening against a range of criteria:**

- Stakeholders: Is there a stakeholder or vulnerable group that should be given priority for targeting adaptive strategies? Are there conflicts over resource

* For similar typologies, see Carter *et al.* (1994), Smith *et al.* (1996, 1995), Smith and Lenhart (1996).

** For similar critieria, see Carter, 1996; Smith and Lenhart, 1996; Smith *et al.*, 1995; Stakhiv, 1996; Watson *et al.* 1996.

use between or among different stakeholders? Would such conflicts affect the ability to design and implement specific adaptive strategies?

- Resilience and effectiveness: Does the adaptation have benefits for a number of objectives and stakeholders? Conversely, does the adaptation only have benefits if climate changes in the expected direction? Is there a critical threshold for adopting the adaptation, or beyond which the response will not be effective? How effective is adaptation in coping with the expected climate change? For example, common performance criteria within the water sector are robustness (the sensitivity of design parameters and economic costs to climate variability), reliability (how often the system is likely to fail), resiliency (how quickly a system recovers from failure) and vulnerability (the severity of the consequences of failure) (Hashimoto *et al.*, 1982a, 1982b).

- Strategic responses: Where the most cost-effective adaptive responses have yet to be identified, fundamental research and stimulation of innovation may be warranted. The role of adaptation in shaping future development needs to be assessed. Costly responses now may limit investment and constrain development.

- Timing: Is there a gap between the implementation of adaptation strategies and the realization of their benefits? What is the planning horizon required to design and implement the adaptation? For how long is the adaptation useful? Matching the timing of an adaptive response and its benefits may need to consider the possibility of irreversible impacts and option values.

- Economic evaluation: Contentious issues of discount rates, valuing environmental quality, and equity need to be addressed in balancing costs and benefits. The initial investment may be a constraint, either because of poverty and lack of credit among some stakeholders or because the expected return is low compared to other economic investments. The difference between public and private objectives and economic decision making may be important in such cases. While most guidelines recommend "low cost" adaptations, the definition of low cost depends on each stakeholder and their opportunity costs. The return on investment depends on the timing of the benefits. The benefits may not accrue to the stakeholders that make the investment. The beneficiaries are future generations, or other present social and economic groups. This is a common problem of equity in public interventions in resource management.

- Constraints: Specific strategies will only be effective if they are widely adopted, with relatively efficient means of dissemination and maintenance. Is information about the strategy, its utility and means of implementing it lacking? Is the adaptation technically reliable, or does it require a level of technical development that is not available for all stakeholders? Do institutional, behavioral, cultural or political conditions influence the range of choice and adoption?

The purpose of adaptation, therefore, is to maximize the utility of available climatic resources of the future – a balance between taking advantage of new resources and preparing to limit the adverse impacts of detrimental changes.

4. Who should adapt?

Adapting to climate change is not entirely automatic or only autonomous. The motivations, constraints and domains of authority of decision makers involved in shaping policy, implementing decisions and coping with the consequences of changes in resources and hazards must be considered (see Grimble and Chan, 1995).

The principal stakeholders range from vulnerable consumers to international organizations charged with research and relief (Table V). Stakeholders will suffer the consequences of climate change to varying degrees and have primary concern for different types of adaptations. This is likely to influence their involvement in planning and implementing adaptive responses.

Consumers, of both food and water, are the ultimate stakeholders in adapting to climate change. For particularly vulnerable groups (such as resource-poor farmers, landless laborers, urban poor, the destitute and displaced or refugee populations), the outcome of strategies to adapt to climate change and climatic hazards may alter their livelihoods. Failure to cope with adverse change could lead to significant deprivation, social disruption and population displacement, and even morbidity and mortality.

Producers have varying interests in climate change. Subsistence farmers are less likely to have the resources to consider anticipatory action than large-scale commercial farmers. Commercial farmers are more likely to be linked to national markets and international agribusinesses and be able to invest in agricultural technology. Water suppliers – private developers and traders and government boards – may take a longer term perspective on development, research and education, depending on the size of the enterprise. Local traders who deliver water from bore holes are unlikely to evaluate the risk of climate change to the same extent as a river basin authority.

One of the key stakeholders in enacting forward-looking strategies is business: from local market traders to international commodity and research organizations. However, commodity traders are not likely to be affected directly by the consequences of climate change, as long as production is viable and trade required somewhere in the world. Incentives may be required to induce agribusiness to adopt a longer planning horizon and to develop and implement adaptive responses. Large water users – irrigation schemes, energy producers and industry – can manage their water use provided adequate information on future supplies and prices. Significant changes in irrigation efficiency or industrial processes, however, take several years to design and implement.

Table V
Stakeholders and adaptive responses

Stakeholders	Conseq.	Adaptive Responses			
		Antic.	Inst.	Res. & Edn.	Devt
Vulnerable consumers	✓				+
Subsistence producers; Private	✓				+
water carriers					+
Commercial producers		+		+	✓
Market traders	+				✓
Irrigation, water and sewage boards		?	+	✓	
Food processing and trading; River basin development agencies	?	?	+	✓	
National and international research		?		✓	+
Govt ministries (planning, agriculture, health and water)	+	+	+	✓	
Aid and community development organizations	+	?	+	✓	

Notes: Conseq. refers to bearing the consequences of climate change impacts, that is those stakeholders who are directly affected. The adaptive strategies correspond to the guidelines: Antic. is Anticipatory Adaptation and strategies targeted for coping with climate change; Inst. is Institutional and Regulatory Adaptation to prevent increased vulnerability; Res. & Edn. is Research and Education to develop and implement new solutions; and Devt is Development Assistance that implements current options for sustainable agricultural development and reducing vulnerability to climatic hazards.
The ratings indicate the type of response likely to be of interest to each stakeholder:
✓ indicates primary interest in adapting to climate change.
+ indicates secondary, but important, interest in adaptive strategies.
? indicates uncertain but potential role in adaptation.

The bulk of responsibility at present for designing, evaluating and implementing strategic responses (anticipatory actions, planning institutional change and research/education) are national governments, national and international research centers, and aid organizations (particularly bilateral and multilateral, although some international NGOs take an interest in adaptation policies). Since the majority of water supplies in Africa are provided through direct access and public institutions, the role of private water companies is relatively less important than development of a national strategy and response capability.

Examples of adaptive responses for agriculture and water

The full range of adaptive responses to climate change in Africa has yet to be compiled and evaluated. Based on available literature and our experience in resource management in Africa, we illustrate some of the issues identified above (Table VI). Four groups of strategies—farm-level agronomy, national economic planning, global agricultural policy and reducing vulnerability to drought—are qualitatively evaluated.

Anticipatory adaptation encompasses a range of strategies to improve agriculture. Planning for irrigation schemes, particularly in regions where water supplies are uncertain, should include a risk factor for climate change. The most certain aspect of climate change is increased CO_2 concentrations. Efforts to enhance the positive CO_2 responses in new cultivars may be worth the investment in plant breeding and agricultural technology, irrespective of changes in moisture availability. This research and development program would be undertaken by national or international research centers.

Inexpensive adaptation includes establishing strategic food reserves to buffer potential increases in the variation of local and national production. This is only suitable at the national or international level. Connections to local grain banks are required, but increasing local reserves because of climate change may not be warranted at present.

Protection against present and future extreme events should be a priority. Drought early warning and preparedness is urgent, building upon the considerable improvements that are already underway in many regions of Africa. Making better use of climate predictions is a key aspect of this adaptive strategy (e.g. Cane *et al.*, 1994; Chen *et al.*, 1995; Gibberd *et al.*, 1996).

Protection against irreversible impacts or losses of valued resources may be warranted in some situations. Thus, if coastal erosion and sea level rise threaten valuable coastal resources, protection measures may be cost-effective. For example, ground water pumping may be required to lower the water table if saline intrusion affects agriculture in low-lying areas. It is unlikely that such projects are a priority in the near future. However, protection measures should be considered in the design of new developments. The cost of such developments would only be undertaken by commercial enterprises, with national or international backing.

Four inter-related approaches for water management are: new investment for capacity expansion; operation of existing systems for optimal use; maintenance and rehabilitation of existing systems; and modifying water demand (Rogers, 1993). At the project design stage the uncertainty in climatic conditions over the life of the project should be incorporated into the performance evaluation. To the extent that climate change may increase this uncertainty, anticipatory adaptation should be considered. This is most likely for long-term investments (over 30 years), such as major reservoirs, particularly in regions where water supplies are uncertain. In some cases, critical water resources are at-risk from climate change or from policies to adapt to climate change. Critical resources that might be irreversibly lost due to climate change include groundwater in areas subject to salt water intrusion.

Institutional and regulatory adaptation may be warranted in planning development in semi-arid regions where climate change may be adverse. Water resources for irrigation may not be reliable, and salinisation of soils may reduce agricultural potential. Planning for such development should at least evaluate the effect of climatic variations on project performance. An example where this was not done was the South Chad Irrigation Project in the 1970s (Kolawole, 1987). Establishing priorities for development based on future land capabilities may be premature for most regions. Flexibility in development priorities should be retained, and new information taken into account.

Regulation of resource allocation and development is deficient in much of Africa. The ability of community groups to manage rapid resource changes may warrant further support. Market structures often support crops with a high level of risk and fail to support markets for drought-tolerant crops. Regulations constraining free trade may increase the volatility of local markets and food supplies in response to climatic variations.

Large-scale changes in resource allocations may require interventions in institutions and regulations. This is warranted particularly when land use changes increase vulnerability to climate change or where institutions constrain adoption of effective responses to climate change.

Water management in Africa is often poorly integrated, with decisions taken in a range of institutions from local users to international agreements. The clear need is to promote greater flexibility, rather than focusing on specific strategies. Frameworks for sustainable water resource management proposed by the World Bank (1993), Agenda 21 and National Environmental Action Plans provide points of departure. Most African countries are committed to these environmental initiatives, either through World Bank loans, on which other development funds are often conditional, or through their Rio obligations (UNCED, 1992). Responses to climate change can be incorporated into more general sustainable development and resource management strategies, and remain sensitive to African priorities.

Managing water demand may require adjusting the institutions that price water and promote conservation. Analyzing the opportunity costs of water can identify cross-sectoral differences in water availability. The implementation of water pricing or other demand management tools (property rights, tradable permits, quotas) can encourage consumers to adopt more efficient practices.

Research and education is required to develop cultivars that optimize responses to CO_2 enrichment (see above). More generally, development and testing of new cultivars suitable for a range of likely climatic conditions is required. Such research capacities are best undertaken at the national level, with support from international centers and commercial enterprises.

Education on environmental issues is warranted, although it is probably too soon to undertake specific campaigns designed to adapt to climate change. For example, urging consumers to change their dietary preference in preparation for drier climates is not warranted. However, a broad capacity to address environmental issues and communicate understanding to stakeholders is urgently needed. This is even more critical in linking greenhouse gas abatement with sustainable development issues.

Development of national water strategies requires support from research centers, encompassing the regional distribution of water and its variability to technologies for efficient end uses. Such research capacities are best developed at the national level, with support from international centers and commercial enterprises.

Implementation of demand management requires targeted education. Although anticipatory adaptation to climate change need not be stressed among water users, promoting greater flexibility in water resource management requires a partnership between consumers, producers and managers.

Development assistance to support sustainable agricultural development in Africa includes better use of climate information and resources to intensify production, manage water resources, and cope with climatic risks and reducing vulnerability through sustainable development, drought mitigation and preparedness, and integration of regional economies. "No regrets" strategies benefit society. These are ongoing development objectives, but further assistance is warranted in light of the risk of changes in climatic hazards.

Agricultural responses that illustrate relevant strategies that should be considered at present include farm-level adaptive responses, national agricultural development, global strategies of trade and investment, and activities to reduce drought vulnerability.

Common *farm-level adaptive responses* include substitution of agronomic practices, altered inputs and agricultural development. The priority stakeholder is likely to be the smallholder farming sector. Commercial farms would be less likely to need assistance in these sorts of adaptive strategies. On the other hand, these strategies are less likely to be effective for agropastoralists and pastoralism in general. There may be some competition for development assistance, but in general these agronomic packages do not entail serious resource use conflicts between farming groups and others or within farming communities.

All of the adjustments can be implemented relatively quickly, often within a single season. Even investment in soil and water conservation represents a relatively modest investment, compared against the potential risk of climate change. The aggregate evaluation suggests that agronomic improvements are effective, can be readily implemented and have few substantial constraints to their adoption.

Irrigation schemes may be a special case in considering responses to climate change. They are sensitive to both direct impacts of climate change and to changes in water supply. The design and investment cycle is such that major schemes are expected to be operational for at least several decades, which puts irrigation planning into the time scale of expected climate change.

Table VI
Examples of responses to climate change

Response strategy	Potential examples
Anticipatory adaptation	
(a) long life-times	Reservoirs and irrigation schemes: increased capacity, operating rules, water use efficiency
(b) beneficial	Maximize CO_2 effects in development of crops
(c) inexpensive	Strategic food reserves and increased water storage in planned reservoirs to accommodate increased variability
(d) extreme climatic events	Drought preparedness, early warning and response capabilities
(e) irreversible impacts	Prevent salinisation: availability of water for flushing irrigation schemes, degradation of groundwater
Institutional and regulatory reform	
(a) land use	Regulate coastal developments susceptible to saline intrusion or sea level rise, restrict major water development in semi-arid regions
(b) institutions	Social and economic support to cope with economic restructuring inherent in adapting to new resources
Research and education	
(a) new solutions	Develop new crops, agronomic practices, water-saving technologies
(b) behavioral change	Change dietary preferences for foods no longer suitable, promote water conservation
Development assistance for capacity building	
(a) ongoing investments and responses	Crop substitution, incremental adjustment in inputs, extension of new varieties and practices, enhance local and regional water management institutions

At the national level, economic policies to promote *agricultural development* focus on maintaining a positive food balance and exports. Three types of strategies can be envisioned. Maintaining strategic reserves allows the government (or marketing bodies) to dampen price fluctuations and release food in emerging crises. Quite large national reserves have been held in the past few decades, in some countries enough food to meet consumption for a year or more. In the 1990s, these reserves were reduced under structural adjustment agreements. International lending organizations noted that such reserves are costly to maintain and absorb a significant fraction of government resources. Better monitoring and more timely responses were seen as more efficient ways to cope with food shortages.

An alternative strategy would be to adjust markets and trading conditions to promote private sector responses to climate change and climatic variability. This might take the form of tax incentives for carry-over stocks or bonds to smooth income between adverse and good trading years. The stakeholders in such a strategy would be producers, including market traders, millers and agribusiness in general. This kind of strategy would build upon present efforts toward reduced trade barriers, with some specific adjustments to accommodate to climate change.

The third realm of national or regional planning is to promote agricultural development in general. This does not require action specifically because of climate change. However, the gap between research and practice is as large as the gap between present yields and agricultural potential in Africa. The need to adapt to climate change could be used as one argument for fresh initiatives in promoting adaptive agricultural research and development in Africa.

The primary beneficiaries of national economic planning are consumers and commercial producers who depend on markets for food consumption. Market adjustments may entail some trade-offs between consumers and producers, or between relatively prosperous farmers and vulnerable smallholders who may not have access to inputs and markets. Yet, the potential for multiple benefits is high (except for strategic reserves which are a burden on the economy). Taken as a group, these strategies would be reasonably effective in preparing for climate change.

These strategies can be readily implemented, are not likely to have irreversible impacts (depending on the nature of specific developments), and generally have a strategic role in promoting a resilient economy. Benefits could be realized throughout the economy, although the incremental investment would take 5-10 years to pay off.

Ultimately, prospects for African agriculture depend on global investment, demand and trade. At the *global level*, some policies to prepare for climate change may be justified. As for national and regional economic development, suggested strategies range from building strategic reserves, encouraging free trade and transfer of agricultural technology.

The arguments for building global strategic reserves, both for major foods and of financing, follows the same argument as at the national level. Climate change may require additional trade to smooth out fluctuations in national production. Maintaining international prices within acceptable limits would benefit poorer countries who might not be able to afford large imports in times of scarcity (as might occur in a replay of the 1980s drought on the 1972 international scarcity of grains). It should be more effective to hold reserves at the global level, or shared among regional trading partners, rather than each country seeking to buffer its internal production. In the transition toward a new climate, such an international capacity to prevent food deficits becoming survival emergencies appeals to humanitarian goals of ending famine and reducing hunger.

Encouraging free trade between countries should stimulate agricultural markets in regions with a comparative advantage. This may be a major benefit to some countries, and a significant cost to others, as the impacts of climate change alter traditional markets. In principle, free trade allows national surpluses and deficits to be accommodated more efficiently. Supply and price fluctuations are thus buffered at the global level, widening the potential pool of responses to climate change. Free trade, of course, is already on the international agenda and little further encouragement is required. However, some incentives to the private sector to absorb additional risks may be required.

The most costly and long-term strategy proposed in this review is to develop international mechanisms to promote agrotechnology transfers to developing countries. An initial agreement might focus on basic foodstuffs: wheat, rice, and maize. International agencies might license new technologies developed by biotechnology firms for dissemination and use in developing countries. Adaptation and abatement might be explicitly linked, with a requirement that beneficiaries have agreed to limit greenhouse gas emissions. Funding requirements would be significant, although connections to emission taxes could made.

The immediate beneficiaries of global linkages are commodity brokers and private companies, although aid and government agencies have strong interests. As for national policies, some resource allocation issues may imply trade-offs between regions, commodities and farming populations. Global policies should be highly effective, with a relatively low specificity to climate change or dependence on specific climate scenarios.

The planning horizon is on the order of five years, with benefits realized somewhat later. Except for agrotechnology transfer, there are few constraints to implementing global policies (other than bureaucratic inertia and funding).

Drought hazard and vulnerability are present risks in Africa and likely to be the most damaging locus of impacts of climate change. Concerted action is required in three areas: mitigation to reduce vulnerability, monitoring drought and vulnerability, and preparedness to respond effectively to emerging crises. Considerable progress has been made in the past decade, a further decade of development might reap substantial rewards in efforts to eliminate widespread famine and enhance livelihood security, at least in times of drought.

The priority stakeholders should be the most vulnerable socioeconomic groups affected by drought crises, although many levels of local, national and international actors are required to implement drought monitoring, mitigation and emergency responses.

Drought policies provide multiple benefits to the extent that they contribute to development in general by reducing investment risk. However, crisis interventions can be counter-productive if they create a dependency syndrome or compete for resources from other activities with longer term benefits.

Reducing risk can have strategic importance. Increased monitoring and response capabilities should improve the ability to respond to long-term climate change and to economic management of the agricultural sector in general. With foresight, crises can be used to promote sound resource policies, although this remains the anomaly in most of the world rather than the norm.

Drought monitoring, mitigation and preparedness take time to develop and implement. Once operational the benefits are immediate, although they are only significant during times of potential crisis. There are few irreversible impacts and the initial investment can be fairly modest.

Constraints include the need for sustained information collection, processing and reporting, often requiring significant development of technologies and organizations. While most planners and vulnerable populations agree that drought hazard planning and reduction are desirable, the lack of reliable systems implies further social, economic and political constraints. One that is commonly cited is the short attention cycle—drought planning peaks about a year after the drought and is forgotten until the next crisis. If drought becomes more frequent, this constraint may be overcome.

5. Conclusion: Recommendations for Research and Environmental Policy

This broad review of climate change and adaptation in Africa suggests that some displacement of agriculture and water resources is likely, and this may affect economic investment and population movements (see Myers and Kent, 1995, for example). If resource managers are not prepared, these seemingly modest changes could be substantial, possibly threatening the livelihoods of millions of the resource poor and vulnerable (see Downing, 1996). However, modest investment in preparing for climate change would significantly reduce the risk of catastrophic effects, at least at the regional and national level.

Issues that need to be considered in planning adaptive responses in Africa include:

Which stakeholders or vulnerable groups should be given priority for targeting adaptive strategies? Would conflicts over resource use between or among different stakeholders affect adaptation?

Which adaptive strategies have benefits for a number of objectives and stakeholders, and are thus more likely to be pursued? Conversely, does adaptation only have benefits if climate changes in the expected direction?

How can adaptive responses be timed to maximize the stream of benefits? Irreversible impacts and option values should be considered. Strategic responses that stimulate innovation may be warranted.

Are information, technical development, institutional arrangements, social and cultural factors, economic requirements or political conditions constraints for some stakeholders and some strategies? The definition of "low-cost" depends on each stakeholder and their opportunity costs. Public and private objectives may differ.

Perhaps the most critical need in Africa is to foster organizations that can promote sound adaptive strategies in the context of sustainable development objectives. Despite notable successes, in many places conditions have not promoted commu-

Table VII
Uncertainty surrounding future climate change

Variable	Confidence and assessment
CO_2 concentration	Certain to increase
Global-mean temperature	Confident in likely range
Global-mean sea level	Confident in likely range
Patterns of regional temperature	Likely to increase, but possibly wider range of estimates than for global-mean temperature
Patterns of regional rainfall and other variables	Diverging scenarios, but within a reasonable range
Soil moisture	Diverging scenarios, but within a reasonable range
Variability (daily and interannual)	Largely unknown
Extreme events	Largely unknown

nity and civic groups with the personnel, funding and technical skills required for prompting sound environmental policies.

Two strategies are paramount–improving present resource management and reducing vulnerability to climatic hazards. In particular, improving seasonal climate forecasts and use of climate information could have major benefits in much of Africa. Where large projects and development might increase vulnerability to climate change, specific, anticipatory adaptation may be warranted. The future of Africa with climate change clearly depends on progress in social and economic development in the decade ahead.

6. Appendix: What are the Prospects for Climate Change in Africa?

It is not possible at present to forecast climate change in Africa—there are too many unknowns and potential surprises, such as volcanic eruptions and ocean-atmosphere linkages. And, scenarios of climate change are contingent upon projections of greenhouse gas emissions, themselves subject to economic conditions and policy choices. However, some elements of climate change are better understood than others (see table VII). We are quite sure about future increases in atmospheric CO_2 concentrations, which are fairly evenly distributed around the world. We can be relatively confident about the range of projections of global-mean temperature and sea level, but are very uncertain about regional patterns of precipitation and soil moisture and largely ignorant about changes in the frequencies and intensities of extreme events.

At the global level, a simple climate model estimates the range of years associated with 1°C of global warming, with respect to 1961-90 (Raper *et al.*, 1996; Wigley and Raper, 1992). The projections assume no policy interventions to stabilize or reduce GHG emissions, and three estimates of the climate sensitivity*. Global warming of 1°C is likely to occur by about 2050, or earlier if cooling due to sulfate aerosols is less than expected. This is a rate of warming of between 0.15° and 0.2°C per decade. Already, 0.2°C of this global warming has been observed by the decade 1986-1995 (Houghton *et al.*, 1996: 26). The low and high estimates are for 1°C warming by about 2070 or 2035, reflecting the range of uncertainty in climate sensitivity. The increase in CO_2 concentration from the 1990 level (355 ppmv) associated with this 1°C warming would be 40% (to 502 ppmv by 2050, including aerosol effects).

Four patterns of change in annual temperature (Figure 1) and rainfall (Figure 2) over Africa illustrate typical climate change scenarios. These scenarios are derived from four different climate change experiments performed by the UK Meteorological Office over a period of nearly ten years—the first three generations of GCM experiments. In each case, the model is forced by changes in greenhouse gases alone. Each pattern has been standardized by the global warming of the respective experiment, following the common IPCC guidelines (Carter *et al.*, 1994). The patterns of temperature and rainfall changes are therefore associated with 1°C of global warming, enabling a direct comparison between scenarios.

The UK GCM experiments show different patterns of climate change at the continental scale. And, these scenarios do not necessarily portray the entire range of future climates simulated in the several dozen experiments conducted to-date. Regarding African climate change scenarios, the major model limitations include:

- Simulation of El Niño/Southern Oscillation (ENSO) events. Since some regional rainfall regimes in Africa are highly sensitive to ENSO (e.g. southeastern Africa, coastal East Africa, parts of north-east Africa), whether or not the GCM is simulating realistic ENSO events is important for evaluating the credibility of the scenario. There is some evidence that successive generations of GCM experiments have consistently improved their simulation of ENSO (e.g. Tett, 1995). This does not mean that there is a consensus about whether ENSOs are likely to change substantially in character as a result of climate change (see Knutson and Manabe, 1995).
- Simulation of observed interannual and interdecadal variability of African rainfall (i.e., the correct frequency spectrum). For example, the prolonged desiccation of the Sahel during the 1970s and 1980s and into the 1990s has not always been well reproduced by climate models.
- Representation of land cover-climate interactions over Africa. Sensitivity experiments with climate models have shown that changes in land cover characteristics (e.g., deforestation) *can* have major impacts on continental climate

* Climate sensitivity refers to the long term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (oC/Wm^{-2}).

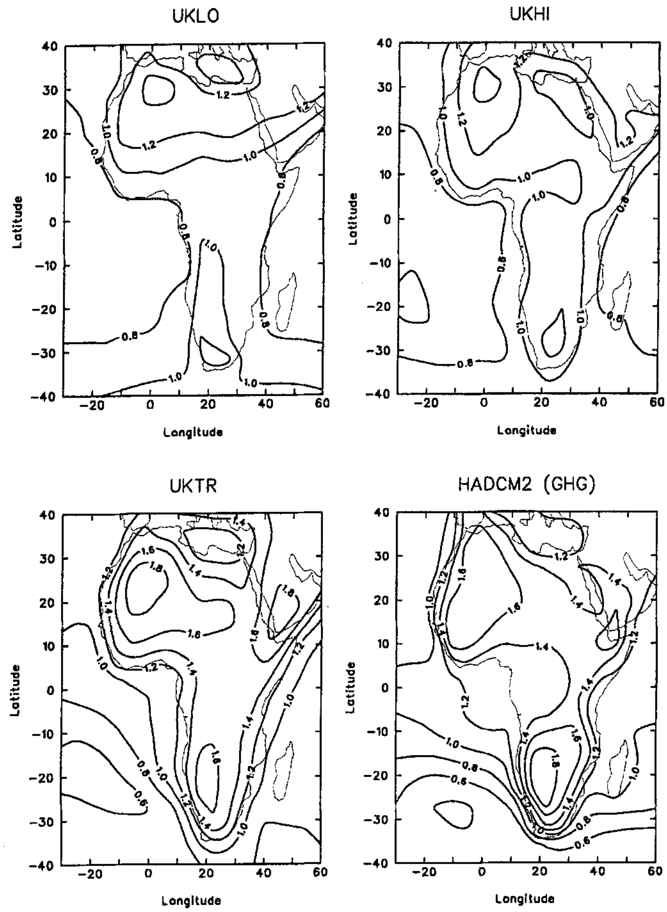

Figure 1. Change in mean annual temperature (degrees Celsius) over Africa associated with 1°C of global warming from four climate change experiments performed with successive versions of the UK Met. Office/Hadley Centre GCM: UKLO (1st generation, 1987), UKHI (1st generation, 1989), UKTR (2nd generation, 1992) and HADCM2 (3rd generation, 1995). All patterns show greenhouse gas only forcing. Source: Ringius *et al.* (1996).

if the perturbations are large enough (Xue and Shukla, 1993). Present GCM scenarios do not allow land cover characteristics to change.

- Representation of precipitation, cloud cover and radiation changes because of uncertainties in the cloud and tropical convection parameterisation schemes.

For these reasons, it is incautious to suggest a consensus or best guess scenario of climate change in Africa. In the next few decades, it is likely that average temperatures will increase. Precipitation is likely to change, although the seasonal range and pattern of changes is not clear. Scenarios of future climatic hazards–

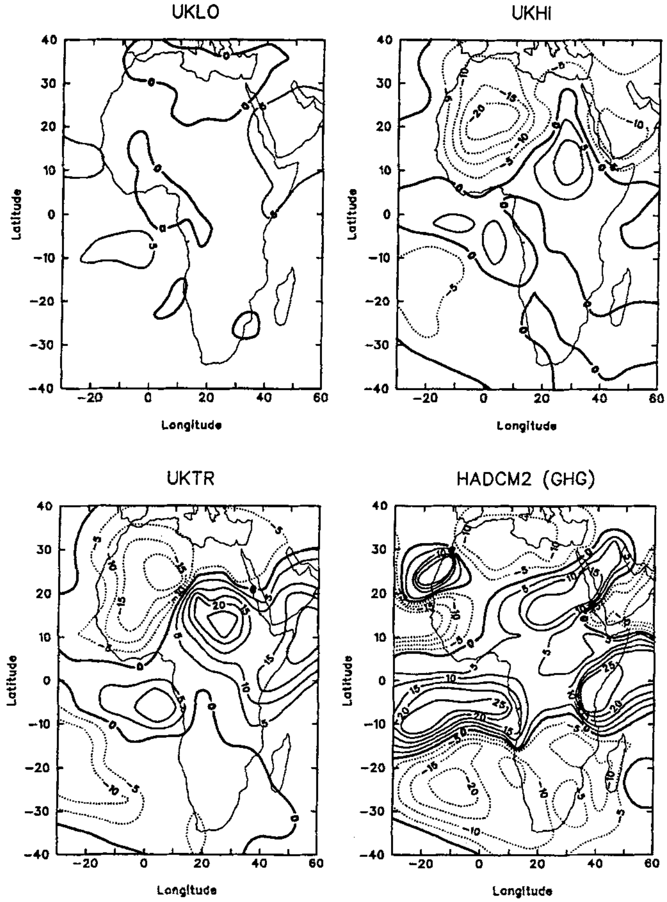

Figure 2. Percent change in mean annual rainfall over Africa associated with 1°C of global warming from four climate change experiments performed with successive versions of the UK Met. Office/Hadley Centre GCM: UKLO (1st generation, 1987), UKHI (1st generation, 1989), UKTR (2nd generation, 1992) and HADCM2 (3rd generation, 1995). All patterns show greenhouse gas only forcing. Source: Ringius *et al.* (1996).

drought and flood–are highly uncertain. Preparing for climate change is an exercise in risk assessment with large uncertainties.

References

Ausubel, J.: 1991. A second look at the impacts of climate change. *American Scientist* **79**(May/June): 210-221.

Cane, M. A., Eshel, G. and Buckland, R. W.: 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature* **370**, 204-205.

Carter, T. L.: 1996. Assessing climate change adaptations: The IPCC guidelines. In *Adapting to Climate Change: Assessments and Issues*. J. B. Smith, N. Bhatti, G. Menzhulin et al. (eds.). New York, Springer: 27-43.

Carter, T. R., Parry, M. L., Nishioka, S. and Harasawa, H.: 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. London and Tsukuba, University College London and Centre for Global Environmental Research.

Chen, D., Zebiak, S. E., Busalacchi, J. and Cane, M. A.: 1995. An improved procedure for El Niño forecasting: implications for predictability. *Science* **269**, 1699-1702.

Conway, D., Krol, M., Alcamo, J. and Hulme, M.: 1996. Future availability of water in Egypt: The interaction of global, regional and basin-scale driving forces in the Nile Basin. *Ambio* **25**, 336-342.

Dansgaard, W., et al.: 1993 Evidence for general instability of past climate from a 250-kyr ice-core record *Nature*. 364, 218-20.

Downing, T. E.: 1992. *Climate Change and Vulnerable Places: Global Food Security and Country Studies in Zimbabwe, Kenya, Senegal and Chile*. Oxford, Environmental Change Unit.

Downing, T. E., Ed.: 1996. *Climate Change and World Food Security*. Berlin, Springer.

Falkenmark, M. and Widstrand, C.: 1992. *Population and Water Resources: A Delicate Balance*. Washington, DC, Population Reference Bureau.

Fischer, G. and van Velthuizen, H. T.: 1996. *Climate Change and Global Agricultural Potential Project: A Case Study of Kenya*. Laxenburg, International Institute for Applied Systems Analysis.

Gibberd, V., Rook, J., Sear, C. B. and Williams, J. B.: 1996. *Drought Risk Management in Southern Africa: The Potential of Long Lead Climate Forecasts for Improved Drought Management*. Chatham Maritime, Natural Resources Institute.

Grimble, R. and Chan, M.-K.: 1995. Stakeholder analysis for natural resource management in developing countries: Some practical guidelines for making management more participatory and effective. *Natural Resources Forum* **19**(2), 113-124.

Hashimoto, T., Loucks, D. and Stedinger, J.: 1982. Robustness of water resources systems. *Water Resource Research* **18**(1), 21-26.

Hashimoto, T., Stedinger, J. and Loucks, D.: 1982. Reliability, resiliency and vulnerability criteria for water resource system performance evaluation. *Water Resource Research* **18**(1), 14-20.

Henderson-Sellers, A.: 1996. Climate modelling, uncertainty and responses to predictions of change. *Mitigation and Adaptation Strategies for Global Change* **1**(1), 1-21.

Hernes, H. et al.: 1995 *A Climate Strategy for Africa. Building Blocks for Environmentally Sustainable Development in Africa*. Paper no. 10. Washington DC., Africa Technical Department, World Bank.

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K., Eds.: 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge, Cambridge University Press.

Hulme, M., Ed.: 1996. *Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications for the SADC Region*. Norwich and Gland, Climatic Research Unit and WWF International.

Hulme, M., Conway, D., Kelly, P. M., Subak, S. and Downing, T. E.: 1995. *The Impacts of Climate Change on Africa*. Stockholm, Stockholm Environment Institute.

Kolawole, A.: 1987 Environmental change and the South Chad Irrigation Project (Nigeria). *Journal of Arid Environments* **13**, 169-176.

Knutson, T. R. and Manabe, S.: 1994. Impact of increased CO2 on simulated ENSO-like phenomena. *Geophysical Research Letters* **21**, 2295-2298.

Makadho, J. M.: 1996. Potential effects of climate change on corn production in Zimbabwe. *Climate Research* **6**, 147-151.

Matarira, C. H., Kamukondiwa, W., Mwamuka, F. C., Makadho, J. M. and Unganai, L. S.: 1996. Vulnerability and adaptation assessments in Zimbabwe. In *Vulnerability and Adaptation to Climate Change: A Synthesis of Results from the U.S. Country Studies*. J. B. Smith, S. Huq, S. Lenhart, L. J. Mata, et al. (eds). Kluwer Academic Publishers, Dordrecht, pp. 129–140.

Muchena, P.: 1994. Implications of climate change for maize yields in Zimbabwe. In *Implications of Climate Change for International Agriculture: Crop Modelling Study*. C. Rosenzweig and A. Iglesias (eds.). Washington, DC, U.S. Environmental Protection Agency.

Myers, N. and Kent, J.: 1995. *Environmental Exodus: An Emergent Crisis in the Global Arena.* Washington, Climate Institute.

Overpeck, J.T.: 1996 Warm climate surprises *Science* **271** (5257): 1820-21.

Raper, S. C. B., Warrick, R. A. and Wigley, T. M. L.: 1996. Global sea level rise: past and future. In *Sea-level Rise and Coastal Subsidence: Causes, Consequences and Strategies.* J. D. Milliman and B. U. Haq (eds.). Dordrecht, Kluwer Academic Publishers: 11-45.

Ringius, L., Downing, T.E., Hulme, M., Waughray, D. and Selrod, R.: 1996 *Climate Change in Africa – Issues and Challenges in Agriculture and Water for Sustainable Development.* CICERO Report 1996:8. Oslo, CICERO.

Rogers, P.: 1993. *What Water Managers and Planners Need to Know about Climate Change and Water Resources Management.* Conference on Climate Change and Water Resources Management, Fort Belvoir, US Army Institute for Water Resources.

Salewicz, A.: 1995. Impact of climate change on the operation of Lake Kariba hydropower scheme on the Zambezi River. In *Water Resources Management: The Face of Climatic and Hydrologic Uncertainties.* Z. Kaczmarek (ed.). Dordrecht, Kluwer.

Schulze, R. E., Kiker, G. A. and Kunz, R. P.: 1993. Global climate change and agricultural productivity in southern Africa. *Global Environmental Change* **3**, 330-349.

Schulze, R. E., Kiker, G. A. and Kunz, R. P.: 1996. Global climate change agricultural productivity in southern Africa: Thought for food and food for thought. In *Climate Change and World Food Security.* T. E. Downing (ed.). Heidelberg, Springer: 421-448.

Schelling, T. C.: 1992. Some economics of global warming. *The American Economic Review* **82** (1), 1-14.

Smith, J. B., Bhatti, N., Menzhulin, G., Benioff, R., Budyko, M. I., Campos, M., Jallow, B. and Rijsberman, F. and Dixon, R. K. (eds.): 1996. *Adapting to Climate Change: Assessments and Issues.* New York, Springer.

Smith, J. B., Carmichael, J. J. and Titus, J. G.: 1995. Adaptation policy. In *As Climate Changes: International Impacts and Implications.* K. M. Strzepek and J. B. Smith (eds.). Cambridge, Cambridge University Press: 201-210.

Smith, J. B. and Lenhart, S. S.: 1996. Climate change adaptation policy options. *Climate Research* **6**, 193-201.

Stakhiv, E. Z.: 1996. Managing water resources for climate change adaptation. In *Adapting to Climate Change: Assessments and Issues.* J. B. Smith, N. Bhatti, G. Menzhulin et al. (eds.). New York, Springer: 232-242.

Strzepek, K. M., Onyeji, S. C., Saleh, M. and Yates, D. N.: 1995. An assessment of integrated climate change impacts on Egypt. In *As Climate Changes: International Impacts and Implications.* K. M. Strzepek and J. B. Smith (eds.). Cambridge, Cambridge University Press: 180-200.

Strzepek, K. M. and Smith, J. B., Eds.: 1995. *As Climate Changes: International Impacts and Implications.* Cambridge, Cambridge University Press.

Tett, S.: 1995. Simulation of El Niño/Southern Oscillation-like variability in a global AOGCM and its response to CO2 increase. *Journal of Climate* **8**, 1473-1502.

Tsuji, G. Y., Uehara, G. and Balas, S., Eds.: 1994. *DSSAT Version 3.* Honolulu, University of Hawaii.

UNCED (United Nations Conference on Environment and Development) (1992). Protection of the quality and supply of freshwater resources. *Agenda 21.* New York, UNCED. **2**.

Watson, R. T., Zinyowera, M. C. and Moss, R. H., Eds.: 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change, Scientific-Technical Analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

Wigley, T. and Raper, S.: 1992. Implications for climate and sea level of revised IPCC emissions scenarios. *Nature* **357**(1992), 293-300.

World Bank (1993). *Water Resources Management.* Washington, DC, World Bank.

World Resources Institute (1994). *World Resources, 1994-95.* New York, Oxford.

Xue, Y. and Shukla, J.: 1993. The influence of land surface properties on Sahel climate. Part I: desertification. *Journal of Climate* **6**, 2232-2245.