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Climate prediction and agriculture: current status and future challenges

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ABSTRACT: The past 2 decades have seen significant improvements in the forecasting of climate variability, based on advances in our understanding of ocean-atmosphere interactions. Such improvements permit the development of applications that predict climate at seasonal to interannual timescales, helping decision makers in the agricultural sector to deal more effectively with the effects of climate variability. The present study describes the current status of agriculture and the need for climate forecasts in light of risk management in rainfed farming, competition for limited water resources, impacts of natural disasters and the multi-dimensional impacts of extreme variability. The short history of climate prediction science demonstrates the progress made in understanding climate variability and the reliability of the predictions in the tropical Pacific region. Several case studies of climate forecast applications are described, illustrating the wide interest in such applications to help the farm sector cope with climate variability. Despite the progress achieved, several challenges lie ahead in enhancing the wider applications of climate forecasts in the agricultural sector. These include the need for improvements in the accuracy of models; generating quantitative evidence about the usefulness of climate forecasts as tools for agricultural risk management; addressing the key issues for promoting beneficial use of forecasts; responding to diverse needs of the users and involving the stakeholders more actively in climate prediction applications; giving greater priority to extension and communication activities; learning from non-adoption situations; deriving more economic benefits through climate prediction applications to trade and storage; and improving the institutional and policy environment.

KEY WORDS: Seasonal climate forecasts · Applications of forecasts · Agriculture · User needs · CLIMAG

1. INTRODUCTION

Prior to the 1980s, few farmers around the world imagined that the distant tropical Pacific and Indian Oceans would influence the weather and climate over their own farms. For example, few Australian farmers realized that the top 3 m of the ocean can store and move as much heat as the whole atmosphere and that ocean currents in the tropical Pacific and Indian Ocean have a major influence on how much and when rain falls across the Australian continent. Similarly, Sahelian farmers had little understanding that the Indian and Atlantic Oceans have an impact on their farming conditions. The Atlantic Ocean also impacts farming conditions in northeast Brazil, but farmers there had no notion of such impacts. The reality is that the atmosphere responds to ocean temperatures within a few weeks. However, the ocean takes 3 mo or longer to respond to changes in the atmosphere. Because oceans change much more slowly than the atmosphere, when a mass of warm water forms, it takes months to dissipate and may move thousands of kilometers before transferring its heat back to the atmosphere. It is this persistence of the ocean that offers the opportunity for climate prediction (CSIRO 1998). Until 20 yr ago, seasonal climate predictions were based exclusively on empirical-statistical techniques that provided little understanding of the physical mechanisms responsible for relationships between current conditions and the climate anomalies (departures from normal) in subsequent seasons. Mathematical models analogous to those used in numerical weather prediction, but

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including representation of atmosphere–ocean interactions, are now being used to an increasing extent in conjunction with, or as an alternative to, empirical methods (AMS Council 2001).

While the science of climate prediction is relatively new, the tradition of agriculture is quite ancient. Blending the new science with an ancient tradition is not always easy, especially in most of the developing countries with a long history of agriculture. This said, the opportunities of ensuring food security with climate prediction information are real, especially in some parts of the world. The first International Workshop on Climate Prediction and Agriculture (CLIMAG), held at the World Meteorological Organisation (WMO) in Geneva, Switzerland in September 1999 (Sivakumar 2000) considered a number of important issues relating to climate prediction applications in agriculture:

- Capabilities in long-term weather forecasting for agricultural production
- Downscaling
- Scaling-up crop models for climate prediction applications
- Use of weather generators in crop modeling
- Economic impacts of shifts in ENSO event frequency and strengths
- Economic value of climate forecasts for agricultural systems.

The workshop also discussed regional applications of climate prediction in several parts of the world and developed a number of recommendations. One important recommendation was that the CLIMAG project should be viewed as a partnership of researchers with multiple (potential) users and stakeholders. The workshop also recommended the implementation of proof-of-concept regional demonstration projects in Asia, Africa and South America. A limited number of projects were subsequently carried out in these 3 continents and one major lesson learnt is that a greater attention must be focused on relating climate forecast products to user needs.

The CLIMAG workshop held in 1999 led to several important initiatives by a number of organizations including START (global change SysTems for Analysis, Research, and Training—part of IGBP, the International Geosphere–Biosphere Programme), IRI (International Research Institute for Climate and Society), WMO (World Meteorological Organization), NOAA (National Oceanic and Atmospheric Administration) and the World Bank. Regional CLIMAG demonstration projects have been conducted in South Asia and West Africa. Within the Packard Foundation-funded Advanced Institute on Climate Variability and Food Security 18 research projects have recently been completed and the achievements of these projects were reviewed at the 'Synthesis Workshop of the Advanced Institute on Climatic Variability and Food Security' held at WMO on 9 and 10 May 2005. The Assessments of Impacts and Adaptations to Climate Change (AIACC) project of START supported a number of regional studies dealing with adaptation to climate change within the agriculture sector (available at: www.aiaccproject.org). The IRI (iri.columbia.edu) is engaged in many of the activities envisaged under the original CLIMAG work plan. The WMO implemented a number of recommendations of the CLIMAG workshop through its Agricultural Meteorology Programme, as well as through the Climate Information and Prediction Services (CLIPS) and the Climate Variability and Predictability (CLIVAR) project of the World Climate Research Programme (WCRP, http://wcrp.wmo.int). NOAA's Office of Global Programs has supported a number of other relevant research projects. The Earth System partnership of the IHDP (International Human Dimensions Programme on Global Environmental Change), IGBP (International Geosphere–Biosphere Programme), WCRP and DIVERSITAS promoted the development of activities under the Global Environmental Change and Food Systems (GECAFS) Joint Project (www.gecafs.org). The World Bank has also held several regional meetings on the need to initiate a global-scale agricultural science and technology assessment.

It is time to review what has been accomplished over the past 5 yr and highlight the future priorities in order to further enhance climate prediction applications in agriculture.

2. STATUS OF AGRICULTURE

As well as being the primary source of food, agriculture—together with its associated industries—comprises the largest sector of employment in most developing countries (Oram 1989). It is estimated that hunger is currently affecting 1 of every 7 people on Earth. In developing countries, over 800 million people, mostly children, are chronically undernourished (FAO 2001). Over 80 countries are currently placed into the category of low-income food-deficit countries. At least half of these are in sub-Saharan Africa, with the rest in Asia, the Pacific, Eastern Europe, Latin America, the Caribbean and North Africa. It is projected that by the year 2020, the global population will exceed 8 billion. Unsustainable human activities are diminishing the capacity of the natural resource base to sustain life. As a consequence, land degradation, desertification, deforestation and pollution are occurring in many regions (Sivakumar 2006). Agriculture is an important sector for the economies of many developing countries; it employs 60% of the workforce in

India, 50% in China, 23% in Brazil, and 70% in Nigeria. Most of the countries produce cash crops such as wheat, rice, coffee, bananas, cotton and sugarcane for export, while subsistence farmers grow a range of crops for their household consumption as well as for the local market.

Agricultural production is highly dependent on weather, climate and water availability, and is adversely affected by weather- and climate-related disasters. For instance, in many developing countries where rainfed agriculture is the norm, a good rainy season means good crop production, enhanced food security and a healthy economy. Failure of rains and occurrence of natural disasters such as floods and droughts can lead to crop failures, food insecurity, famine, loss of property and life, mass migration, and negative national economic growth. According to a study by the Corporación Andina de Fomento-Bolivia (CAF), the impact of El Niño in 1997–1998 had a significant impact on Bolivia, with the resulting drought contributing to 53% of the total damage of US$ 527 million suffered by the country (Jovel et al. 1998).

Year-to-year variability of climate significantly affects the agricultural fortunes of most farmers. For example, the all-Australian crop value fluctuates by as much as 6 billion dollars from year to year, and these fluctuations are highly correlated with seasonal ocean temperature changes (Nicholls 1985). Farmers have to take a number of crucial land and water management decisions during the growing season, based on climatic conditions, and sometimes these decisions have to be taken several weeks in advance. Vlek et al. (1997) cite climate variability, with its resulting risk of financial loss in poor years, as the key reason for under-investment in fertilizer inputs. To address such challenges, it is important to integrate the issues of climate variability into resource use and development decisions. Vulnerability of agriculture to natural climate variability can be reduced through a more informed choice of policies, practices and technologies and this will, in many cases, also reduce agriculture's long-term vulnerability to climate change. For example, in the Asia-Pacific tropical region, El Niño is associated with clear skies and droughts, while La Niña is related to overcast skies and floods (Centeno et al. 2000). The introduction of seasonal climate forecasts into management decisions can reduce the vulnerability of the agriculture to floods and droughts caused by ENSO (El Niño Southern Oscillation) phenomena.

Applications in climate prediction and agriculture are based on the premise that advantage should be taken of currently available databases, increasing climate knowledge and improved prediction capabilities to facilitate the development of relevant climate information and prediction products. These can be applied in agriculture to take advantage of favourable conditions, reduce negative impacts due to climate variations and to enhance planning activities based on the developing capacity of climate science.

Magalhaes (2000) argues that climate should be treated as a component of the natural capital endowment of the region and as a factor that may trigger crises that impact people, economic and social activities, and the environment. Hence climate prediction information should be introduced into the planning process as an input into the design of adaptation/mitigation plans.

2.1. High risk in rainfed farming

Farming in many parts of the world, especially in the arid and semi-arid regions of the developing countries, is risky, because climate — one of the essential inputs — is highly variable. In contrast to Asia, the area under irrigation in vast regions of Africa is very limited, and since agricultural production is predominantly rainfed, rainfall variability translates into variable crop production. In some countries as much as 80% of the variability in agricultural production is due to the variability in weather conditions. This production variability in agriculture has immediate and important macroeconomic impacts.

A timely seasonal forecast of favourable conditions could permit farmers to adjust cropping patterns and input use in order to benefit fully from these conditions. Also a timely forecast could give the marketing system and downstream users, such as the food processing industry, time to prepare for a bountiful harvest (Arndt et al. 2000).

It is important to remember that under rainfed conditions, even a less reliable, but earlier forecast may be more valuable than an accurate but late forecast (Mjelde et al. 1998). The gains stem from efficient use of inputs, primarily nitrogen fertilizer, as well as better scheduling of farm operations with the availability of weather/climate information.

2.2. Water for agriculture

Along with climate change, the availability of water resources presents one of the greatest challenges that humanity will face this century. Scientists and policy-makers alike are concerned about dwindling water resources and how the world's limited water resources can be effectively managed to meet the current and future needs of humanity. Today, more than 1 billion people do not have access to potable water, and 31 developing countries representing 2.8 billion people face chronic freshwater availability problems with respect to quantity as well as quality. The vulnerability of both developing and developed countries to water deficit conditions is increasing. By 2025, the population in water-scarce countries could rise to 2.4 billion, representing roughly 30% of the projected global population. It is predicted that over the next 2 decades, the world will need 17% more water to grow food for increasing populations in the developing countries in Asia, and the total water use will increase by 40%. In most developing countries, 70% of the available fresh water is used for irrigation and most of the irrigation systems are working inefficiently as they lose about 60% of the withdrawals to evaporation or return flow to rivers and ground water aquifers.

Seasonal to inter-annual climate predictions could improve water management for agriculture and could help water managers in their critical decisions concerning water allocation to agriculture, industry and domestic uses. Berri (2001) found a statistically significant relationship between the seasonal volume of the Diamante River in western Argentina and the SST anomalies observed in the equatorial Pacific Ocean. The SST model was able to provide the water resource operator information about the amount of water available in the system during the following summer, even before the wintertime snowfalls that feed the system.

2.3. Effect of natural disasters

Climate variability and the severe weather events that are associated with natural disasters have enormous impact on the socio-economic development of many nations, especially the developing countries. One severe extreme event can set back the GDP of countries for several years, thus hampering their sustainable development. Annual economic costs related to natural disasters have been estimated at about US$ 50 to 100 billion, with extreme highs of US$ 440 billion (Munasinghe 1998).

Since subsistence agriculture continues to be the principal mode of livelihood for millions of resource-poor farmers in the developing world, the incidence of natural disasters such as droughts and floods carries disastrous consequences for their livelihoods (Sivakumar 2005). For example, the drought in China in 2001 was the second most widespread since 1949—surpassed only by the 1978 dry spell—and affected 73 million hectares of farmland.

Appropriate measures taken to predict and reduce the impacts of natural hazards can help avert major disasters that would result in immense societal impacts affecting lives, livelihoods, national or local economies and environments. Enhanced application of science and technology, including prediction and early warning (with good lead times) of impending weather and climate hazards, minimizes loss of life and property damages. For example, predictions of droughts in Indonesia or heavy rains in Peru associated with a warm ENSO event (Cane 2001) should lead to appropriate preparedness strategies to cope with droughts or floods in these countries. Information and technology transfer have an important role to play in the 3 critical areas of preparedness, effective response and reduction of vulnerability. Arndt et al. (2000) argue that if predictable droughts are less damaging than randomly occurring droughts, and if predictable favourable climate is significantly more beneficial than random occurrences of favourable climate, then climate information can provide substantial leverage to increase the value of natural resources.

2.4. Multi-dimensional impacts of extreme variability

Quinn & Niell (1987) pointed out that a strong ENSO event occurred every 42 to 45 yr between 1525 and 1983, but the recently strong El Niños appear to be occurring more frequently, i.e. every 15 yr (1982, 1997). Climate-change-induced shifts in ENSO frequency will have economic consequences. These consequences involve changes in both the level and variability of agricultural prices and decline in the general well-being of farm families.

As the frequencies and intensities of extreme events continue to increase, there could be serious implications for several industries such as the agro-based industries (including fisheries), as well as for tourism, construction, transportation and insurance. As Arndt et al. (2000) explained, inadequate or poorly timed rainfall implies not only low yields, wasted inputs and high prices, but also, in many cases food insecurity or famine, necessitating large scale imports of food, deterioration in balance of payments, substantial government spending on drought relief programs, depressed demand for non-agricultural goods, and an increase in rural–urban migration.

3. STATUS OF CLIMATE PREDICTION

The principal scientific basis of seasonal forecasting is founded on the premise (see e.g. Palmer & Anderson 1994) that lower-boundary forcing, which evolves on a slower timescale than that of the weather systems themselves, can give rise to significant predictability of atmospheric developments. These boundary conditions include sea surface temperature (SST), sea-ice cover and temperature, land-surface temperature and albedo, soil moisture and snow cover, although they are not all believed to be generally of equal importance. Relatively slow-changing conditions on the Earth's surface can cause shifts in storm tracks that last from a year to a decade (Hallstrom 2001).

3.1. Climate anomalies

Climate variations, also called anomalies, are differences in the state of the climate system from normal conditions (averaged over many years, usually a 30 yr period) for that time of the year. The strongest evidence for long-term predictability comes largely from the influence of persistent SST anomalies on the atmospheric circulation, which, in turn, induces seasonal climate anomalies. The most dramatic, most energetic and best-defined pattern of interannual variability is the global set of climatic anomalies referred to as ENSO, an acronym derived from its oceanographic component, El Niño, and its atmospheric component, the Southern Oscillation (Cane 2004).

The TOGA (Tropical Oceans and Global Atmosphere) programme (1985–1994) of WMO was the first organized effort to study, understand, and predict the year-to-year variations of the climate system, as these variations are strongly influenced by interactions between the atmosphere and the underlying ocean and land surfaces. The origin of the empirical and prediction studies of the TOGA programme can be traced to the work of Sir Gilbert Walker, who assumed the post of Director General of the Observatory in India in 1904. Walker established the existence of the Southern Oscillation as a global spatial pattern of interannual climate variations with identifiable centres of action (Walker 1924). He suspected that oceanic processes were responsible for the oscillation, but was unable to explore his ideas due to lack of data (Walker & Bliss 1932).

Bjerknes (1966) connected the large-scale fluctuations in the trade-wind circulations in both the northern and southern hemispheres of the Pacific sector to the Southern Oscillation. On the basis of empirical evidence, Bjerknes hypothesized that ENSO was the result of the coupling between eastern and western atmospheric circulations in the Pacific sector and also a coupling between the current and thermal structure of the upper ocean in the eastern equatorial Pacific Ocean. On the basis of a hypothesis linking temperature and wind anomalies, Wyrtki et al. (1976) made the first ENSO forecast. Six major oceanic field programs begun during 1976–1987 provided an observational basis for a better understanding of the annual cycle and interannual variability of the 3 tropical oceans. Large-scale features of the equatorial ocean circulation appeared to be linked to changes in the surface wind stress on monthly to seasonal timescales.

While ENSO was the largest and the most coherent signal in the seasonal to interannual range, connection of anomalies of sea surface temperature in the tropical Atlantic with precipitation over northeast Brazil and the Sahel (Hastenrath & Heller 1977, Moura & Shukla 1981), and the connections of anomalies of sea surface temperature in the eastern Indian Ocean with rainfall anomalies over Australia (Streten 1983) provoked significant interest.

3.2. Climate modeling

The major modeling advance of the TOGA period was the successful simulation of the ENSO cycle using coupled models of the atmosphere and ocean for the region of the tropical Pacific (WCRP 1985). The first successful coupled model of ENSO consisted of a Gill-type model (Gill 1980) of the atmosphere, with improved moisture convergence (Zebiak 1986) coupled to a reduced-gravity ocean model with an embedded surface mixed layer (Zebiak & Cane 1987). Prediction schemes for ENSO based on statistical models were introduced by Graham et al. (1987a,b), Xu & von Storch (1990) and Penland & Magorian (1993). Evaluated over a longer record, the performances of dynamical and statistical models were comparable for lead times of 4 mo or less; however, more recent dynamical predictions are increasingly superior, with longer lead times (Latif et al. 1994).

The coupled numerical model system is allowed to evolve freely for a given lead time and the forecast is the state of the coupled model after that lead-time. Sometimes the initial atmospheric state is not known even though the ocean initial state is known, so that an ensemble of forecasts is made starting from various possible atmospheric initial states. This approach provides an envelope of possible forecasts, and, from the distribution of the final ensemble members, an estimate of the uncertainty of the forecasts. At the IRI, ensembles of 9 runs or more are produced from each of the currently used models, where the ensemble members are exposed to the same predicted (or persisted) SST but initialized with differing atmospheric initial conditions (Barnston 2004). The set of ensemble forecasts from one given model represents an estimate of the probability distribution of the climate in response to the anomalous SST forcing.

Use of multiple models, each running their own ensemble from varying initial conditions, provides an improvement in skill not available from a single model alone (Harrison 2003). In Europe, under the DEMETER

(Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction) project, a multimodel ensemble of fully coupled global climate models (GCMs) was developed, and an extensive set of reforecasts over the ERA-40 reanalysis period (1951–2000) was made (Palmer 2005). As a result, a real-time operational multi-model seasonal forecast system is now being run routinely at the European Centre for Medium-range Weather Forecasts (ECMWF). Similar efforts have been made in the USA under the DSP (Dynamic Seasonal Prediction) projects, and internationally under the SMIP (Seasonal Forecast Model Intercomparison Project). A new multi-organisation centre, the Asia-Pacific Climate Network (APCN; based in Seoul, South Korea), is now established and will also use multiple model inputs (Harrison 2003). Also a new EU-funded project entitled ENSEMBLES has the ambitious goal of developing a unified ensemble system for climate prediction across a range of timescales, from seasons, through decades to centuries (Palmer 2005).

A wide range of forecast methods, both empirical-statistical techniques and dynamical methods, are employed in climate forecasting at regional and national levels (WMO 2003). Empirical-statistical methods in use at various centres include analysis of general circulation patterns; analogue methods; time series, correlation, discriminant and canonical correlation analyses; multiple linear regression; optimal climate normals; and analysis of climatic anomalies associated with ENSO events. Dynamical methods (used principally in major global prediction centres) are model-based, using atmospheric GCMs, coupled Atmosphere–Ocean GCMs (CGCMs), and 2-tiered models. Hybrid models, such as a simple dynamical or statistical model of the atmosphere coupled with an ocean dynamical model, are not being used operationally by any National Meteorological and Hydrological Service (NMHS) at the present.

A recent trend is to examine the potential use of Regional Climate Models (RCMs). These are complex atmospheric models that only handle a relatively small region (approximately the size of Europe) but with far more resolution than is possible using present global models, and that use boundary conditions supplied by a pre-run of a global model (Harrison 2003). It is hoped that outputs from such models will provide greater temporal and spatial detail than is available from the global models. Relatively cheap workstations, and even Pentium 4-equipped PCs, are all that is required to run a RCM, and a number of experimental systems are running in various countries with and without other numerical capabilities using boundary conditions supplied by a global centre.

3.3. Delivery of climate forecasts

Unlike the seemingly random set of climate hazards in a typical year, those associated with El Niño are predictable a year or more ahead (Chen et al. 2004) and forecasts are now freely accessible around the globe via the Internet, often in a form directly available to users and in a manner that can be utilised by the NMHSs. One good example is the Experimental Long-Lead Forecast Bulletin (ELLFB), issued quarterly by the Center of Ocean–Land–Atmosphere (COLA) Studies of the Institute of Global Environment and Society (IGES) (http://grads.iges.org/cola.html) in Maryland, USA. This publication provides a forum for experimental long-lead forecasts (i.e. forecasts made at least 2 wk before the beginning of the forecast period) of short-term climate fluctuations in real time. Accompanying each forecast is a brief discussion of the forecast method and its estimated skill. The intention is to achieve an exchange of ideas on long-lead forecasting in order to stimulate research in this area. The ELLFB is intended mainly to forecast the surface climate in the USA, but also includes many forecasts of other features and events, such as ENSO, hurricane-season severity, and surface climate in other parts of the world.

In several regions of the world, interpretation and delivery of the climate prediction information has been promoted more through the development of Regional Climate Outlook Forums—in which both meteorological services and agricultural end users participate—than through information availability on the Internet. Currently climate outlook forums are being held in different parts of the world on a regular basis to develop consensus climate forecasts (IRI 2001). These regional climate assessments are based on consensus agreement between coupled ocean–atmosphere model forecasts, physically based statistical models, results of diagnosis analysis and published research on climate variability over the region and expert interpretation of this information in the context of the current situation (Berri 2000). Seasonal forecasts of precipitation are usually expressed in probabilistic terms.

A survey undertaken during the year 2000 on behalf of the CLIPS project (Kimura 2001) revealed that about one-third of the WMO member countries already had, or planned to obtain in the near future, the capability to provide some form of operational seasonal to interannual prediction (SIP). According to Kimura (2001), by far the majority of the models in use predict rainfall only for their own country and are usually the forecasts for a single 3 mo season (or a part of this period) at zero lead time, and in the vast majority of cases empirical models are used. Most of the member countries do not have the necessary human and financial resources to develop and issue their own predictions.

3.4. Constraints

Climate model forecasts are still far from perfect, especially with respect to changes in those local conditions having the most extreme human consequences (Cane 2000a). One of the major limitations with the models currently in use is that they have little skill in predicting smaller fluctuations, some of which may influence climate elsewhere in the world. According to Cane (2000b), the factors limiting the current skills of forecasts include inherent limits to predictability, flaws in the models, gaps in the observing system and flaws in the data assimilation systems used to introduce the data into the models. Few CGCMs are capable of realistic simulations. As Cane (2004) explained, this problem is addressed through 'flux corrections', empirical terms added to push the model away from its own climatology toward the observed one. This procedure raises questions as to whether or not the flux-corrected model will have the correct variability or the correct sensitivities to greenhouse gases.

There are several impediments to the optimal use of seasonal climate forecasts, including inappropriate content from a user perspective, external constraints, complexity of target systems for which the forecasts are intended, and communication problems (Nicholls 2000). Users are increasingly demanding information on specific events such as the start of the rainy season and the occurrence of dry spells (Phillips et al. 2001). There is also a greater need to carry out hindcast studies to test forecasting capabilities. To ensure that GCMs can successfully interface with user application models, either the output from the climate models has to be downscaled, or the user application models have to be upscaled (Palmer 2005). The 2 basic methodologies for downscaling, i.e. statistical-empirical relationships linking variability on the grid scale to variability on subgrid scales, and dynamical methods based on limited-area models, need more rigorous evaluation. Finally, availability of data is the single most important concern linking all issues. There is widespread agreement on the importance of addressing these issues and research is under way at several locations around the world to provide more reliable and accurate climate forecasts.

4. CASE STUDIES

4.1. CLIMAG project

The CLIMAG project is an international project initiated by START and linked to the WCRP and IHDP. It has the aim of applying predictions of climate variability, on timescales of a month to a year, to crop management and decision making in order to increase agricultural productivity from farm level up to national scales. At the International Workshop on CLIMAG, pilot projects building on existing experience and facilities were proposed for Latin America, southern Asia and Africa (Sivakumar 2000).

As part of the broader CLIMAG program, the Asia-Pacific Network for Global Change Research (APN) and START supported a multidisciplinary research project to assess the potential for seasonal climate forecasts to reduce vulnerability to climate variability in South Asia. By using a systems analytical approach in Southern India and Northern Pakistan, the project demonstrated how cropping systems management can be altered by adapting to the underlying climatic variability. Using a participatory research approach, the project team collected baseline data for case study sites in India and Pakistan. Agricultural systems analysis for northern Pakistan showed considerable potential to intensify the current wheat–fallow–wheat system by introducing grain legumes into the rotation. Sensitivity studies showed that a skilful seasonal forecast could become important under different cost/price scenarios. These findings demonstrate the importance of this systems analytical approach for policy decisions. At the 2 study sites in Tamil Nadu, India, cotton and peanut crops — currently the 2 most profitable crops — are sensitive to rainfall shortages in different periods. The study showed considerable potential to increase mean income and to reduce production risk by tailoring farm land allocation between these crops according to seasonal forecasts (R. Selvaraju pers. comm.). In positive Southern Oscillation Index (SOI) years, peanuts outperformed cotton in 70% of years, but income difference can still range from –340 (i.e. a loss) to +340 US$ ha^{-1}. However, under falling SOI conditions peanuts had only a minor advantage in 40% of years (up to 85 US$ ha^{-1}). Such information provides an important basis for well-informed crop choice decisions.

Based on the success of the CLIMAG South Asia pilot study, an interdisciplinary network entitled RES AGRICOLA ('Farmer's business' in Latin), has been developed that will draw on the collective expertise of the global research community to develop 'resilient' farming systems. RES AGRICOLA is conceived as a network for farmers, scientists, policy advisers, extension specialists and other stakeholders concerned with connecting climate, agricultural science and decision making to develop resilient farming systems (Meinke & Stone 2005). Currently seed financial support has been obtained from APN, START and NOAA-OGP (NOAA Office of Global Programs).

4.2. Pilot studies by the IRI

The IRI, an important contributor to the CLIMAG project, also has a programme of agricultural activities in various parts of the world, both within and separate from the CLIMAG umbrella. Pilot studies with various crops and cropping systems have indicated that, while it is still too early to be entirely specific about the potential value of climate predictions for agriculture, there is reason to be optimistic concerning future opportunities that can be realized by further research (Hansen 2002). Several modeling studies have estimated the potential value of climate prediction to farmers in the United States. These studies generally show that climate prediction is sufficiently well developed to produce large net benefits to society. Adams et al. (1995) estimated the potential value of climate prediction to agriculture in the southeastern USA to be US$ 100 million yr^{-1} at 1990 dollar levels. Solow et al. (1998) estimated the value of an El Niño forecast to be in the range of US$ 240 to 323 million yr^{-1} for the entire USA.

4.3. Applications in Australia

The Australian Government has continued to invest in climate variability research and development in recognition of the threats and opportunities to farmers and resource managers (www.managingclimate.gov.au). There has also been substantial investment by State governments, industrial organisations and other research and development corporations (Hassal & Associates 2002). Of the farmers surveyed in Australia 72% were aware of seasonal climate forecasts, with the highest percentage of awareness in Queensland and Western Australia and the lowest in Northern Territory and Victoria (Carberry et al. 2002). The awareness was highest in sugar, cotton and cereal industries and lowest for the fruit and vegetable industry (Hassal & Associates 2002).

Mullen (2003) provided a description of case studies in Australia, referring to several web-sites that provide a combination of climate monitoring products as well as outlook information that can be used by those in agriculture — notably, the Australian Bureau of Meteorology web site (www.bom.gov.au), SILO (www.bom.gov.au/silo), Queensland Department of Primary Industry (QDPI) Long Paddock (www.longpaddock.qld.gov.au) among others. The 'Aussie GRASS' project (Australian Grassland and Rangeland Assessment by Spatial Simulation) also supplies climate and resource information specifically for pasture assessment and management via the Web (www.nrm.qld.gov.au/longpdk/AboutUs/ResearchProjects/AussieGRASS). Recent work has focussed on translating probability-based climate outlooks into tools that can be used by the farmer. This has included projects using agricultural simulation models, development of software programs for scenario analysis, training workshops as well as a weekly 'interactive' fax-back service. The Agricultural Production Systems Research Unit (APSRU) in Queensland has developed a software tool, 'Whopper Cropper', to help predict the production risk faced by growers (Cox et al. 2004). This combines seasonal climate forecasting with cropping systems modeling to help producers choose the best management options (Hammer et al. 2001). Farmers can investigate the impact of changing sowing date, plant population, nitrogen fertilizer rate and other variables. This provides a discussion support system for further management decisions. QDPI has developed a Regional Commodity Forecasting System (RCFS) that integrates a shire-based stress-index wheat model with seasonal climate forecasts based on the ENSO. The system assesses the likelihood of exceeding long-term median shire yields, and has potential to make use of seasonal forecasts in commodity forecasting for government policy support and for decision making in industry (Potgieter 2005). The system was designed primarily in relation to policy needs and will shortly become operational for this purpose.

Meinke & Hochman (2000) present a case study of tactical decision-making for a dryland grain-cotton farmer on the southern Darling Downs, Queensland. The farmer has used climate forecasting in tactical crop management decisions for several years and has recently intensified and streamlined his efforts. He takes the seasonal forecast into account for all his management decisions and aims to increase the proportion of cotton in his rotational system without compromising the long-term sustainability. This approach aims to maximize the profitability of the whole farm operation.

4.4. Farming in Zimbabwe

In Southern Africa, consensus on the long-term prospects of each rainfall season is established through regional climate outlook forums held under the auspices of the Southern Africa Development Community (SADC) Drought Monitoring Center (DMC) based at Harare (Chikoore & Unganai 2001; www.dmc.co.zw/SeasonalForecasts). The national forecasts are disseminated in late September or early October through radio and TV, printed press, the Internet and climate bulletins (www.weathersa.co.za/FcastProducts/LongRange/3MonthRainfall.jsp). Radio broadcasts are the most efficient means of communicating climate forecasts to rural communities in southern Africa.

According to the farmers, the most useful forecast information is early warning of a poor season, commencement of the season and whether the rains will be adequate (Phillips et al. 2001). In a 3 yr study on the intended and actual usage of rainfall forecasts across a range of rainfall zones in Zimbabwe, Phillips et al. (2000) showed that farmers in the high rainfall region cut back area planted to all crops in expectation of a very wet year in 1998–1999 to minimize the production losses, while farmers in the drier zones took advantage of the expected rainy season to substantially increase the area planted to increase total farm production of both food and cash crops.

4.5. Forest plantation establishment in the USA

In Florida, aspects of forest plantation establishment that may be adjusted according to seasonal climate prediction include scheduling of planting to coincide with El Niño (wet) winters (Breuer et al. 2004). With prediction of a La Niña (dry) winter, when seedlings are more likely to die, a landowner could choose to reschedule planting to another season, or plant in low areas where soil moisture is likely to be more available. Similarly, planting density could be varied. Alternatively, a landowner could plant at a higher density to compensate for anticipated seedling mortality with prediction of a moderate La Niña (dry) winter. Increased growth of competing vegetation (following planting during an El Niño winter) could call for additional weed control.

4.6. Livestock raising in South Africa

Hudson & Vogel (2003) presented a study that explored opportunistic management when drought conditions are either forecasted or actually occur for livestock farmers in the western parts of the North-West Province of South Africa. The El Niño-driven drought that occurred in the summer of 1992 in this region killed 243 000 head of cattle and 101 000 head of small stock in the 3 communal districts of the western North-West Province (Rwelamira 1997). For the 1997–1998 El Niño, however, farmers received advanced warnings about the anticipated drought, and ~29 % of the farmers surveyed in the region said they made management decisions for the 1999–2000 growing season based on climatic forecasts (Hudson & Vogel 2003). Commercial farmers tended to decrease their herd size and maintained higher average weight on their livestock, while communal farmers tend to maintain their herd size and have lower weight per animal. Despite such applications, some problems still remain in the dissemination and communication of the messages, including translating the probabilistic forecasts into a simple language that the farmers can understand, and the timeliness of forecasts.

4.7. Regional-scale agricultural planning

One international project is focused more towards regional-scale agricultural planning. Funded in part by the European Union, PROMISE (PRedictability and variability Of Monsoons and the agricultural and hydrological ImpactS of climate changE) is a collaborative effort between 13 European organisations along with the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC, Brazil), the Indian Institute of Technology Madras (IITM), the Institute for Meteorological Training and Research (IMTR, Kenya) and the Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG, China). One principal objective of PROMISE is to examine the potential for seasonal prediction and the benefits that would accrue in terms of management of water resources and agriculture. An equivalent second objective deals with climate change. The project focuses mainly on the monsoon regions and has a substantial modeling component, for both predictability of monsoon climates and applications for water resource management and crop productivity (www.ictp.trieste.it/~moltenif/projects/promise.html).

4.8. Applications for the agro-industry

After the initial case studies on the applications of climate forecasts to agriculture at the field level, increased attention is now being paid as to how these forecasts could help the primary processing industry enhance their profits. Through a simple cost benefit analysis, Lumsden et al. (2000) showed that the use of seasonal climate forecasts could potentially give rise to significant economic benefits for the South African sugar industry. Seasonal climate forecasts, coupled with crop simulation models, present the sugar industry with the possibility of obtaining improved crop yield forecasts. Supply-area scale forecasts could be applied in the planning of mill operations such as the determination of mill opening and closing dates, haulage scheduling, and determination of crushing and extraction rates. Everingham et al. (2002) also showed that there is the need for climate forecast systems to target the varying needs of the sugarcane industry.

As an initiative of the UK Government, the 'Seasonal Weather Forecasting for the Food Chain' project proved remarkably successful (Foresight Steering Committee 2001). Although run in a country with relatively limited seasonal predictability, for 3 of the 4 sub-projects — focusing on field vegetables, sugar beet and tomatoes (apples were the exception) — it was concluded that value could be obtained from the predictions. In field vegetables, under which peas and baby leaf salads formed the major focus, most benefit appears to be within the frozen produce sector. Numerous operational decisions could benefit from seasonal forecasts in the growing of sugar beet, including various scheduling aspects as well as planning of agrochemical use, while tomato growers will benefit from integration of forecasts on a range of scales. Only in the apple growing industry and supply chain did there appear to be no forecast benefit. One important conclusion was that optimal benefit is obtained through coordinated actions throughout the food chain based on the forecasts rather than through stakeholders making decisions independently.

5. FUTURE CHALLENGES

5.1. Improving the accuracy of models

Because the behavior of the atmosphere is chaotic, results from even well performing models can diverge, or develop increasing uncertainty at longer time ranges (Nyenzi & Malone 2004). The feasibility of seasonal forecasting depends on the fact that over a season, the effects of shorter-term (weather) events tend to average out, revealing the smaller but more consistent influence of the ocean and land surface on the atmosphere. Prediction in the intermediate range of about 2 wk to 2 mo is rendered more challenging by the presence of a higher 'noise level' imposed by the inherently unpredictable day-to-day atmospheric variability, which is averaged out to a lesser extent (AMS Council 2001). It is important to note the caution from the AMS Council that although it may be possible to predict certain statistical properties of climate for the next season and for the season after that, there is no scientific basis for the deterministic prediction of day-to-day weather beyond 1–2 wk.

Good science and support tools are fundamental prerequisites for ensuring adoption of climate forecasts by farmers. In ensemble prediction (and multiple model ensemble prediction, which is simply a combination of ensembles from individual ensemble systems), different forecast runs are made with slightly different initial conditions to 'explore' possible outcomes. Output shows areas of forecast certainty and uncertainty — useful information for interpretation of the forecasts. To gain the confidence of the users in applying the climate forecasts, it is important to improve the accuracy of the models. It is equally important to improve downscaling techniques and to ensure the availability of adequate historical and current climate data, relevant to the localities of the users, and in sufficient spatial detail.

5.2. Forecasts as tools for risk management

Although there have been several case studies on the application of climate forecasts for improved management of risks under a variable climate, wider and more consistent applications can only be promoted when more quantitative evidence can be generated about the usefulness of climate forecasts. Current research on climate forecast applications needs to be refined and expanded to collect such evidence. To ensure more widespread on-farm applications of climate prediction, it is important that the outcomes sought are well defined in terms of time and feasibility, and that a rigorous monitoring and evaluation framework is developed to judge the economic benefits of these outcomes. Evaluation of the model products is a challenge that needs to be properly addressed to ensure that appropriate steps are taken to improve model performance. It is important that evaluation also be made on the utility of the information to the users, on the various applications of the information by the users and the impacts and economic value of the climate prediction products to various sectors.

For the providers of climate services in the NMHSs, the agriculture sector is now one of the primary clients of climate prediction services. This provides an excellent opportunity for the NMHSs to put climate risk management on the national agenda and in the process gain more visibility. Climate forecasters are so actively involved with climate research, ocean and atmospheric monitoring and climate model development that they have little or no interaction with the agricultural community. They tend to regard use of the climate forecasts as being the domain of the farming community itself; however, feedback from the agricultural community is crucial to collect the quantitative evidence about the benefits of climate forecasts, so that these can be made more applicable to agriculture. This process is facilitated by National Committees on Agrometeorology, operating in some of the Member countries of WMO, since the membership of these Committees is multi-disciplinary and includes, among others, staff of NMHSs, agricultural and environment ministries. Agricultural research and extension services no doubt recognize the value of climate forecasts, but they regard them as only one of the several components that go into the crop production packages that they develop and transfer to the farming community. Hence it is imperative that a 4-way communication be established between climate forecasters, agrometeorologists, agricultural researchers and the agricultural extension community, to ensure that research on climate forecast applications is refined and expanded.

There is a greater need for a better networking between agricultural and climate researchers through joint projects and case studies. Through such networking it will be possible to develop and foster the necessary scientific skills and capacity. Such networking would also ensure leadership and catalytic support to research that is designed for identified needs and priorities, as well as providing a multi-disciplinary research team that can collect more quantitative evidence of climate forecast benefits.

5.3. Responding to user needs and involving stakeholders

As Hansen (2002) pointed out, the use of climate forecasts requires that the right audience receives and correctly interprets the right information at the right time, in a form that can be applied to the decision problem(s). Hence forecasts are only useful if they are skillful, timely and relevant to actions which users can incorporate into production decisions (Stern & Easterling 1999). It is important that both users and climate forecasters are able to anticipate outcomes associated with each decision option under different forecast conditions. Investment in climate prediction applications in agriculture will not achieve the desired outcomes unless the products are effectively and more broadly adopted by the sector.

Early assumptions about the value of climate forecasts were often exaggerated due to a lack of understanding of the variety of user decision-making environments. An important lesson learned from the past decade of activities in the application of climate forecasts is that users cannot be lumped into a homogeneous set (Phillips et al. 2000). The categories of users could vary from the farming community, research community, governmental bodies, private sector, public and international agencies.

Primary producers use climate information to assist with many decisions on seasonal to interannual timescales. The decisions relate to: crop choice (e.g. wheat if good conditions expected; sorghum if drier); choice of cultivar (early or late flowering); mix of crops; fertilizer use; timing of the harvest; area planted to a given crop (and/or rotation of fields); timing and amount of tillage; and stocking rates.

The climate forecast information needs of seed suppliers and grain traders vary distinctly from those of farmers at the local level, e.g. if there is a likelihood of drought, seed suppliers could enhance the supply of seeds of drought resistant varieties and drought-hardy species. It is equally important to consider the forecast applications to industry as well as primary processors of agricultural produce. It will be necessary to develop a comprehensive profile of these different users including socio-economic data, education status, agroecological characteristics of the regions (with emphasis on the quantitative understanding of the climate risk) where they operate, the nature of climate risk management strategies they currently use, their access to inputs, and information on the nature of climate forecast information they need for on-farm management decisions. Such comprehensive profiles could help categorize the users into different groups based on their vulnerability to impacts of climate variability, develop suitable climate forecast products targeted to those who are in a position to benefit from them and decide on the kind of feedback mechanisms that should be put in place to evaluate the products provided to them. It is important to involve the social scientists right from the beginning in developing these profiles.

When stakeholders are well informed about the utility of climate prediction information and when they are more directly involved in testing the benefits of such information, they tend to offer more direct support for climate prediction applications. For example, Hassal & Associates (2002) reported that the National Farmers Federation of Australia has shown a continued level of support for climate prediction applications and has written to the Minister for Agriculture, Fisheries & Forests encouraging continuance of the program. In addition, 5 Australian research and development corporations (for dairy, grains, sugar and rural industries, and Land & Water Australia) have also actively contributed to this program. State governments have also heavily invested in some projects.

As producers and disseminators of climate information relevant to agriculture, NMHSs need to be proactive in interacting with the farmers regarding their needs for climate information, and also to use the feedback to make constant improvements in the products they generate for the agricultural sector. Many stakeholders have little idea of how to incorporate climate forecast information into their management planning. Organization of training workshops by the NMHSs, in collaboration with the agriculture research and extension services, is vital for encouraging early adoption. The recent initiative by WMO in organizing Roving Seminars on Weather, Climate and Farmers is clearly a step in the right direction.

5.4. Priority for extension and communication activities

Hansen (2002) argued that sustained use of climate prediction to improve decisions depends on adequate communication. Adequate communication of information implies that the user is receptive to 'proper' channels, i.e. sources that they already know and trust. Hence agricultural extension agencies must be involved from an early stage, since they are in regular contact with farmers. Depending on the context, other trusted sources include farmer associations, NGOs, village leaders etc. Hence care must be taken to foster strong linkages with these different bodies and players. Another aspect of 'proper' information is related to the communication process of translating the probabilistic forecasts into easily understandable language for farmers. Improper interpretation of the probabilities can lead to loss of trust and the subjection of farmers to unnecessary risks. Appropriate and beneficial production decisions are often related to timing, and hence the communication of climate forecast information also must also be made in a timely manner.

Currently climate information and products are disseminated to users through the Internet, the media (both electronic and printed matter), and special bulletins. Information and warnings are also shared with the public via daily newspapers, radio, TV, telephone and by facsimile. Dissemination of information through these modes does not reach some of the end-users, especially in remote areas that have no access to such facilities. Introduction of systems that facilitate dissemination of information in a timely manner to the intended end-users is a major challenge. However introduction of systems like RANET (RAdio and interNET) will help to solve some of these problems. RANET is an international collaboration to make weather, climate, hydrological and related information more accessible to remote and resource-poor populations through radio and other technologies (see: www.ranetproject.net). RANET works at the community level to ensure that individuals and communities can manage their resources and prepare against natural hazards. The African Centre of Meteorological Applications for Development (ACMAD) has demonstrated the advantages of RANET in reaching the rural communities in Africa (Boulahya et al. 2005).

5.5. Learning from non-adoption situations

Since climate prediction application in agriculture is a relatively new area, it is important that when efforts are made to promote adoption by rural communities, plans for studying the reasons for non-adoption are built into the project. Reasons for the adoption or otherwise of new technologies can be identified through farmer surveys, model-based analysis of farming systems, and through studying farmer motivations and behaviour. All 3 approaches provide a different and often complementary perspective and insight into the decision making process and help improve future climate prediction products and their uptake by farmers.

Exploratory surveys serve to elicit farmer perceptions in order to prioritize information needs. Care must be taken in such surveys to collect information on indigenous forecasts which farmers traditionally use and the nature of information they extract from such forecasts in their decision making, since these could influence the way they would apply the climate forecasts. Most NMHSs do not have the appropriate expertise in carrying out the surveys suggested here and it is imperative that they involve agricultural economists right from the beginning in this activity.

5.6. Economic benefits to trade and storage

Hallstrom (2001) argues that despite a good deal of optimism on the social benefits of understanding and predicting climate variation, there has been limited actual use of long-lead climate forecasts. He noted that trade and storage are important instruments for responding to agricultural production shocks caused by climate variation. Trade can mitigate the negative impacts of a climatic disturbance in a given location by allowing demand to be met by production that took place elsewhere. Similarly, storage allows demand at one point in time to be met by production that occurred at an earlier point in time. Markets unfettered by trade restrictions, with well developed mechanisms for communicating price information, and with transportation and storage infrastructure, make much better use of climate prediction than markets where any of these complementary requirements are absent. The main conclusion is that a country that is relatively isolated from world markets is more vulnerable to an unexpected shock to agricultural production than a country that is integrated into world markets. Hence, the value of climate prediction to an isolated country is significantly less than in countries more integrated into world markets, especially when significant storage occurs.

Clearly, there is much potential to undertake case studies on climate prediction, trade and storage in collaboration with economists and market specialists.

5.7. Improving the institutional and policy environment

According to Hansen (2002), sustained operational use of forecasts beyond the life of a project requires institutional commitment to providing forecast information and support for its application to decision-making, and policies that favor beneficial use of climate forecasts. One of the major challenges to promotion of climate forecast applications in most of the economic sectors at the national level is the lack of a clear national climate agenda. An example of such a climate agenda is the National Biodiversity and Climate Change Action Plan 2004–2007 approved by the Australian government, which was drawn up to help coordinate the activities of different jurisdictions to address the impacts of climate change on biodiversity. Absence of such policy documents leads to problems such as a lack of clear guidance as to which institutions have the main responsibility to produce and distribute climate products, inadequate research capacity and lack of a 'critical mass' of expertise to deal with the key climate issues. It is important that such issues be dealt with on a priority basis to create improved institutional and policy environments so that policy makers are provided with information on the value of seasonal climate forecasts that can help justify decisions on specific applications.

6. CONCLUSIONS

Considerable advances have been made in the past decade in our collective understanding of climate variability and its prediction in relation to the agricultural sector and scientific capacity. There is a need to further refine and promote the adoption of climate prediction tools. It is equally important to identify the impediments to further use and adoption of prediction products.

Sophisticated and effective climate prediction procedures are now emerging rapidly, and through Regional Climate Outlook Forums the use of such predictions is increasing worldwide. Seasonal climate forecasts are currently operational in several parts of the world and there are good opportunities for further enhancement of operational applications. However, there is a need to further improve the models to enhance the skill in predicting smaller fluctuations, which often concern the users at the field level. The issue of downscaling predictions to facilitate more accurate local forecasts continues to be a challenge.

Active uptake of forecast information by the users is limited by the complexity of the presentation methods, difficulties in understanding the probabilities and in interpreting the information for on-farm decision-making. Comprehensive profiling of the user community in collaboration with social scientists, and regular dialogue between scientists and users of information could help remove some of these impediments. Active collaboration is essential between climate forecasters, agrometeorologists and agricultural research and extension agencies in developing appropriate products for the user community.

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