Evolution of Agrometeorology at the Global Level

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Introduction

Agriculture is probably the most weather-dependent of all human activities. Variations in climate have been, and continue to be, the principal source of fluctuations in global food production, particularly in the semi-arid tropical countries of the developing world. Throughout history, extremes of heat and cold, droughts and floods, and various forms of violent weather have wreaked havoc on the agricultural systems that depend on for food. There has always been a general recognition among farmers and livestock herders that weather and climate have a major influence on the production of farm and livestock produce and a number of risk-mitigating or -avoidance strategies have been developed by them to live with the uncertain weather. Hence Agricultural Meteorology has its roots in centuries of experience gathered and organized by farmers (Monteith, 2000).

Agricultural planning and use of agricultural technologies need applications of agricultural meteorology. Agricultural weather and climate data systems are necessary to expedite generation of products, analyses and forecasts that affect agricultural cropping and management decisions, irrigation scheduling, commodity trading and markets, fire weather management and other preparedness for calamities , and ecosystem conservation and management.

Global agricultural scenario and agricultural meteorology

Historically, when agriculture was first developed on earth some 12,000 years ago, the world population was about 10 million. From the beginning of the Christian era 2000 years ago, until the industrial revolution in the eighteenth century, it reached more than the first one billion. The second billion took another 100 years. In the thirty year period between 1961-63 and 1990-92, population in the developing countries almost doubled from 2.1 to 4.1 billions, while in the developed world population growth during this period represented about 27% increase (from 0.9 billion to 1.3 billions). In 1995 alone, the world added an estimated 87 million people to its population, as many people as live in the United Kingdom, Belgium, Denmark, Norway and Sweden (Brown, 1996). Projections indicate that by the middle of next century, the world population would grow to 11 billion and level off, perhaps, at around 11.6 billion towards the middle of the 22nd century.

The per caput food supply in the developing countries of 2, 520 calories day^{-1}, is 25% below that of the developed countries. More than a billion people in the world earn less than a dollar a day, most of them in the developing countries and face chronic under nutrition. One out of every six persons in developing countries does not have access to the food for a healthy and productive life. One third of all preschool children in developing countries - 185 million children are malnourished and are underweight for their age (Pinstrup-Anderson, 1996).

The world added 1.15 billion metric tons of food grains between 1950 and 1990, but with the present trends, the next four decades will see the addition of only 369 million metric tons. Thus while the annual increase from 1960 to 1984 was 30 million metric tons, between 1984 and 1992, it dropped to 12 million metric tons (Jain 1996). With population continuing to grow by nearly 90 million per year, the amount of grain produced per person is decreasing. Grain harvest per person showed a continuous decline from 1984 onwards.

The levelling off of grain yields coupled with increased food consumption has greatly reduced the carry-over stocks of grain and world grain stocks are dropping to an all-time low. Experience from 1973 (when grain stocks reached a low of 55 days of consumption), showed that when grain carryover stocks fall below 60 days of consumption, markets can become very volatile, easily influenced by weather.

Developing countries are projected to increase their cereal demand by about 80% between 1990 and 2020 while the world as a whole will increase its cereal demand by about 55% (Pinstrup-Anderson, 1996). The projected demand for cereals, meat and roots and tubers varies significantly among the developing-country regions. Sub-Saharan Africa is projected to increase its demand for these three commodity groups by at least 150%. Net cereal imports of the developing countries are expected to increase from 90 million tons in 1990 to 190 million tons by 2020 (Pinstrup-Anderson, 1996). The demand for meat will increase by 58 percent to reach 313 million tons.

Almost all of the increase in world food demand will take place in developing countries, which will account for about 85 percent of the global demand for cereals. The demand for meat will grow much faster than for cereals in the developing world, by 2.8 percent per year for meat compared with 1.8 per cent for cereals. Hence the demand for cereals for feeding livestock is expected to double in developing countries and the world farmers will have to produce 40 percent more grain in 2020, most of which will have to come from yield increases.

Food production in the developing world is expected to increase much faster (51%) than the developed world (24%), while cereal production will not keep pace with demand. Cereal imports are expected to double to fill the gap between food production and demand. Irrigated area is projected to grow at an average annual rate of 0.6 percent per year during 1995-2020, less than half the annual growth rate of 1.5 percent during 1982-93. Soil degradation, especially in the developing countries, is a growing problem. Worldwide 38% of all agricultural land had become degraded.

The global agricultural scenario described above places a great deal of premium on our ability to continue to enhance productivity on a per hectare basis since the scope of extending cultivation to new areas is quite limited in scope. Given that rainfed agriculture continues to be the main mode of agricultural production, especially in the developing world, productivity enhancements per unit area in the rainfed ecosystems are a must. There is a need for a greater understanding of the effects of weather and climate variability on the rate of development, growth and yields of rainfed crops and for improved methods of managing weather and climate risks in the rainfed ecosystems. Applications of agricultural meteorology are crucial in both these endeavours.

Evolution of Agrometeorology – the early History

Prior to Vedic and Pre-Vedic period in India (3,500 BC), there had been a system of monsoon forecasting based on original text of the songs sung by Thiru Idaikkadar Swamigal. There are also reports that the annual cycle of crop cultivation was based on careful observation of phenological phenomena by the Chinese farmers some 4000 years ago. In the first century BC, a Chinese agronomist Fan Yeng-Chih was reported to have to have said that “after thawing, the breath of earth comes through so the soil breaks up for the first time. With the summer soltice, the weather begins to become hot and the yin breath strengthens” (Shih, 1974).

In the western literature, the first reference to agrometeorology was reported to have been made by Aristotle that “Wind is more influential than sun in evaporating water”. Prior to 1900,
seasonal and diurnal variations in temperature, humidity and wind were measured and summarized. Analytical description of the basic understanding of heat exchange and diffusion were made by Wollny (1878, 1883).

Evolution of Agrometeorology – 20th Century

In the early 1900s in North America, there was a recognition that the year-to-year variations in yields and regional commodity production were associated with variations in climate (Decker, 1994). Statistical analysis of correlations of yields with monthly rainfall (Smith, 1914) and a book on "Agricultural Meteorology" by Smith published by Macmillan in 1920 provide evidence to the enormous interest in this subject at that time. An year later, in 1921, R.H. Hooker, the President of the Royal Meteorological Society referred to the fact that a few writers on the Continental Europe were making contributions to the general subject of agricultural meteorology, particularly in Italy (Hooker, 1921). Fisher (1925), was the first to evaluate the relationship between yields and rainfall using multiple correlation.

The general response of biological organisms to variations in the weather and climate was a subject that stimulated a great deal of interest and an example of the estimates of the rate of development of maize seedlings under varying temperature conditions was provided by Lehenbauer (1914). At many laboratories and experimental fields in the U.S., Europe and the Asian subcontinent, measurement of the characteristics of the microclimate continued during the first half of 1900s (Geiger, 1927; Ramdas et al. 1935). Studies on the links between soil physical properties and the heat exchange and water movement were conducted (Russell and Keen, 1938)

From 1920 to 1960, agricultural meteorology and micrometeorology took root and began to flourish after the Second World War in several European countries, in North America, in Australia, India, China and Japan. Barger and Thom (1949) developed a method for estimating the deviations of yield from the average on the basis of the probability of precipitation amounts.

An important stimulus was the emergence of new instrumentation for measuring and recording the physical environments of both crops and livestock and their responses to microclimate. In the 1920s and 30s, in central and eastern Europe, systematic instrumental observations of microclimate and its effects on plant growth were made and insightful interpretations of cause, effect and interactions were made. Naegeli, in Switzerland, carried out studies on windbreak microclimate. In the United States, the Missouri Climatic Laboratory was set up to study the physiological response and production of dairy cattle to variations in temperature, wind and radiation loads (Brody, 1948). The establishment of Erhardt Laboratory in California to quantitatively document biological response to varying environmental conditions (Went, 1950, 1957) served as the model for development of growth chambers and Climatrons.

From the 40s to the 60s, a number of reknowned agrometeorologists including Thornthwaite, Holtzman, Penman, Monteith, Priestley, Tanner, Cocheme, Franquin, Shaw and others carried out methodical studies on a number of agrometeorological aspects (Rosenberg, 1989) and

- contributed to our understanding of why crops and forests grow where they do;

- how their growth is affected by weather, climate and microclimate;

- how alterations of earth's surface changes the balance of radiation and energy and hence the microclimate, the climate and weather; and

- how scientific principles identified can be applied to better management of our fields and forests

International Cooperation in Agricultural Meteorology

The importance of meteorology to agriculture, internationally, was probably recognized at least as early as 1735 when the Directors of European meteorological services first met to discuss meteorology on an international scale. The first reference to co-operation between meteorology and agriculture was in correspondence between the International Meteorological Organization (IMO) and certain national institutes of agriculture and forestry, seeking an exchange of meteorological Information and data. A formal Commission for Agricultural Meteorology (CAgM) of IMO was appointed in 1913 but a meeting was delayed by the First World War. The Commission was re-constituted in 1919 and held its first meeting at Utrecht, The Netherlands, in 1923. Subsequently it held six additional meetings; the seventh and last being at Toronto in Canada 1947.

IMO underwent re-organization after 1947 and, in 1951, became the World Meteorological Organization (WMO), one of the specialized agencies of the United Nations. Policies and programmes of the last meeting of the IMO/CAgM became the foundation of the new CAgM under WMO. CAgM is responsible for matters relating to applications of meteorology taking into account new developments in the scientific and practical fields and the development of agricultural meteorological services of Members by transfer of knowledge and methodology and by providing advice.

The CAgM, which meets approximately once in four years, has so far held thirteen sessions since 1951 The technical work of the Commission is performed mainly by working groups appointed at the sessions and these groups undertake work between sessions. Although much of their work was undertaken by correspondence, each working group holds at least one meeting in the WMO Secretariat. As this is expensive, and in some cases ineffective, the idea of a specific topic being studied and reported on by one or more individuals (rapporteur(s)) was introduced at CAgM-IV. Since then the number of topics being considered by working groups has decreased while those considered by rapporteurs has increased. At its thirteenth session, held in Ljubljana, Slovenia, CAgM adopted a new structure of Open Programme Area Groups (OPAGs), Implementation and Coordination Teams (ICTs) and Expert Teams (ETs).

The International Society for Agricultural Meteorology (INSAM) was launched in 2002 to promote the science and applicaions of agricultural meteorology at the international level. Currently INSAM is a web-based society and there are no charges for membership. INSAM serves as a clearing house for information on agricultural meteorology worldwide and all agrometeorologists are encouraged to become members. All the national societies for agricultural meteorology are invited to become members of INSAM to provide strong leadership to develop agricultural meteorology in future.

Topics and trends in Agrometeorology in the second half of 20th Century

One of the many accomplishments of CAgM was to provide the stimulus for the establishment of the first periodical devoted exclusively to research and development in agricultural meteorology. This periodical was first published in 1964 as a journal with the title "Agricultural Meteorology" and in 1984, the journal broadened its scope and became identified as "Agricultural and Forest Meteorology".

Titles of papers published in the journal provide a good indication of the topics and trends in the science of agricultural meteorology. In an analysis of the the papers published in the journal from December 1964 to June 1972 and from June 1966 to June 1998, Monteith (2000) concluded that some early papers were characteristic of the descriptive and statistical phases of agricultural meteorology; but over the years a third mechanistic phase became dominant, stimulated by the development of accurate instrumentation both for recording and processing data (Monteith, 2000).

An analysis was made of all the papers published in the Agricultural and Forest Meteorology journal from 1985 to 2002 for the major topics which received attention and the major trends. From the list of major topics (Table 1), it can be seen that 21.3% of all the papers published were on the subject of water relations, while energy balance/heat transfer was the second most important subject with 16.8% of the papers published on this topic. Papers on forest growth and yield covered 5.5% of the papers published, a trend that is consistent with the broadening of the scope of the journal to forestry in 1984. Equally consistent was the greater attention paid to the subject of climate change with over 76 papers or 4.6% of the total number of papers published. Given the interdisciplinary nature of agricultural meteorology, it is not surprising that some 38 papers published covered the subject of integrated pest management and 23 papers on remote sensing.

To elicit the trends, the papers published were categorized based on whether studies were conducted in the field or used a simulation/model or mathematical formulae/estimation methods. The other categories were whether they were forestry studies or primarily instrumentation development/calibration or greenhouse studies. It can be seen (Table 2) that the major trend (26.9% of the papers published) is towards field studies. Papers based on simulation/models covered 22.1% of all the papers published, reflecting clearly the importance of this area of work in agricultural meteorology. Some 320 papers or 19.3% of all the papers covered mathematical formulae/estimation studies. Studies on forestry is a growing trend with over 17.3% of all the papers. Papers addressing primarily aspects of instrumentation covered 8.1% while 3.3% of the papers published were based on greenhouse studies.

Evolution of Agrometeorology

While tracing the evolution of agrometeorological science and applications over the past several decades, the following aspects can be identified as having contributed most to its development:

a) Advanced instrumentation

b) Modern data management systems and procedures

c) Advances in research

d) Simulation modelling

e) Agrometeorological adaptation strategies to climate variability and climate change

f) Improvements in the dissemination of information

g) New environmental conventions and opportunities

h) Education and Training

a) Advanced Instrumentation

One of the most important aspects in the evolution of agrometeorological science and applications is the development of first class instrumentation both for recording and processing of data (Monteith, 2000). Two innovations within the integrated circuits industry spurred the rapid development of environmental measurement instrumentation (Tanner, 2001). The first was the development of CMOS logic integrated circuits (ICs) in the early 1970s. This technology greatly reduced the power requirement of electronics, making the 12-volt battery operation practical for long-term field applications. The second was the introduction of the microprocessor in the mid-1970s. This innovation simplified the design of data loggers, telecommunication peripherals, and sensors while providing greater sophistication and functionality. The resulting developments in the design and applications of automatic weather stations (AWS) helped the establishment a number of AWS measurement networks that enhanced agrometeorological applications around the world. The development of the Bowen ratio and eddy correlation methods for estimating latent and sensible heat transfer made it easier to carryout energy balance studies over a wide range of crops and forestry. Advances in infrared thermometry enabled remote measurements of canopy temperatures for a range of applications.

b) Modern data management systems and procedures

The availability of a proper meteorological and agrometeorological data base is a major prerequisite for studying and managing the processes of agricultural and forest production. The acquisition of pertinent climate and agrometeorological data, processing, quality control, archiving, timely access and database management are important components that will make the information valuable and used in agricultural research and operational programmes (Doraiswamy et al. 2000). Advances over the past 25 years in PC hardware and software and significant progress in programming languages and data management software development have enabled management of large volumes of data by individual users much easier as opposed to centralized management of data by large computers in the earlier years. Among the developments in languages and software for agrometeorological applications, one can cite the following significant developments:

- C, C++, Visual Basic for data processing, data import/export, data quality control, and modeling
- SAS for statistical analysis, geographic display, modeling and database management/development
- Oracle for data storage, data base management and data analysis
- LOTUS/ MS Excel for data time series plots, regression analysis, geographic display and spreadsheet analysis
- MS Access for application data interfacing and link to spreadsheets

Developments in crop and soil data management software which make it now easy to handle large volumes of data with relative ease. A large number of software packages are currently available for agroclimatic data processing, analysis and dissemination. Motha (2001) provided an informative list of currently available software packages for crop and soil data management.

Over the last two decades, the development of space technology has led to a substantial increase in satellite earth observation systems. Simultaneously, the Information and Communication Technology (ICT) revolution has rendered increasingly effective the processing of data for specific uses and their instantaneous distribution on the World Wide Web (WWW). Remote sensing provides spatial coverage by measurement of reflected and emitted electromagnetic radiation, across a wide range of wavebands, from the earth's surface and surrounding atmosphere. The improvement in technical tools of meteorological observation, during the last twenty years, has created a favourable *substratum* for research and monitoring in many applications of sciences of great economic relevance, such as agriculture and forestry. Each waveband provides different information about the atmosphere and land surface: surface temperature, clouds, solar radiation, processes of photosynthesis and evaporation, which can affect the reflected and emitted radiation, detected by satellites. The challenge for research therefore is to develop new systems extracting this information from remotely sensed data, giving to the final users, near-real-time information.

In certain countries where only few stations are in operation as in Northern Turkmenistan (Seitnazarov, 1999), remotely sensed data can improve information on crop conditions for an early warning system. Due to the availability of new tools, as Geographic Information Systems (GIS), management of an incredible quantity of data such as traditional digital maps, database, models etc., is now possible. The advantages are manifold and highly important, especially for the fast cross-sector interactions and the production of synthetic and lucid information for decision-makers. Remote sensing provides the most important informative contribution to GIS, which furnishes basic informative layers in optimal time and space resolutions. The ultimate use of GIS lies in its modelling capability, using real world data to represent natural behaviour and to simulate the effect of specific processes. Modelling is a powerful tool for analyzing trends and identifying factors that affect them, or for displaying the possible consequences of human activities that affect the resource availability.

c) Advances in research

Agricultural meteorology, by definition, is an interdisciplinary science. This is both its greatest strength and its weakness. The strength is obtained from our understanding of the interactions of the physical and biological world. The weakness is due to the political reality that agricultural meteorology is not fully appreciated by the more traditional physical and biological sciences. Agricultural meteorologist's perspective is more holistic and there are many significant advances in agrometeorological research over the past few decades.

A few examples of the advances made in agrometeorological research can be cited as follows:

- Strategic agroclimatological studies eg., Agrometeorology of the semi-arid regions south of the Sahara (Cocheme and Franquin, 1967), Agroclimatology of Niger (Sivakumar et al., 1993), Burkina Faso (Sivakumar and Faustin, 1987), Mali (Sivakumar et al. 1984) etc.,

- Agroecological zoning studies using integrated land and water resource information systems, based on GIS technology (FAO, 1978)

- Spatialization of climatic data using simple interpolation models, geostatistical techniques etc.

- Energy balance studies of natural ecosystems and of the surface changes made by mankind that can affect climate

- Open-air chamber studies and open-air studies of carbon dioxide enrichment effects on photosynthesis, plant growth and evapotranspiration

- Operating networks of AWS systems that provide near-real time information on agriculturally important weather parameters

- Efficiencies of the use and management of resources, including the whole production environment: climate, water, light, nutrients, space, germplasm, biomass

- Agrometeorological aspects of management in agriculture including research on microclimate modification, land and water management methods, management of inputs in farming systems, integrated pest and disease management, and on-farm validation of new technologies and approaches

- Validation and application of models (phenology, morphological predictions, yield etc.,)

- Research methods and approaches at the eco-regional level, including assessment of the socio-economic effects of weather/climate variability on food production

- Combining GCMs and crop models to study the impact of climate variability and/or change on agricultural production and on world food supply

- Agrometeorological impacts of the likely effects of enhanced global temperatures

- Use of seasonal to inter-annual climate forecasts in operational agriculture

- Strategies for mitigation and reduction of the impacts of natural disasters in agriculture, forestry and fisheries

d) Simulation modelling

Crop modelling evolved in the late 1960's as a means of integrating knowledge about plant physiological processes in order to explain the functioning of crops as a whole (Bouman et al., 1996). Insights into various processes were expressed using mathematical equations and integrated in so-called simulation models. In the sixties, the first attempt to model photosynthetic rates of crop canopies was made (de Wit, 1965). Results obtained from this model were used among others, to estimate potential food production for some areas of the world and to provide indications for crop management and breeding (de Wit, 1967; Linneman et al., 1979). This was followed by the construction of an ELementary CROp growth Simulator (ELCROS) by de Wit et al. (1970). This model included the static photosynthesis model and crop respiration was taken as a fixed fraction per day of the biomass, plus an amount proportional to the growth rate. In addition, a functional equilibrium between root and shoot growth was added (Penning de Vries et al., 1974). The introduction of micrometeorology in the models (Goudriaan, 1977) and the quantification of canopy resistance to gas exchanges allowed the models to improve the simulation of transpiration and evolve into the BAsic CROp Growth Simulator (BACROS) (de Wit and Goudriaan, 1978).

BACROS model was subsequently used as a reference model for developing other models and as a basis for developing summary models such as SUCROS (Simple and Universal CROp growth Simulator) (van Keulen et al., 1982).

The Decision Support System for Agrotechnology Transfer (DSSAT) developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) helps in seeking solutions to such specific issues (IBSNAT, 1988a). The DSSAT itself (IBSNAT, 1988b; Jones, 1993; Tsuji et al., 1994) is a shell that allows the users to organize and manipulate crop, soils, and weather data and to run crop models in various ways and analyze their outputs. Among the semi-arid crops included in the DSSAT are the CERES cereal model for maize, sorghum, pearl millet, rice and wheat and the CROPGRO model for groundnut, soybean and peas (Tsujii et al., 1994).

Kiniry et al. (1991) described the ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model which contains a general crop growth model in which genotype-specific coefficients describe differences in the growth of different crops and crop cultivars. These coefficients control the simulation of development and senescence of leaf area, conversion of intercepted photosynthetically active radiation to biomass, growth of the root system, nutrient composition of the tissue, development of economic yield, and sensitivity of the crop to temperature, water, and nutrient stresses.

The repercussions of global changes for agriculture and natural ecosystems are potentially serious and simulation models were used to explore these effects. Models used in these studies range from descriptive models that couple the information from General Circulation Models (GCMs) with the current knowledge regarding the environmental constraints that limit the area of cultivation of crops (Bindi et al., 1992; Parry et al., 1990), to explanatory models that predict the more detailed effects of warming and of increasing CO_2 on crop development and yield (Adams et al., 1990; Miglietta and Porter, 1992). Simulation models can be used to explore the effects of the increase in temperature and CO_2 concentrations on crop development, growth and yield, harvest index and water use, and can help breeders to anticipate future requirements (Goudriaan et al., 1984). For evaluating long term sustainability issues, models such as CropSyst (Donatelli et al., 1997) and Erosion Prediction Impact Calculator (EPIC) of Jones et al. (1991) were employed.

Following development of object-oriented programming and the recent advances in Internet applications, Pan et al. (1997) developed an object-oriented and internet-based generic plant growth simulator for research and educational purposes on the World Wide Web. With a Java-embedded web browser, the user can link to the run-time model from the web site of the authors.

e) Agrometeorological adaptation strategies to climate variability and climate change

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 environmental conditions. Climate variability affects all economic sectors, but there was an early recognition that agriculture and forestry sectors are perhaps two of the most vulnerable and sensitive activities to such climate fluctuations. Many sectors are currently not optimally managed with respect to today's natural climate variability because of the nature of policies, practices and technologies currently in vogue. Decreasing the vulnerability of agriculture and forestry to natural climate variability through a more informed choice of policies, practices and technologies will, in many cases, reduce the long-term vulnerability of these systems to climate change. Efforts were made to develop locally agrometeorological adaptation strategies to increasing climate variability and climate change especially in regions where food and fibre production is most sensitive and vulnerable to climatic fluctuations.

Salinger et al. (2003) listed adaptation strategies to cope with climate variability/climate change for the tropical and temperate regions. For the tropical regions, these include monitoring of crop development and growth together with appropriate climate information to improve management; development of water conservation strategies, both from traditional and modern practices; implementation of sustainable agriculture and forestry practices to conserve land and improve yields over the long-term; development of innovative new technologies (e.g climate forecasting) alongside traditional methods (e.g intercropping, mulching) for yield improvement and development of adaptation strategies at the local community level to engage active participation of the land users.

Adaptation and mitigation strategies in the temperate regions include earlier planting and sowing of crops; earlier planting with the use of long season varieties in cooler climate regions where soil moisture is adequate and the risk of heat stress is low; introduction of shorter season varieties in hotter regions to avoid or reduce summer heat and water stress; changing land allocation for the stabilization of production and conservation of soil moisture; shorter crop rotations and routine crop thinning in areas that experience higher precipitation; reducing the impacts of drought and erosion by utilizing larger spacing in forestry plantation planting and later thinning; increasing the planting of shelterbelts around crops for the reduction of erosion and conservation of moisture and increasing the application of integrated pest management techniques.

f) Improvements in the dissemination of information

The growing demands for food and concerns with the need for achieving greater efficiency in the natural resource use while conserving the environment are placing a much greater emphasis on understanding and exploiting climatic resources for the benefit of agriculture and forestry. The Internet, satellite technology and geographic information systems (GIS) are prime examples of information and communication technologies (ICTs) that are changing the way people view information dissemination and exchange. The effectiveness of ICTs for agrometeorological information dissemination is being enhanced by linking them to other communication media which are accessible to farmers – such as rural radio (Weiss et al. 1999). A good example of such an activity is the Radio and Internet (RANET) project being implemented by the African Center of Meteorological Applications for Development (ACMAD) in Africa. Several meteorological and climatological databases can be easily accessed from the Internet. In Brazil, two systems have been developed by the National Institute of Meteorology for dissemination of agrometeorological information called VISUAL CLIMA. WMO is currently implementing the World Agrometeorological Information Service (WAMIS) through which all agrometeorological products and advisories being issued by different countries around the world are made available on the World Wide Web. Such avenues are continuing to expand rapidly the potential to enhance the international exchange of ideas, concepts, data and information at the global level.

g) New Environmental Conventions and opportunities

Current concerns with the sustainability of agroecosystems in different parts of the world have hightened the awareness for careful use of the natural resource base on which agriculture depends. For proper and efficient use of soils and plant/animal genetic material, knowledge of the role of climate is an essential precondition. Several elements of the chapters in Agenda 21, a global plan of action agreed at the United Nations Conference on Environment and Development (UNCED), require the attention of the agrometeorologists. Three International Conventions which have a bearing on sustainable agriculture including the United Nations Framework Convention on Climate Change (UNFCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD) were negotiated and ratified since 1992. The World Food Summit Plan of Action (WFSPA), which was developed in 1996, includes several commitments to make agricultural production sustainable. Some of the priorities for agrometeorologists to address sustainable agriculture in the 21st Century outlined in the three Conventions and the WFSPA (Sivakumar et al. 2000) include improvement and strengthening of agrometeorological networks, development of new sources of data for operational agrometeorology, improved understanding of natural climate variability, promotion and use of seasonal to inter-annual climate forecasts, establishment and/or strengthening of early warning and monitoring systems and promotion of geographical information systems and remote sensing applications and agroecological zoning for sustainable management of farming systems, forestry and livestock. Other priorities include use of improved methods, procedures and techniques for the dissemination of agrometeorological information, development of agrometeorological adaptation strategies to climate variability and climate change, mitigation of the effects of climate change, more active applications of models for phenology, yield forecasting etc., active promotion of tactical applications such as response farming at the field level and promoting a better understanding of the interactions between climate and biological diversity. These present important challenges and great opportunities for agrometeorologists to play a proactive role in promoting sustainable development in the 21st Century.

h) Education and training

As discussed above, Agricultural Meteorology, which is an interdisciplinary science, has a major role to play in the efforts to promote sustainable development in the 21st century. In many countries, governments have expressed the desire to use meteorological information to a much larger extent in day-to-day farm planning and operations. As a consequence, a number of universities are currently offering M.Sc and Ph.D. degrees with agricultural meteorology as a major. As Lomas et al. (2000) explained, most of these universities are in agriculture, and not in meteorology or atmospheric sciences. Lomas et al. (2000) also showed that the dominant contribution to the development of agricultural meteorology comes from agronomy and that agricultural scientific community contributes 57% of the research effort in agricultural meteorology. Only 16% of the research effort comes from the meteorological community. For example, the Indian Council of Agricultural Research (ICAR) in India identified agricultural meteorology as a priority subject and encouraged state agricultural universities to establish separate departments of agricultural meteorology.

The Wageningen Agricultural University in the Netherlands implemented the Picnic Model of research education and training in agricultural meteorology to strengthen sustainable research capacity of African Universities. Research is carried out in the student's home country but the data analysis and the preparation of the thesis was done at the Wageningen Agricultural University (Stigter et al. 1995).

WMO recognizes 19 Regional Meteorological Training Centres (RMTCs) around the world which provide training facilities for member countries in various fields of meteorology, including agricultural meteorology and in various languages. WMO RMTCs where agricultural meteorology courses are offered are located in Algeria, Argentina, Barbados, Brazil, China, Egypt, India, Iran, Iraq, Israel, Kenya, Niger, Nigeria and the Philippines.

It must be mentioned that the number of graduates studying agricultural meteorology is small in comparison to other graduate subjects. Basic instruction in elementary meteorology is lacking in educational programmes of weather and climate sensitive professions such as agriculture. One of the ways of addressing this problem is for the agricultural meteorologists to be actively involved in the B.Sc. degree programmes and in related disciplines to prepare students for graduate studies in agricultural meteorology (Lomas et al. 2000).

Needs and perspectives for Agrometeorology in the 21st Century

WMO organized an International Workshop on Agrometeorology in the 21st Century: Needs and Perspectives, in co-sponsorship with a number of national, regional and international organizations in February 1999 in Accra, Ghana. Stigter et al. (2000) summarized the needs and perspectives for agrometeorology in the 21st Century under two major headings:

1) Agrometeorological Services for Agricultural Production

2) Agrometeorological Support Systems for such services

- Data
- Research
- Policies
- Training/Education/Extension

Issues in agricultural production were differentiated following the classic themes: (1) Land use, as a strategical issue; (2) Choices of farming and cropping systems details and (3) Decisions on day to day operations, both as tactical issues. For an extensive discussion on the various important needs and perspectives in agricultural meteorology under the two major headings, the reader is referred to the paper by Stigter et al. (2000).

Conclusions

Agricultural meteorology has advanced during the last 100 years from a descriptive to a quantitative science using physical and biological principles. The agricultural community is becoming more aware that using climate and weather information will improve their profitability and this will no doubt increase the demand for agrometeorological services. Hence it is timely that the needs and perspectives for agrometeorology in the 21st Century are grouped under two major headings: agrometeorological services for agricultural production and agrometeorological support systems for such services. Emphasis must be placed on the components of such support systems comprising of data, research, policies and training/education/extension. As Monteith (2000) mentioned, food supplies ultimately depend upon the skill with which farmers can exploit the potential of good weather and minimize the impact of bad weather. Recent developments in instrumentation, data management systems, climate prediction, crop modelling, dissemination of agrometeorological information etc., provide agrometeorologists the tools necessary help the farmers improve such skills. The future for operational applications of agricultural meteorology appears bright and such applications could contribute substantially to promote sustainable agriculture and alleviate poverty.

References

Adams, R.M., Rosenzweig, C., Peart, R.M., Ritchie, J.T., McCal, B.A., Glyer, J.D., Curry, R.B., Jones, J.W., Boote, K.J., and Allen, L.H. 1990. Global climate change and US agriculture. Nature 345:219-224.

Barger, G.L. and Thom, H.C.S. 1949. A method for characterizing drought in Iowa. Agron. J. 41:13-19.

Bindi, M., Ferrini, F., and Miglietta, F. 1992. Effect of CO_2 induced climatic change on the cultivated area of olive trees. Agric. Meteorol. 122:41-44.

Bouman, B.A.M., van Keulen, H., van Laar, H.H. and Rabbinge, R. 1996. The "School of de Wit" crop growth simulation models: a pedigree and historical overview. Agricultural Systems 52:171-198.

Brody, S. 1948. Environmental physiology with special reference to domestic animals: I. Physiological background. MO Agric. Exp. Stn. Bull. 423.

Brown, L.R., Flavin, C. and Hane, H. 1996. Vital signs 1996-97. The trends that are shaping our future. London: Earthscan Publications Ltd.

Cocheme, J. and Franquin, P. 1967. An agroclimatological survey of a semi-arid area in Africa south of the Sahara. Technical Note No. 86, Geneva: World Meteorological Organization.

Decker, W.L. 1994. Developments in agricultural meteorology as a guide to its potential for the twenty-first century. Agric. For. Meteorol. 69:9-25.

de Wit, C.T. 1965. Photosynthesis of leaf canopies. Agricultural Research Report n°663. PUDOC, Wageningen, The Netherlands.

de Wit, C.T. 1967. Photosynthesis: its relationship to overpopulation. p. 315-320. *In* Harvesting the sun. Academic Press, New York.

de Wit, C.T., Brouwer, R., and Penning de Vries, F.W.T. 1970. The simulation of photosynthetic systems, in Prediction and measurement of photosynthetic productivity. Proceedings of International Biological Program/Plant Production Technical Meeting. Setlik, I., Ed., Trebon, PUDOC, Wageningen, The Netherlands.

de Wit, C.T. and Goudriaan, J. 1978. Simulation of assimilation, respiration and transpiration of crops. Simulation monograp. PUDOC, Wageningen, The Netherlands.

Donatelli, M., Stockle, C., Ceotto, E., and Rinaldi, M. 1997. Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy. Eur. J. Agron. 6:35-45.

Doraiswamy, P.C., Pasteris, P.A., Jones, K.C., Motha, R.P.and Nejedlik, P. 2000. Techniques for methods of collection, database management and distribution of agrometeorological data. Agrl. For. Meteorol. 103:83-97.

FAO (Food and Agriculture Organization). 1978. Report on the agroecological zones project. World Soil Resources Report No. 48. Rome: FAO.

Fisher, R.A. 1925. The influence of rainfall on the yield of wheat at Rothamsted. Phil. Trans. R. Soc. Series B, 213:89-142.

Geiger, R. 1927. Das Klima der Bodennahen Luftschicht. Vieweg, Braunschweig.

Goudriaan, J. 1977. Crop micrometeorology: a simulation study. Simulation monograph. PUDOC. Wageningen, The Netherlands.

Goudriaan, J., van Laar, H.H., van Keulen, H., and Louwerse, W. 1984. Simulation of the effect of increased atmospheric CO_2 on assimilation and transpiration of a closed crop canopy. *In* Wissenschafliche Zeitschrift Humboldt Universitaet Berlin. Math-Nat. R. 33:352-356.

Hooker, R.H. 1921. Forecasting the crops from the weather. Quart. J. R. Meteorol. Soc. 47:75-99.

IBSNAT. 1988a. Documentation for IBSNAT crop model input and output files, Version 1.1 for the Decision Support System for Agrotechnoloy Transfer (DSSAT V2.1). IBSNAT Tech. Rep. 5. Dep. of Agronomy and Soil Sci., College of Tropical Agric. and Human Resources, University of Hawai, Honolulu.

IBSNAT. 1988b. Experimental design and data collection procedures for IBSNAT, IBSNAT Tech. Rep.1. 3rd ed., rev. Dep. Of Agronomy and Soil Sci., College of Tropical Agric. and Human Resources, University of Hawai, Honolulu.

Jain, H.K. 1996. Agriculture in the 21st century: a global order for research. pp. 33-44 *In* (C. Bonte-Friedheim and K. Sheridan, eds.) The Globalization of Science: The Place of Agricultural Research. The Hague: International Service for National Agricultural Research.

Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W., and Griggs, R.H. 1991. EPIC: and operational model for evaluation of agricultural sustainability. Agric. Systems 37:341-350.

Jones, J.W., 1993. Decision support systems for agricultural development. *In* F.W.T. Penning de Vries et al. (ed) Systems approaches for agricultural development. Vol. 2, Proc. Symp., Bangkok, Thailand, 2-6 Dec. 1991. Kluwer Acad. Publ., Dordrecht, The Netherlands.

Kiniry, J.R., Rosenthal, W.D., Jackson, B.S., and Hoogenboom, G. 1991. Predicting leaf development of crop plants. p.29-42. *In* T. Hodges (ed.) Predicting Crop Phenology. CRC Press, Boca Raton, FL.

Lehenbauer, P.A. 1914. Growth of maize seedlings in relation to temperature. Physiol. Res. 1:247-288.

Linneman, H., Dehoogh, J., Keyzer, M.A. and van Heemst, H.D.J. 1979. Moira, model of international relations in agriculture. North Holland Publishing Company, Amsterdam.

Lomas, J., Milford, J.R. and Mukhala, E. 2000. Education and training in agricultural meteorology: current status and future needs. Agrl. For. Meteorol. 103:197-208.

Miglietta, F., and Porter, J. 1992. The effects of CO2 induced climatic change on development in wheat: analysis and modelling. J. Exp. Bot. 43:1147-1158.

Monteith, J.L. 2000. Agricultural meteorology: evolution and application. Agrl. For. Meteorol. 103:5-9.

Motha, R.P. 2001. Executive summary. Pages vii-xviii *In*: (R.P. Motha and M.V.K. Sivakumar, Eds.) Software for Agroclimatic Data Management, Proceedings of an Expert Group Meeting, 16-20 October 2000, Washington DC, USA. Washington DC, USA: United States Department of Agriculture and Geneva, Switzerland: World Meteorological Organization.

Pan, X., Hesketh, J.D., and Huck, M.G. 1997. An object-oriented and internet-based simulation model for plant growth. p. 345-351. *In* Seventh International Conference on Computers in Agriculture. USDA-ARS, Urbana.

Parry, M.L., Porter, J.H., and Carter, T.R. 1990. Agriculture: climatic change and its implications. Trends in Ecology and Evolution 5:318-322.

Penning de Vries, F.W.T., Brunsting, A.B., and van Laar, H.H. 1974. Products, requirements and efficiency of biological synthesis, a quantitative approach. J. Theor. Biol. 45:339-377.

Pinstrup-Andersen, P. 1996. Perspectives for world food security: challenges for the International Agricultural Research System. pp. 28-42 *in* (M. Reule and W. Ritter eds.) Perspectives for World Food Security - Challenges for Agricultural Research. Bonn: The German Alliance for International Agricultural Research (AIDA).

Ramdas, L.A., Kalamkar, R.J. and Gadre, K.M. 1935. Agricultural studies in microclimatology. Indian J. Agric. Sci. 5:1-11.

Rosenberg, N.J. 1989. Speculations on the future of agricultural and forest meteorology. Bull. Am. Meteorol. Soc. 70:784-786.

Russell, E.W. and Keen, B.A. 1938. Studies in soil cultivation, VII the effect of cultivation on crop yields. J. Agric. Sci. 28:212-233.

Salinger, M.J., Sivakumar, M.V.K. and Motha, R.P. 2003. Reducing vulnerability of agriculture andforestry to climate variability and change in the 21st century: workshop summary and recommendations. Climatic Change *(In press).*

Seitnazarov, I. 1999. Technology and methods of collection, distribution and analyzing of agrometeorological data in Dashhovuz velajat, Turkmenistan. In CAgM Report 77, Contributions from members on Operational Applications presented at the International Workshop on Agrometeorology for the 21st Century: Needs and Perspectives, Accra, Ghana. Geneva: World Meteorological Organization.

Shih, Sheng-Han. 1974. An agriculturalist book of China. On Fan Sheng-Chih Shu. Science Press, Beijing, China (English translation).

Sivakumar, M.V.K. and Gnoumou Faustin. 1987. Agroclimatology of Burkina Faso. Information Bulletin No. 28, Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics. 192 pp.

Sivakumar, M.V.K., Gommes, R. and W. Baier. 2000. Agrometeorology and sustainable agriculture. Agrl. For. Meteorol. 103:11-26.

Sivakumar, M.V.K., Konate, M. and Virmani, S.M. 1984. Agroclimatology of West Africa : Mali. Information Bulletin No.22, Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics. 294 pp.

Sivakumar, M.V.K., Maidoukia, A. and Stern, R.D. 1993. Agroclimatology of West Africa: Niger (Second Edition), Information Bulletin No. 5, ICRISAT, Patancheru, India. 108 pp.

Smith, J.W. 1914. Effect of weather upon the yield of corn. Mon. Weather Rev. 42:78-87.

Stigter, C.J., Wang'ati, F.J., Ng'ang'a, J.K. and Mungai, D.N. (Eds). 1995. The TTMI-project and the Picnic model: an internal evaluation of approaches and results and of prospects for TTMI units. Wageningen Agricultural University.

Stigter, C.J., Sivakumar, M.V.K. and Rijks, D.A. 2000. Agrometeorology in the 21st Century: workshop summary and recommendations on the needs and perspectives. Agrl. For. Meteorol. 103:209-227.

Tanner, B.D. 2001. Evolution of automated weather station technology through the 1980s and 1990s. Pages 3-20 In: (K.G. Hubbard and M.V.K. Sivakumar (Eds)) Automated Weather Stations for Applications in Water Resources Management: Current Use and Future Perspectives. Proceedings of an International Workshop held in Lincoln, Nebraska, USA, 6-10 March 2000. Lincoln, Nebraska: High Plains Climate Center and Geneva, Switzerland: World Meteorological Organization.

Tsuji, G.Y., Uehara, G. and Bala, S.S. (ed.) 1994. *DSSAT v3*. University of Hawaii, Honolulu, Hawaii.

van Keulen, H., Penning de Vries, F.W.T. and Drees, E.M. 1982. A summary model for crop growth. p. 87-98. *In* (F.W.T. Penning de Vries and H.H. van Laar. eds.) Simulation of plant growth and crop production. Simulation Monographs, PUDOC. Wageningen, Netherlands.

Weiss, A., Van Crowder, L. and Bernardi, M. 2000. Communicating agrometeorological information to farming communities. Agric. For. Meteorol. 103:185-196.

Went, F.W. 1950. The Earhart Plant Research Laboratory. Chron. Bot. 12:91-108.

Went, F.W. 1957. The experimental control of plant growth. Chron. Bot. 17: 335.

Wollny, E. 1878. Untersuchungen uber den Einfluss der Bodenfarbe auf der Erwarmung des Bodens. Forsch. Geb. Agr. Phy. 1:43-72.

Wollny, E. 1883. Untersuchungen uber den Einfluss der Pflanzendecke und der Beschatlung auf die physikalischen Eigenschaften des Bodens. Forsch. Geb. Agr. Phy. 6:197-256.

Table 1. Major topics in agricultural meteorology summarized from the papers published in the *Agricultural and Forest Meteorology* journal during 1985 to 2002.

Major Topic	**Number**	**Percentage**
Water relations	354	21.3
Energy balance/heat transfer	280	16.8
Solar radiation	213	12.8
Crop growth and yield	166	10.0
Other variables	105	6.3
Forest growth and yield	92	5.5
Photosynthesis	79	4.7
Climate change	76	4.6
Temperature	54	3.2
Rainfall	46	2.8
Climatic analysis	43	2.6
IPM	38	2.3
Phenology	31	1.9
Remote sensing	23	1.4
Future direction/general	21	1.3
Shelter belts	9	0.5
Livestock	8	0.4
AWS	5	0.3

Table 2. Major trends in agricultural meteorology summarized from the papers published in the *Agricultural and Forest Meteorology* journal during 1985 to 2002.

Major trend	Number	Percentage
Field studies	445	26.9
Simulation/models	367	22.1
Mathematical formulae/estimation	320	19.3
Forest studies	286	17.3
Instrumentation	134	8.1
Greenhouse studies	55	3.3