REDUCING VULNERABILITY OF AGRICULTURE AND FORESTRY TO CLIMATE VARIABILITY AND CHANGE: WORKSHOP SUMMARY AND RECOMMENDATIONS

M. J. SALINGER[1], M. V. K. SIVAKUMAR[2] and R. MOTHA[3]

[1]*National Institute of Water and Atmospheric Research, P.O. Box 109-695, Newmarket, Auckland, New Zealand*
E-mail: j.salinger@niwa.co.nz
[2]*World Meterological Organization, 7bis Avenue de la Paix, 1211 Geneva 2, Switzerland*
[3]*United States Department of Agriculture, 1400 Independence Ave, SW Room 5143, Washington DC 20250, U.S.A.*

Abstract. The International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change held in Ljubljana, Solvenia, from 7 to 9 October 2002 addressed a range of important issues relating to climate variability, climate change, agriculture, and forestry including the state of agriculture and forestry and agrometeological information, and potential adaptation strategies for agriculture and forestry to changing climate conditions and other pressures. There is evidence that global warming over the last millennium has already resulted in increased global average annual temperature and changes in rainfall, with the 1990s being likely the warmest decade in the Northern Hemisphere at least. During the past century, changes in temperature patterns have, for example, had a direct impact on the number of frost days and the length of growing seasons with significant implications for agriculture and forestry. Land cover changes, changes in global ocean circulation and sea surface temperature patterns, and changes in the composition of the global atmosphere are leading to changes in rainfall. These changes may be more pronounced in the tropics. For example, crop varieties grown in the Sahel may not be able to withstand the projected warming trends and will certainly be at risk due to projected lower amounts of rainfall as well. Seasonal to interannual climate forecasts will definitely improve in the future with a better understanding of dynamic relationships. However, the main issue at present is how to make better use of the existing information and dispersion of knowledge to the farm level. Direct participation by the farming communities in pilot projects on agrometeorological services will be essential to determine the actual value of forecasts and to better identify the specific user needs. Old (visits, extension radio) and new (internet) communication techniques, when adapted to local applications, may assist in the dissemination of useful information to the farmers and decision makers. Some farming systems with an inherent resilience may adapt more readily to climate pressures, making long-term adjustments to varying and changing conditions. Other systems will need interventions for adaptation that should be more strongly supported by agrometeorological services for agricultural producers. This applies, among others, to systems where pests and diseases play an important role. Scientists have to guide policy makers in fostering an environment in which adaptation strategies can be effected. There is a clear need for integrating preparedness for climate variability and climate change. In developed countries, a trend of higher yields, but with greater annual fluctuations and changes in cropping patterns and crop calendars can be expected with changing climate scenarios. Shifts in projected cropping patterns can be disruptive to rural societies in general. However, developed countries have the technology to adapt more readily to the projected climate changes. In many developing countries, the present conditions of agriculture and forestry are already marginal, due to degradation of natural

Climatic Change (2005) 70: 341–362

resources, the use of inappropriate technologies and other stresses. For these reasons, the ability to adapt will be more difficult in the tropics and subtropics and in countries in transition. Food security will remain a problem in many developing countries. Nevertheless, there are many examples of traditional knowledge, indigenous technologies and local innovations that can be used effectively as a foundation for improved farming systems. Before developing adaptation strategies, it is essential to learn from the actual difficulties faced by farmers to cope with risk management at the farm level. Agrometeorologists must play an important role in assisting farmers with the development of feasible strategies to adapt to climate variability and climate change. Agrometeorologists should also advise national policy makers on the urgent need to cope with the vulnerabilities of agriculture and forestry to climate variability and climate change. The workshop recommendations were largely limited to adaptation. Adaptation to the adverse effects of climate variability and climate change is of high priority for nearly all countries, but developing countries are particularly vulnerable. Effective measures to cope with vulnerability and adaptation need to be developed at all levels. Capacity building must be integrated into adaptation measures for sustainable agricultural development strategies. Consequently, nations must develop strategies that effectively focus on specific regional issues to promote sustainable development.

1. Introduction

Climate change and variability, drought and other climate-related extremes have a direct influence on the quantity and quality of agricultural production and in many cases, adversely affect it; especially in developing countries, where technology generation, innovation and adoption are too slow to counteract the adverse effects of varying and changing environmental conditions. The interdisciplinary nature of these issues requires a long lasting and where possible more substantial role for agrometeorology in the efforts to promote sustainable agricultural development during the 21st century. There is a need to develop locally new and better agrometeorological adaptation strategies to increasing climate variability and climate change, especially in vulnerable regions where food and fibre production is most sensitive to climatic fluctuations.

Because of uncertainties associated with regional projections of climate change, the Intergovernmental Panel on Climate Change has attempted to assess the vulnerability of natural and social systems to changes in climate, rather than attempt to provide quantitative predictions of the impacts of climate change at the regional level. The range of adaptation options for managed systems such as agriculture and forestry is generally increasing because of technological advances, thus opening the way for reducing the vulnerability of these systems to climate change. Some regions of the world, particularly developing countries, have limited access to and absorption capacity for these technologies. They lack local appropriate information on how to implement them under their conditions. However, innovations from within are of more than equal importance (Salinger et al., 2000). Incorporation of climate change concerns into resource use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

The issues of climate variability and climate change need to be integrated into resource use and development decisions. Climate variability affects all economic sectors, but agricultural and forestry activities are perhaps two of the most vulnerable and sensitive sectors to such climate fluctuations. Agrometeorological services derived from a more informed choice of policies, practices and technologies will, in many cases, reduce the long-term vulnerability of these systems to climate change. For example, the introduction of farmer-oriented seasonal climate forecasts (Lemos at al., 2002) into management decisions may reduce the vulnerability of agriculture to floods and droughts caused by the El Niño-Southern Oscillation (ENSO) phenomena.

The International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change, held in October 2002 in Ljubliana, Slovenia, where the papers in this volume were presented assessed the varying global climates and their likely changing impacts, and examined adaptation options. Resources and strategies, including education and training, in reducing the vulnerability of agriculture and forestry, were also discussed.

2. The Varying Climate

The Intergovernmental Panel on Climate Change (IPCC, 2001a) has shown that prior to the 20th century Northern Hemisphere average surface air temperatures have varied in the order of 0.5 °C back to AD 1000. Various climate reconstructions indicate that slow cooling took place until the beginning of the 20th century. Subsequently, global-average surface air temperature increased by about 0.6 °C, with the 1990s being the warmest decade on record. The pattern of warming has been greatest over mid-latitude northern continents in the latter part of the century. At the same time the frequency of air frosts has decreased over many land areas, and there has been a drying in the tropics and subtropics. The late 20th century changes have been attributed to global warming because of increases in atmospheric greenhouse gas concentrations due to human activities.

Salinger (2005) has shown that beneath the longer-term trends there is decadal scale variability in the Pacific basin at least induced by the Interdecadal Pacific Oscillation (IPO). On interannual timescales ENSO causes much variability throughout many tropical and subtropical regions and some mid-latitude areas. The North Atlantic Oscillation (NAO) provides climate perturbations over Europe and northern Africa.

Projections from the IPCC (2001a, 2001b) indicate that in the course of the 21st century global-average surface temperatures are very likely to increase by 2 to 4.5 °C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall (causing floods) and drought are expected to increase in many areas.

The combinations of global warming, with decadal climate variability (IPO) and interannual fluctuations (ENSO, NAO) are expected to lead to a century of increasing climate variability and change. This could bring with it unknown climate surprises and their impacts, such as flooding from unmanageable catchments and inundation of land areas due to storm surges and sea level rise. In the perspective of human settlement and agriculture and forestry activities over the last 10,000 yr at least climate changes have been quite small, and certainly in the documented record for the last 1,000 yr small variations in global temperature have occurred compared with the glacial/interglacial changes. Although the changes of the past and present have stressed food and fibre production at times, the 21st century changes will be extremely challenging to agriculture and forestry. As the century progresses, the interannual and decadal phenomena will be superimposed on an unprecedented global warming trend. Together these will produce rapid climate change, increasing climate variability and more climate extremes. Thus agriculture and forestry will face unprecedented stresses in the 21st century. Some of these concerns were addressed in an earlier international agrometeorological workshop (Stigeter et al., 2000).

3. Impacts

3.1. TROPICAL REGIONS

Roughly 40% of the world population lives in the tropics, and agriculture is a very important sector for the economies of most countries in the tropics. For example, in tropical Asia, more than half of the labour force is employed in agriculture, accounting for 10–63% of the GDP in most countries of the region (IPCC, 1998). Given the current scenarios of enhanced temperatures and increased frequency of extreme events, climate change is likely to have significant impact in the tropics.

Sivakumar et al. (2005) pointed out that the arid and semiarid regions account for approximately 30% of the world total area and are inhabited by 1.1 billion people or approximately 20% of the total world population. The arid and semiarid regions are home to about 24% of the total population in Africa, 17% in the Americas and the Caribbean, 23% in Asia, 6% in Australia and Oceania, and 11% in Europe (UNSO, 1997). According to Zhao et al. (2005), humid and subhumid tropical conditions are found over nearly 50% of the tropical land mass and 20% of the earth's total land surface. Tropical Central and South America contain about 45% of the world's humid and subhumid tropics; Africa, about 30% and Asia, about 25%.

Sivakumar et al. (2005) described the agricultural climate of the arid and semiarid tropical regions in Asia, Africa and Latin America, which is characterized by low and variable rainfall and consistently high temperatures during the growing season. Climate variability—both inter- and intra-annual—is a fact of life in these regions with a traditionally low agricultural productivity. The projected climate change and the attendant impacts on water resources and agriculture in the arid and semiarid tropical regions add additional layers of risk and uncertainty to agricultural systems that are already affected by land degradation due to growing population pressures.

It is interesting to note the observations of Sivakumar et al. (2005) that in certain agroecological zones such as the southern Sahelian zone of West Africa, where the predominant soils are sandy in nature, increased *mean* temperature could affect the *maximum* temperatures at the soil surface substantially. They pointed out that surface soil temperatures could exceed even 60°C and that under such temperatures, enzyme degradation will limit photosynthesis and growth. Increased temperatures will also result in increased rates of potential evapotranspiration. In the long term, the very establishment and survival of species in both the managed and unmanaged ecosystems in this region may be threatened, resulting in a change in the community structure.

The prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995). Projected temperature increases are likely to lead to increased open water and soil/plant evaporation. As a rough estimate, potential evapotranspiration over Africa is projected to increase by 5–10% by 2050. Since Africa is the continent with the lowest conversion factor of precipitation to runoff (averaging 15%), and precipitation in some areas may decrease, the dominant impact of global warming is predicted to be a reduction in soil moisture in subhumid zones and a reduction in runoff.

The general conclusion is that climate change will affect some parts of Africa negatively, although it will enhance prospects for crop production in other areas (see Downing, 1992, for case studies of agriculture in Kenya, Zimbabwe, and Senegal). Expansion of agriculture is important in the east African highlands. For example, agroecological suitability in the highlands of Kenya would increase by perhaps 20% with warming of 2.5 °C based on an index of potential food production (Downing, 1992). In contrast, semiarid areas are likely to be worse off. In eastern Kenya, 2.5 °C of warming results in a 20% decrease in calorie production.

The water and agriculture sectors are likely to be most sensitive and hence vulnerable to climate change-induced impacts in arid and semi-arid tropical Asia. Croplands in many of the countries in the region are irrigated because rainfall is low and highly variable (IPCC, 2001b). The agriculture sector here is potentially highly vulnerable to climate change because of degradation of the limited arable land. The predicted increase in frequency and/or severity of extreme events coupled with any increase in intensity of tropical cyclones could further exacerbate adverse impacts of climate change on the agricultural sector.

Sivakumar et al. (2005) referred to several studies aimed at understanding the nature and magnitude of gains/losses in yield of particular crops at selected sites in Asia under elevated CO_2 conditions (e.g., Luo and Lin, 1999). These studies suggest that, in general, areas in mid- and high- latitudes will experience increases in crop yield, whereas yields in areas in the lower latitudes will decrease. Generally climatic variability and change will seriously endanger sustained agricultural production in tropical Asia in coming decades. The scheduling of the cropping season as well as the duration of the growing period of the crops would also be affected. Studies conducted in India, Indonesia and the Philippines confirmed that spikelet sterility and reduced yields negate any increase in dry-matter production as a result of CO_2 fertilization. Amien et al. (1996) found that rice yields in east Java could decline by 1% annually as a result of increases in temperature. Sivakumar et al. (2005) referred to studies in Asia that showed adverse effects on sorghum in rainfed areas of India, for corn yields in the Philippines and on the tea industry of Sri Lanka.

Agricultural production in lower-latitude and lower-income countries is more likely to be negatively affected by climate change (IPCC, 1998; 2001b). It is seen that climate variability and climate change, particularly in terms of frequency/intensity of droughts, have larger impacts on the subhumid than on the humid regions. If climate variability-induced disasters become more common, widespread, and persistent, many countries in the humid and subhumid tropical regions will have difficulty in sustaining viable agricultural and forest practices. A good number of researchers have all concluded that climate change would affect agriculture as a result of increased temperatures, changes in rainfall patterns and increased frequency of extreme events, which could cause changes in pest ecology, ecological disruption in agricultural areas and socioeconomic shifts in land-use practices.

Extremes in climate variability already severely affect agriculture in Latin America (IPCC, 2001b). The largest area with marked vulnerability to climate variability in Latin America is northeast Brazil. Sivakumar et al. (2005) pointed out that periodic occurrences of severe El Niño-associated droughts in northeastern Brazil have resulted in occasional famines. Under doubled-CO_2 scenarios, yields are projected to fall by 17 to 53%, depending on whether direct effects of CO_2 are considered. Lemos et al. (2002) show the difficulties of absorption of seasonal climate forecasts in this region.

In Africa, most mid-elevation ranges, plateaus, and high-mountain slopes are under considerable pressure from commercial and subsistence farming activities. Mountain environments are potentially vulnerable to the impacts of global warming. This vulnerability has important ramifications for a wide variety of human uses—such as nature conservation, mountain streams, water management, agriculture, and tourism (IPCC 1998).

Zhao et al. (2005) referred to studies on the survival rate of pathogens in winter or summer which could vary with an increase in surface temperature. Higher temperatures in winter will not only result in higher pathogen survival rates but also lead to extension of cropping area, which could provide more host plants for pathogens. Thus, the overall impact of climate change is likely to be an enlargement of the source, population, and size of pathogenic bacteria. Damage from diseases may be more serious because heat-stress conditions will weaken the disease-resistance of host plants and provide pathogenic bacteria with more favourable growth conditions.

Sivakumar et al. (2005) and Zhao et al. (2005) pointed to the environmental and social stress caused by climate change in many of Asia's rangelands and drylands. Precipitation is scarce and has a high annual variance in dryland areas of the tropics. Very high daily temperature variance is recorded with frequent sand storms and intense sunshine. The combination of climatic variability and human land use make rangeland ecosystems more susceptible to rapid degeneration of ecosystem properties. For example, because of an alteration in the amount and pattern of rainfall, the occurrence of extreme events (e.g., hurricanes, drought), and the ENSO which could become more frequent and bring more severe weather under the $2 \times CO_2$-climate, the northern South America Savannas could fail to function as they do now (Aceituno, 1988).

Climate affects livestock in four ways: through (i) the impact of changes on availability and price of feedgrain, (ii) impacts on livestock pastures and forage crops, (iii) the direct effects of weather and extreme events on animal health, growth, and reproduction, and (iv) changes in the distribution of livestock diseases.

It was pointed out that almost two-thirds of domestic livestock are supported on rangelands, although in some countries a significant share of animal fodder also comes from crop residue. The combination of elevated temperature and decreased precipitation in arid and semiarid rangelands could cause a manifold increase in potential evapotranspiration, leading to severe water stress conditions. Many desert organisms are near their limits of temperature tolerance. Because of the current marginality of soil water and nutrient reserves, some ecosystems in semiarid regions may be among the first to show the effects of climate change. Climate change has the potential to exacerbate the loss of biodiversity in this region.

Zhao et al. (2005) mentioned that for developing countries, the impact of climate variability on livestock is generally negative in the humid and subhumid tropics, particularly in the latter. For animals, heat stress has a variety of detrimental effects with significant effects on milk production and reproduction in dairy cows, and swine fertility. Moreover, warming in the tropics during warm months would likely affect livestock reproduction and production negatively (e.g., reduced animal weight gain, dairy production, and feed conversion efficiency). Impacts however may be minor for relatively intense livestock production systems.

Livestock in humid areas in Africa are prone to disease such as those carried by the tsetse fly. With warming, its distribution could extend westward in Angola and northeast in Tanzania but with reductions in the prevalence of tsetse in some current areas of distribution.

Because of the increasing trend for meat consumption, there is a higher demand for livestock feed. Production of feed grain in Asia, especially maize, is adversely affected by climate variability and climate change.

Tropical forests represent about 40% of the world's forested area and contain about 60% of global forest biomass. As many as 16 countries of tropical Asia are situated within the humid tropical forest region. Climate change is expected to affect the boundaries of forest types and areas, primary productivity, species population and migration, the outbreak/incidence of pests and diseases and forest degeneration in these countries.

Zhao et al. (2005) referred to the results of research from Thailand which suggest that climate change would have a profound effect on the future distribution, productivity, and health of Thailand's forests. It was estimated that the area of subtropical forest could decline from the current 50% to either 20% or 12% of Thailand's total forest cover (depending on the model used), whereas the area of tropical forests could increase from 45% to 80% of total forest cover. Estimates from Sri Lanka showed a decrease in tropical rainforest of 2–11% and an increase in tropical dry forest of 7–8%. A northward shift of tropical wet forests into areas currently occupied by tropical dry forests also is projected. In semiarid regions of Tropical Asia, tropical forests generally are sensitive to changes in temperature and rainfall, as well as changes in their seasonality.

Most tropical forests are likely to be more affected by changes in soil water availability (e.g., seasonal droughts). Some evergreen species of the humid forest clearly will be at a disadvantage in those areas that experience more severe and prolonged droughts. Significantly, drought affects the survival of individual species; those without morphological or physiological adaptations to drought often die. Species in moist tropical forests, including economically important hardwoods, are the least drought-adapted in the tropics, and their survival in some areas must be considered at risk from climate change. Droughts would favor forest fire; therefore, with a likely increase of droughts, the incidence of forest fires may also increase.

More than 50% of the world's terrestrial plant and animal species are in the frontier forests in Asia. There already are trends of increasing risks to this rich array of living species being seen in China, India, Malaysia, Myanmar and Thailand, partly due to the degeneration of their habitat (IPCC, 2001b). Since distribution of species are limited to a narrow range of environmental conditions, there are possibilities that climate change could alter these conditions which could make them unsuitable. This could cause the loss of a large number of unique species that currently inhabit the world's tropical forests.

There is high confidence that if the extent of deforestation in Amazonia expands to substantially larger areas, reduced evapotranspiration would lead to less rainfall during its dry periods. If this dry period becomes larger and more severe, it could have deleterious impacts on the forest. Many trees could die due to increased water stress. Greater severity of droughts coupled with deforestation could lead to erosion in what remains of the forests in this region. Moreover, occasional severe droughts likely to occur during the EI Niños would kill many trees of susceptible species and would result to a replacement of tropical moist forests with drought-tolerant species (Shukla et al. 1990).

There are other features of agricultural vulnerability to climate change which are also likely to vary across people, regions, continents and countries. One of these is vulnerability to food security because there would then be rapid changes in supply and demand structures most especially in the developing countries, especially in the tropics. For example, food-importing countries like those in Africa are at risk of adverse impacts of climate change, especially because these impacts are intricately linked with changes in world markets as with changes in local and regional biophysical systems. The already deficient food production in many areas of Africa could also this way result in worsening problems of food security.

3.2. TEMPERATE REGIONS

Maracchi et al. (2005) and Motha and Baier (2005) presented overviews of impacts for Europe and North America, respectively. Increased climate variability has resulted in greater fluctuations in crop yields during recent decades. Extreme weather events such as drought, flooding, and heat waves have had severe impacts on agriculture and forestry, as have changes in drought tendencies, soil moisture availability and frost-free growing seasons. Agriculture has also played a role in greenhouse gas emissions. The clearing of forests, the draining of wetlands, and the ploughing of rangelands have led to a significant increase in atmospheric CO_2, as organic carbon was decomposed. Nitrous oxide (N_2O) originates as a by-product of nitrogen fertilizer application and in water-logged soils. Thus, in higher latitudes, a spring burst of N_2O emissions occurs with rapid snowmelt. Heavy rains in low-lying areas also cause a N_2O burst of emissions. Methane (CH_4) emitted from agriculture is produced by the microbial breakdown of plant material and in the digestive system of cattle.

There are measures to mitigate agriculture's role in greenhouse gas emissions. Atmospheric CO_2 can be returned to the land by afforestation, conservation tillage by a cover crop, and no-till conservation practices. Soil microorganisms can remove both N_2O and CH_4 with improved pasture conditions and cover crops on cultivated land to lower the amount of inorganic nitrogen in the soil. Higher quality cattle feeds can reduce CH_4 emissions from domestic livestock.

The combined effect of climate change and enhanced CO_2 on crop production varies. Yields of C3 crops (vegetables, wheat, grapes) generally increase. Yields of C4 crops (corn, sugarcane, tropical grasses) generally decrease. However, annual variability of crop yields increase.

Distinct regional patterns by latitude were discernible in future climate scenarios for Europe and North America (Maracchi et al., 2005; Motha and Baier, 2005). Temperatures are expected to increase in nearly all areas but the largest temperature increases are projected over southern portions of both the United States and Europe. Consequently, the extreme cold of winter is expected to diminish but a greater likelihood of heat waves is projected in summer. An increase in the frequency and intensity of heavy precipitation is expected, even in southern Europe and the southern United States, despite projections of total precipitation to decrease.

Northern crop areas of both Europe and the United States will have a longer growing season and an expansion of suitable area for crop production. With higher crop production, however, the increased risk of nutrient leaching and an accelerated breakdown of soil organic matter may affect the quality of northern agricultural lands. Lower crop yields are expected in southern crop areas due to the warmer and drier summers.

4. Adaptation and Applications

Agrometeorological adaptation strategies to increasing climate variability and climate change have been in focus already for a long time (Salinger et al., 2000). Adaptation should be viewed as a broad concept involving choices at national and international levels as well as locally. Adaptation involves more than measures; it is also a matter for national agricultural and development policies. Under the UN Framework Convention very little attention has been given to technical adaptation. The debate has centered on the need for technology transfer but adaptation technology has not been emphasized in the rush to promote technology transfer for greenhouse gas emission reductions.

Burton and Lim (2005) note that national agricultural policy is developed in the context of local risks, needs, and capacities, as well as international markets, tariffs, subsidies and trade agreements. Stakeholder participation in policy development is frequently recommended as a measure that can help to reduce the distance between national policy processes and the farm and community level.

Agriculture can be described as highly adaptable and resilient, or as resistant to change, and is related to the diffusion and success of technical innovations at the farm level. Successful adaptation over decades and centuries at this level goes a long way toward explaining the confidence now being expressed in the ability of agriculture to cope with the potential impacts of climate change. On the other hand there are concerns that the modernization of agriculture is having serious environmental and social consequences.

Prospects at the global level are good, but severe local and regional disruptions and inequalities are possible, even likely. This diagnosis suggests the need to pay more attention to national policy and global negotiations in order to alleviate inequalities between and within nations. From the perspective of climate change and development the place where local and global converge is at the level of national policy.

Some new approaches to national policy for climate change adaptation are now being developed and applied. These include the National Adaptation Programmes of Action (NAPAs) agreed at the Conference of the Parties to the Framework Convention on Climate Change (COP 7). The Adaptation Policy Framework (APF) now being elaborated builds upon past work and experience and is being developed by UNDP at a generic level. The World Health Organization is developing a set of guidelines for the assessment of adaptation to climate change in the health sector. Similar activities with partners would be timely.

One new technology allowing for adaptation measures is that of seasonal to interannual climate prediction. Harrison (2005) noted that this uses knowledge of sea surface temperature anomalies on which to base a forecast of temperature and rainfall conditions in teleconnected parts of the globe. There are two types of models used in long-range prediction where the objective is to produce a prediction of the average climatic conditions throughout a season across a region measuring several hundred kilometers along each side. Rainfall is a major concern for agrometeorology but it is variable in both space and time and many applications are more sensitive to the timing and amounts of rainfall through a season than they are to the total amount. Downscaling does not improve the accuracy of the forecast and Harrison (2005) recommends that more research is needed on improving methods for forecast validation, verification, and interpretation, and that optimal strategies be devised through more pilot projects.

According to Meinke and Stone (2005) seasonal climate forecasting can increase preparedness and lead to better social, economic and environmental outcomes for agrometeorology. However, climate forecasting is one of many risk management tools that sometimes play an important role. To apply these effectively, a participatory, cross-disciplinary research approach, that brings together institutions (partnerships), disciplines (i.e., climate science, agricultural systems science and rural sociology) and people (scientist, policy makers and direct beneficiaries) as equal partners to reap the benefits from climate forecasting, was suggested. Climate science can provide insights into climatic processes, agricultural systems science can translate these insights into technically possible solutions (management options) and rural sociology can help to determine the options that are most feasible or desirable from a socioeconomic perspective. Any future scientific breakthroughs in climate forecasting capabilities are much more likely to have an immediate and positive impact when conducted within such a framework. Seasonal to interannual climate forecasts are best applied with a good understanding of variability, both temporally and spatially, and a probabilistic approach to outcome dissemination should be considered. In practice there are serious absorption difficulties (Lemos et al., 2002).

For temperate regions, adaptation strategies for agriculture to cope with climate variability and climate change include changes in crop varieties and agronomic practices, improvements in moisture conserving tillage methods, proper irrigation management, and changes in land allocation.

5. Technologies and Strategies

There are a number of technologies and strategies that could help reduce the vulnerability of agriculture and forestry to climate variability and climate change. Stigter et al. (2005) referred to the fact that countless farming communities managed to survive and, in some cases, even to thrive by exploiting natural resource bases which their forebears have used for generations. Through a process of innovation and adaptation, indigenous farmers have developed numerous different farming systems finely tuned to many aspects of their environment.

Traditional knowledge, indigenous practices and identified local innovations contain valuable information that should be used as a basis for improved technologies and strategies to cope with projected changes. Climate variability and related disasters can be mitigated by temporary or permanent protective measures or by avoidance strategies that try to escape the peak values or their consequences. These are all aspects of preparedness strategies.

As Stigter et al. (2005) explained, in the context of climate change, traditional knowledge and indigenous technologies that mitigate consequences of variabilities of (i) heavy moisture flows or the lack of water, (ii) changing heat flows and related temperatures, (iii) and cropping seasons need special attention. Drought being already a serious threat, indications for longer dry spells in rainy seasons and longer sequences or higher frequencies of abnormal rainfall seasons, with respect to total rainfall and rainfall distribution, make the indigenous ways of coping with drought situations even more important.

One of the popular indigenous technologies described by Stigter et al. (2005) is traditional water harvesting methods and technologies of the use of underground water. A related technology of which also the IPCC advocates more intensive use is that of water impoundment. Several useful examples are given from Indonesia, Sri Lanka, Niger, and Burkina Faso. Permaculture, water harvesting and infiltration pits, together with the use of drought tolerant crops, have been more recently extended in Zimbabwe, particularly by women, with the help of NGOs, in reply to the recurrent droughts.

Many of the same traditional adaptation strategies with agrometeorological components that we presently try to apply also hold for the situations of increasing climate variability and Stigter et al. (2005) present evidence from China to substantiate this fact.

Response farming evolved as a promising technology in the past two decades to alter cropping systems/cropping patterns in relation to fluctuations in seasonal weather. Stigter et al. (2005) suggest that response farming should not only be considered with respect to fitting the cropping seasons to variable rainfall patterns but also for fitting it to variable temperature patterns. They cite the case study from Vietnam (Van Viet, 2001) where either planting date or a combination of planting date and variety could be varied, to make sure that rice was flowering in decades for which the required optimal temperatures had been forecasted. For example the detailed knowledge available on the influence of temperature, temperature extremes and temperature distributions on growth, development and yield of rice (Salinger et al., 1997) makes this possible.

Where temperature is a limiting factor to photosynthesis, traditional farmers may react to cooling/warming by changing their cropping system. Stigter et al. (2005) give the example of changing cropping patterns from North China Plain.

They also give relevant examples of microclimate management and manipulation to cope with temperature changes, e.g., parkland agroforestry and other stabilizing intensive management of scattered or clumped or alleyed trees.

One promising new technology that offers much promise is the application of seasonal to interannual climate forecasts. Disaster preparedness strategies, both of governments and NGOs, have begun to take account of such forecasts, and there is considerable interest in assigning them an economic value. The challenge of course is to reduce the gap between the information needed by small scale farmers and that provided by the meteorological services (Blench, and Marriage 1998; Lemos et al., 2002). As Stigter et al. (2005) noted, low-income farmers are interested in a broader range of characteristics of precipitation, notably, total rainfall, patchiness of rainfall, intensity, starting date, distribution of rainfall, end of the rains and prospects for dry spells and their length. It is precisely in this area that scientific extensions and improvements of response farming approach would bring highly needed solutions (Stewart, 1988). Demonstration projects such as the CLIMAG (Climate Prediction and Agriculture) project currently being implemented in South Asia and West Africa could provide useful information for implementation of similar pilot projects in other regions.

The substantial losses in soil C due to anthropogenic activities have prompted a great deal of interest in the recent past in the concept that agricultural lands have the potential to regain some of this C and that globally between 0.4 and 0.8 Pg / Yr of C could be sequestered in agricultural soils for 50 to 100 yr through good soil management.

Desjardins et al. (2005) discussed a number of agricultural land management practices that have shown potential for increasing C content in agricultural soils. Adoption of permanent cover is one of these practices. Converting cropland into perennial forage may result in a substantial increase in C sequestration. Prevention of overgrazing is also a mitigation strategy that can improve soil carbon levels in pastures significantly.

Conservation tillage or no-till management, when combined with the use of cover crops, proper crop rotations, fertilizer strategies and manure applications, is one of the most efficient practices for sequestering C in cropland.

Reduction of summer fallow in crop rotations which results in greater cropping intensity will increase crop production and thus increase C inputs to soil and increase soil organic carbon. This will also increase water use, keeping soils dryer longer and thus reduce soil decomposition.

Most studies have shown a consistent contribution of forages to soil carbon sequestration. Perennial grasses or legumes in rotation, high yielding varieties and soil management practices that permit the return of large amounts of crop residues to the soil can potentially increase soil organic matter, thus increasing the likelihood for sequestering atmospheric CO^2. The use of legumes in crop rotations can also appreciably reduce the requirements for N fertilizers for various cropping systems, thereby reducing net fossil fuel use during manufacturing of N fertilizers.

Desjardins et al. (2005) also referred to the fact that most agricultural ecosystems are nitrogen-limited. Adding N fertilizer usually results in increased crop production and may therefore increase C sequestration in soils. However, in considering the net effect on the GHG budget, it is important to take into account the fact that nutrient additions via fertilizer can lead to higher N_2O emissions and may also tend to reduce the CH_4 uptake by soils. Further, there is C emitted in the manufacturing and transportation of N fertilizer that must also be accounted for.

6. Communication, Education and Training

Communicating drought information especially to remote rural populations is a major challenge for drought monitoring and prediction in Africa. Without access to reliable communication networks, the vast majority of Africa's farmers and herders do not have available the scientific and technological advances that support agricultural decision-making in richerr parts of the world. Boulahya et al. (2005) working with the African Centre of Meteorological Applications for Development (ACMAD) and herders and farmers designed the RANET system. Named for its innovative linkage of radio and Internet, RANET brings new communications and information technologies together with the oral traditions of Africa to deliver scientific drought information over a distributed network owned and managed by local communities. RANET combines data from global climate data banks in the United States, seasonal rainfall predictions from the international scientific community, data and forecasts generated in Africa, along with food security and agricultural information, to disseminate a comprehensive information package via a network of digital satellite, receiving stations, computers, radio, and oral intermediaries. This is one very effective method for the communication of climate information and forecasts to rural communities, especially in Africa.

Agricultural meteorologists are concerned with many operational aspects of the effects of climate on livestock and crop production. For them to continue to make a contribution to the economy of a country they must continually sharpen their skills and remain updated on the latest information available. Walker (2005) recommends that training should include a variety of skills including transferable skills (e.g., communication, numeracy), professional skills (including cognitive skills) and information technology skills. Problem-based learning can be used to promote critical thinking, decision making and analytical skills. More use should be made of Computer Aided Learning for agricultural meteorologists' in-service training. In particularly the Internet or CDs could be used to disseminate specific recently developed techniques and applications to improve the understanding of the variability in the climate and its effect on agricultural production. Computer-aided learning is becoming more accessible and user-friendly. New modules are continually being developed, and this method of learning will always expand. It is becoming an essential learning tool for agricultural meteorologists. Examples that can address the vulnerability of farmers include crop-climate matching, the use of indices, crop modelling and risk assessment together with seasonal outlooks. A strategy needs to be formulated to address these farmers' needs and implement changes in the education and training of agricultural meteorologists.

There is also a requirement to form a network for filling the gap between state-of-art development and operational use in agrometeorological services. This can be done by the establishment of a Regional Meteorological Training Centre (RMTC) where agrometeorologists can enhance their information technology skills because of increasing demands on climate and agronomic data for climate analysis at the regional scale, the inevitable use of computer technologies such as simulation models and GIS, and the need for agrometeorological information sharing among countries for sustainable agriculture.

Finally, any education and training programme for agricultural meteorologists must include practical applications oriented toward the unique local situations, and, ways and means to maintain good services to the public despite constantly changing circumstances.

7. Research and Development

Given the range of impacts of climate variability and projected climate change on agriculture and forestry in different regions of the world (see the section on impacts above), it is imperative that development and adoption of suitable adaptation strategies to cope with these impacts in different regions should be backed up by appropriate basic research. As Pérarnaud et al. (2004) described, it is indispensable to single out two types of adaptation depending on the final user: those which can be implemented by the farmer himself (modification of sowing dates, varietal choice, use of seasonal forecasts, etc.) and those of decision makers, land and natural resource managers which necessitate investment in development and construction of infrastructures.

Needs and perspectives for agrometeorology in the 21st centuy were obtained from a previous WMO (CAgM workshop, where research priorities were identified as support systems to agrometeorological services (Stigter et al., 2000). PéArarnaud et al. (2005) identified the following as the priority areas for research, most of which takes place in industrialized countries, and its use in order to cope with climate variability and future climate change.

7.1. IMPROVED UNDERSTANDING OF THE VARIATION OF THE CURRENT CLIMATE AND ITS IMPACT ON AGRICULTURE

To study the impacts of climate change on agriculture and forestry and improve our understanding of certain mechanisms, it is important to gather regular information on the ecosystems (inventories of land use per species, phenological observations, production statistics, etc.), and their evolution over the past few decades on a large scale. It is also important to analyze the extended series of climatic data on national territories over a period which extends from the end of the nineteenth century to the present day. These data should also be complemented by phenological series coming either from observations of the natural vegetation or forest species, or from the cultivated species, in particular the perennial species (fruit trees, vines, etc.).

7.2. SIMULATION OF FUTURE CLIMATE

Even though the predictions on global temperature are generally consensual, disparities exist in the behavior of the hydrological cycle in the regional responses to the increase in atmospheric greenhouse gas content. Questions also remain on the response of our natural environment to global warming, e.g., land use changes (particularly the natural or cultivated vegetation), the storage of carbon (particularly in the ocean and in the continental biosphere) or the possible modifications in oceanic circulation. Research on the regionalization of climatic changes must be carried out, with focus on improving the techniques themselves, but also the evaluation of the impact of climate change on agriculture and the environment. In relation to the forecasts currently available, there is a need to enlarge the range of variables considered, e.g., global solar radiation, as well as air humidity and wind speed, variables which affect agricultural and forestry production. Also, it would be necessary to obtain information not only on the average values, but also on the extremes (for example, for rainfall or wind speed) and exceeded threshold values (the case of frost).

7.3. FORECASTING CROP PRODUCTION

Climatic change carries several kinds of impacts on agriculture, e.g., on production (in terms of quantity and also quality), on the environment, on the species and land use changes, etc. The integration of these various components represents the main challenge to the research to be done and coordinated in the near future. Predictions must increasingly rely on crop simulation models that could effectively combine the effects of CO_2 and other climate variables on the physiological processes. Retrospective evaluation of the models with series of observed data, together with their sensitivity and uncertainty analyses are essential steps to build up confidence in model predictions. Taking account of the indirect effects linked to diseases, insects, as well as weeds, however, still remains a challenge.

It is essential to apply the simulation models to a spatial unit defined according to use (simulation unit) and then aggregate the results (yield, quantity of water consumed by the crop, etc.) on the desired regional scale. One of the greatest difficulties lies in taking account of the spatial heterogeneity of the soil, which is not always available in digital form and, might suffer from a lack of precision in terms of georeferencing. The use of crop simulation models, which are not perfect, fed with spatialized information from diverse origins with varying degrees of uncertainty, leads to the propagation of errors which may distort the final results. It is therefore appropriate to carry out theoretical research to quantify such errors and try to minimize them.

7.4. FORECASTING THE DEVELOPMENT OF PARASITES, PESTS AND WEEDS

In natural ecosystems, and also in cultivated or forest ecosystems, climate change is capable of disturbing the balance between the species, whether they are plant and/or animal, both in terms of the individual and the population. These changes will also modify the development of weeds, diseases and parasites among the crops, as well as their area of distribution. In order to forecast these changes, epidemiological models should be coupled to crop simulation models. However, development of such models necessitates the acquisition of field data and practical knowledge on the development of diseases in the field. At the present time, few such models are available and it is essential that progress is made in this direction.

7.5. BETTER UNDERSTANDING OF THE ROLE OF BIODIVERSITY

By exceeding the local species tolerance limits or altering the balance between these species, climate change is capable of having a major direct or indirect impact (fire, anthropogenic pressures) on the biodiversity of natural as well as cultivated ecosystems. Conversely, it is possible that biodiversity constitutes a stability factor in the face of climate change. Understanding the dynamics between species therefore necessitates new functional ecophysiological and behavioral studies (for animals) but also the development of specific models which enable their simulation.

7.6. PREDICTING THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON SOIL

Future changes in the climate and the composition of the atmosphere as reflected by the evolution of thermal and rainfall regimes, the vegetation, and land use, will have an effect on the soil and its dynamics. Research needs to provide answers to questions on the role of soil as a sink as well as a source of CO_2 changes in soil usage, etc. Modelling will be able to provide information on the consequences of changing agrosystems and ecosystems management practices simultaneously.

7.7. QUANTIFYING CARBON SEQUESTRATION IN FORESTS

Climate change is projected to affect forests in different ecosystems around the world and in terms of research, it is important to

- quantify the stocks and fluxes of carbon in the large forest ecosystems,
- simulate the future of the sequestration of carbon in these major forest types based on a climatic scenario with high spatial resolution,
- inventory the various forestry practices which have a significant impact on the stocks and fluxes of carbon and estimate the impact of various forestry options on the sequestration of carbon in these ecosystems and their harvested products, and
- assess the vulnerability of woodland species to allow alternative proposals to be made: replacement of species, fire prevention methods, etc.

7.8. DEVELOPING NEW CROPPING SYSTEMS

Agriculture in the 21st century will have to make its contribution to the reduction of GHG emissions (principally CO_2, CH_4, N_2O) but also and above all to adapt to climate change to continue to satisfy the vital needs of populations for food, energy, fibres, etc. There are a number of promising technologies such as minimum tillage techniques combined with the use of mulches and ground cover plants, improved agroforestry systems etc., which could increase soil carbon storage while sustaining productivity, but it is often difficult to persuade farmers to adopt these often promising solutions for various economic or social reasons. It is therefore important to use integrated approaches, which take into account the farmers' decision-making process, to design operational systems. The development of innovative systems in response to many criteria necessitates combination of experimentation on the ground and complex models with varied but coupled processes.

8. Recommendations on Adaptations

Global surface average temperature and sea level are projected to rise under all IPCC scenarios. At the same time climate variabilility is expected to continue on seasonal to interannual and decadal time scales owing to natural variability induced by such factors as ENSO events and the IPO. These will promote increasingly stronger impacts on agriculture and forestry. The workshop produced a number of recommendations. However, presently agronomic adaptation has been effective in mid-latitude developed countries, but less effective in lower latitude developing countries. With increasing climate change and variability though a wide range of adaptation strategies will be essential, coupled with mitigation options.

8.1. ADAPTATION RECOMMENDATIONS

1. Whether or not there will be significant climate change, inherent climatic variability makes adaptation unavoidable. These are embedded on issues such as sustainability of land productivity, changes in erosion, degradation and environmental quality, which also require due consideration.
2. Improved management strategies are required for coping with increasing climate variability and change. These can be drawn from both traditional and new technologies.
3. Standardization of crop models for widespread agrometeorological application are needed, with more modelling on the rainfall distribution and commencement for the rainy season in tropical and subtropical regions.
4. Changes in agronomic practices, such as earlier planting dates or cultivar substitution, and methods of microclimatic modification, for example, to cool animal environments as the climate warms.
5. Development of physiological based animal models with well developed climate components are needed urgently to cover gaps in knowledge and for future projections.
6. Improvement of carbon sequestration is required from agriculture and forestry by adopting permanent land cover, utilizing conservation tillage, reducing fallow land in summer, incorporating rotations of forage and improving nutrient management with fertilizers.

8.2. ADAPTATION AND MITIGATION IN TROPICAL REGIONS

1. Monitoring of crop development and growth together with appropriate climate information will improve management.
2. Development of water conservation strategies, both from traditional and modern practices is recommended for more efficient usage.
3. Increase the planting of shelterbelts or the use of scattered trees amongst crops for the reduction of erosion and wind damage and conservation of moisture.
4. Implementation of sustainable agriculture and forestry practices will both conserve land and improve yields over the long-term.
5. Development of innovative new technologies (e.g, climate forecasting) alongside traditional methods (e.g, intercropping, mulching) will be needed for yield improvement.

6. Development of adaptation strategies such as response farming at the local community level will engage active participation of the land users.

8.3. ADAPTATION AND MITIGATION IN TEMPERATE REGIONS

1. Earlier planting and sowing of crops as temperatures increase are recommended. This will utilize the higher temperatures earlier in the growing season and result in conserving soil moisture.
2. Earlier planting with the use of long season varieties to increase crop yields is a recommended adaption strategy in cooler climate regions where soil moisture is adequate and the risk of heat stress is low.
3. In hotter regions, the introduction of shorter season varieties will provide a measure to avoid or reduce summer heat and water stress.
4. Introduce changed land allocation for the stabilization of production and conservation of soil moisture.
5. Plan the use of shorter crop rotations and routine crop thinning in areas that experience higher precipitation.
6. Reduce the impacts of drought and erosion by utilizing larger spacing in forestry plantation planting and later thinning.
7. Increase the application of integrated pest management techniques.

8.4. MITIGATION OPTIONS

1. Prevention of overgrazing of grasslands will produce a moderate improvement in soil carbon levels.
2. Allocation of summer fallow areas is recommended for pasture and rangeland agriculture so as to reduce emissions of nitrous oxide.
3. Introduction of reduced tillage intensity and summer fallow areas, improved manure management and feed rations with improved drainage and irrigation will all contribute to less emissions of carbon dioxide, methane and nitrous oxide.
4. Introduction of forage cropping into rangeland and pasture rotations can be applied for increasing the carbon sequestration.
5. Improved nutrient management with suitable fertilizers will aid the sequestration of carbon.

References

Aceituno, P.: 1988, 'On the functioning of the Southern-Oscillation in the South America sector', *Mon. Wea. Rev.* **116**, 505–524.

Amien, L., Rejekiningrum, P., Pramudia, A., and Susanti, E.: 1996, 'Effects of interannual climate Variability and Climate Change on Rice Yield in Java, Indonesia', in Erda, L., Bolhofer, W., Huq, S., Mukherjee, S. K., Smith, J. B., and Wisniewski, J. (eds.), *Climate Change Variability and Adaptation in Asia and the Pacific*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 29–39.

Blench, R. and Marriage, Z.: 1998, 'Climatic uncertainty and natural resource policy: What should the role of government be?' *Nat. Resour. Perspectives* **31**, 8.

Boulahya, M. S., Cerda, M. S., Pratt, M., and Sponberg, K.: 2005, 'Climate, communications, and innovative technologies: Potential impacts and sustainability of new radio and internet linkages in rural African communities', *Clim. Change* **70**, 299–310.

Burton, I. and Lim, B.: 2005, 'Achieving adequate adaptation in agriculture', *Clim. Change* **70**, 191–200.

Desjardins, R., Smith, W., Grant, B., Campbell, C., Janzen, H., and Riznek, R.: 2005, 'Management strategies with particular emphasis on carbon sequestration to mitigate greenhouse gas emissions from agroecosystem', *Clim Change* **70**, 283–297.

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

Harrison, M.: 2005, 'The development of seasonal and inter-annual climate forecasting', *Clim. Change* **70**, 201–220.

IPCC: 1998, *'The Regional Impacts of Climate Change: An Assessment of Vulnerabilty* Special Report of IPCC Working Group II, in Watson, R. T., Zinyowera, M. C., and Moss, R. H., (eds.), Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, 517 pp.

IPCC: 2001a, *Climate Change 2001: The Scientitic Basisi*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change in Houston, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, K., Maskell, X., and Johnson C. A. (eds.) Cambridge university Press, Cambridge, UK.

IPCC: 2001b, *Climate Change 2001: Impacts, Adaptation and Vulnerabilty*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, in McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., (eds.), Cambridge University Press, Cambridge, UK.

Lemos, M. C., Finan, T. J., Fox, R. W., Nelson, D. R., and Tucker, J.: 2002, 'The use of seasonal climate forecasting in policy making: Lessons from northeast Brazil', *Clim. Change* **55**, 479–507.

Lou, Q. and Lin, E.: 1999, 'Agricultural vulnerability and adaptation in developing countries: The Asia Pacific region', *Clim. Change* **43**, 729–743.

Maracchi, G., Sirotenko, O., and Bindi, M.: 2005, 'Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe', *Clim Change* **70**, 117–135.

Meinke, H. and Stone, R.: 2005, 'Seasonal and inter-annual climate forecasting: The new tool for increasing preparedness to climate variability and change in agricultural planning and operations', *Clim. Change* **70**, 221–253.

Motha, R. and Baier, W.: 2005, 'Impacts of present and future climate variability on agriculture and forestry in the temperate regions: North America', *Clim. Change* **70**, 137–164.

Pérarnaud, V., Seguin, B., Malezieux, E., Deque, M., and Loustau, D.: 2005, 'Agrometeorological research and applications needed to prepare agriculture and forestry adapt to 21st century climate change', *Clim. Change* **70**, 319–340.

Riebsame, W. E., Strzepek, K. M., Wescoat, J. L., Jr., Perrit, R., Graile, G. L., Jacobs, J., Leichenko, R., Magadza, C., and Phien, H. Urbiztondo, B. J., Restrepo, P., Rose, W. R., Saleh, M., Ti, L. H., Tucci, C., and Yates, D.: 1995, 'Complex River Basins', in Strzepek, K. M. and Smith, J. B. (eds.), *As Climate Changes, International Impacts and Implications*, Cambridge University Press, Cambridge, UK, pp. 57–91.

Salinger, M. J.: 2005, 'Overview - Climate variability and climate change: Past, present and future', *Clim. Change* **70**, 9–29.

Salinger, M. J., Desjardins, R. L., Jones, M. B., Sivakumar, M. V. K., Strommen, N. D., Veeresamy, S., and Wu, Li. 1997, WMO Technical Note 199, WMO, Geneva, p. 124.

Salinger, M. J., Stigter, C. J., and Das, H. P.: 2000, 'Agrometeorological adaptations strategies to increasing climate variability and climate change', *Agri. For. Meteorol.* **103**, 167–184.

Shukla, J., Nobre, C., and Sellers, P.: 1990, 'Amazon deforestation and climate change', *Science* **247**, 1322–1325.

Sivakumar, M. V. K., Brunini, O., and Das, H. P.: 2005, 'Impacts of present and future climate variability on agriculture and forestry in the arid and semi-arid tropics', *Clim. Change* **70**, 31–72.

Stewart, J. I.: 1988, 'Principles and Performance of Response Farming', in Muchen, R. C. and Bollany, J. A. (eds.), *Climatic Risk in Crop Production: Models and Management for the Semi-Arid Tropics and Subtropics*, CAB Internationa, Wallingford', 361–382.

Stigeter, C. J., Sivakumar, M. V. K., and Rijks, D. A.: 2000, 'Agrometeorology in the 21st century: workshop summary and recommendations on needs and perspectives', *Agri. For. Meteorol.* **103**, 209–227.

Stigter, C. J., Zheng Dawei,, Xurong, M. and Onyewoto, L. O. Z.: 2005, 'Using traditional methods and indigenous technologies for coping with climate variability', *Clim. Change*, **70**, 255–271.

UNSO: 1997, *Aridity Zones and Dryland Populations. An Assessment of Population Levels in the World's Drylands*, Office to Combat Desertification and Drought (UNSO/UNDP), New York.

Walker, S.: 2005, 'Role of education and training in agricultural meteorology to reduce vulnerability to climate variability', *Clim. Change*, **70**, 311–318 .

Van Viet, N.: 2001, 'The Influence of Climatic Variation on the Production of Winter-Spring Rice in the North Delta of Vietnam and the Means to Cope with It', In, *Contributions from Members on Operational Applications in Agrometeorology and from Discussants on the Papers Presented at the International Workshop: "Agrometeorology in the 21st Century - Needs and Perspectives"*, CAgM Report No. 77b, WMO/TD No. 1029, WMO, Geneva.

Zhao, Y., Wang, C., and Wang., S.: 2005, 'Impacts of present and future climate variability on agriculture and forestry in the sub-humid and humid tropics', *Clim. Change*, **70**, 73–116.

(Received 15 December 2003; in revised form 3 May 2004)