# CHAPTER 9

# APPLICATIONS OF METEOROLOGY TO AGRICULTURE

## 9.1 INTRODUCTION

The application of meteorology to agriculture is essential, since every facet of agricultural activity depends on the weather. This chapter discusses many examples of the usefulness of applied meteorology in order to make users aware of the potential benefits that farmers can gain to improve efficiency and ensure sustainability of their farm management; to protect and ensure the continuing health of their crops, livestock and environment; to increase their yield and the market value of their crops; and to solve selected operational problems. Other agricultural decision-makers derive benefit from agrometeorological applications, including government policymakers seeking to ensure adequate food supplies, affordable food prices for consumers and sufficient farm income for farmers, and to reduce the impact of agricultural practices on the environment. Decision-makers in international agricultural organizations also use applications of meteorology to ensure food security and to react to potential famine situations. At any level, these objectives can be achieved only through active cooperation among National Meteorological and Hydrological Services (NMHSs), agricultural extension services, farmers and their associations, agricultural research institutes, universities and industry.

The topics discussed in this chapter are based on a classification of applications of micrometeorology to various agricultural problems given in WMO Technical Note No. 119 (WMO, 1972). They are grouped according to the general type of problem, namely, improving production; averting dangers to production; physiology and growth; strategy; and tactics. These main topics were retained for this edition of the Guide and only the subtopics have been modified depending on recent applications. The physiology and growth topics for specific crops are covered in Chapter 10.

The main objective of this chapter is give to brief overviews and examples of applications at the local or farmer level. There are also important applications that will be discussed at the government or international organization level, however. In selecting the examples of applications of meteorology to agriculture, priority has been given to those that are used operationally. Also, an attempt has been made to cite examples for the different climates and regions of the world.

### 9.1.1 Users of agrometeorological information

The successful application of weather and climate information needs to integrate three components: data, analysis and users. Therefore, the ultimate goal of any application is to serve the needs of the users. A solid foundation of data is a prerequisite for successful agricultural meteorological applications (see Chapters 1 and 2). Then an analysis of these data that seeks to solve or address an agricultural problem is needed. These analyses are described in this Guide. Ultimately, the users of agrometeorological information and applications must be kept in mind when developing new applications. The user can be defined as any agricultural decision-maker such as a farmer, extension agent, government official, media person or the general public. Rijks and Baradas (2000) provide an overview of clients (users) of agrometeorological information. They discuss who the clients are, what they require, what products agrometeorological services can offer, and how to approach clients and assess the value of the product.

### 9.1.2 Temporal and spatial scales of agrometeorological information and applications

Agrometeorological information and applications can be considered in temporal and spatial contexts. In a temporal context, strategic applications are defined as those aiding in issues and decisions that are assessed on a seasonal or yearly basis or only once, such as in a planning process. These applications aid in the planning process whether the decision is choosing a specific crop variety to plant, if an area should be exploited for forage products and livestock, how to design and plan where or if greenhouses or animal shelters should be built, or how to assist governments in setting agricultural pricing polices. Such decisions can be based on climatological analyses, agroclimatic information, and the use of complex soil–plant–atmospheric models. Tactical applications are considered to be short-term operational decisions relating to a period ranging from a few hours to a few days. These often involve decisions, based on the state of the crop and current or forecast weather, for such farm operations as cultivating, irrigating, spraying and harvesting.

*Agrometeorological Aspects of Organic Agriculture, Urban Agriculture, Indoor Agriculture and Precision Agriculture* (WMO, 2003) provides a good description of macroclimate and mesoclimate in the context of agrometeorological applications. Macroclimate is the largest and covers broad areas of a continent (millions of square kilometres), and deals with the interaction of large-scale topography (mountain ranges, large lakes and ocean influences) with airmasses. At this scale, climate characteristics should provide information on the suitability of a farm and whether the farm could be weather-limited by pest, disease and operational timing problems. Mesoclimate reflects the farmer's view of the weather experienced in a region. Local surface features such as hills, small mountains, large forests or extensive plains have a distinct effect at this scale. A country may have one or two macroclimate zones, but it will have many mesoclimates. It is at this scale that specific calculations can be made to define agroclimatic regions.

At the smallest scale, microclimate is defined by Rosenberg et al. (1983) as the climate near the ground, or in other words, the climate in which most plants and animals live. In terms of meteorology, *The Application of Micrometeorology to Agricultural Problems* (WMO, 1972) describes micrometeorology as dealing with the physical processes taking place within the boundary layers between the top of the plant, tree or animal and the bottom of the roots of the soil. Most of the applications in this chapter are based on micrometeorological principles.

A monograph by Gordeev et al. (2006) presents the results of an assessment of the bio-climatic potential in the Russian Federation, surrounding countries, Europe and the United States. Particular attention is given to climatic and agroclimatic peculiarities in these territories in relation to solving certain social and economic problems.

### 9.1.3 Benefits derived from applications

Many benefits result from the application of meteorological services to agriculture. The productivity of a region or of a particular enterprise may be increased by the reduction of many kinds of loss resulting from unfavourable climate and weather, and also by the more rational use of labour and equipment. Greater economy of effort is achieved on the farm, largely through a reduction in activities that have little value or are potentially harmful. All of these increase the competitiveness of production, reduce risk and help to lower the cost of the final products.

In the developed world, a significant portion of recent work in agricultural meteorology has shifted from increasing yields to reducing the environmental impact of agricultural fertilizer and pesticide use and combating pests and diseases. In the developing world, much of the focus remains on increasing agricultural production, but there is also an emphasis on sustainable agricultural production and reducing the impact of diseases and pests such as desert locusts.

The following are brief examples of economic benefits of agrometeorological applications from Rijks and Baradas (2000). In Sudan, precise calculations of water requirements for the main irrigated crops (cotton, sorghum and groundnut) were compared with available irrigation water to allow for more accurate estimates of potential irrigated wheat area. The net result was an additional 8 000 ha of wheat grown, which added more than US$ 2 million to the national economy at a cost of a few thousand dollars for data, analysis and staff. In the Gambia, groundnuts are stored in the open air and if the dry pods become wet, they are at high risk of developing aflatoxin, which can reduce farmer prices for the crop by up to 60 per cent. If farmers are warned of rainfall by forecasts transmitted via local radio, they can cover the crop with plastic sheeting. It is estimated that for each percentage point of production saved, the benefit is US$ 60 000. In the Sahel, bush fires are common every year, but the bush vegetation is needed for cattle and sheep grazing. By using wind, temperature and humidity observations to indicate speed and direction of the fire, controlled burning can take place to prevent the fires from spreading. Reducing the burned area on 1 per cent of the grazing land allows 5 000 more sheep to graze, which represents an additional annual value of US$ 100 000 to the national economy. A WMO report on meteorology and plant protection (WMO, 1992*a*) provides a framework for analysing costs and benefits of agrometeorological applications in plant protection.

The results of studying the peculiarities of climate and weather conditions to optimize various cultural practices (namely, determination of an advisable structure of areas under crops, dates and methods of soil treatment, optimum fertilizer application periods and doses) aimed at boosting the productivity of plants growing in Russia, can be found in several papers by Fedoseev (1979, 1985). The economic efficiency of applied agrometeorological recommendations is given.

Other examples can be found in *The Economic Value of Agrometeorological Information and Advice* (WMO, 1980*a*) and in materials from a conference on the economic benefits of meteorological and hydrological services (WMO, 1994*b*).

## 9.2 APPLICATIONS FOR GOVERNMENTS AND OTHER LARGE ADMINISTRATIVE BODIES

Governments and other large administrative bodies need high-quality and reliable information for operational assessments of agricultural production. With regard to planning, this would involve questions about what kind of crops the country could produce economically and where they could be grown. Planning questions of this nature can be answered by macro- and mesoscale agroclimatic surveys.

### 9.2.1 Operational assessments

There are several examples of operational assessments of crop production that countries and international agencies perform. These examples highlight the utility of integrating data, staff and resources to produce reliable crop production assessments among different agencies at a country level and among different countries, non-governmental organizations (NGOs), and other organizations at an international level, as well as the need to do so. Boken et al. (2005) provide many examples of successful drought monitoring and crop monitoring applications at these levels.

The Food and Agriculture Organization of the United Nations (FAO) established the Global Information and Early Warning System (GIEWS) in 1975 in response to the global food crisis of the early 1970s. GIEWS provides information on food production and food security for every country based on crop monitoring assessments that involve remote-sensing and ground-based weather station data (Mukhala, 2005). A number of these assessments are based on the FAO Crop Water Requirement Satisfaction Index (WRSI) model that determines a cumulative water balance for 10-day periods from planting to maturity. The WRSI model is a combination of dynamic water balance and statistical approaches and the index represents at any time of the growing season the ratio between the actual and potential evaporation.

The World Agricultural Outlook Board (WAOB) of the United States Department of Agriculture (USDA) is mandated to provide official monthly United States Government forecasts of agricultural commodities through the World Agricultural Supply and Demand Estimates (WASDE) publication (Motha and Stefanski, 2006). These supply and demand estimates are based on official country reports, United States embassy reports, travel reports of USDA personnel, economic analysis, remote-sensing information and, of course, global weather information. USDA meteorologists routinely collect, monitor and analyse global weather conditions and agricultural information to determine the impact of growing-season weather conditions on crops and livestock production prospects. These activities are supported by meteorologists from the United States National Weather Service who are located within WAOB offices to serve the agricultural community (Puterbaugh et al., 1997; Motha and Heddinghaus, 1986).

Rusakova et al. (2006) describe the application of an automated Russian forecasting system that allows for the presentation of information about observed weather conditions, state of crops, crop yield forecast and the total harvest in the various regions of Russia. Comprehensive application of climatic and weather information at the governmental and field levels is demonstrated with the Russian information and advice system meant for resolving some practical problems in the planning and organization of agricultural production (Zhukov et al., 1989).

In Brazil, several centres generate daily updated agrometeorological information to support decision-making, including Agritempo (http://www.agritempo.gov.br), which provides information for the whole country, and regional centres such as Cepagri/Unicamp (http://www.cpa.unicamp.br) and IAC (http://www.ciiagro.iac.sp.gov.br) for the state of Sao Paulo, IAPAR/SIMEPAR (http://www.iapar.br/sma) for the state of Parana, and Ciram (http://www.chlimerh.rct.sc.br) for the state of Santa Catarina. Farmers' cooperatives also provide agrometeorological information to their farmers and field technicians (for example, http://www.fundacaoabc.org.br) (Pinto, personal communication).

Other examples include the Famine Early Warning System, or FEWS (Rowland et al., 2005), the

European Union's Monitoring Agriculture with Remote Sensing (MARS) (Negre, 2006), the National Agricultural Monitoring System (NAMS) in Australia (Leedman, 2007), the Farmweather service (WMO, 2004) and agrometeorological services in Kazakhstan (WMO, 2004).

### 9.2.2 **Agroclimatic surveys**

Concerning macroscale agroclimatic surveys, the joint inter-agency project on agroclimatology sponsored by FAO, WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) has been very successful in producing five publications and is the foundation of current agroclimatic zoning studies. The most important practical applications of macroclimatic surveys include: choosing crops, varieties and domestic animals; determining favourable periods for sowing, haymaking and harvesting; establishing areas where dryland farming is possible and where irrigation has to be applied; planning afforestation and reforestation; finding the optimum range of climatic variables for increasing yields and agricultural production in general; establishing potentials for the agricultural use of rangelands; and determining requirements and potentialities for efficient storage and transportation of crops.

The agroclimatology in the semi-arid and arid zones of the Near East has focused on the estimation of the boundary areas where dryland farming is possible and where irrigation is needed (WMO, 1963*e*). The agroclimatology of semi-arid areas in West Africa has dealt with dryland farming in West Africa and the length of growing seasons, which is strictly associated the rainy season (WMO, 1967). The agroclimatology of the highlands of eastern Africa has focused on which crop water requirements are met in the various localities of this area (WMO, 1973). The agroclimatology of the Andes has looked at the unique effects of high elevation and high solar radiation input on crops (WMO, 1978*a*). An agroclimatology survey of the humid tropics of South-East Asia (WMO, 1982) illustrates the role of agroclimatology in determining strategies to increase food production in the humid tropics.

### 9.2.3 **Mesoscale agroclimatic surveys**

With the advent of widespread computing capability (personal computers) and Geographical Information Systems (GISs), climatic and agroclimatic mapping has become widespread. There are many examples of the use of these methods for climatological and agroclimatic analyses. The European Union-sponsored European Cooperation in Science and Technology (COST) Action 719 on the Use of Geographic Information Systems in Climatology and Meteorology provides several examples of these agroclimatic mapping methods, including temperature mapping, climate parameter mapping in mountainous areas, and an agroecological decision system (Dryas et al., 2005). The Parameter–Elevation Regressions on Independent Slopes Model (PRISM) has been used to map daily weather and climatic parameters in mountainous areas (Hunter and Meentemeyer, 2005; Daly et al., 1994).

Zoidze and Ovcharenko (2000) assessed the agricultural potential of climate in the territory of the Russian Federation and some of its regions for each crop, based on general indices of heat and water supply, radiation regime, unfavourable agroclimatic phenomena, soil fertility, and relief essential to develop strategic and tactical agricultural policies in different regions. These authors also reviewed measures to optimize environmental conditions.

Motroni et al. (2002) focused on the development of a methodology to assess climatic and agroclimatic risks. Land capability was classified for Sardinia by using climate, geographic and soil data. A climatic risk index was computed on the basis of 30-year averages of climatic data.

Petr (1991) described a mesoscale agroclimatic classification scheme for Czechoslovakia based on a hydrothermic coefficient, $HTC = R/(0.1TS10)$ where $R$ is the rainfall sum in millimetres and $TS10$ is the degree-days above 10°C. Such an approach could be used with any degree-day base temperature and adapted for specific crops.

In Brazil, there have been recent nationwide efforts in agroclimatic risk zoning for agricultural crops that characterizes the potential and climatic risks for several crops, including maize, soybeans, beans, wheat, barley, rice, cotton, coffee, cassava and different species of fruits (Pinto, personal communication). The recommendations are used by the Brazilian Government to provide financing to the farmers at very low rates. Furthermore, those who follow the recommendation of the agricultural zoning can obtain official insurance at special rates. To be eligible for the bank credit, the farmers must also adopt the best agronomical practices recommended by the extension service. These efforts, combined with farmers' use of optimum planting dates, have increased the productivity of Brazilian agriculture (Pinto, personal communication).

## 9.3 APPLICATIONS FOR FARMERS OR GROUPS OF FARMERS

### 9.3.1 Improvements to production

As stated in the introduction, the original topics were based on a classification of applications of micrometeorology to various agricultural problems in WMO Technical Note No. 119 (WMO, 1972).

#### 9.3.1.1 Irrigation

In its broadest terms, irrigation involves water balance calculations based on rainfall, estimation of water infiltration (effective rainfall), runoff, evapotranspiration (ET) and soil moisture. There are several reliable direct measurements for soil moisture, such as those obtained using manual gravimetric and neutron probe methods, which are suitable for routine application in agricultural practice (see Chapter 2). Indirect measurements based on remotely sensed information are also possible (see Chapter 4). Early irrigation and soil moisture applications can be found in HMSO (1967), Baier and Robertson (1965) and WMO (1958, 1968*b*). Over the years a great deal of attention has been given to irrigation issues, especially measuring and estimating evapotranspiration. A number of textbooks provide good overviews of this subject, including Rosenberg et al. (1983).

Smith (2000) provides a survey of the widely accepted practical procedures that have been developed by FAO et al. to estimate crop water requirements and yield response to water stress. The methodologies of crop water requirements were first published in 1974 as FAO Irrigation and Drainage Paper No. 24, and they were revised in 1977 (FAO, 1977). A review and update of the methodologies are contained in FAO Irrigation and Drainage Paper No. 56, which deals with crop evaporation (FAO, 1998). These methodologies use the Penman–Monteith equation, which estimates daily reference crop evapotranspiration (mm/day) based on net radiation, soil heat flux, average air temperature, wind speed, vapour pressure deficit, and other humidity parameters. The two publications listed above give details on estimating all these parameters based on weather and climate data and when data sources are limited. The FAO CROPWAT software program incorporates these methodologies and procedures to simulate crop water use under various climate, crop and soil conditions. This software is available from FAO at http://www.fao.org/nr/water/infores_databases_cropwat.html.

A report published by the WMO Commission for Agricultural Meteorology (WMO, 2000*b*) describes several operational applications to increase water use efficiency, including an irrigation advisory system in Israel calculated on the basis of a modified Penman potential ET equation. The same report contains a paper describing the Irrigation Planner, which has been developed into a computer software application for irrigation of grassland in the Netherlands (WMO, 2000*a*). Results show that using the system can reduce irrigation water by 15–20 per cent.

Kroes (2005) provides on overview of the soil–water–atmosphere–plant (SWAP) model, which integrates water flow, solute transport and crop growth. The SWAP model can be used at the local scale by farmers and extension agents for irrigation demand, potentials and strategies. At the regional level, it can be used by policymakers for spatial and sectoral irrigation strategies.

Venäläinen et al. (2005) used numerical weather forecast model data to model soil moisture for input into irrigation models. Potential evaporation was calculated using the Penman–Monteith equation based on data from a high-resolution, limited-area model. The data were input into the AMBAV and SWAP irrigation models.

#### 9.3.1.2 Shelter from the wind

WMO Technical Note No. 59 (WMO, 1964) and Chapter 9 of Rosenberg et al. (1983) deal comprehensively with windbreaks and shelterbelts; van Eimern (1968) discusses problems of shelter planning. Grace (1977, as cited by Rosenberg) provides an overview of the direct influences of wind on plant growth.

Rosenberg et al. (1983) define windbreaks as structures that reduce wind speed, and shelterbelts as rows of trees planted for wind protection. Both of these can reduce physiological stresses on plants and animals due to wind. Rosenberg and his co-authors reviewed the literature and found that shelter effects on the microclimate include reduced potential and actual evapotranspiration; improved internal plant water relations (greater internal water potential and lower stomatal resistance); improved opportunity for photosynthesis; and finally, a general increase in yield as a result of shelter. These generalities are subject to variation depending on soil moisture, and the benefits may be most dramatic in dry years or under critical moisture shortages. Examples of the widespread use of windbreaks can be seen in the Great Plains in the United States after the Dust Bowl years of the 1930s (Rosenberg et al., 1983), the Rhone Valley in south-eastern France and the Netherlands (van Eimern, 1968). Marshall (1967) has reviewed the literature on the effect of shelter on the productivity of grasslands and field crops, and showed how the proportional decrease in wind speed with distance from the shelter corresponds to a decrease in evaporation. Night-time temperature decrease, relative humidity and the increase in daytime air and soil temperatures vary with distance from the barrier, but decline to no effect at a distance of about 12 times the height of the shelter. In connection with these parameters, the greatest soil moisture availability and crop yield are found in the zone at a distance of 2 to 4 times the height of the shelter.

Windbreaks reduce the force of the wind in the sheltered zone. WMO Technical Note No. 59 (WMO, 1964) shows that a dense barrier may protect an area about 10–15 times the height downwind, and by increasing the porosity of the barrier to about 50 per cent, the downwind influence can be increased to 20–25 times the height. Rosenberg et al. (1983) state that for the best wind reduction and greatest downwind influence, the windbreak should be most porous near the ground and the density of the barrier should increase logarithmically with height in accordance with wind speed profile. Wind reduction is a function of shelter location as well as the height above the plants. Questions of orientation and spacing of shelter can be regarded as meteorological applications, particularly if mesoclimatic wind surveys are used in advance.

#### 9.3.1.3 Shade

Shelters of various types can also be used to provide shade from the sun; a well-known example is the use of taller-growing “shade trees” to protect cacao, coffee or tea plants.

*Agrometeorology of the Coffee Crop* (WMO, 1994*a*) states that because coffee originally developed as an understorey shrub in the rain forests of central Africa, it might be assumed that shading or arborization of coffee trees is a well-defined cultural practice. There has been much discussion on the validity of this practice, however. Most of the commercial crop in Brazil is unshaded, while shading is a common practice in Colombia, Costa Rica, El Salvador, Guatemala, Uganda, Tanzania and in the higher-elevation areas of North-east Brazil. In most of Brazil, an unshaded crop facilitates the harvesting and natural ground drying of the crop as the microclimate is sunnier, and hence warmer and drier. In most places, coffee berries are hand-picked at the cherry stage, and if this stage is extended it provides for an easier and longer harvest period. Therefore, shading can be advantageous since it increases the cherry stage of the crop because the microclimate is cooler and moist, which slows the maturation process. Shading also aids in maintaining high soil organic matter. This publication (WMO, 1994*a*) also cites several characteristics of good shading trees and several other advantages and disadvantages.

Shelters may also be used to reduce production losses from lactating dairy cows because of the heat load during the summer (Hahn and McQuigg, 1970).

#### 9.3.1.4 Greenhouses (glass and plastic)

Greenhouses have been used in temperate climates for over 100 years and serve mainly to reduce heat loss and permit complete control over the watering of plants. Recently, $CO_2$ enrichment of the atmosphere has become an additional technique in greenhouse cultivation. A detailed discussion of greenhouses is presented in WMO (1974*a*) and WMO (2003).

A WMO publication on agrometeorological aspects of various types of agricultural activity (WMO, 2003) discusses many benefits derived from indoor agriculture (greenhouses): protection against damage by ultraviolet (UV) light; improved ambient temperature conditions; protection of crops from adverse climatic conditions; increased productivity; reduced production costs; controllable harvest; and better product quality. They also list several climate elements that must be managed for good performance from greenhouses. The covering of the greenhouse is important with regard to visible light transmission for plant photosynthesis. Knowledge of the climatology of a greenhouse site, including solar radiation, cloudiness, relative humidity, temperature and wind profiles, is important.

Turning to construction materials, most greenhouse coverings are made of glass, fibreglass and plastic, while plastic agricultural tunnels are less widely used (WMO, 2003). In order to choose the best covering suited to a geographical location, the maximum, minimum and average temperatures; the possibility of frost; the climatology of the wind and relative humidity, rainfall distribution and intensity; solar radiation; and specific crops need to be taken into account.

A climatological analysis of solar radiation, temperature and relative humidity is important for siting greenhouses. These parameters will determine how much internal environmental control will be needed for optimum plant growth depending on the plants grown. Wind speed and direction are very important factors when designing a greenhouse. High winds could damage the structure or coverings. Wind is also used in simple greenhouse designs to maintain the thermal balance by reducing energy costs for heating or cooling. Wind ventilation can be used for balancing internal temperatures by means of air circulation, reducing relative humidity, promoting crop pollination, and replenishing carbon dioxide and removing oxygen for plant photosynthesis.

For some crops the degree of control is such that firm advice can be given on the optimum temperatures for different growth stages (tomatoes are a good example); it is possible to differentiate between the environmental temperatures that should be maintained during the day and during the night. This knowledge has led to the design of "blueprints" for the production of certain crops.

There is scope for further assistance by meteorologists in research on environmental control. Practical help can also be given at the advisory level, in terms of greenhouse siting, design, and fuel consumption. Meteorological factors are probably most useful in siting greenhouses. In analysing possible greenhouse sites, standard radiation data can be adjusted for latitude and mean cloudiness to give an estimate of the radiation input (and therefore plant growth) at each location. Such factors as shelter and radiation must be balanced; highly exposed sites are undesirable because of extra fuel consumption and the risk of physical damage. As for fuel consumption, if a crop requires the temperature to be kept at a given level, the quantity of fuel needed can be calculated from the number of degree-days below that temperature.

#### 9.3.1.5 Ground cover (mulching)

Soil mulches of various kinds (namely, straw cover or artificial materials such as plastics) are used to modify the heat and moisture balance in the soil to benefit plants. WMO Technical Note No. 136 (WMO, 1975*b*) provides a good overview of the effects of mulching on plant climate and yield and states that mulches are particularly useful in conserving moisture, reducing temperature extremes and minimizing erosion. Chapter 6 of Rosenberg et al. (1983) provides several examples of various mulches used with different crops.

*Agrometeorology of the Coffee Crop* (WMO, 1994*a*) lists the following advantages of grass-straw mulching with the coffee crop in Kenya: it protects the soil from excessive heating that destroys the soil structure; it lowers temperatures, which results in lower evaporation rates; it provides organic matter to the soil; and it reduces soil erosion from heavy rainfalls and minimizes weeds. It also cites studies indicating that mulching can reduce the frequency of irrigation. On the negative side, mulching requires a large amount of grass, and more importantly, straw mulches can aggravate frost problems as the air temperature above the mulch is much warmer during the day and cooler at night. The mulch also prevents the ground from absorbing heat during the day, which is subsequently released during the night. Studies on the effect of straw mulching on air temperatures indicate that at 5 cm above the ground, the maximum temperature is 6.6°C higher and the minimum is 1.7°C lower than the bare ground (WMO, 1994*a*). Gurnah and Mutea (1982, as cited in WMO, 1994*a*) tested the effect of different plastic coverings on the soil temperature and concluded that on areas subject to frost, transparent plastic should be used and white plastic should be used elsewhere, since it approximately has the same thermal regime as bare soil.

#### 9.3.1.6 Animal housing

Meteorological data are required when assessing whether and how animal housing should be put into use. Evaluation should also take into account the potential economic returns, energy cost and availability (WMO, 1980*d*). Animal housing is utilized because thermal imbalances lead to adverse effects on animal productivity.

Weather and climate can determine the efficiency of livestock production by direct and indirect influences (WMO, 1980*d*). Direct influences affect the heat balance of the animal and include extreme meteorological events. Indirect influences are disease and parasites. Excessive heat or cold increases the metabolic energy required to maintain the animal's body temperature, thus reducing the energy available for productivity. This energy imbalance is usually corrected by increased feed, which entails an additional cost to the farmer. The use of climatological data and analysis is useful in this case. *Weather, Climate and Animal Performance* (WMO, 1980*d*) provides many examples of using weather and climate information in the application of animal housing. It mentions that siting, external wind, temperature and humidity affect both entry conditions and patterns of internal air movement in environmentally controlled housing. Smith (1964) has shown the importance of the ventilation rate in animal housing, and how it may be estimated by a psychrometric method simple enough to be applied on a farm scale. The siting of animal shelters is also important, particularly in relation to other shelters, as alternating positive and suction pressures may result from nearby obstructions.

#### 9.3.1.7 Storage

For some crops, storage is as important as production and weather may affect the quality of the food product and modify the storage environment, causing loss of product and economic value.

##### 9.3.1.7.1 *Fruit and vegetables*

*The Effect of Weather and Climate upon the Keeping Quality of Fruit* (WMO, 1963*a*) states that the storage life of fruit is terminated by the onset of rotting caused by specific fungi, physiological diseases and senescent breakdown. The rate of development of these storage disorders is determined by storage conditions such as temperature and concentration of $CO_2$ and oxygen, and by pre-storage treatments. *Agroclimatology of the Apple Crop* (WMO, 1996) states that the maturity of the apple fruit has a major impact on the quality of fruit during storage and that there have been many studies on modelling apple maturity using climatic data.

A WMO survey of operational models for agrometeorological services related to potato production (WMO, 1990*b*) states that monitoring of the storage environment and weather forecasts are used in many countries to determine the optimum conditions for potato tubers. In the former Czechoslovakia, humidity and temperature data (the mean number of hours exceeding the limits of 3°C, 7°C and 10°C during the winter months) were used for the design and construction of large potato storage facilities. Another WMO report (WMO, 2002) contains a review of the scientific literature on the quality and storage of grapes and potatoes. It cites the most important meteorological parameters for grape quality as temperature and solar radiation and lists several quality models for these crops. Potato storage quality is determined by evaporation, transpiration, respiration and germination.

##### 9.3.1.7.2 *Grain*

The previous WMO Technical Note on this subject has been revised (WMO, 1990*a*). Agrometeorology can provide guidance for the construction of grain storage based on local climate modification and environmental control. Stored grain interacts with its environment, exchanging heat and moisture. The level of biological activity of grain and potentially damaging organisms must be minimized. For safe storage, grain must be kept cool and dry, requirements that are affected both by the characteristics of the building or structure for housing and by the external environment. Heat uptake from outside must be minimized while heat loss from storage must be maximized. The moisture exchange between the grain and the external environment should generally lead to a reduction in grain moisture content. When hot dry grain must be cooled to prevent insect infection, the resulting moisture increase must be kept to an acceptable level.

The siting of storage facilities and their design and construction materials can all be influenced by meteorological factors. For example, in hot, dry regions with no refrigeration, there are advantages to storage facilities of high thermal capacity, with air space ventilated at night when the air is coolest. In warm, wet regions with small diurnal temperature ranges, good storage may be difficult to design.

Meteorological factors become more important to the farmer when natural air drying systems are used for grain. In the state of Ohio, United States, for example, best results for shelled corn occur when the climatic conditions provide temperatures in the range of –1°C to 10°C and relative humidities in the range of 60 to 70 per cent (Hansen et al., 1990). In most western Ohio counties, October and November provide high probabilities for good climatic conditions for natural air drying of soybeans and shelled corn.

There is also an impact of weather conditions due to rainfall before storage that can be important. High temperature and rain that occur shortly before harvest are the most important direct weather effects on the quality of spring barley (WMO, 2002).

### 9.3.2 Averting dangers to production

These dangers may be the direct result of weather (for example, frost) or they may be indirect and carried by biological agents that are affected by the weather (such as pests and diseases that attack plants and animals).

### 9.3.2.1 Direct weather hazards

#### 9.3.2.1.1 *Frost*

The occurrence of frost has been studied in detail by many agrometeorologists mainly because of its economic effect on high-value crops, and because some crops can be protected. Some examples were taken from WMO publications (WMO, 1963*d*, 1971) in the previous edition of this chapter. Two WMO publications (WMO, 1978*b*, 1997*d*), Rosenberg et al. (1983), and a more recent FAO report on frost protection (FAO, 2005) provide overviews and examples of protection against frost damage.

Frost-risk maps and dates of first and last frost are simple but useful applications of climate data applied to agriculture. These maps are made at the macro- to mesoscale and are useful for specifying general planting dates for cereal crops and for the assessment of crop damage when combined with phenological data.

##### 9.3.2.1.1.1 Sites

Assessment of potential sites for frost-sensitive crops, especially high-value crops such as tree fruit and coffee, is crucial since it will discourage growers from planting in frost areas. Topoclimatology and local-scale agroclimatic zoning are important tools and methodologies in this regard. An early overview of concepts and some examples are given in WMO (1974*b*). *The Effect of Temperature on the Citrus Crop* (WMO, 1997*b*) describes agrotopoclimatology as being concerned with the local differences in climate arising from topography, soil and vegetation within a uniform macroclimatic zone (this was defined earlier in this chapter as mesoclimate). They show some examples of using topoclimatological analysis to develop maps indicating the probability of frost occurrence over complex terrain. With the increase in availability and speed of personal computers in recent years, applications of this kind have increased (see Chapter 4 on GIS applications). One example uses a spatial interpolation method to determine the spring frost hazard in the hilly areas of French vineyards based on digital elevation data and weather station temperatures (Madelin and Beltrando, 2005).

##### 9.3.2.1.1.2 Protection against frost damage

Rosenberg et al. (1983) describe two kinds of frosts that can affect crops and call for different protection techniques. Advection frost usually occurs during or after a change in airmass and is accompanied by strong winds (cold front). The number of protection techniques against this kind of frost is limited. Radiation frost occurs under the influence of a high-pressure system and typically the winds associated with this kind of frost are very light. They list the following frost protection methods: site selection, radiation interception, thermal insulation, air mixing, direct convective air heating, radiant heating, release of the heat of fusion and soil manipulation. Most of these methods are effective only against radiation frosts, but some can be applicable to both advection and radiation frosts.

*Techniques of Frost Prediction and Methods of Frost and Cold Protection* (WMO, 1978*b*) describes many direct (or active) and indirect (or passive) frost protection methods, which are taken from mostly Russian and European sources. Direct methods of frost protection include: protective covers; smoke generation and artificial fogs; open-air heating of plants and areas; irrigation and sprinkling; and mixing air. Indirect methods include: biological methods such as hardening, seed treatment, selection of frost-hardy strains, development of new frost-hardy varieties and regulation of bud development. Ecological methods such as control of mineral nutrition and crop site selection are other indirect approaches.

The FAO publication *Frost Protection: Fundamentals, Practice, and Economics* (FAO, 2005) lists many recommended methods of passive and active frost protection along with detailed practical overviews of each method. It describes recommended passive methods such as site selection, managing cold air drainage, plant selection, canopy trees, plant nutrition management, pest management, pruning, plant and soil covers, soil cultivation, irrigation, removal of cover crops, trunk wraps and painting, and bacterial control. Recommended active methods of frost protection include the use of heaters, wind machines, helicopters, various types of sprinklers, surface irrigation, foam insulation, and some combination of these methods. It also provides a review of critical temperatures for annual, biennial and perennial crops, fruit and citrus trees, grapes, and other small fruits. A companion volume details several practical Excel software spreadsheets that help users to compute the probability that temperatures will fall below critical levels (TempRisk.xls) and the risk of frost damage specific to a crop (DEST.xls), and to determine the economic risk of frost damage protection (FrostEcon.xls).

#### 9.3.2.1.2 *Hail*

Hail can destroy high-value crops within a short time and many countries have therefore sought to reduce its frequency or to reduce the damage that it causes. *Protection of Plants against Adverse Weather* (WMO, 1971) contains a short summary of the protection methods that involve adding condensation nuclei to hail-forming clouds, by means of missiles or aircraft, with the object of producing small hailstones or soft hail.

Large reductions in hail have been claimed by a number of groups. According to the WMO Commission for Atmospheric Sciences, the weight of scientific evidence to date is inconclusive, neither confirming nor refuting the efficacy of hail-suppression activities. It is recommended that interested parties consult the WMO Statement on the Status of Weather Modification for further information (http://www.wmo.int/pages/prog/arep/wwrp/new/documents/WM_statement_guidelines_approved.pdf).

### 9.3.2.2 Indirect weather hazards

#### 9.3.2.2.1 *Introduction to crop and animal pests/diseases*

The application of meteorology to overcome the effects of pests and diseases on plants and animals involves a complete understanding of the complex life cycles of the pathogen and its host, as well as the environmental conditions that influence growth and development. Plant pathologists have developed a disease triangle with host (a susceptible animal or plant), environment (environmental conditions suitable for disease or pest establishment and development), and disease (the presence of the disease or pest) at the different points of the triangle, as depicted in Figure 9.1. These concepts help to describe the situation for virtually all known pests and diseases. All three sides of the triangle must exist for the pest/disease to be established and develop. If one of the sides is missing, then establishment of the pest/disease will not occur. Meteorological factors are very important for the growth and development of the host plant and animal species, for the pest/disease, and the airborne transport of the pest/disease. Orlandini (1996) lists temperatures, solar radiation, precipitation, leaf wetness and humidity, and wind as the major meteorological factors in relation to plant pathology. The duration of leaf surface wetness caused by dew, fog or rain is often a critical variable controlling the germination of disease spores. It must be computed from standard meteorological data or measured with leaf wetness sensors (Sentelhas et al., 2004).

Meteorology can be applied via observation of temperature, relative humidity and rainfall. More sophisticated applications include numerical weather prediction models for wind direction and speed with regard to the disease or pest (see 9.3.2.2.2.1 on the desert locust and 9.3.2.2.4.1 on foot-and-mouth disease). For the host or plant food source, temperature can be used for phenological development, rates of infection and disease/pest survival (extreme temperatures). Rainfall is important for host plant and disease/pest development. All of these aspects can then be modelled and used in operational applications for the agricultural decision-maker.

One important use of weather and climate information is in the field of Integrated Pest Management (IPM). IPM strategies include avoiding the use chemicals unless there is economic damage to the crop. There have been numerous studies and models of the influence of temperature on plant and insect growth and development. Pruess (1983) gives an overview of degree-day methods for pest management.

WMO Technical Note No. 192 (WMO, 1988*b*) provides many examples of agrometeorological aspects of operational crop protection, including protection against plant diseases, insect pests and weeds; meteorological data requirements; and application of weather forecasts. *Definition of Agrometeorological Information Required for Vegetable Crops* (WMO, 1997*a*) provides a brief overview of the meteorological factors relating to vegetable pests and diseases. Pedgley (1982) provides a good overview of the meteorology of windborne pests and diseases, accompanied by examples. Sections of

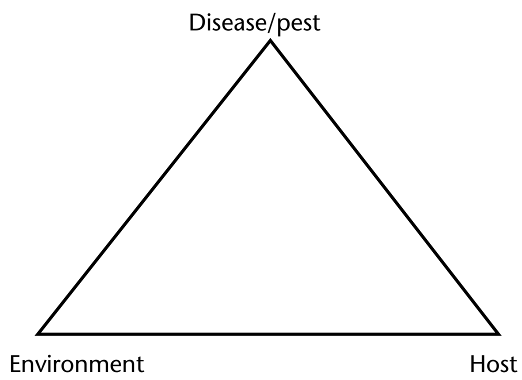


**Figure 9.1. Disease/pest triangle**

the book deal with weather at take-off, organisms staying airborne, downwind drift, insect flight within and above the boundary layer, swarms, dispersion and concentrations, and forecasting.

#### 9.3.2.2.2 *Crop pests*

There are many applications of meteorology involving crop pests. Based on the concepts in the pest/disease triangle, applications focus on using temperatures to predict insect development and host plant development. Any additional weather parameters can then be added, depending on the nature of crop pest.

##### 9.3.2.2.2.1 Desert locust

There has been much work on weather and desert locusts. Early studies include meteorology and desert locust migration (WMO, 1963*c*) and the accompanying training seminars (WMO, 1965). Later work focused on meteorology for locust control (WMO, 1991, 1992*b*, 1992*c*, 1997*c*).

*Extreme Agrometeorological Events* (WMO, 1997*c*) gives a good overview of the meteorological factors for locust control. Rainfall largely determines the extent and intensity of breeding and therefore is the most important factor in the development of an outbreak or plague. Rainfall location is more important than actual amounts, and this is where satellite rainfall estimates are particularly useful. Once there is a significant rainfall event in the desert (25 mm or more during a month or two), the tender grass vegetation, which is the main food source for desert locusts, starts to grow. It is these abnormal rainfall events that can trigger locust outbreaks and plagues. There have been cases in the Arabian Peninsula in which a tropical cyclone making landfall has spurred a locust outbreak, for instance in 1969. Temperature affects the rate of development of all stages of the desert locust life cycle. Since this pest is native to hot desert climates, temperatures gain in importance typically when swarm take-off is needed on a daily basis or when the desert locust migrates outside the desert climates. Likewise, wind direction and speed are needed to determine swarm flight and to perform tactical spraying applications from aircraft or the ground.

The biological activity of desert locusts determines the kind of weather data needed over a given period. The desert locust is normally a solitary insect and does not threaten crops and food security. This state is called the recession period and rainfall data are needed to determine where locust control personnel should scout for locust activity. During a desert locust outbreak or plague, the type and amount of meteorological information increases to include daily temperatures and forecasts of temperature and rainfall, as well as wind forecasts, which are especially important. Recently, more attention has been given to high-resolution regional numerical weather prediction models.

##### 9.3.2.2.2.2 Other crop pests

WMO Technical Note No. 41 (WMO, 1961) was prepared for the European and Mediterranean Plant Protection Organization to delineate the areas where the climate is suitable for the permanent settlement of the Japanese beetle in Europe. Most of the life of the beetle is spent beneath the ground as a grub. The appropriate environmental model therefore takes account of summer rainfall (as a substitute for soil moisture) and summer and winter soil temperatures. Volvach (1987) describes the model used to consider the effect of agrometeorological conditions on the principal characteristics of Colorado beetle activity: duration of development, reproduction and death of individuals. The preliminary amount of chemical treatments to be applied to potato is calculated on the basis of the forecast intensity of Colorado beetle reproduction, then it is corrected in the light of observed weather conditions.

There have been many studies relating meteorological factors to important crop pests, such as the cotton leaf worm and pink bollworm (WMO, 1980*b*), the Colorado potato beetle (WMO, 1975*a*), various pests of sugarcane (WMO, 1988*a*) and cassava mites (WMO, 1980*c*).

#### 9.3.2.2.3 *Crop diseases*

The application of meteorology as an aid to the farmer in combating plant disease differs according to the mechanisms by which each pathogen is spread. The pathogen may be a year-round resident that increases and spreads whenever the weather is suitable for the pathogen and the host plant, which is the case with the fungal disease called potato blight, for example. In some areas a pathogen may not be capable of surviving the year, and may not reappear unless transported in sufficient quantity from a distant source, as in the case of black wheat rust, for example. In recent years the development of crop disease models has focused on crops with high economic value, such as fruit trees, vineyards and vegetables, since the models need meteorological observations in field settings that usually require the establishment of costly automatic weather stations.

9.3.2.2.3.1 Potato blight

There are two approaches available for the forecasting of late blight with a view to reducing agrochemical use compared to routine 7- and 10-day spraying:

(a) Simple meteorological rules related to the life cycle of *Phytophthora infestans* that use rainfall, temperature and humidity over 12–48 h periods to predict spore production ("critical periods") and possibly subsequent periods when risk of infection is greatest. These methods can be used with either hourly observation data or synoptic weather maps;
(b) Computer-based decision support systems (DSSs), usually utilizing the simple rules that rely on data from in-field automatic weather stations or available as digital files from (usually) Internet sources.

The rules (Table 9.1) differ only in detail and require some regional or site-specific calibration. Mercer et al. (2001) indicate that ideal conditions for spore production are relative humidity above 95 per cent and temperature above 10°C at night-time; free water must be available on the crop surface for serious infection to occur, so rainfall and prolonged high relative humidity are also required after spore production. Simple rule-based methods predict critical periods from late spring until late summer using the following general rules:

(a) Minimum temperature >10°C for a period of between 12 to 48 hours;
(b) Relative humidity >90 per cent for the same time period;
(c) Rainfall in the period following (4 hours to 10 days later).

Evidence of disease is expected between 7 and 21 days after a critical period has been predicted and a suitable crop protection strategy can be put in place. If possible, prediction should be based on hourly observation of temperature and relative humidity. Synoptic maps can be used (particularly where observations are sparse) to make predictions based on the likelihood that current and forecast weather systems will create suitable conditions for a critical period to occur, such as the passage of warm, moist tropical air giving rise to high humidity and temperature, and slow-moving depressions giving rise to overcast, humid, rainy conditions (WMO, 1955; Austin Bourke, 1957).

The use of DSSs (Table 9.2) typically requires site-specific automatic weather station data, but interfaces with alternative data sources are also possible (Hansen, 1999). The systems automate the use of the simple rule-based methods and usually provide spray strategy recommendations as well.

9.3.2.2.3.2 Wheat diseases

WMO Technical Note No. 99 (WMO, 1969) provides an overview of the various wheat rusts that occur around the world and the meteorological factors that contribute to the transport of spores and disease outbreaks for various types of wheat rusts.

A WMO report (WMO, 2000*d*) provides a survey of many crop disease models, including several for wheat. It describes EPIPRE as a system devised to support decision-making in pest and disease control in winter wheat with the aim of reducing pesticide use. The system integrates six fungal diseases and three aphid pests of wheat. Spirouil–Epure was developed in France and has been used for many years to support extension services for brown wheat rust. The model uses meteorological data, along with some agronomic and phenological data, and provides advice on the dates for first fungicide application within microregions and well-defined crop zones.

9.3.2.2.3.3 Apple scab

Apple scab is caused by the *Venturia inaequalis* fungus and is an economically important disease for apple producers. *The Influence of Weather Conditions on the Occurrence of Apple Scab* (WMO, 1963*b*) provided one of first overviews of the disease, investigations in various countries and descriptions of the early warning systems. More recently, the apple scab model ASCHORF was developed in Germany. This model can be used to provide practical recommendations to plant protection services and apple growers (Friesland, 2005). The modelled infection risk is dependent on temperature and leaf wetness duration. Leaf wetness duration is calculated but not measured and is based on energy balance principles. The model uses a sliding 10-day time series by inputting data for the previous four days from the standard meteorological network and then inputting grid point data from numerical weather prediction models.

9.3.2.2.3.4 Downy mildew

Downy mildew (*Plasmopara viticola*) is one of the most important fungal diseases for wine grapes (*Vitis vinifera*) and can lead to considerable losses in

**Table 9.1. Examples of "critical period" prediction methods indicating the types of modification made for various regions where potatoes are grown (not an exhaustive list)**

| *Method* | *Temperature* | *Humidity* | *Other* | *Rainfall* | *Reference* |
|---|---|---|---|---|---|
| Dutch rules<br>1926<br>Europe | >10°C min at night | 4 h below dewpoint at night | 8/10ths following day | Followed by >0.1 mm rain | van Everdingen (1926) |
| Beaumont periods<br>1947<br>United Kiingdom | >10°C min for a minimum 48 h period | 75% during the 48 h period | | | Beaumont (1947) |
| Irish rules<br>1953<br>Ireland | >10°C min for a 12 h period | >90% for the 12 h | Free moisture on leaves for 2 h after the 12 h period or the rainfall criterion | Between the 7th and 15th h around the end of the 12th h of the 12 h period | Keane (1982) |
| Hyre rules<br>1954<br>North-eastern United States | 5-day average <25.5°C excluding days with minimum <7.2°C | | Looks for 10 consecutive risk days | Total rain in 10-day period >30 mm | Hyre (1954) |
| Smith periods 1956<br>United Kingdom and Ireland | >10°C min for 2 × 24 h periods | >90% for 11 h in each of the 2 periods | | | Smith (1956) |
| Negative prognosis<br>1966<br>Germany | Uses temperature bands and multiplies the hours in each band by a weighting factor<br>>10°C and <24°C | At low temperature only use hrs when >90% or a rainfall limit for 4 h blocks. At higher temperature use a 10 h block | Can subtract from risk when RH is <70% | At low temperature only use h when >0.1 mm rainfall or RH limit for 4 h blocks. At higher temperature use a 10 h block | Ullrich and Schrodter (1966) |
| Young rules<br>1978<br>South Africa | >10°C and <24°C for 2 × 24 h periods | >70% at 2 p.m. during each of the 24 h periods | | | van Rij and du Preez (2004) |
| Forsund rules<br>1983<br>Norway | Maximum 17°C–24°C<br>Minimum >10°C for 2 × 24 h periods | >75% at noon during each 24 h period | | >0.1 mm during each 24 h period | Forsund (1983) |
| Winstel rules<br>1993<br>Belgium | Phase 1: Average daily >10°C and <23°C for 10 h and then 10 h >10°C<br>Phase 2: Maximum daily >23°C and <30°C for 2 × 24 h between 1 and 10 days after Phase 1 | Phase 1: >90% | | | Winstel (1993) |
| Washington State rules<br>1996<br>North-western United States | Rainfall indicators calculated for periods when minimum >5°C during April and May and then July and August | | Calculates probability of a year being an "outbreak" year using discriminant functions and binary logistic regression | Days with >0.25 mm and temperature >5°C | Johnson et al. (1996) |

**Table 9.2 Examples of DSS-type systems for prediction and management of blight outbreaks (after Bouma and Hansen, 1999)**

| *Model* | *Country and e-mail* | *Original development year* | *Main target users* | *Input* | *Output* |
|---|---|---|---|---|---|
| Televis | Norway<br>Arne.Hermansen@planteforsh.no | 1957 | Farmers, advisers | Weather data | Epidemiological data |
| Guntz-Divoux | France<br>fredec.nord.pas-de-Calais@wanadoo.fr | 1963 | Advisers, extension service | Weather data | Advice line |
| Simphyt | Germany<br>Bkleinhenz.lpp-mainz@agrarinfo.rpl.de | 1982 | Plant protection service, extension officers | Weather data<br>Field data | Field data<br>Advice |
| ProPhy | Netherlands<br>info@Opticrop.nl | 1988 | Farmers, advisers, extension officers | Weather data<br>Field data<br>Other data | Weather overviews<br>Field data<br>Advice |
| Plant-Plus | Netherlands<br>Plantplus@dacom.nl | 1990 | Farmers, advisers, suppliers, processors | Microclimate<br>Crop + product information | Disease maps<br>Fungicide protection periods |
| I.P.I. | Spain | 1990 | Farmers, advisers | Weather data | 1st spray timing<br>Epidemiological data |
| NegFry | Denmark<br>JensG.Hansen@agrisci.dk | 1992 | Farmers, advisers | Weather data<br>Field data | 1st spray timing<br>Fungicide applications |
| PhytoPRE + 2000 | Switzerland<br>Hansrudolf.forrer@fal.admin.ch | 1995 | Farmers, advisers, plant protection service | Weather data<br>Field data<br>Other data | Regional data<br>Field data |
| Guntz-Divoux | Belgium<br>pcg@ping.be | 1996 | Advisers, extension service | Weather data | Advice line |

grape yield and quality. Friesland et al. (2005) developed the PERO model to calculate the start of infection of the grapevine disease *Peronospora*, which is determined by temperature and leaf wetness. The PERO model is based on laboratory and field experiments and the inputs are hourly air temperature, relative humidity, calculated leaf wetness, daily extreme temperatures and daily rainfall. The model outputs are infection dates and oil spot balances (lesions), which are used for agrometeorological advice.

PLASMO (*Plasmopora* simulation model) was developed to simulate the biological cycle and the disease leaf area of grapevine downy mildew, allowing for the best timing for fungicide treatments (Orlandini et al., 2005). Data inputs are hourly temperature, relative humidity, rainfall and leaf wetness. The results are expressed in percentage of leaf area covered by oil spot lesion. The PLASMO model has been developed into a computer program for distribution and is also available on the Internet for greater access. Weather data can be uploaded to the model Website for running of the model (Rossi et al., 2005).

#### 9.3.2.2.3.5 Other applications

Norway has developed a Web-based site-specific warning system called VIPS that calculates warnings for several pests and diseases in selected fruits, vegetables and cereals (Folkedal and Brevig, 2004). The warnings are linked to over 70 weather stations and colour-coded warnings ranging from danger (red) to no danger (green) are given for each county for the previous five days and are forecast for the upcoming five days. VIPS incorporates previous work done in Norway on pests and diseases such as NORPRE (Magnus et al., 1991). NORPRE is a cereal disease and pest control system that uses daily weather data as input to a number of different submodels. The system uses field observations of pest disease occurrence from farmers to validate the models and adjust threshold values. The system includes the following pest models: cabbage moth, turnip moth, carrot fly and codling fly (WMO, 2000*c*).

There have been many surveys of crop disease models undertaken over the years. A WMO report (WMO, 2000*d*) contains a survey focused on fungal pathogens and lists 58 crops and 133 pathogens.

### 9.3.2.2.4 *Animal pests/diseases*

The approach of the meteorologist to problems of animal disease is basically the same as for plant disease. *Weather and Animal Diseases* (WMO, 1970) provides a good overview of practical links between weather and animal disease that may be windborne, parasitic, fungal or the result of environmental or nutritional stress. More recent reviews include WMO (1989) and WMO (1980*d*), which detail internal animal parasites and cold and hot weather stress. *Weather, Climate and Animal Performance* (WMO, 1980*d*) states that there are two lines of enquiry in using climate information as a measure of disease incidence. The first uses climatic factors to develop climatic indices known to influence the development of the animal parasite during its life cycle outside the animal. The second uses biological development rates, calculated from the study of parasites under laboratory conditions in constant temperature chambers, to determine the influence of temperature variation on parasite development in actual field conditions. Besides the animal diseases listed below for which meteorological applications have been developed, this publication also provides information on nematodiriasis and parasitic gastro-enteritis.

#### 9.3.2.2.4.1 Foot-and-mouth disease

The 1968/1969 foot-and-mouth disease epidemic in the United Kingdom led to research indicating that meteorological factors are major contributors to the spread of the virus during a foot-and-mouth outbreak (Smith and Hugh-Jones, 1969; Wright, 1969). The virus is spread when it is exhaled by animals as the nuclei of water droplets, which are then dispersed by winds. The most important meteorological factors are wind, humidity and rainfall; the synoptic situation will determine to some degree the distance over which the virus can spread. Wind speed and direction will determine the pattern of dispersion of the virus. Stable atmospheric conditions favour dispersion over large distances because vertical distribution is minimized, while high winds and turbulence usually reduce the transport range. Humidity will determine the duration that the virus remains protected by its water droplet. Maximum infectivity is associated with relative humidity above 60 per cent (Murphy et al., 2004). Rainfall will influence when the virus is deposited from the atmosphere. In rainy conditions the virus will be deposited on herbage within short distances of the source, rather than moving to infect other animals.

The more recent epidemic in the United Kingdom in 2001 resulted in the development, utilization and testing of models for predicting the spread of virus based on: the predicted viral load at a source location; the predicted spread due to surface weather conditions (Gloster et al., 2003; Mikkelsen et al., 2003; McGrath and Finkle, 2001); and latitude and topography. McGrath and Finkle (2001) noted that older models depend on synoptic observations and thus suffer error due to potential remoteness of observation stations from outbreak sources. Mikkelsen et al. (2003) tested four dispersion models: (i) 10 km Gaussian Plume (Gloster et al., 1981); (ii) Nuclear Accident Model (NAME) (Ryall and Maryon, 1998); (iii) RIsø Mesoscale PUFF model (RIMPUFF) (Mikkelsen et al., 1984); and (iv) Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen, 1998). NAME and DERMA are long-range models driven by numerical weather prediction (NWP) output, and produced similar results despite being driven by different NWP models. The local-scale models, driven by nearby observation data, were also used to analyse local infection. It was concluded that 24-hour average virus concentrations do not adequately represent infection risk and that short-term high concentration levels are needed to account for the pattern of infection that was observed (Gloster et al., 2003).

For local-scale prediction, the most important observation/NWP output is 10 m wind speed, estimates of three-dimensional dispersion, the relative humidity and the chance of rainfall occurring. For regional-scale modelling, 1- to 3-hour NWP output is preferred and should include wind speed, wind direction, relative humidity, cloud cover and precipitation.

#### 9.3.2.2.4.2 Facial eczema of sheep

A warning system for this fungal disease was devised in New Zealand (WMO, 1960, 1968*a*). Even before a definite link was established between the disease and fungus present in grass, soil temperatures and rainfall were used for warning. High humidities and ambient temperatures in the 21°C–27°C range are favourable for the spores, and the discovery of the fungus reinforced the empirical approach. Spore traps and counts are now being used to confirm the meteorological evidence.

#### 9.3.2.2.4.3 Fascioliasis in sheep

Fascioliasis (commonly called liver fluke disease) is a parasitic disease that affects sheep and is caused by *Fasciola hepatica*. The complicated life cycle consists of the passing of fluke eggs in dung by infected sheep, and these eggs then hatch into free-swimming larva in the open pasture and infect the fluke's intermediate host, a snail, *Lymnea trunculata*. This is the most sensitive stage of the life cycle. The larvae will die if they cannot enter a snail within 24 hours. Ollerenshaw (1966) describes a wetness index (Mt) based on monthly rainfall, potential transpiration and the number of rain days, which was developed in England and Wales. Data for the index are accumulated over a season, and based on comparison with historical disease statistics, thresholds for treatments can be established.

Part I of *Weather and Parasitic Animal Disease* (WMO, 1978*c*) provides an updated and through overview of the use of weather information in the various models of this disease in Europe, and states that the most important meteorological factors in the emergence of *Fasciola hepatica* are temperatures above 10°C for the development of the parasite inside the snail host and the presence of free water. *Weather, Climate and Animal Performance* (WMO, 1980*d*) also lists several analytical and simulation models that predict parasite populations in pasture and in the host. It cites the use of analytical models for strategic disease control policies and simulation models for tactical control procedures. Part II of *Weather and Parasitic Animal Disease* (WMO, 1978*c*) contains several examples of the use of weather information to study and/or model nematodiriasis in sheep, as well as tapeworms, ticks and nematodes.

## 9.4 OTHER APPLICATIONS

There are many other applications of meteorology for agriculture besides those already mentioned. They are covered in other chapters in detail because of their importance. One important group relates to the physiology and growth of plants, from germination to final yield. These are affected somewhat by the applications already dealt with, for example, irrigation, shelter, cover and disease. Other applications can be cited, including the use of degree-days or other indices to determine the phenological stages of crops, such as flowering, reproduction and maturity. These stages are very important for pest/disease management. Typically, growing degree-day or heat-unit calculations are made by subtracting a threshold temperature from the average daily temperature and then accumulating these units over time to model plant and insect development. The simplest form on a daily basis is:

$$\text{Degree-day} = [(T_{max} + T_{min})/2] - T_{base}$$

Hodges (1991) provides a good overview of modelling crop phenology for many crops. *Weather-Based Mathematical Models for Estimating Development and Ripening of Crops* (WMO, 1983) describes these calculations as temperature-remainder models

(TRIM) and lists many methodologies to calculate crop development. See Chapters 6 and 10 for a more detailed review of these concepts. Another group of applications concerns field operations. Since cultivation, drilling, spraying and harvesting are all highly weather-dependent, the meteorologist can give considerable help in assessing the probability of weather suitable for these operations, which may greatly affect the requirements for labour and machinery.

Fedoseev (1979) showed that lodging results in a significant crop yield drop (by as much as 20–30 per cent) and degradation of grain and straw quality, and also creates problems for harvesting. Operation of harvesting units with lodged crops is extremely difficult and their efficiency decreases by 25–50 per cent, which results in longer harvesting times. But even under optimum harvesting conditions, the grain loss is in the range of 10–25 per cent. Depending on the lodging conditions, biological losses are between 5 and 40 per cent on average.

In all applications meant for the farmer, it is of the utmost importance that the meteorologist work closely with the specific experts on individual problems.

# REFERENCES


Austin Bourke, P.M, 1957: *The Use of Synoptic Weather Maps in Potato Blight Epidemiology*. Technical Note No. 23. Dublin, Irish Meteorological Service.

Baier, W. and G.W. Robertson, 1965: Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.*, 45:276–284.

Beaumount, A., 1947: The dependence on weather of the dates of potato blight epidemics. *Trans. Br. Mycol. Soc.*, 31:45–53.

Boken, V.K, A.P. Cracknell and R.L. Heathcote (eds), 2005: *Monitoring and Predicting Agricultural Drought: A Global Study*. New York, Oxford University Press.

Bouma, E. and J.G. Hansen, 1999: Overview of standard descriptions of *Phytophthora* Decision Support Systems. In: *Proceedings of the Workshop on the European Network for Development of an Integrated Control Strategy of Potato Blight*. Uppsala, Sweden, 4–13 September 1998 (H. Schepers and E. Bouma, eds). Lelystad, Pub. Applied Research for Arable Farming and Field Production of Vegetables.

Daly, C., R.P. Neilson and D.L. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.*, 33: 140–158.

Dyras, I., H. Dobesch, E. Grueter, A. Perdigao, O.E. Tveito, J.E. Thornes, F. van der Wel and L. Bottai, 2005. The use of Geographic Information Systems in climatology and meteorology: COST 719. *Meteorol. Appl.*, 12:1–5.

Fedoseev, A.P., 1979: *Field Management and Weather.* Leningrad, Hydrometeoizdat.

———, 1985: *Agrometeorological Conditions for the Effectiveness of Fertilization*. Leningrad, Hydrometeoizdat.

Folkedal, A. and C. Brevig, 2004: VIPS – A web-based decision support system for crop protection in Norway. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogotaj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Food and Agriculture Organization of the United Nations (FAO), 1977: *Guidelines for Predicting Crop Water Requirements* (J. Doorenbos and W.O. Pruitt). FAO Irrigation and Drainage Paper No. 24, Revised. Rome, FAO.

———, 1998: *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements* (R.G. Allen, L.S. Pereira, D. Raes and M. Smith). Irrigation and Drainage Paper No. 56. Rome, FAO.

———, 2005: *Frost Protection: Fundamentals, Practice, and Economics*. Vols. 1 and 2 (R.L. Snyder, J. de Melo-Abreu and S. Matulich). FAO Environment and Natural Resources Service Series, No. 10. Rome, FAO.

Forsund, E., 1983: Late blight forecasting in Norway 1957–1980. *EPPO Bulletin*, 13:255–258.

Friesland, H., 2005: Description and testing of the model ASCHORF for apple scab infections. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogataj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Friesland, H., S. Orlandini and A. Sušnik, 2005: Description and testing of the model PERO for grapevine downy mildew predictions. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogataj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Gloster, J., R.M. Blackall, R.F. Sellers and A.I. Donaldson, 1981: Forecasting the airborne spread of foot-and-mouth disease. *Veterinary Record*, 110:47–52.

Gloster, J., H.J. Champion, J.H. Sorensen, T. Mikkelsen, D.B. Ryall, P. Astrup, S. Alexandersen and A.I. Donaldson, 2003: Airborne transmission of foot-and-mouth disease virus from Burnside Farm, Heddon-on-the-Wall, Northumberland, during the 2001 epidemic in the United Kingdom. *Veterinary Record*, 152:525–533.

Gordeev, A.V., A.D. Kleschenko, B.A. Chernyakov and O.D. Sirotenko, 2006: *Bioklimaticheskii potentsial Rossii: teoriia i praktika*. [Bioclimatic Potential of Russia: Theory and Practice]. Moscow, KMK Scientific Press.

Hahn, D. and J.D. McQuigg, 1970: Evaluation of climatological records for rational planning of livestock shelters. *Agric. Meteorol.*, 7:131–141.

Hansen, J.G., 1999: *NegFry – A Decision Support System for Scheduling the Chemical Control of Potato Late Blight. User Manual*. Tjele, Danish Institute of Agricultural Sciences.

Hansen, R.C., H.M. Keener and R.J. Gustafson, 1990: *Natural Air Grain Drying in Ohio*. Extension Factsheet AEX-202-90. Columbus, Ohio State University.

Her Majesty's Stationery Office (HMSO), 1967: *Potential Transpiration*. Technical Bulletin No.16. London, Ministry of Agriculture, Fisheries and Food.

Hodges, T. (ed.), 1991: *Predicting Crop Phenology*. Boca Raton, CRC Press.

Hogg, W.H., 1967: *Atlas of Long-term Irrigation Needs for England and Wales*. London, Ministry of Agriculture, Fisheries and Food.

Hunter, R.D. and R.K. Meentemeyer, 2005: Climatologically aided mapping of daily precipitation and temperature. *J. Appl. Meteor.*, 44:1501-1510.

Hyre, R.A., 1954: Progress in forecasting late blight of potato and tomato. *Plant Disease Reporter*, 38:245–253.

Johnson, D.A., J.R. Alldredge and D.L. Vakoch, 1996: Potato late blight forecasting models for the semiarid environment of south-central Washington. *Phytopathology*, 86:480–484.

Keane, T., 1982: *Weather and Potato Blight*. Agrometeorological Memorandum No. 8. Dublin, Irish Meteorological Service.

Kroes, J.G., 2005: An introduction to the SWAP model. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogataj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Leedman, A., 2007. The Australian National Agricultural Monitoring System: A national climate risk management application. In: *Management of Natural and Environmental Resources for Sustainable Agriculture* (R. Stefanski and P. Pasteris, eds). Proceedings of the USDA/WMO Workshop on Management of Natural and Environmental Resources for Sustainable Agricultural Development, Portland, Oregon 13–16 February 2006. Technical Bulletin No. WAOB-2008, NRCS-2008 and AGM-10 (WMO/TD-No.1428). Washington, DC, USDA; Geneva, WMO.

Madelin, M. and G. Beltrando, 2005: Spatial interpolation-based mapping of the spring frost hazard in the Champagne vineyards. *Meteorol. Appl.*, 12:51–56.

Magnus, H.A., K. Munthe, E. Sundheim and A. Ligaarden, 1991: PC-technology in plant protection warning systems in Norway. *Danish J. Plant Soil Sci.*, 85(S–2161): 1–6.

Marshall, J.K., 1967: The effect of shelter on the productivity of grasslands and field crops. *Field Crop Abs.*, 20:1–14.

McGrath, R. and K. Finkle, 2001: *HIRLAM Foot-and-Mouth Disease Dispersion Model*. Hirlam Progress Report 21. Dublin, Met Éireann.

Mercer, P.C., A. Bell, L.R. Cooke, L. Dowley, B. Dunne, T. Keane, T. Kennedy and R. Leonard, 2001: Crop and animal disease forecasting and control: regional perspectives. In: *Agro-Meteorological Modelling: Principles, Data and Applications* (N.M. Holden, ed.). Dublin, Agmet.

Mikkelsen, T., S. Alexandersen, P. Astrup, H.J. Champion, A.I. Donaldson, F.N. Dunkerley, J. Gloster, J.H. Sørensen and S. Thykier-Nielsen, 2003: Investigation of airborne foot-and-mouth disease virus transmission during low-wind conditions in the early phase of the UK 2001 epidemic. *Atmos. Chem. Phys.*, 3:2101–2110.

Mikkelsen, T., S.E. Larsen and S. Thykier-Nielsen, 1984: Description of the Risø puff diffusion model. *Nucl. Technol.*, 67:56–65.

Motroni A., P. Duce, D. Spano and S. Canu, 2002: Estimation of climatic risk for agriculture in a Mediterranean region. In: *Proceedings of the 15th Conference on Biometeorology and Aerobiology Joint with the 16th International Congress on Biometeorology of the International Society of Biometeorology*, Kansas City, Missouri, 28 October–1 November 2002.

Motha, R. and T. Heddinghaus, 1986. The Joint Agricultural Weather Facility's Operational Assessment Program. *Bull. Amer. Meteor. Soc.*, 67:1114–1122.

Motha, R. and R. Stefanski, 2006: United States Department of Agriculture's weather and climate information system for operational applications in agriculture. *Meteorol. Appl.*, 13(1):31–47.

Mukhala, E., 2005: Food and Agriculture Organization and agricultural drought. In: *Monitoring and Predicting Agricultural Drought: A Global Study* (V.K. Boken, A.P. Cracknell and R.L. Heathcote, eds). New York, Oxford University Press.

Murphy, T.M., D.J. O'Brien and J.S. Gray, 2004: Weather, pests and epidemiology of animal diseases. In: *Climate, Weather and Irish Agriculture*. Second edition. (T. Keane and J.F. Collins, eds). Dublin, Agmet.

Negre, T., 2006: EU/JRC Agrometeorological monitoring and national services: opportunities and challenges. In: *Strengthening Operational Agrometeorological Services at the National Level.*

Proceedings of the Inter-Regional Workshop, Manila, Philippines, 22–26 March 2004. (R. Motha, M.V.K. Sivakumar and M. Bernardi, eds). Technical Bulletin No. WAOB–2006–1 and AGM-9 (WMO/TD-No. 1277). Washington, DC, USDA; Geneva, WMO; Rome, FAO.

Ollrenshaw, B., 1966: The approach to forecasting the incidence of fascioliasis over England and Wales, 1958–1962. *Agric. Meteorol.*, 3:35-53.

Orlandini, S., 1996: Agrometeorological models for crop protection. In: *Proceedings of the International Symposium on Applied Agrometeorology and Agroclimatology*, Volos, Greece, 24–26 April 1996. COST 77, 79, 711. Brussels, European Commission.

Orlandini, S., A.D. Marta, H. Friedland and A. Sušnik, 2005: Description and testing of PLASMO model for the simulation of grapevine downy mildew. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogataj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Pedgley, D., 1982: *Windborne Pests and Diseases: Meteorology of Airborne Organisms*. New York, John Wiley and Sons.

Petr, J., 1991: *Weather and Yield*. Developments in Crop Science 20. Amsterdam, Elsevier.

Pruess, K.P., 1983: Day-degree methods for pest management. *Environ. Entomol.*,12: 613–619.

Puterbaugh, T., R. Stefanski and M. Brusberg, 1997: The Joint Agricultural Weather Facility's operational procedures for processing and analyzing global crop and weather data. In: *Proceedings of the 13th Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Long Beach, California, 2–7 February 1997. Boston, American Meteorological Society.

Rijks, D. and M.W. Baradas, 2000: The clients for agrometeorological information. *Agric. For. Meteorol.*, 103:27–42.

Rosenberg, N.J., B.L. Blad and S.B. Verma, 1983: *Microclimate: The Biological Environment*. Second edition. New York, John Wiley and Sons.

Rossi, F., S. Orlandini, M. Magli and G. Maracchi, 2005: PLASMO Project: an Internet application. In: *Irrigation and Pest and Disease Models: Evaluation in Different Environments and Web-based Applications* (G. Maracchi, L. Kajfez-Bogataj, S. Orlandini, F. Rossi and M. Barazutti, eds). COST Action 718: Meteorological Applications for Agriculture. Brussels, European Commission.

Rowland, J., J. Verdin, A. Adoum and G. Senay, 2005: Drought monitoring techniques for famine early warning systems in Africa. In: *Monitoring and Predicting Agricultural Drought: A Global Study* (V.K. Boken, A.P. Cracknell and R.L. Heathcote, eds). New York, Oxford University Press.

Rusakova, T.I., V.M. Lebedeva, I.G. Gringof and N.M. Shklyaeva, 2006: Modern technology of stage-by-stage forecasting of crop yield and gross collection. *Meteorol. Hydrol.*, 7:101–108.

Ryall, D.B. and R.H. Maryon, 1998: Validation of the UK Met. Office's NAME model against the ETEX dataset. *Atmos. Environ.*, 32:4265–4276.

Sentelhas, P.C., T.J. Gillespie, M.L. Gleason, J.E.B.A. Monteiro and S.T. Helland, 2004: Operational exposure of leaf wetness sensors. *Agric. For. Meteorol.*, 126:59–72.

Smith, C.V., 1964: Animal housing and meteorology. I: Ventilation and associated pattern of air flow; II: The rating of ventilation systems for animal houses; III: A quantitative relationship between environment, comfort and animal productivity. *Agric. Meteorol.*, 1: [page numbers unknown].

Smith, L.P., 1956: Potato blight forecasting by 90 per cent humidity criteria. *Plant Pathology*, 5:83–87.

Smith, L.P. and M.E. Hugh-Jones, 1969: The effects of wind on the spread of foot-and-mouth disease. *Nature*, 223:712–715.

Smith, M., 2000: The application of climate data for planning and management of sustainable rainfed and irrigated crop production. *Agric. For. Meteorol.*, 103:99–108.

Sørensen, J.H., 1998: Sensitivity of the DERMA long-range dispersion model to meteorological input and diffusion parameters. *Atmos. Environ.*, 32:4195–4206.

Ullrich, J. and H. Schrodter, 1966: Das Problem der Vorhersage des Aufretens der Kartoffelkrautfaule (*Phytophthora infestans*) und die Möglichkeit seiner Losung durch eine Negativprognose. *Nachrichtenblatt Dt. Pflanzenschutzdienst* (Braunschweig), 18:33–40.

van Eimern, J., 1968: Problems of shelter planning. In: *Agroclimatological Methods: Proceedings of the Reading Symposium*. Paris, UNESCO.

van Everdingen, E., 1926: Het verband tusschen de weergesteldheid en de aardappelziekte (*P. infestans*). *Tijdschrift Plantenziekten*, 32:129–140.

van Rij, N.C. and E.D. du Preez, 2004: Use of empirical rules in the development and implementation of a potato late blight (*Phytophthora infestans*) incidence map for KwaZulu-Natal. Presented at 42nd Annual Congress of the Southern African Society for Plant Pathology, Underberg, KwaZulu-Natal, 18–21 January 2004. http://www.saspp.org/abstracts2004/SASPP2004.pdf.

Venäläinen, A., T. Salo and C. Fortelius, 2005: The use of numerical weather forecast model predictions as a source of data for irrigation modeling. *Meteorol. Appl.*, 12:307–318.

Volvach, V.V., 1987: *Simulation of the Effects of Agrometeorological Conditions on the Development of Colorado Beetle*. Leningrad, Hydrometeoizdat.

Winstel, K., 1993: Kraut- und Knollenfaule der Kartoffel eine neue Prognosemöglichkeit-sowie Bekampfungsstrategien. *Med. Fac. Landbouww. Univ. Gent*, 58(3b):1477–1483.

World Meteorological Organization, 1955: *The Forecasting from Weather Data of Potato Blight and Other Plant Diseases and Pests* (P.M. Austin Bourke). Technical Note No. 10 (WMO-No. 42), Geneva.

———, 1958: *Measurement of Evaporation Humidity in the Biosphere and Soil Moisture* (N.E. Rider). Technical Note No. 21 (WMO-No. 71), Geneva.

———, 1960: Facial eczema: an account of research into the causes and its relation to weather factors (N.G. Robertson). In: *Meteoropathological Forecasting* (M. Crawford), Geneva.

———, 1961. *Climatic Aspects of the Possible Establishment of the Japanese Beetle in Europe* (P.M. Austin Bourke) Technical Note No. 41 (WMO-No. 110), Geneva.

———, 1963*a*: *The Effect of Weather and Climate upon the Keeping Quality of Fruit* (G.C. Green). Technical Note No. 53 (WMO-No. 137), Geneva.

———, 1963*b*: *The Influence of Weather Conditions on the Occurrence of Apple Scab* (J.J. Post, C.C. Allison, H. Burckhardt and T.F. Preece). Technical Note No. 55 (WMO-No. 140), Geneva.

———, 1963*c*: *Meteorology and the Migration of Desert Locusts* (R.C. Rainey). Technical Note No. 54 (WMO-No. 138), Geneva.

———, 1963*d*: *Protection against Frost Damage* (M.L. Blanc, H. Geslin, I.A. Holzberg and B. Mason). Technical Note No. 51 (WMO-No. 133), Geneva.

———, 1963*e*: *A Study of Agroclimatology in Semi-arid and Arid Zones of the Near East*. (G. Perrin de Brichambaut and C.C. Wallén). Technical Note No. 56 (WMO-No. 141), Geneva.

———, 1964: *Windbreaks and Shelterbelts* (J. van Eimern, R. Karschon, L.A. Razumova and G.W. Robertson). Technical Note No. 59 (WMO-No. 147), Geneva.

———, 1965: *Meteorology and the Desert Locust: Proceedings of the WMO/FAO Seminar on Meteorology and the Desert Locust*, Tehran, 25 November–11 December 1963. Technical Note No. 69 (WMO-No. 171), Geneva.

———, 1967: *An Agroclimatology Survey of a Semi-arid Area in Africa South of the Sahara* (J. Cochemé and P. Franquin). FAO/UNESCO/WMO Interagency Project on Agroclimatology. Technical Note No. 86. (WMO-No. 210), Geneva.

———, 1968*a*: Facial eczema and its relation to meteorological factors (N.G. Robertson). *Agricultural Meteorology: Proceedings of the WMO Seminar*, Melbourne, Australia, 28 November–16 December 1966, Volume 2.

———, 1968*b*: *Practical Soil Moisture Problems in Agriculture* (G. Stanhill, W. Baier, J.J. Doyle, M. Gangopadhyaya, L.A. Razumova and E.J. Winter). Technical Note No. 97 (WMO-No. 235), Geneva.

———, 1969: *Meteorological Factors Affecting the Epidemiology of Wheat Rusts* (W.G. Hogg, C.E. Hounam, A.K. Mallik, J.C. Zadoks) (Report of the Working Group on Meteorological Factors Affecting the Epidemiology of Wheat Rust of the Commission for Agricultural Meteorology). Technical Note No. 99 (WMO-No. 238), Geneva.

———, 1970: *Weather and Animal Diseases*. (L.P. Smith). Technical Note No. 113 (WMO-No. 268), Geneva.

———, 1971: *Protection of Plants against Adverse Weather* (G.W. Hurst and R.P. Rumney). Technical Note No. 118 (WMO-No. 281), Geneva.

———, 1972: *The Application of Micrometeorology to Agricultural Problems* (L.P. Smith, ed.) (Report of the Working Group on Agrometeorological Aspects of Micrometeorology of the Commission for Agricultural Meteorology). Technical Note No. 119 (WMO-No. 298), Geneva.

———, 1973: *A Study of the Agroclimatology of the Highlands of Eastern Africa* (L.H. Brown and J. Cochemé). FAO/UNESCO/WMO Interagency Project on Agroclimatology. Technical Note No. 125 (WMO-No. 339), Geneva.

———, 1974*a*: *Climate Under Glass* (J. Seemann). Technical Note No. 131 (WMO-No. 373), Geneva.

———, 1974*b*: *An Introduction to Agrotopoclimatology*. (L.B. MacHattie and F. Schnelle). Technical Note No. 133 (WMO-No. 378), Geneva.

———, 1975*a*: *Meteorology and the Colorado Potato Beetle* (G.W. Hurst). Technical Note No. 137 (WMO-No. 391), Geneva.

———, 1975*b*: *Mulching Effects on Plant Climate and Yield* (J.W. Davies). Technical Note No. 136 (WMO-No. 388), Geneva.

———, 1978*a*: *Estudio agroclimatológico de la zona andina* (M. Frère, J.Q. Rijks and J. Rea). FAO/UNESCO/WMO Interagency Project on Agroclimatology. Technical Note No. 161 (WMO-No. 506), Geneva.

———, 1978*b*: *Techniques of Frost Prediction and Methods of Frost and Cold Protection* (A. Bagdonas, J.C. Georg and J.F. Gerber). Technical Note No. 157 (WMO-No. 487), Geneva.

———, 1978*c*: *Weather and Parasitic Animal Disease* (T.E. Gibson). Technical Note No. 159 (WMO-No. 497), Geneva.

———, 1980*a*: *The Economic Value of Agrometeorological Information and Advice* (M.H. Omar). Technical Note No. 164 (WMO-No. 526), Geneva.

———, 1980*b*: *Meteorological Factors Affecting the Epidemiology of the Cotton Leaf Worm and the Pink Bollworm* (M.H. Omar). Technical Note No. 167 (WMO-No. 532), Geneva.

———, 1980*c*: *Meteorological Factors and their Influence on the Epidemiology of the Cassava Mites* (Z.M. Nyiira). CAgM Report 5, Geneva.

———, 1980*d*: *Weather, Climate and Animal Performance* (J.R. Starr). Technical Note No. 190 (WMO-No. 684), Geneva.

———, 1982: *A Study of the Agroclimatology of the Humid Tropics of South-East Asia* (L.R. Oldeman and M. Frère). FAO/UNESCO/WMO Interagency Project on Agroclimatology. Technical Note No. 179 (WMO-No. 597), Geneva.

———, 1983: *Weather-Based Mathematical Models for Estimating Development and Ripening of Crops* (G.W. Robertson). Technical Note No. 180 (WMO-No. 620), Geneva.

———, 1988*a*: *Agroclimatology of the Sugar-Cane Crop* (B.C. Biswas). Technical Note No. 193 (WMO-No. 703), Geneva.

———, 1988*b*: *Agrometeorological Aspects of Operational Crop Protection* (Report of the CAgM Working Group on Agrometeorological Aspects of Operational Crop Protection). Technical Note No. 192 (WMO-No. 687), Geneva.

———, 1989: *Animal Health and Production at Extremes of Weather* (Reports of the CAgM Working Groups on Weather and Animal Disease and Weather and Animal Health). Technical Note No. 191 (WMO-No. 685), Geneva.

———, 1990*a*: *Meteorology and Grain Storage* (C.V. Smith and M.C. Cough). Technical Note No. 101 (WMO-No. 243), Geneva.

———, 1990*b*: *Report of the RA VI Working Group on Agricultural Meteorology. Part I: Survey of Operational Models in Use for Agrometeorological Services for Potato Crop Production* (S. Pashairdis). CAgM Report No. 35 (WMO/TD-No. 381), Geneva.

———, 1991: *Meteorology for Locust Control. La météorologie au service de la lutte anti-acridienne.* CAgM Report No. 36 (WMO/TD-No. 404), Geneva.

———, 1992*a*: Meteorology and plant protection: an introduction. In: *Agrometeorologia y proteccion de plantas. Actas del coloquio de Asunción* (D. Rijks and B. Hopper, eds), Geneva.

———, 1992*b*: *La météorologie au service de la lutte anti-acridienne. Contribution d'un service météorologique national* (B. Ambar). CAgM Report No. 53 (WMO/TD-No. 527), Geneva.

———, 1992*c*: *Report of the Joint Rapporteurs on Agricultural Meteorology of the Regional Association for Africa*. Part II. *Report on Locust and Crop Pests.* Partie II. *Rapport sur la lutte contre les acridiens et autres ennemis des cultures* (O. Sadi). CAgM Report No. 39 (WMO/TD-No. 480), Geneva.

———, 1994*a*: *Agrometeorology of the Coffee Crop* (A.P. Paes de Camargo and A.R. Pereira). CAgM Report No. 58 (WMO/TD-No. 615), Geneva.

———, 1994*b*: *Conference on the Economic Benefits of Meteorological and Hydrological Services*. Extended abstracts of papers. (WMO/TD-No. 630), Geneva.

———, 1996: *Agroclimatology of the Apple Crop* (A.S. Porteous). CAgM Report No. 68 (WMO/TD-No. 750), Geneva.

———, 1997*a*: *Definition of Agrometeorological Information Required for Vegetable Crops* (H.P. Das). CAgM Report No. 75 (WMO/TD-No. 866), Geneva.

———, 1997*b*: *The Effect of Temperature on the Citrus Crop* (Z. Gat, Y. Erne and E.E. Goldschmidt). Technical Note No. 198. (WMO-No. 840), Geneva.

———, 1997*c*: Agrometeorological information for locust control (D.E. Pedgley). In: *Extreme Agrometeorological Events*. CAgM Report No. 73 (WMO/TD-No. 836), Geneva.

———, 1997*d*: Methods and techniques for microscale modification to avoid or reduce losses in agricultural production (A. Brunetti). In: *Weather/Climate and Sustainable Agricultural Production and Protection*. CAgM Report No. 74 (WMO/TD-No. 838), Geneva.

———, 2000*a*: The Irrigation Planner: A management instrument for irrigation of grassland in the Netherlands (M. Molendijk). In: *Report of the RA VI Working Group on Agricultural Meteorology*. CAgM Report No. 82 (WMO/TD No.-1022), Geneva.

———, 2000*b*: Operational applications of agrometeorological information to increase the efficiency of water and energy uses (J. Lomas). In: *Report of the RA VI Working Group on Agricultural Meteorology*. CAgM Report No. 82 (WMO/TD-No. 1022), Geneva.

———, 2000*c*: An outlook to the models, forecasting methods and information systems used for plant protection against pests (L. Leskinen). In: *Report of the RA VI Working Group on Agricultural Meteorology*. CAgM Report No. 82 (WMO/TD No. 1022), Geneva.

———, 2000*d*: Survey of models of plant diseases (L. Seghi, S. Orlandini and B. Gozzini). In: *Report of the RA VI Working Group on Agricultural Meteorology.* CAgM Report No. 82 (WMO/TD No.-1022), Geneva.

———, 2002. Review of the scientific literature on the effect of climate and weather, especially during the ripening period, on the quality and storage capacity of grapes, spring barley and potatoes (H. Friesland). In: *Report of RA VI Working Group on Agricultural Meteorology*. (WMO/TD-No. 1113), Geneva.

———, 2003: *Agrometeorological Aspects of Organic Agriculture, Urban Agriculture, Indoor Agriculture and Precision Agriculture* (N.M. Holden and M.C. Ortiz). CAgM Report No. 90 (WMO/TD-No. 1158), Geneva.

———, 2004: *Experts for Collection of Case Studies of Economically Beneficial Agrometeorological Applications and Services and Other Success Stories in Agrometeorology for Policy Matters* (W. Baier). CAgM Report No. 93 (WMO/TD-No. 1202), Geneva.

Wright, P.B., 1969: Effects of wind and precipitation on the spread of foot-and-mouth disease. *Weather*, 24:204–213.

Zhukov, V.A., A.N. Polevoy, A.N. Vitchenko and S.A. Daniyelov, 1989: *Mathematical Methods for the Assessment of Agroclimatic Resources*. Leningrad, Hydrometeoizdat.

Zoidze, E.K. and L.I. Ovcharenko, 2000: *Comparative Assessment of the Agricultural Potential of Russian Climate and the Degree of Utilization of its Agroclimatic Resources by Crops*. St Petersburg, Hydrometeoizdat.