PRACTICAL USE OF AGROMETEOROLOGICAL DATA AND INFORMATION FOR PLANNING AND OPERATIONAL ACTIVITIES IN AGRICULTURE

Prepared by

Dr. J.F. Villalpando (Chairman), Dr. B.C. Biswas, Mr. R. Cáreres Mariscal, Mr. A. Coulibaly, Mrs. Z. Gat, Dr. R. Gommes, Mme. C. Jacquart, Mr. B.S. Lomoton, Dr. K.B. Perry, Dr. E.S. Ulanova and Mr. A. Ussher

(Members of the CAgM IX working group)

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SUMMARY

The practical use of agrometeorological data and information for agricultural planning and management is summarized in this manual in five chapters.

Chapter 1 is concerned with agrometeorological data and information. Emphasis on the type of data that would be collected at agrometeorological stations, as well as the accuracy these data should have in order to prepare quality agrometeorological information for users, are detailed.

Chapter 2 on practical use of agrometeorological data and information for agricultural planning includes practical methods for the assessment of agroclimatic resources for land use and management, comprehensive information on agroclimatic requirements of crop varieties, and some case studies to illustrate available techniques to select crop varieties for different climatic regions.

Chapter 3 on agrometeorological information for crop management and production deals with the analysis of these affect crop management and production practices such as tillage, irrigation scheduling, application of fertilizers and others. In this chapter is also included the agrometeorological information required to develop crop-weather relationships which are useful tools for forecasting phenological phases and yields of crops as well as forecasting of pests and diseases that eventually damage the crop.

In the fourth chapter on the preparation and dissemination of agrometeorological information to users, several approaches currently in use are discussed. A description of conventional methods and new technologies is also presented.

The last chapter on training and education to users, covers the practical applications of agrometeorological information. Some guidelines are given about organization of training, events in agrometeorological application and the ways by which education in agrometeorology can be provided to users and to the general public.

Finally, some conclusions and recommendations are presented.
PREFACE

The Commission for Agricultural Meteorology (CAgM) decided at its 9th session (Madrid, 1986) to establish a Working Group on the Practical Use of Agrometeorological Data and Information for Planning and Operational Activities in all Aspects of Agriculture, including Farming Systems, with the following terms of reference:

(a) To survey and summarize the practical use of Agrometeorological data and information for planning (e.g. land use, selection of varieties of plants and breeds of animals), and for operational activities (e.g. land management, crop protection, irrigation requirements) in agriculture and for the understanding and further development of less well-described farming systems;

(b) To include in such a summary details on accuracy and frequency of information, and on dissemination requirements;

(c) To prepare information on (a) and (b) in a form suitable for publication as a reference handbook and as very simple guidance material in all working languages of the Organization;

(d) To submit annually information on progress of activities and a final report to the president of CAgM not later than six months before the next session of CAgM;

The Commission invited the following members to serve on the working groups:

Dr. C. Biswas (India), Dr. A. Coulibaly (Cote D'Ivoire), Mrs. Z. Gat (Israel), (late) Mr. B. S. Lomoton (The Philippines), Dr. K. Perry (USA) Mr. R. Cáceres Mariscal (Peru), Dr. E.S. Ulanova (former USSR), Dr. R. Gommes (FAO) and Dr. J.F. Villalpando (México), Mme. C. Jacquet (France) and Mr. Ussher (Ghana) were invited to serve as members working by correspondence. Dr. Villalpando was designated as Chairman.

A meeting of the working group was held in Geneva from 26-30 September 1988. The format of the final report and broad contents of the different chapters were discussed and approved. The responsibilities for writing the different sections were assigned.

The Chairman, edited the contributions from the different members of the group and submitted a final report.

The tenth session of CAgM which reviewed the report recommended that the report be published in the form of a manual, in order that it could be updated periodically. The group agreed that the report be published as a CAgM Report in the first instance.

J.F. Villalpando
Chapter 1

Agrometeorological Observations Required for Planning and Operational Applications

1.1 Agrometeorological station networks

1.1.1 Introduction

Quality agrometeorological data collected in an appropriate network design are essential for meaningful planning and operational applications. Many of the observations that are deemed agrometeorological are the standard parameters of synoptic and climatological stations. Thus, in developing an agrometeorological network one must consider the agrometeorological stations as being complemented by the existing synoptic and climatic stations. However, one must also ensure that the necessary density of stations exists in the agricultural areas for which planning and operational applications are to be made. For agricultural planning, data should be collected from regions where no agricultural operations are currently underway. Such data could be used in feasibility studies for opening new production sites.

WMO Technical Regulations (WMO No.544, Vol.I, Annex V to the WMO Technical Regulations, Part III - Surface Based Systems), provide four category of Agricultural Meteorological Stations. These are also given in Section 2.2.1 of the WMO Guide to Agricultural Meteorological Practices (WMO-No 134). The four categories are principal, ordinary, auxiliary and for specific purposes. For planning and operational applications networks should be made of ordinary and auxiliary stations. An ordinary station provides, on a routine basis, simultaneous meteorological and biological information and may be equipped to assist in specific research problems. An auxiliary station provides meteorological and biological information. The meteorological information may include such items as soil temperature, soil moisture, potential evapotranspiration, duration of vegetative wetting, and detailed measurements in the very lowest layer of the atmosphere. The biological information may cover phenology, onset and spread of plant diseases and emergence or varying developmental stages of insect pests.

Guidance for exposure conditions and instrument requirement of these stations are given in the WMO Guide to Meteorological Instrument and Observing Practices (WMO-No.8). Site selection and layout of station instruments are described in Sections 2.2.2 and 2.2.3 of the WMO Guide to Agricultural Meteorological Practices (WMO-No.134).

1.1.2 Types of Routine Agrometeorological Observations

Agrometeorological observations include documentation of the physical and the biological environment. These two types of observations taken together spatially and temporally are
essential for planning and operational applications.

1.1.2.1 Meteorological Observations

As stated in the WMO Guide to Agricultural Meteorological Practices (WMO-No.134), an agrometeorological station should include observations of some or all of the following parameters characterizing the physical environment:

1. Temperature
   (a) air
   (b) soil
2. Moisture content of the air
   (a) dewpoint
   (b) wet bulb temperature
   (c) relative humidity
3. Moisture content of the soil
4. Radiation
   (a) total solar radiation
   (b) photosynthetically active radiation
5. Precipitation
   (a) form (e.g. rain, snow, hail, sleet, etc.)
     (i) amount
     (ii) duration
6. Wind
   (a) speed
   (b) direction
7. Evaporation
8. Dew
   (a) amount
   (b) duration

These parameters should be measured at standard heights, depths and at standard time intervals as a basic requirement with additional times and locations added according to planned usage of the data and, of course, economic constraints. Detailed guidance about instrument and observing practices to be used are well documented in the WMO Guide to Climatological Practices (WMO-No.100), the WMO Guide to Meteorological Instruments and Observing Practices (WMO-No.8) and the WMO Guide to Agricultural Meteorological Practices (WMO-No.134). The same directions should be followed for agrometeorological applications as for synoptic or climatological needs. Specific data requirements for various applications are described in the section on Information on agrometeorological data (section 2.2). Accuracy requirements is also included.
1.1.2.2 Biological and Phenological Observations

To apply what is known about the relationship between plant and animal crop performance and their environment and to allow further knowledge of the relationship to be obtained, it is essential that biological and phenological observations be made along with the meteorological ones. It must be kept in mind that these observations are made on living systems which may have inherent individual variations. It is therefore very important to remember the limitations of these data in the context of planning or operational applications.

Biological observations have been divided into the following six broad categories (See WMO-No.134, section 2.3.2):

(i) Observations of natural phenomena (wild plants, animals, birds and insects) taken over a large area.

(ii) Observations of cultivated plants and animals. These should include observations on dates of events in animal and plant development, e.g. calving for animals; emergence, flowering, silking, tasseling, etc. for plants; and cultural operations, e.g. dates of cultivation, planting, transplanting, irrigation (amount), and harvest.

(iii) Observations of damage to cultivated systems by meteorological events (frost, hail, flood, high wind, drought) and occurrence of pests and diseases and the severity of damage caused by them.

(iv) Observations of great detail and accuracy taken during an experiment to address a specific objective.

(v) Observations of a less complex nature than in (4) above taken over a much greater geographical area and at a large number of sites, which are required for operational use shortly after they are taken.

(vi) Global biological observations for assessing the aerial extent of definite biological events.

A detailed discussion of these categories is included in sections 2.3.1 through 2.3.6 of the WMO Guide to Agrometeorological Practices.

1.1.2.3 Special Agrometeorological Observations and Surveys

Additional information may be necessary to determine local mesoscale or even microscale meteorological elements affecting existing or potential agricultural production. It may also be beneficial to document the causes of these local variations, such as surface relief and bodies of water. To gather such information, temporary stations, usually working for one to five years, mobile stations or use of special instruments may be employed. These may then be statistically linked to the permanent network stations.
1.2 Agrometeorological Information Needed for Planning and Operational Activities

1.2.1 Introduction

The agrometeorological data and their accuracy depend on the kind of study to be performed. Several types of studies with different objectives may be developed, and the data to be collected and their accuracy must be specified according to those objectives.

Thus, the data to monitor and their accuracy requirements may differ for a pest management study in comparison with an investigation related to, for example, selection of varieties of plants.

Another important aspect to be taken into account is the frequency of data required. For planning purposes monthly or 10-day data may perhaps be sufficient, while for operational applications daily or even hourly data are needed.

1.2.2 Land Use and Management

Climate imposes many restrictions on land use. Examples are the arid zones where deserts prevail and the sub-polar and polar regions where snow, ice and low temperatures impose severe limitations on land use (Landsberg, 1976; cited by WMO, 1986). This is why before giving recommendations about land use, it is necessary to know the environmental availabilities.

In quantifying these availabilities for land use and management purposes, certain agroecological information is required. Parameters and accuracies required are given as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water storage capacity of the soils</td>
<td>± 1 cm</td>
</tr>
<tr>
<td>Susceptibility of lands to soil erosion</td>
<td>High/low/medium</td>
</tr>
<tr>
<td>Rainfall</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Solar radiation (Insolation)</td>
<td>10 % (± 0.1 h)</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.5 - 1°C</td>
</tr>
<tr>
<td>Climatological risks (frosts, hail, etc.)</td>
<td></td>
</tr>
</tbody>
</table>

Monthly or 10 day-period data are sufficient for the above purposes.

1.2.3 Selection of Varieties of Plants

In order to select plant species or varieties, a prior agroclimatic characterization is required. This characterization generally include crop phenology, agroecological requirements and yield responses to several environments.
The characterization of crop phenology commonly require daily and hourly temperature data, which are used to obtain derived parameters (thermal parameters) such as heat units or chill units (Neild and Greig, 1972; Anderson and Richardson, 1987).

Agroecological requirements are determined using daily or weekly data of temperature, rainfall, solar radiation, evaporation, wind speed, relative humidity and photoperiod.

To quantify the yield responses of crops to environmental conditions, precipitation, solar radiation and evapotranspiration are the most relevant variables. Several models based on these data besides phenological and physiological information have been proposed to predict information growth and development of crops such as SORGF (Maas and Arkin, 1978), and CORNF (Stapper and Arkin, 1980).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature:</td>
<td>0.5 - 1 °C</td>
</tr>
<tr>
<td>Rainfall:</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Insolation:</td>
<td>10 % (± 0.1 h)</td>
</tr>
<tr>
<td>Evaporation:</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Photoperiod:</td>
<td>10 % (± 0.1 h)</td>
</tr>
<tr>
<td>Wind speed:</td>
<td>± 0.5 m/s</td>
</tr>
</tbody>
</table>

1.2.4 Selection of Breeds of Animals

To assess the suitability of an environment to animal production, two elements of climate emerge as very important: temperature and relative humidity (Hahn and McQuigg, 1970; Johnson, 1980). However, it is necessary to recognize that the physiology and performance of livestock is really influenced in a wider manner by the climate. The influences of radiation, wind, photo-period, and precipitation are also important (Johnson, 1982; WMO, 1986; both cited by Starr, 1988).

All of these climatological variables can determine the efficiency of livestock production by influences that are both direct and indirect, affecting health, reproductive efficiency, productive conversion of feed and indeed, the very survival of the animal-particularly at critical stages of the life cycle (Starr, 1988).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature:</td>
<td>0.5 - 1 °C</td>
</tr>
<tr>
<td>Rainfall:</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Relative humidity:</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Insolation:</td>
<td>10 % (± 0.1 h)</td>
</tr>
</tbody>
</table>

The standard recommendations on accuracy prescribed for other parameters are sufficient for application to animal production and protection.
1.2.5 Crop Management and Production

1.2.5.1 Irrigation

Irrigation requirements of crops can be estimated using different approaches. A simple approach is that which makes use of meteorological data. To estimate water requirements of crops usually daily meteorological data are used. Weather elements commonly used include: solar radiation (insolation), relative humidity (wet bulb and dry bulb temperatures), wind speed, maximum and minimum temperature, and evaporation (class A open pan). The accuracy required for these meteorological elements is as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.5 - 1.0°C</td>
</tr>
<tr>
<td>Solar radiation (insolation)</td>
<td>10 % (± 1 h)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Evaporation</td>
<td>± 1 mm</td>
</tr>
<tr>
<td>Wind speed</td>
<td>± 0.5 m/s</td>
</tr>
<tr>
<td>Wet and dry bulbs</td>
<td>&lt; 0.5°C</td>
</tr>
</tbody>
</table>

1.2.5.2 Pests and Diseases

In crop protection service meteorological data is mainly used for predicting timing and spread of insects and disease attacks, for taking preventive against damages. WMO Technical Note No. 192 gives a detailed description of meteorological data requirements for crop protection activities including space/time resolution requirements. Minimum weather data set required for pest management and plant diseases are temperature and humidity or its derived parameters such as heat units or accumulated degree-days (A.D.D.). The following paragraphs briefly review recent literature on this subject.

**Temperature**

\[
\text{A.D.D.} = \frac{\sum (\text{Tmax} + \text{Tmin})}{2} - \text{Tbase}
\]

Tbase is the threshold temperature below which no further development of the pest is expected.

Values of DD are accumulated day after day and the arrival of the pest at various stages of its life cycle is signalled by specific DD totals. Depending on the habitat of the insect, the best model results may be obtained with soil, air, leaf litter, or plant temperatures. Except for air temperatures, these usually are measured 'on-site' since the conditions at a meteorological station are very different from those at the insect's location. Due to the great difficulty of measurement,
plant temperatures are not used directly in any known operational pest management scheme, except as a computed intermediate step in estimating surface wetness duration.

Temperature also controls the growth rate of many plant disease organisms, but nearly always in combination with moisture. For plant diseases, the use of temperature may vary from specifying a threshold such as 10°C for potato blight or a range 15-25°C for mildew hours.

**Moisture**

Moisture (includes relative humidity (RH), rainfall and surface wetness duration), is an essential element of most plant disease prediction schemes and also for farming outbreaks of some insect pests.

Dry and wet bulb psychrometers and thermohygrographs are widely used for measurement of RH values required. Certain disease organisms respond directly to RH (Downy mildews on grapes and onions) as well as certain insects.

In disease forecasting many times presence of liquid water is more important than high relative humidities. RH higher than 85-95% is taken as a good approximation of the duration of liquid wetness of the plant.

In rainfall the amount is less important for plant diseases development than the timing, duration and rate of rainfall.

Surface wetness duration caused by rain dew or fog is very important in plant diseases. (This can be measured directly or estimating using micrometeorological models based on standard radiation, wind, humidity and temperature). Wind speed and direction are important in pest management schemes. Near surface winds control dispersal of insects and disease spores for short distances. Wind also disperse pesticide sprays to neighboring areas. Wind speed affects indirectly progress of disease. For longer range transport of insects or spores wind profiles of speed and direction are required up to 3 Km. level.

**Accuracies required**

For temperature 0.5 - 1°C accuracy is reasonable. Wet-bulb depression should be measured with an accuracy of less than 0.5°C in order to keep relative humidity errors less than 10%. For relative humidity higher than 85%, accuracy of ± 1% is important in prediction. For rainfall, accuracy of 0.2 mm up to 10 mm and ± 2% for greater amounts are required. Surface wetness duration measurements with accuracy ± 10% are adequate for useful prediction.

Accuracy required for bright sunshine and solar radiation is 10% or ± 1 h.

Conventional wind measuring systems provide sufficient accuracy for some of the wind data. For spray drift and dew duration estimates, however wind information at velocities that are below
the starting speeds of the anemometers may be required.

1.2.6 **Crop-weather relationships**

1.2.6.1 **Minimum data set and accuracy**

It is a really difficult task to define minimum data requirement because it depends on the objectives on the programme to be carried out and the accuracy required of parameters used in the programme or evaluating a model. Data collected must be minimum required for simple analysis of environment interaction and comparative crop performance. The data set should be sufficient for calculation of simple biophysical indices, for verifying the simplest crop model and for testing of empirical yield prediction models. The data required vary from model to model and place to place. Broadly speaking different types of data are required. They include:

**Weather data** - global solar radiation, maximum and minimum temperature, precipitation, evaporation, wind speed and grass minimum temperature are required for most of the agrometeorological activities.

**Soil data** - initial and final (post-harvest) soil water status in the profile must be determined. For this field capacity, wilting point and bulk density need to be known.

**Crop data** - Main phenological stages of crops, as date of seeding, anthesis, harvest, etc. should be recorded for analyzing environmental effects at different phenological phases of the crop and total biomass product.

**Management data** - For evaluating the result of an experiment, records of all treatments, their timing and level of input (fertilizer, irrigation, insecticide, etc.) are needed. Records of land use history of the plot can be of diagnostic value.

1.2.6.2 **Period of analysis**

Time unit for analyzing climatic data should be chosen in such a way that effect of distribution can be counted properly. Secondly, it should not involve undue computational steps and time. Usually, a month is taken as a unit of time. But a month is too long a period compared to the entire modern cereal crop life. Due to introduction of hybrid crop, duration of crop life span is of the order of 100 days. Under this condition, the use of one month period, especially in accounting the effect of rainfall, suffers from many defects. There are areas where, even during the rainy season, rainfall varies immensely in amount. The rainfall normally received in a month occur at times only in a few days of the month while the rest of the month goes dry. If this happens during the early part of the life of a crop, it may cause irreparable damage to it.

In the tropics where the rainfall is showery type and highly variable in intensity and distribution (both in time and space), it is necessary to use a shorter period. On the other hand, use of daily rainfall for agrometeorological research as well as for operation is very difficult
because (i) crop growth in a day is very small and (ii) evaluation of weather impact on crop is impossible. Hence, a shorter period like a week or ten days may be used as time unit for analyzing agrometeorological data. This also helps disseminate operational advisories.
Chapter 2

Practical Use of Agrometeorological Data and Information for Agricultural Planning

2.1 Land Use and Land Management

2.1.1 Introduction

Climate and weather variability play a vital role in agricultural planning and production. The success or failure of a new or modified agricultural undertaking for any region depends largely on the effect of climatic conditions. Therefore, the assessment of agroclimatic resources is an indispensable component in order to make a proper use and management of land. The use of agrometeorological data and information in agriculture allows planning and management of crops in suitable regions where the use and management of land must not result in its degradation through different physical and chemical processes.

2.1.2 Assessment of agroclimatic resources for land use and management

The assessment of agroclimatic resources for land use and management varies according to the agro-ecological conditions of the region itself and to the information requirements of the users. However, in most regions the agroclimatic indices to be determined include those derived from solar radiation, rainfall, moisture, temperature and others.

2.1.2.1 Solar radiation

Solar radiation is practically the source of energy for all physical and biological processes. It can be said that agriculture is an exploitation of solar energy which is possible with the adequate supply of water and nutrients. Therefore, knowledge of the regime and distribution of solar energy during the crop growing season or any other time during the year, is of paramount importance for agricultural planning.

Solar radiation can be evaluated as global radiation which includes direct and diffuse radiation, and net radiation, depending on the available data. Often radiation data are not available and then it has to be estimated using sunshine records.

To estimate global radiation for a given location using sunshine records, the following equation has been proposed:

\[ R_g = ((a + b) n/N) R_a \]

Where:
\[ g = \text{global solar radiation expressed in cal/cm}^2/\text{day or MJ/m}^2 \]
\[ n/N = \text{is the percentage of possible sunshine} \]
\[ Ra = \text{theoretical solar radiation received at the top of the atmosphere} \]
\[ \text{(Angot's values which vary according to latitude)} \]
\[ a, b = \text{regression coefficients} \]

Frere and Popov (1979), based on many sunshine and global solar radiation data from different zones of the world, suggested the following coefficients:

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>Zone type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.55</td>
<td>Cold and temperate zones</td>
</tr>
<tr>
<td>0.25</td>
<td>0.45</td>
<td>Tropical dry zones</td>
</tr>
<tr>
<td>0.29</td>
<td>0.42</td>
<td>Tropical humid zones</td>
</tr>
</tbody>
</table>

Global solar radiation estimates can also be obtained using satellite-derived data. Galindo, et al. (1991) using GOES satellite data obtained mean monthly solar radiation estimates for 31 different sites in Mexico with a standard error of the estimates with respect to ground-truth data of 3 to 5%.

Solar radiation and sunshine information can be used in land use and land management in different ways, among other applications the following are given:

- Determination of planting dates for annual crops in irrigated areas, in such a way that the crop growing cycle matches with the optimal solar radiation requirements of crops. Figure 1 shows the optimal period for growing corn in Aguas Calientes, Mexico, according to the distribution of global solar radiation during the year;

- Under optimal conditions of water, nutrients and management, it is feasible through solar radiation data to calculate the total dry matter and eventually the potential yield of a crop. Furthermore, solar radiation regime and distribution may allow crop zonation based on seasonal requirements of solar radiation of crops;

- Planning of more adequate periods during the year for forage, grains and legumes drying, according to solar radiation and sunshine availability;

- Global or net solar radiation is a required component to estimate potential evapotranspiration and eventually the water requirements of crops using empirical formulae;

- Solar radiation is a component to estimate the energy balance and its relationship to the environment both for plants and animals.
2.1.2.2 Rainfall

Agricultural production in rainfed areas depends mostly on the amount and distribution of rainfall. In these areas, the development of agricultural technology aimed at increasing and stabilizing crop production, requires knowledge about variability of rainfall both in space and time in order to meet agricultural technology needs. Under these
conditions, evaluation of rainfall in terms of probability estimates instead of arithmetic means is mandatory, since in most cases rainfall becomes the key climatological element to determine land suitability for agriculture.

The forms in which rainfall data can be evaluated for agricultural planning purposes include the following: onset, termination and duration of the rainy season; rainfall probabilities for specific phenological periods (planting time, flowering, harvesting, etc.), or for the whole cropping season: number of days with significant rainfall amount for agricultural purposes: maximum rainfall in 24 hours, etc. These rainfall-derived parameters and others can be calculated using the INSTAT program (INSTAT, 1986), which can be run in IBM-compatible microcomputers. Rainfall probabilities can be usually estimated using the gamma distribution since it fits better than other mathematical distributions to observed rainfall data.

The gamma distribution is described by the following equation:

\[ f(X) = \frac{1}{\alpha \beta \Gamma(\alpha)} X^{\alpha-1} e^{X/\beta} \]

where:

- \( X \) = represents the rainfall variable
- \( \beta \) = a parameter that gives the scale of \( X \)
- \( \alpha \) = a parameter that gives the curve's shape
- \( \Gamma(\alpha) \) = the gamma function of \( \alpha \)
- \( e \) = 2.7183

Both \( \alpha \) and \( \beta \) parameters are positive and greater than 0.

To calculate rainfall probabilities using this distribution it is required to estimate the parameters \( \alpha \) and \( \beta \). Using the maximum likelihood as suggested by Thom (1966), the computation is as follows:

\[ \alpha = \frac{4y}{1 + (1 + 4y/3)^{1/2}} \]

\[ y = \ln X - (\Sigma \ln X/n) \]

\[ \beta = X/\alpha \]

For rainfall series where several years show no precipitation, to estimate rainfall probabilities, the following equation is suggested to be used:

\[ PT = 1 - (1 - p)^g \]
Where:

\[
\begin{align*}
\text{PT} &= \text{total probability} \\
p &= m/n \\
m &= \text{number of years with rainfall} \\
n &= \text{total number of years of rainfall data} \\
g &= \text{probability value obtained using the gamma distribution for the years with rainfall}
\end{align*}
\]

A detailed description on the procedure to estimate rainfall probabilities using the gamma distribution is given in Villalpando (1991), where step by step several examples as well as its interpretation are presented.

In tropical and subtropical regions the assessment of the onset and termination of the rainy season using rainfall probabilities, are important parameters for planning the planting dates of crops. Table 1 shows the number of years out of ten that a rainfed crop could be planted according to the onset of the rainy season (precipitation $\geq 30$ mm in a decade) for the climatological station of Cuquio, Mexico.

Table 1. Number of years out of ten that a rainfed crop could be planted in different decades according to the onset of the rainy season (precip. $\geq 30$ mm in a decade) for the area of Cuquio, Mexico

<table>
<thead>
<tr>
<th>Decade</th>
<th>Average rainfall (mm)</th>
<th>Precip $\geq 30$ mm (prob. %)</th>
<th>Number of years out of ten Precip. $\geq 30$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10 May</td>
<td>1.6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>11-20 May</td>
<td>8.4</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>21-31 May</td>
<td>20.1</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>1-10 June</td>
<td>24.1</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>11-20 June</td>
<td>49.7</td>
<td>61</td>
<td>6</td>
</tr>
<tr>
<td>21-30 June</td>
<td>74.9</td>
<td>78</td>
<td>8</td>
</tr>
<tr>
<td>1-10 July</td>
<td>78.3</td>
<td>94</td>
<td>9</td>
</tr>
</tbody>
</table>

Through rainfall probabilities calculated for specific crop growing stages or for the whole cropping season, several agricultural practices can be determined and optimized, such as: planting dates; the best time for harvesting; adequate dates for forage cutting and drying; determination of the amount of fertilizer to be applied to a crop; design of soil management practices to increase the harvest of rain in dryland agriculture; identification of crop growing stages where rainfall amounts are not enough to meet the water requirement of crops, etc.

Selection of crops and varieties based on the duration of the rainy season for selected rainfall probability levels, i.e. 60%, 70% or 80% is another practical use of rainfall in tropical and subtropical regions.
2.1.2.3 Moisture

In assessing moisture availability of crops, moisture indices which take into account the soil water-holding capacity are more precise parameters for land evaluation than rainfall indices, especially in regions where soil depth is highly variable and consequently soil moisture retention.

Moisture indices can be determined using rainfall and potential evapotranspiration, the resulting quotient becomes the moisture index. This type of indices are often called climatological moisture indices. To calculate them, the following equation can be used:

\[ \text{CMI} = \sum_{i=1}^{n} \frac{R_i}{PET_i} \times 100 \]

where:

- \( \text{CMI} \) = climatological moisture index
- \( R \) = rainfall
- \( PET \) = potential evapotranspiration
- \( i \) = period of time under calculation (1 day, 10 days, one month, etc.)
- \( n \) = number of periods, \( i = 1, 2, 3, \ldots, n \)

To calculate moisture indices where the soil water-holding capacity is considered, the following expression can be used:

\[ \text{AMI} = \sum_{i=1}^{n} \frac{AET_i}{PET_i} \times 100 \]

where:

- \( \text{AMI} \) = agroclimatic moisture indice
- \( AET \) = actual evapotranspiration
- \( PET, i \) and \( n \) are as defined before

Table 2 illustrates the water balance components and the method used to compute the seasonal moisture index for a soil with 60 mm of water-holding capacity in a dry year (1982) at the meteorological station of Ojuelos, Mexico.
Table 2. Calculation of the water balance and the moisture index during the seasonal period of June to October for the year of 1982 (a dry year) for the meteorological station of Ojuelos, Mexico.

\[
\text{Soil water-holding capacity} = 60 \text{ mm}
\]

<table>
<thead>
<tr>
<th>Month</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>Total (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decade</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
</tr>
<tr>
<td>Precip</td>
<td>0 0 0</td>
<td>36 94 13</td>
<td>0 0 0</td>
<td>0 31 7</td>
<td>3 0 0</td>
<td>184</td>
</tr>
<tr>
<td>PET</td>
<td>53 50 54</td>
<td>45 39 58</td>
<td>49 55 56</td>
<td>47 45 48</td>
<td>45 43 41</td>
<td>728</td>
</tr>
<tr>
<td>Moisture</td>
<td>0 0 0</td>
<td>0 55 10</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>65</td>
</tr>
<tr>
<td>AET</td>
<td>0 0 0</td>
<td>36 39 58</td>
<td>10 0 0</td>
<td>0 31 7</td>
<td>3 0 0</td>
<td>184</td>
</tr>
<tr>
<td>Deficit</td>
<td>53 50 54</td>
<td>9 0 0</td>
<td>39 55 56</td>
<td>47 41 42</td>
<td>43 41</td>
<td>544</td>
</tr>
<tr>
<td>Surplus</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>AMI</td>
<td>0 0 0</td>
<td>.80 1 1</td>
<td>.20 0 0</td>
<td>.0 0 0</td>
<td>.69 .15 .07</td>
<td>3.91</td>
</tr>
</tbody>
</table>

Using historic rainfall records for 10-day periods, moisture indices can be calculated for soils of different moisture capacities. Figure 2 shows the cumulative frequency distribution of moisture indices calculated for 26 years of rainfall records. Moisture indices presented in terms of probability of occurrence are useful tools to assess: (1) land suitability considering the risk factor, (2) the number of years out of ten that crops will require additional irrigation, (3) the number of years out of ten where there will be a moisture surplus, etc.

Another type of index for assessing moisture and drought is the hydrothermal coefficient developed by Selyaninov (1958) and used in the Russian Federation. This index is described as follows:

\[
\text{HTC} = \sum \frac{OC}{0.1} \sum t
\]

there HTC is the hydrothermal coefficient; \( \sum OC \) is the sum of precipitation in mm during the month (or longer period); \( \sum t \) is the sum of temperatures in degrees during the month (or longer period).

The HTC values for assessing moisture and drought are as follows:

- 0.3 and less: Very severe drought
- 0.31 - 0.6: Severe drought
- 0.61 - 0.8: Moderate drought
- 0.81 - 1.0: Slight drought
- 1.01 - 1.5: Optimal moisture
- 1.51 and more: Excess moisture
Moisture Index
Meteorological Station at Ojuelos, Mexico

Fig. 2. Cumulative distribution of moisture index for the period 1964-89, meteorological station at Ojuelos, Mex.

Following and analysis of a large quantity of observations, Ulanova (1975) established quantitative indices for assessing precipitation and reserves of available moisture in the top metre of soil during the main spring-summer vegetation for winter in chernozem soils (Table 3).
Table 3. Indices for assessing reserves of available moisture in the top metre of soil during the main spring-summer vegetation period for winter wheat.

<table>
<thead>
<tr>
<th>Period</th>
<th>Reserves of available moisture (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Renewal of vegetation</td>
<td>151-200</td>
</tr>
<tr>
<td>Stem growth</td>
<td>141-180</td>
</tr>
<tr>
<td>Ear formation</td>
<td>81-140</td>
</tr>
<tr>
<td>Ripening of grain</td>
<td>81-100</td>
</tr>
</tbody>
</table>

In years with low spring moisture reserves (less than 100 mm in the top metre of soil), the winter wheat yield becomes dependent on precipitation in April, May and June. The optimal sum of precipitation in each of these months is 40-80 mm. Monthly precipitation sums of 20-40 mm and 80-100 mm can be considered satisfactory but less than 20 mm is insufficient and more than 100 mm is excessive.

2.1.2.4 Temperature

Temperature is directly related to adaptation, development and efficient production of crops. Traditionally this weather element has been utilized using monthly or annual mean values of the average, maximum or minimum air temperatures. However, these parameters are not enough when assessing temperature resources for agriculture. Therefore, temperature indices that can be related to crop adaptation, crop phenology, or the possible harmful effect caused by extreme temperatures to crops should be determined.

In assessing temperature resources for land use and land management, in addition to the traditional temperature parameters, the following parameters and thermal indices should be evaluated: day and night temperature; growing degree-days computed using different base temperatures, i.e. 5°C, 10°C and 15°C; chill hours and chill units during the winter; number of days with temperature above or below certain limits; and mean soil temperature for 5, 10 and 30 cm depth.

Day and night mean temperature can be estimated using the following equation:

\[
\text{Temperature (day)} = \text{mean temperature} + \frac{(T_{\text{max}} - T_{\text{min}})(11 + T_0)}{11 - T_0 + 4\pi (12 - T_0) \sin \pi \cdot \frac{11 + T_0}{11 - T_0}}
\]
Temperature (night) = mean temperature - \( \frac{(T_{\text{max}} - T_{\text{min}})}{11 + To} \)

\[ \frac{11 - To}{4\pi (12 - To) \sin \pi} \]

where:

\[
\begin{align*}
To &= 12 - 0.5 \, N \\
N &= \text{daylength} \\
\sin &= \text{sine in radians} \\
\pi &= 3.1416
\end{align*}
\]

The growing degree-days (GDD) are usually estimated using the maximum and minimum daily temperatures:

\[
GDD = \sum_{i=1}^{n} \frac{T_{\text{max}} + T_{\text{min}} - Tb}{2}
\]

where:

\[
\begin{align*}
Tb &= \text{base temperature} \\
i &= 1, 2, 3, \ldots, n \, \text{days, decades, etc.}
\end{align*}
\]

Base temperatures to calculate GDD for various crops are given in Table 4.

Table 4. Base temperature for growing and development of selected crops

<table>
<thead>
<tr>
<th>Species</th>
<th>Base temperature °C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>5</td>
<td>Nutttonson (1955)</td>
</tr>
<tr>
<td>Rice</td>
<td>10</td>
<td>Stansel and Fries (1980)</td>
</tr>
<tr>
<td>Corn</td>
<td>10</td>
<td>Shaw (1975)</td>
</tr>
<tr>
<td>Barley</td>
<td>5</td>
<td>Nutttonson, quoted by Iwata (1975)</td>
</tr>
<tr>
<td>Sorghum</td>
<td>15</td>
<td>Peacock and Heinrich (1984)</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>18</td>
<td>Bacchi and others, quoted by Biswas (1986)</td>
</tr>
<tr>
<td>Bean</td>
<td>10</td>
<td>Gould, cited by Iwata (1975)</td>
</tr>
<tr>
<td>Soybean</td>
<td>10</td>
<td>Da Mota (1978)</td>
</tr>
<tr>
<td>Sunflower</td>
<td>7</td>
<td>Robinson (1978)</td>
</tr>
<tr>
<td>Peanut</td>
<td>10</td>
<td>Ong (1986)</td>
</tr>
<tr>
<td>Potato</td>
<td>7</td>
<td>Polevoy (1986)</td>
</tr>
<tr>
<td>Tomato</td>
<td>15</td>
<td>Holmes and Robertson, quoted by Iwata (1975)</td>
</tr>
<tr>
<td>Grape</td>
<td>10</td>
<td>Turmanidze (1986)</td>
</tr>
<tr>
<td>Deciduous fruit trees</td>
<td>4.5</td>
<td>Lombard &amp; Richardson (1979)</td>
</tr>
</tbody>
</table>
Chill hours and chill units are temperature-derived indices necessary for planning and management of deciduous fruit trees. A chill hour is defined as an hour where the temperature is equal or below 7.1°C in the case of deciduous fruit trees. To estimate accumulated chill hours during winter time, daily or weekly thermograph records are used. Where these data are not available, empirical formulae have been used (Weinberger, 1956; Da Mota, 1979), especially to evaluate chill hours on a regional basis.

The chill unit concept was proposed to characterize the chill requirements of deciduous fruit trees (Richardson, et al. 1974, Lombard and Richardson, 1979). A chill unit is defined as an hour where the temperature is 6°C. Above and below 6°C the accumulation of chill units is less than one unit as shown in Table 5. No chill units are accumulated below 1°C and above 18°C.

Table 5. Conversion of hourly temperatures to chill units (Richardson, et al. 1974)

<table>
<thead>
<tr>
<th>Temperature stratum °C</th>
<th>Chill units</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>1.5 -2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2.5 -9.1</td>
<td>1.0</td>
</tr>
<tr>
<td>9.2 -12.4</td>
<td>0.5</td>
</tr>
<tr>
<td>12.5-15.9</td>
<td>0.0</td>
</tr>
<tr>
<td>16.0-18.0</td>
<td>-0.5</td>
</tr>
<tr>
<td>&gt;18.0</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

2.1.2.5 Others

Other agroclimatic resources to be evaluated on a regional basis include wind speed and direction, relative humidity, cloudiness, fog and dew. The way to evaluate these climatological parameters depends on the specific agricultural application. Evaluation of wind speed and direction especially during flowering time of fruit trees is important for orchards location and management. Evaluation of the number of hours above or below certain established limits of relative humidity is of great value in planning and management drying conditions for the seed industry. It is also well known the application of relative humidity levels to assess the risk of potential diseases that eventually may cause damage to crops.

2.1.2.6 Case studies

2.1.2.6.1 For rainfed agriculture

In planning agricultural production in tropical and sub-tropical rainfed areas, rainfall and moisture indices are the most important tools, since in these regions crop
production depends almost entirely on precipitation amount and its distribution through the growing season. On the contrary, in high altitude areas and temperate regions, temperature assumes importance at times more than precipitation. Of course, other climatic elements, depending on the region become also important and have to be evaluated and characterized as well.

The methodology to evaluate agroclimatic resources for rainfed agriculture has extensively been presented in several publications (WMO (1973); (1978); (1986); (1988); (1980); and (1982).

The question, however, of how many indices are required to fully characterize an agricultural region, may have different answers depending on the objective to be achieved, i.e. general assessment of agroclimatic resources, zoning of rainfed crops, agroclimatic zoning of crop varieties, etc. For zoning of rainfed crops, for example, The agroclimatic indices to be evaluated will be those that affect crop adaptation and yield. The identification of relevant indices is a matter of knowledge and experience both of the crops and the selected region to work with.

In order to illustrate one of the various approaches available for crop zoning in rainfed areas, the following case study is presented:

A case study: Rainfed corn zonation in the state of Jalisco, Mexico

The objective of this study was to determine the agroclimatic efficiency for growing rainfed corn in the state of Jalisco, Mexico. Climatological data of 136 weather stations with records longer than 15 years were used (Nuno, 1988). Based on our knowledge of the region and the climatic requirements of the corn crop, three indices were selected out of about 25, which were in turn used to estimate the assessment of agroclimatic resources of the state of Jalisco (Villalpando and Garcia, 1993). To assess the agroclimatic efficiency for corn, the following model was developed (Villalpando, 1988; Nuno and Villapando, 1988):

\[ 1.5(DEC70) + 1.0(IH70) + 0.75(TM) \]

\[ IEAM = \frac{1.5(DEC70) + 1.0(IH70) + 0.75(TM)}{3.25} \times 100 \]

Where:

- \( IEAM \) = Agroclimatic efficiency index for rainfed corn
- \( DEC70 \) = Duration of the growing season estimated using 70% of assured precipitation
- \( IH70 \) = Moisture index estimated for the growing season using 70% of assured precipitation (\( IH70 = P70/PET \))
- \( TM \) = Mean temperature for the growing season (June-October)
The values of 1.5, 1.0 and 0.75 for the coefficients of DEC70, IH70 and TM, respectively, are weighed values which were assigned according to the relative influence these indices have on corn adaptation and yield in this region. The value 3.25 results from the sum of 1.5 + 1.0 + 0.75.

The agroclimatic efficiency level for rainfed corn, according to the model above, depends on the length of the growing season, the moisture index level and the mean temperature present during the growing season. Therefore, based on climatic requirements of the corn crop, each one of these individual indices was stratified and weighed accordingly. The weight factors used for each stratum of the three individual indices were the following:

### Index: DEC70

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Weight factor</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEC70 &gt; 130 days</td>
<td>1.00</td>
<td>optimal</td>
</tr>
<tr>
<td>100 days &lt; DEC &lt; 130 days</td>
<td>0.67</td>
<td>sub-optimal</td>
</tr>
<tr>
<td>DEC &lt; 100 days</td>
<td>0.33</td>
<td>limited</td>
</tr>
</tbody>
</table>

minimum observed value = 0 days  
maximum observed value = 194 days

### Index: IH70

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Weight factor</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 &lt; IH70 &lt; 1.2</td>
<td>1.00</td>
<td>optimal</td>
</tr>
<tr>
<td>IH &gt; 1.2</td>
<td>0.67</td>
<td>excessive</td>
</tr>
<tr>
<td>IH &lt; 0.8</td>
<td>0.33</td>
<td>deficit</td>
</tr>
</tbody>
</table>

minimum observed value = 0.35  
maximum observed value = 2.76

### Index: TM

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Weight factor</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C &lt; TM &lt; 24°C</td>
<td>1.00</td>
<td>optimal</td>
</tr>
<tr>
<td>TM &lt; 20°C</td>
<td>0.67</td>
<td>sub-optimal</td>
</tr>
<tr>
<td>TM &gt; 24°C</td>
<td>0.33</td>
<td>excessive</td>
</tr>
</tbody>
</table>

minimum observed value = 18.6°C  
maximum observed value = 28.4°C
Using this model, the IEAM was computed for the 136 climatological stations used in this study. The IEAM ranged from 33 up to 100 with an average of 71.

To make easier the interpretation of the results obtained through this study, the 136 IEAM values were grouped into four levels of agroclimatic efficiency, as follows:

<table>
<thead>
<tr>
<th>IEAM level (%)</th>
<th>Number of weather stations</th>
<th>Agroclimatic efficiency for corn</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 55</td>
<td>37</td>
<td>very low</td>
</tr>
<tr>
<td>56-70</td>
<td>32</td>
<td>low</td>
</tr>
<tr>
<td>71-85</td>
<td>37</td>
<td>medium</td>
</tr>
<tr>
<td>86-100</td>
<td>30</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>136</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 shows the geographical distribution of the four levels of agroclimatic efficiency for rainfed corn. The results obtained in this study were verified against ground-truth data. The comparison made showed a high agreement between the estimated IEAM and the actual corn yields both at local and regional levels.

Studies of this type are especially important and should be carried out before the allocation of economic resources for a given agricultural undertaking be made. Zoning of rainfed crops in terms of agroclimatic efficiency allows the identification of land either of high agricultural potential, or land of low agroclimatic efficiency which should be used for other crops or activities.

2.1.2.6.2 For irrigated agriculture

The assessment of agroclimatic resources in irrigated lands should include, first of all, an evaluation of water resources available for agriculture. This evaluation should be made in terms of quantity and quality of water to be used to irrigate crops. On the other hand, evaluation of evaporation and evapotranspiration through the year are required to estimate the water requirements of alternative crops and the approximated land surface that could be irrigated.

Adaptation and yield of crops grown under irrigated conditions are determined mostly by temperature and solar radiation. Other meteorological elements such as air humidity, wind speed and direction, and precipitation at undesired stages of crops, depending on the crop, may also eventually affect yield and quality of agricultural produce.

Irrigated crops usually include orchards, vegetables, forages, and sometimes cereal and industrial crops. These crops may be perennial or seasonal crops, so that, the assessment of agroclimatic indices should be prepared accordingly. The relevant agroclimatic indices to be determined will vary with the crop type and regional climatic conditions.

For example, for deciduous fruit trees grown in temperate and sub-tropical regions, relevant agroclimatic indices should include: accumulated chill hours or chill units during winter time, and accumulated growing degree-days from sprouting to maturity. No adequate planning and management of fruit trees can be done without knowing these two
agroclimatic parameters. Pan evaporation and evapotranspiration are other parameters required for planning the use and management of water in the orchard.

For irrigated annual crops grown in temperate regions, the optimal period is determined taking into account, first of all, the frost-free period. For this, solar radiation regime and the relevant temperature indices (growing degree-days, day and night temperature, mean temperature, etc.) are determined in order to identify the optimal growing period according to climatic requirements of crops and varieties.

In tropical regions, irrigated annual crops can virtually be planted any time in the year. Here, however, it is necessary to identify and evaluate periods with excessive day and night temperatures in order to make an adequate planning of growing periods for crops and varieties sensible to high temperatures.

To identify the best growing period for annual crops, the method of available agroclimatic resources versus climatic requirements for the selected crop may be used. Examples regarding this method will be presented later in section 3.2.4 of this chapter.

2.1.3 Conclusions

Assessment of agroclimatic resources is an indispensable component to make a proper use and management of land. Agroclimatic characterization should be made according to regional needs and climatological information should be presented as agroclimatic indices that can easily be used in agricultural planning.

Agricultural planning should be based on the use of rainfall amounts probabilities instead of normal rainfall especially in low rainfall areas. In assessing agroclimatic resources care should be taken not only of describing the used methodology but also of including applications of the obtained agroclimatic indices. This can be achieved adding simple examples or if possible some case studies.

2.2 Selection of Varieties of Plants

2.2.1 Introduction

In selecting crop varieties for a given region, one should know, first, the agroclimatic requirements of different varieties in terms of water, temperature, solar radiation, etc., and second, the availability of agroclimatic resources for such a region. In point 3.1 we already dealt with the evaluation of agroclimatic resources, now, we are to present some guidelines on agroclimatic requirements of crop varieties, phenology of crop varieties and techniques
to select crop varieties based on agroclimatic requirements.

2.2.2 Agroclimatic Requirements of Crop Varieties

The determination of agroclimatic requirements of crop varieties is a fundamental issue in operational agrometeorology. Agroclimatic characterization of crop varieties includes heat, moisture, solar radiation and humidity needs among other climatic parameters. The agroclimatic requirements of crop varieties can be determined from the agrometeorological data collected in agrometeorological stations, and phenological data of selected crop varieties to be characterized. This method may take from two to three years depending on the number of observing sites, the number of planting dates and the region size for which this information will be used.

Another method to determine the climatic requirements of crop varieties is that developed under controlled conditions, where water, temperature, humidity and solar radiation or photoperiod levels, can be controlled for any crop growing stage. Growth chambers, greenhouses, shelters and lysimeters are the conventional methods used.

2.2.2.1 Water

Crop water requirements have extensively been reviewed by several research workers. Excellent reviews can be found in Jensen, 1973; Pruitt, 1977; and Hatfield (1990).

In determining water requirements of crop varieties, several factors must be taken into account, no matter the method used to estimate the amount of water required by a crop variety. Meteorological factors responsible for water demand of crops include solar radiation, air humidity, wind and temperature. Under normal conditions, solar radiation accounts for about 80% of water loss from a crop (Shaw, 1982). Under the same meteorological conditions, water requirements for a crop variety will vary depending on the amount of crop leaf area, crop phenology and rooting depth. Soil factors that may influence water requirement of a crop variety include soil water-holding capacity, and the supply of moisture in the root zone through the cropping season.

According to the above-mentioned, the amount of water required for a crop will vary depending on the variety characteristics. As it was mentioned before, crop water requirements can be estimated either under controlled conditions (lysimeters) or under field conditions where soil moisture is recorded on a daily basis. Table 6 shows the approximated range of water requirements for selected crops. The range may be due to differences in crop varieties and climatic conditions from the places where these data were collected.
Table 6. Approximated range of water requirements for selected crops (Doorenbos and Pruitt, 1977)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Water requirements (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>600 - 1500</td>
</tr>
<tr>
<td>Avocado</td>
<td>650 - 1000</td>
</tr>
<tr>
<td>Banana</td>
<td>700 - 1700</td>
</tr>
<tr>
<td>Bean</td>
<td>250 - 500</td>
</tr>
<tr>
<td>Cocoa</td>
<td>800 - 1200</td>
</tr>
<tr>
<td>Coffee</td>
<td>800 - 1200</td>
</tr>
<tr>
<td>Cotton</td>
<td>550 - 950</td>
</tr>
<tr>
<td>Flax</td>
<td>450 - 900</td>
</tr>
<tr>
<td>Cereals</td>
<td>300 - 450</td>
</tr>
<tr>
<td>Corn</td>
<td>400 - 750</td>
</tr>
<tr>
<td>Onion</td>
<td>350 - 600</td>
</tr>
<tr>
<td>Orange</td>
<td>600 - 950</td>
</tr>
<tr>
<td>Potato</td>
<td>350 - 625</td>
</tr>
<tr>
<td>Rice</td>
<td>500 - 950</td>
</tr>
<tr>
<td>Sorghum</td>
<td>300 - 650</td>
</tr>
<tr>
<td>Soybean</td>
<td>450 - 825</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>1000 - 1500</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>400 - 675</td>
</tr>
<tr>
<td>Tobacco</td>
<td>300 - 500</td>
</tr>
<tr>
<td>Tomato</td>
<td>300 - 600</td>
</tr>
<tr>
<td>Grape</td>
<td>450 - 900</td>
</tr>
</tbody>
</table>

2.2.2.2 Temperature

Temperature requirements of crop varieties include not only the upper and lower limits for crop variety adaptation but also those indices that characterize crop development, yield and quality of the crop varieties.

For annual crops temperature requirements are characterized through several thermal indices such as growing degree-days required from planting to flowering or to maturity; minimum, optimum and maximum soil temperature for seed germination; optimum day and night air temperature for different phenological stages; range of mean air temperature for optimal growth and development, etc.

Agroclimatologists in the Russian Federation have determined quantitative indices of the active temperature sums (growing degree-days) needed for the onset of the main development phases and maturity of cereals taking into their amount their ripening rate. Table 7 shows these indices for the ripening of the main cereal crops and covers early, normal and late-ripening varieties.
Table 7. Active temperature sum above 10°C needed for ripening the main crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Ripening rate of varieties</th>
<th>Active temperature sum above 10°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>Early-ripening</td>
<td>1200 - 1300</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>1400 - 1500</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>1600 - 1700</td>
</tr>
<tr>
<td>Barley</td>
<td>Early-ripening</td>
<td>1000 - 1100</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>1200 - 1300</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>1400 - 1500</td>
</tr>
<tr>
<td>Oats</td>
<td>Early-ripening</td>
<td>1000 - 1200</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>1300 - 1400</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>1500 - 1600</td>
</tr>
<tr>
<td>Millet</td>
<td>Early-ripening</td>
<td>1400 - 1600</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>1700 - 1800</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>1800 - 1900</td>
</tr>
<tr>
<td>Buckwheat</td>
<td>Early-ripening</td>
<td>1200 - 1300</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>1300 - 1400</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>1500 - 1600</td>
</tr>
<tr>
<td>Maize</td>
<td>Early-ripening</td>
<td>2100 - 2200</td>
</tr>
<tr>
<td></td>
<td>Normal-ripening</td>
<td>2600 - 2800</td>
</tr>
<tr>
<td></td>
<td>Late-ripening</td>
<td>3000 - 3200</td>
</tr>
</tbody>
</table>

It can be seen from Table 7 that the crops with the least heat requirements are oats and barley, whose early varieties can ripen with a temperature sum of 1000-1200. On the other hand, the various varieties of wheat start ripening with a temperature sum of 1200-1700, and the different varieties of grain maize with 2100-2200, 2600-2800, and 3000-3200 respectively.

Care should be taken in extrapolating data from one region to another, especially as growing degree-days requirements of crops is concerned. An example of this situation is presented in Table 8 where growing degree-days for “short”, “medium” and “late” season corn varieties were characterized during a three-year study carried out in Central Mexico. For central Mexico the GDD required for a late-season corn variety are about 1800, while in the Russian Federation for a late-ripening corn variety about 3000-3200 GDD are required.
Table 8. Growing degree-days required from planting to physiological maturity for selected corn varieties in Zapopan, Mexico (Villalpando, 1991).

<table>
<thead>
<tr>
<th>Corn variety</th>
<th>Cycle</th>
<th>Growing degree-days (GDD) Average of three years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cafime</td>
<td>Short-season</td>
<td>1467</td>
</tr>
<tr>
<td>VS-201</td>
<td>Short-season</td>
<td>1497</td>
</tr>
<tr>
<td>HV-313</td>
<td>Mid-season</td>
<td>1676</td>
</tr>
<tr>
<td>H-220</td>
<td>Mid-season</td>
<td>1733</td>
</tr>
<tr>
<td>H-311</td>
<td>Late-season</td>
<td>1776</td>
</tr>
<tr>
<td>Asgrow-747</td>
<td>Late-season</td>
<td>1778</td>
</tr>
<tr>
<td>Dekalb B-840</td>
<td>Late-season</td>
<td>1772</td>
</tr>
<tr>
<td>Pioneer P-507</td>
<td>Late-season</td>
<td>1813</td>
</tr>
</tbody>
</table>

Method used:

\[ n \]

\[ GDD = \sum_{i=1}^{n} (T_{max} + T_{min}) - 10 \]

If \( T_{max} > 30 \), \( = 30^\circ C \)

If \( T_{max} < 10 \), \( = 10^\circ C \)

Important indices for a heat supply assessment are those of night frosts, i.e. air temperatures causing damage to crops during the vegetation period. They are shown below in Table 9 (after Stepanov (1957)).
<table>
<thead>
<tr>
<th>Crop</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Cotton (all phases)</td>
<td>&lt; 0°</td>
</tr>
<tr>
<td>Potato (flowering: flowers are damaged)</td>
<td>&gt; 0°</td>
</tr>
<tr>
<td>Rice (sprouting-flowering)</td>
<td></td>
</tr>
<tr>
<td>Grape (flowering, setting of fruit)</td>
<td></td>
</tr>
<tr>
<td>Cucumber, tomato (vegetation period)</td>
<td></td>
</tr>
<tr>
<td>II. Spring wheat, oats, barley (flowering)</td>
<td>-1°, -2°</td>
</tr>
<tr>
<td>Winter wheat and rye (flowering, milky ripeness)</td>
<td></td>
</tr>
<tr>
<td>Maize (flowering)</td>
<td></td>
</tr>
<tr>
<td>Fiber flax (flowering)</td>
<td></td>
</tr>
<tr>
<td>Buckwheat (in all phases)</td>
<td></td>
</tr>
<tr>
<td>Millet (flowering)</td>
<td></td>
</tr>
<tr>
<td>Rice (ripening)</td>
<td></td>
</tr>
<tr>
<td>Potato (damage to sprouts, leaves and stems)</td>
<td></td>
</tr>
<tr>
<td>Grape (opening of flower buds)</td>
<td></td>
</tr>
<tr>
<td>Apple, pear, plum and cherry trees (opening of buds, flowering and setting of fruit)</td>
<td></td>
</tr>
<tr>
<td>Apricot, peach (setting of fruit)</td>
<td></td>
</tr>
<tr>
<td>III. Spring wheat, barley and oats (during milky ripeness)</td>
<td>-1°, -4°</td>
</tr>
<tr>
<td>Maize (shoots, milky ripeness)</td>
<td></td>
</tr>
<tr>
<td>Millet (during milky ripeness)</td>
<td></td>
</tr>
<tr>
<td>IV. Potato (total loss)</td>
<td>-3°, -4°</td>
</tr>
<tr>
<td>Winter crops (middle and end of the stem growth period)</td>
<td></td>
</tr>
<tr>
<td>Maize (total loss of shoots, non-germination from ripe maize grain)</td>
<td></td>
</tr>
<tr>
<td>Sunflower (during flowering)</td>
<td></td>
</tr>
<tr>
<td>Fiber flax (first appearance of shoots)</td>
<td></td>
</tr>
<tr>
<td>Apple, pear, plum and cherry trees (swelling of buds)</td>
<td>-3°, -4°</td>
</tr>
<tr>
<td>Apricot, peach (flowering)</td>
<td></td>
</tr>
<tr>
<td>Swede and turnip (shoots)</td>
<td></td>
</tr>
<tr>
<td>V. Sugarcane (shoots in the initial “wishbone” phase)</td>
<td>-5°, -7°</td>
</tr>
<tr>
<td>Sunflower (sprouting)</td>
<td></td>
</tr>
<tr>
<td>Clover, vetch (sprouting and aftergrowing)</td>
<td></td>
</tr>
<tr>
<td>Cabbage (after seedlings have taken)</td>
<td></td>
</tr>
<tr>
<td>Swede and turnip (mature plants)</td>
<td></td>
</tr>
<tr>
<td>Lettuce (mature plants)</td>
<td></td>
</tr>
<tr>
<td>Carrot (shoots)</td>
<td></td>
</tr>
<tr>
<td>Onion leaves (during the phase with 2-4 leaves present)</td>
<td></td>
</tr>
<tr>
<td>Most pasture grasses</td>
<td></td>
</tr>
<tr>
<td>VI. Winter and wheat and rye (beginning of stem growth)</td>
<td>-7°, -8°</td>
</tr>
<tr>
<td>Spring barley (sprouting period)</td>
<td></td>
</tr>
<tr>
<td>VII. Winter rye and wheat (renewal of vegetation)</td>
<td>-8°, -10°</td>
</tr>
<tr>
<td>Spring wheat, oats (sprouting period)</td>
<td></td>
</tr>
<tr>
<td>Sugar-beet (shoots, but in autumn the root crop is dug up but not gathered in)</td>
<td></td>
</tr>
<tr>
<td>Lucerne (shoots, after growing)</td>
<td></td>
</tr>
</tbody>
</table>
For perennial crops, particularly deciduous fruit trees, regular temperature requirements include characterization of chill hours or chill units requirements. Table 10 contains a compilation of selected varieties for several deciduous fruit trees.

<table>
<thead>
<tr>
<th>Specie</th>
<th>Cultivar</th>
<th>Chill hours requirement</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>Rome Beauty</td>
<td>1000</td>
<td>very high</td>
</tr>
<tr>
<td></td>
<td>Golden Delicious</td>
<td>850</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Starking</td>
<td>850</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Red Delicious</td>
<td>800</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Jonathan</td>
<td>700</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Anna</td>
<td>300</td>
<td>very low</td>
</tr>
<tr>
<td>Peach</td>
<td>Elberta</td>
<td>850</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Hiley</td>
<td>750</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Bonita</td>
<td>500</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Lucero</td>
<td>400</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Flordasun</td>
<td>400</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>Flordawon</td>
<td>200</td>
<td>very low</td>
</tr>
<tr>
<td></td>
<td>Flordagrande</td>
<td>100</td>
<td>very low</td>
</tr>
<tr>
<td></td>
<td>Tetela</td>
<td>20</td>
<td>very low</td>
</tr>
<tr>
<td>Apricot</td>
<td>Moorpark</td>
<td>1000</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Tilton</td>
<td>750</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Mayero</td>
<td>650-750</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Currut</td>
<td>450</td>
<td>low</td>
</tr>
<tr>
<td>Pear</td>
<td>Bartlett</td>
<td>900</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Winter Nellis</td>
<td>750</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>20th Century</td>
<td>550</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Spadona</td>
<td>400</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>Flordahome</td>
<td>250</td>
<td>very low</td>
</tr>
<tr>
<td>Plum</td>
<td>Corazon de Elefante</td>
<td>850-950</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>French</td>
<td>700</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Formosa</td>
<td>600</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Santa Rosa</td>
<td>600</td>
<td>medium</td>
</tr>
<tr>
<td>Almond</td>
<td>Primarski</td>
<td>700</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>Padre</td>
<td>400</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Sonora</td>
<td>275</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>Constantini</td>
<td>150</td>
<td>very low</td>
</tr>
<tr>
<td>Nut</td>
<td>Western</td>
<td>400</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Wichita</td>
<td>400</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>Mahan</td>
<td>400</td>
<td>medium</td>
</tr>
</tbody>
</table>
2.2.2.3 Solar Radiation

According to the efficiency in the utilization of solar radiation and CO₂, agricultural crops can be classified in two groups, namely C₃ and C₄ crops. In C₃ crops (i.e. wheat, barley, soybeans, rice, etc.), the first product of photosynthesis is a 3-carbon organic acid (3-phosphoglyceric acid) while in C₄ crops (i.e. corn, sorghum, sugarcane, etc.), the first product are 4-carbon organic acids (malate and aspartate). In general C₃ crops are adapted to operate in lower solar radiation and temperature levels than the C₄ crops. The later have maximum rates of photosynthesis with light saturation at 1.0-1.4 cal/cm²/min with day-time temperature in the range of 30-35°C. The rate of CO₂ exchange is another difference between C₃ and C₄ crops. In C₃ crops the CO₂ exchange is in the range of 15-30 mg CO₂/dm²/h with light saturation at 0.2-0.6 cal/cm²/min, while in C₄ crops the CO₂ exchange is in the range of 10-100 mg CO₂/dm²/h with light saturation at 1.0-1.4 cal/cm²/min. Because of the high CO₂ exchange rate and very low photorespiration, C₄ crops are more efficient to convert light energy into dry matter (Shibles, 1981; Kassam and Beek, 1982; and Burger, 1984).

Solar radiation requirements of crops can also be determined by photosynthetic active radiation (PAR) which is in the range of 0.4 to 0.7 m of the solar spectrum. This type of solar radiation is the one useful for crop photosynthesis.

Sunshine or insolation is another approach to characterize solar radiation of agricultural crops. Although less sophisticated than the parameters above-mentioned, sunshine hours have proved to be a useful parameter in fruit trees especially during the maturity stage.

2.2.2.4 Humidity

Air humidity is a climatological element that can be related to the adaptation, health and quality of agricultural crops. Then, air moisture requirements for a particular crop may be characterized taking into account one or more factors depending on the objective in mind.

The level of air humidity may be beneficial or detrimental to crops. For most cereal crops the optimum level of relative humidity is the range of 40-70% during the crop life cycle. In general low-air moisture levels keep cereals free from diseases, which are favoured in high air moisture environments (WMO, 1988). The same applies for other crops such as cotton, beans, and sunflower which prefer a microclimate with low air moisture.

On the other hand, high levels of air moisture are required by some tropical crops adapted to humid environments, such as cocoa, vanilla, rice, etc.

Good quality of some vegetables and tropical fruits can only be obtained in humid microclimates which can be natural or under controlled conditions.
2.2.2.5 **Photoperiod**

Photoperiod is a climatological parameter required to characterize the light needs of crops. To follow, a brief description on the reaction of crops to daylength is given. Crops, according to their response to daylength (photoperiod), can be classified in three groups namely, short-day crops, long-day crops and neutral crops. In short-day crops flowering and maturity are stimulated by short days, while for long-day crops such phenological phases are stimulated by long days. Flowering and maturity of neutral crops are not affected by daylength. Table 11 shows the response to photoperiod of selected agricultural crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Scientific name</th>
<th>Response to photoperiod *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>Oriza sativa L.</td>
<td>S</td>
</tr>
<tr>
<td>Corn</td>
<td>Zea mays L.</td>
<td>S</td>
</tr>
<tr>
<td>Wheat</td>
<td>Triticum aestivum L.</td>
<td>L, N</td>
</tr>
<tr>
<td>Barley</td>
<td>Hordeum vulgare</td>
<td>L, N</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Sorghum bicolor (L.) Moench</td>
<td>S</td>
</tr>
<tr>
<td>Rye</td>
<td>Secale cereale L.</td>
<td>L, N</td>
</tr>
<tr>
<td>Oats</td>
<td>Avena sativa L.</td>
<td>L, N</td>
</tr>
<tr>
<td>Pearl Millet</td>
<td>Pennisetum glaucum L.</td>
<td>S</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>Saccharum officinarum L.</td>
<td>S</td>
</tr>
<tr>
<td>Rye grass</td>
<td>Lolium perenne L.</td>
<td>L</td>
</tr>
<tr>
<td>Soya beans</td>
<td>Glycine max Merril</td>
<td>S, N</td>
</tr>
<tr>
<td>Beans</td>
<td>Phaseolus vulgaris L.</td>
<td>S, N</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Medicago sativa L.</td>
<td>L</td>
</tr>
<tr>
<td>Peanut</td>
<td>Arachis hipogae L.</td>
<td>S</td>
</tr>
<tr>
<td>Sesame</td>
<td>Sesamum indicum L.</td>
<td>S</td>
</tr>
<tr>
<td>Cotton</td>
<td>Gossypium hirsutum L.</td>
<td>N</td>
</tr>
<tr>
<td>Safflower</td>
<td>Carthamus tintorius L.</td>
<td>L, N</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Helianthus annuus L.</td>
<td>N</td>
</tr>
<tr>
<td>Flax</td>
<td>Linum usitatissimum L.</td>
<td>L</td>
</tr>
<tr>
<td>Rape</td>
<td>Brassica napus annua Koch</td>
<td>L</td>
</tr>
<tr>
<td>Potato</td>
<td>Solanum tuberosum L.</td>
<td>L, N</td>
</tr>
<tr>
<td>Cassava</td>
<td>Manihot utilissima esculenta Pohl</td>
<td>N</td>
</tr>
</tbody>
</table>

* S = short day   L = long day   N = neutral day

2.2.3 **Phenology of crop varieties**

Agricultural phenology is a branch of agrometeorology that deals with the effect of climate and edaphic conditions on the succession of periodic biological events experienced by crops (Wielgolaski, 1974).
In describing crop phenology it is important to distinguish the terms phase and stage. A phenological phase represents each one of the periodical events experienced by crops, such as emergence, flowering, physiological maturity, etc. While a phenological stage represents the period between two consecutive phases, for example, the period between flowering and physiological maturity represents a phenological stage.

The main variables affecting crop phenology include: planting date (or sprouting in perennial crops), air temperature, soil temperature, photoperiod, soil moisture, soil nutrients availability and crop genetic component (Hodges and Doraiswamy, 1980). Under no soil moisture and nutrient restrictions, phenology of crops can be described using temperature only. Although in crop varieties sensible to daylength the use of temperature and photoperiod give better results.

2.2.3.1 Annual Crops

Phenology of annual crop varieties is affected by soil temperature from planting to emergence of plants. From emergence until maturity air temperature is the dominant factor affecting crop varieties development as shown in Figure 4. In this figure the term Tb represents the base temperature at which no crop development occurs; To is the optimum temperature at which the rate of crop development is maximum. From Tb to To the rate of crop development is about linear. This segment, incidentally, is the one on which growing degree-days are calculated and related to crop development. From To the rate of crop development decreases as the temperature increases up to a limit, Tu where no crop development occurs because of the excessive temperature (Arnold, 1959; Orchard, 1976; Tyldesley, 1978).

As it was mentioned in 3.2.2.5 crop phenology of some crop varieties may be affected by daylength. One of the main effects of photoperiod on crop development is in determining flowering time (Major, 1980). In some crop varieties the flowering phase is hastened as days are shorter, (short-day varieties). Likewise, long-day varieties speed up its flowering phase as days are longer.

Soil moisture stress or nutrient availability may delay or hasten crop variety development. Soil moisture stress occurring close to flowering or physiological maturity tend to reduce the required time to reach these phenological phases. Regarding nutrients availability, excessive nitrogen delays flowering in cereal crops, while application of excessive amounts of phosphorus tend to hasten crop development (Hodges and Doraiswamy, 1979).

The number of phenological phases to be recorded in crop varieties varies depending on the objectives. For research purposes detailed phenological descriptions are taken, as those described for corn and soybeans (Hanway, 1982; Hanway and Barber, 1981). However, for practical applications less phenological phases are required. The phenological phases of emergence, flowering, physiological maturity and perhaps two or three more phases taken in between are enough for most annual crops. Practical guidelines that include description, collection, analysis and application of phenological observations are presented in Todorov (1982), and Villalpando and Ruiz (1993) which can be consulted for further information on this topic.
Fig. 4 Relationship between the rate of development and temperature (Adapted from Orchard, 1976)
2.2.3.2 Perennial crops

Crop phenology of perennial crops is affected by the same environmental factors already described in 2.2.3 and 2.2.3.1. However, the form that these factors affect crop phenology of perennial crops is different. In temperate regions the rest period of deciduous fruit trees and the time of sprouting are temperature dependant. However, in subtropical and tropical regions the rest period and the time of sprouting for grape, guava and other crops, can be controlled by the soil moisture content at rooting depth (Ruiz, 1991).

The collection of phenological observations in perennial crops as well as in annual crops should be a permanent activity in all agronomy meteorological stations. Knowledge of crop phenology is mandatory for adequate planning and management of agricultural land. To collect phenological observations in perennial crops, the manuals prepared by Todorov (1982) and Villalpando and Ruiz (1993) as mentioned before, are recommended.

2.2.4 Techniques to select crop varieties based on agroclimatic requirements

The method to select crop varieties based on agroclimatic requirements, consists of comparing, on one hand, the regional availability of agroclimatic resources and, on the other, the climatic requirements of selected crop varieties on which the selection is to be made. To follow, some examples to illustrate this method in temperate, tropical and arid and semi-arid regions are presented.

2.2.4.1 In Temperate Regions

Example: Selection of sunflower varieties based on growing degree-days in France (Zamorano, et al., 1986)

Table 12 shows the growing degree-days from emergence to flowering, and from emergence to maturity, to short-, mid- and late-season sunflower varieties for France, as determined by CETIOM-Direction de la Meteorologie Nationale).

<table>
<thead>
<tr>
<th>Variety</th>
<th>Emergence-flowering</th>
<th>Emergency-maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDD</td>
<td>GDD</td>
<td>GDD</td>
</tr>
<tr>
<td>Short-season</td>
<td>660</td>
<td>1,500</td>
</tr>
<tr>
<td>Mid-season</td>
<td>740</td>
<td>1,600</td>
</tr>
<tr>
<td>Late-season</td>
<td>770</td>
<td>1,700</td>
</tr>
</tbody>
</table>

Table 12. Growing degree-days calculated using a base temperature of 6°C for three groups of sunflower varieties and two phenological stages Phenological stages.
To select sunflower varieties based on available GDD on a regional basis, a collection of maps was prepared as that shown in Figure 5. This map shows the probability of reaching maturity for short-season varieties for a supposed date of emergence (21 April) and a fixed date for harvest (20 September). As shown in Figure 5, the probability of reaching maturity for a short-season sunflower variety emerging on 21 April increases from North to South. For this particular example, areas with a probability equal or higher than 80% of reaching maturity should be selected for short-season sunflower varieties. The same procedure can be followed to examine the possibilities of success for mid- and late-season sunflower varieties.

2.2.4.2 In Tropical Regions

Example: Selection of rainfed crop varieties based on the growing season length in the state of Jalisco, Mexico

There are several moisture indices that can be used to select crop varieties in rainfed tropical regions. The length of the growing season based on moisture availability to crops is one of them. This agroclimatic index as well as other moisture indices were determined in the evaluation of agroclimatic resources for rainfed agriculture in the state of Jalisco, Mexico (Villalpando and Garcia, 1993). Figure 6 shows the state of Jalisco’s map with the distribution of the growing season length. It should be noted that in determining the growing season length an assured precipitation of 70% level of occurrence was used.

The selection of crop varieties of different maturity levels can be made on a regional basis, by comparing the number of days from planting to maturity for selected varieties, and the available growing season length. For example, for the corn crop a growing seasons length between 90 and 120 days would be adequate for short-season varieties, between 120 and 150 days for mid-season varieties and longer than 150 days would be adequate for late-season varieties. A growing season length less than 90 days is not recommended for growing the corn crop in this region. The selection of corn varieties, as it was mentioned above, is made on the basis that at least 7 out of 10 years these corn varieties, if selected properly, will reach maturity without moisture limitations.

2.2.4.3 In Arid and Semi-Arid Regions

Example a: Efficient utilization of climate resources for rainfed agriculture in Israel (Lomas, 1964).

Under mediterranean climatic conditions, most of the rainfed agricultural production of Israel is to be found in the northern Negev. The total annual rainfall of the region ranges from 200-400 mm and the coefficient of variation is 35-40%.

Historically, this has been a region of opportunistic semi-nomadic land-use “management” based on goats and sheep and some winter cereals.

But recently, wheat growing (Figure 7) is the most economic proposition, provided
Figure 5
Fréquence d'obtention de la maturité d'une variété précoce de tournesol
(type CERFLOR)
Levée : 21 avril - Récolte fixée au 20 septembre

Periode de reference : 1951-1980
suitable agrotechnology aimed at the efficient utilization of rainfall is practiced, i.e.:

- Tillage operations - deep ploughing especially in areas where the rainfall is expected to be 300 mm or above.

- Moisture conservation - furrowdams resulting in the observation of an additional 100 mm of rainwater under fallow or 50 mm of rainwater under winter wheat cultivation.

- Optimal time of planting - which for the northern Negev is approximately the middle of November.

- Fertilizer applications - which will range from 100 Kg/ha at 200 mm of annual rainfall and increasing to 160 Kg/ha at 500 mm of annual rainfall.

- Selection of suitable varieties.

Under such agrotechnological practices and the present economic situation, the 250-300 mm rainfall "border line" divides areas of profitable from non profitable rainfed agriculture.

**Example b:** Topoclimatology as an aid in the siting of the avocado crop

Under local climatic conditions and the considerable rise in the cost of fuel, topoclimatological investigations are the safest and cheapest way of avoiding frost damage. The application of this method to the siting of the avocado crop in Israel is widely used.

It is extremely difficult to provide quantitative climatic threshold values for damage by low temperatures to avocado plantations. This difficulty is due to the fact that the effect of low temperature on the avocado plant depends not only on the threshold temperature itself, but on the timing and the duration of such temperature occurrences as well as physiological responses of the plant itself.

In an attempt to provide practical threshold values, Lomas (1971) suggested that economic damage to avocado plantations will occur when the air temperature drops to minus 2.0°C to minus 4.0°C, depending on the duration of low temperature. Detailed agroclimatic analysis indicates that the probability of the occurrence of negative temperature values is greater than expected by those non familiar with topoclimatology (Figure 8).
Fig. 8 Probability of frost occurrence in the Sharon and Menashe regions, a basis for avocado planting.

Average number of occurrences and hours per season in which the temperature drops below 0°C for all isolines

<table>
<thead>
<tr>
<th>Expected Hours of 0°C and Below</th>
<th>Expected Occurrences of 0°C and Below</th>
<th>Isolines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>+ 1.0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>- 0.0</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>- 1.0</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
<td>- 2.0</td>
</tr>
<tr>
<td>34</td>
<td>8</td>
<td>- 3.0</td>
</tr>
<tr>
<td>66</td>
<td>16</td>
<td>- 4.0</td>
</tr>
<tr>
<td>128</td>
<td>28</td>
<td>- 5.0</td>
</tr>
</tbody>
</table>
Topography plays a predominant role in the distribution of low temperature within a given region (Machattie et al., 1974). This is especially the case during nights with radiational cooling, which are relatively frequent during the winter season in Israel (Figure 9).

Fig 9 The Effect of Topography (- - -) on Avocado Fruit Damage (---) At Amiad During 1972 - 1973

In view of the aforesaid, it was concluded that the distribution of low temperatures and their duration need detailed investigations as it may seriously curtail the introduction and expansion of avocado plantations under Israel’s winter climatic conditions. Indeed, it was expected that minimum temperature differences sufficiently large could be found so that the crop could be planted in advantageous areas that would avoid economic damage.
2.2.5 Conclusions

The selection of varieties of plants at local or regional levels should be based on agroclimatic studies carried out to determine the climatic requirements of the different crop varieties. Agroclimatic characterization of crops include solar radiation, water, temperature, humidity and photoperiod, among the most important climatological factors. The agroclimatic requirements determined for a given crop variety are valid up to a certain geographical limit and care should be taken in extrapolating data between contrasting agroecological regions.

Temperature and photoperiod are the main climatological factors that affect the phenology of crop varieties. Phenological characterization of crop varieties is a useful tool for crop planning and management. Therefore, the collection of phenological observations in perennial as well as in annual crops should be a permanent activity in all agrometeorological stations.
Chapter 3

Agrometeorological Information for Crop Management and Production

3.1 Introduction

Crop production in any place is the integrated result of a number of interacting physical and physiological processes that occur during the life span of a crop. These processes are influenced by weather, soil, management practices and species of crop. Among them, weather which is the most variable factor and at the same time can be least controlled, plays a vital role. In the tropical countries of the world, aberrant weather is a rule rather than an exception. Rainfall is seasonal, erratic and highly variable both in time and space. During low rainfall years, root zone productive moisture, reservoir storage, underground recharge and flow potential of a river decline, thereby reducing availability of not only the irrigation potential but also drinking water for human beings and animals. These create heavy pressure on food, fuel and fodder. Cloudy weather reduces the hours of bright sunshine and amount of radiation in the high rainfall regions, which are very much necessary for proper development of a crop. Temperature is relatively high in most of the regions of the tropics, hence moisture becomes prime parameter of agricultural production. On the other hand temperature is often main climatic factor of agricultural production in the temperate and sub-tropical regions. Adequate care, therefore, needs to be taken to find out suitable temperature periods for crop growth. Identification of frost-free season and adaptation of appropriate crops to match these periods are the basic criteria to achieve an optimum production.

Hazardous phenomena such as flood, cyclone, drought, frost, high wind that occur during the life span of any crop, adversely affect the growth and ultimately the production. These phenomena can hardly be controlled but their adverse affect can be minimized by developing early management strategies to avoid or mitigate economic losses due to their impact.

Efficient crop planning and management, therefore, require proper characterization of agroclimatic conditions. This calls for collection, verification, analysis and interpretation of historical weather data available in the region to identify (i) distribution of rainfall at different risk levels and occurrences of dry spells, (ii) length of possible cropping season in terms of temperature adequacy, (iii) water availability periods for crop growth, (iv) water requirement at different phenophases of crops, (v) adverse weather conditions like droughts, flood, strong winds, hail etc. and their likely occurrences and intensities and (vi) extreme temperatures and their management strategies. Application of weather based management strategies will help in efficient agricultural production.
3.2 Analysis of Agrometeorological Parameters

In the tropical countries, variability of climatic parameters during the growing season is often of much higher order than those in the sub-tropics. Therefore, it is of paramount importance to undertake investigation on appropriate agrometeorological aspects for developing management strategies so that higher production can be achieved. Some of the important parameters which need to be studied are:

3.2.1 Rainfall

Rainfall information for a month, season or a year is usually used to draw agricultural plans. For management of modern agriculture, information on climatic features is required for shorter period as crop growing period is about 100 days. As rainfall is highly erratic in intensity and amount (both in time and space) in the tropics, it is necessary to use a shorter period like a week or ten days as the unit of time to get the impact of variations.

Not only the rainfall amount but also its distribution in an appropriate time scale is very important to evaluate the effect of variation. Coefficient of variation (CV) is usually computed to know the variation of rainfall. CV gives an idea of variation of rainfall amount about its mean. The adequacy of the measurement depends upon the use to which it is put. Normally CV decreases with increasing rainfall amounts up to 100 cm and its variation is not very significant when normal amount is above 100 cm. (see Table 13). For low rainfall amounts of less than 50 cm CV is higher than 35% (Rao, et al., 1971). Hence short period CV analysis, in most of the cases, cannot bring out adequate information for agricultural use. Under this condition, use of probability analysis give better information for agricultural planning and management.

3.2.1.1 Probability Analysis

Extensive studies of short period rainfall show that there is no trend, cycle or periodicity. For agricultural purposes rainfall for short period and over small area is very important. Moreover, in low rainfall areas the normal rainfall (monthly, seasonal or annual) quite often is far too short of the water requirement of crops. But experience shows that on a number of occasions, crops are successfully raised. On such occasions, the rainfall is more than the normal value and meet the water demand of the crops. So for any crop planning, one should know from long records what is the chance of meeting the water requirement of the crops. Hence, the planning has to be done on a probabilistic basis which eventually takes into account the chance of success or failure. There are various mathematical models which can be fitted to rainfall total and expected rainfall amount at different levels can be estimated. Thom (1958) suggested fitting of Gamma distribution to skew data like short period rainfall having lower bound zero. The procedure has also been elaborated by Thom (1966) in Technical Note of World Meteorological Organization. Davy, et al., (1976) used the same distribution to obtain decade rainfall probability in Sudano-Sahelian zone of Africa.

Extensive work on probability analysis has been done by the India Meteorological Department. Fig. 10 gives the assured rainfall pattern of Madha (India) at various probability levels. It helps to identify the risk involved in raising a crop and also the water stress period in
<table>
<thead>
<tr>
<th>STATION</th>
<th>ANNUAL</th>
<th>SEASONAL</th>
<th>MONTHLY</th>
<th>WEEKLY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Jun-Sep</td>
<td>Jun</td>
<td>Jul</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25th</td>
<td>29th</td>
</tr>
<tr>
<td>Hissar</td>
<td>45</td>
<td>47</td>
<td>94</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>(323)</td>
<td>(35)</td>
<td>(105)</td>
<td>(171)</td>
</tr>
<tr>
<td>Indore</td>
<td>42</td>
<td>43</td>
<td>81</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>(919)</td>
<td>(133)</td>
<td>(280)</td>
<td>(232)</td>
</tr>
<tr>
<td>Rajkot</td>
<td>37</td>
<td>38</td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>(554)</td>
<td>(96)</td>
<td>(248)</td>
<td>(126)</td>
</tr>
<tr>
<td>Solapur</td>
<td>29</td>
<td>34</td>
<td>58</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>(516)</td>
<td>(114)</td>
<td>(109)</td>
<td>(104)</td>
</tr>
<tr>
<td>Hyderabad</td>
<td>23</td>
<td>30</td>
<td>52</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>(574)</td>
<td>(107)</td>
<td>(161)</td>
<td>(125)</td>
</tr>
<tr>
<td>Bangalore</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>(482)</td>
<td>(71)</td>
<td>(111)</td>
<td>(137)</td>
</tr>
</tbody>
</table>

(Figure in bracket is normal rainfall in mm of respective periods)

Table 13 Weekly, monthly, seasonal and annual coefficients of variation (percentage) of rainfall for several weather stations in India
between. One can select a crop as per availability of assured rainfall and also suggest time of minimal irrigation.

Figure 10: Rainfall amount at different probability levels, Madha (India)
Figure 41  Initial and conditional probabilities for Anantpur (India)
Sarker, et al. (1978) computed weekly rainfall probability at different levels fitting incomplete gamma distribution model for 105 stations over the dry farming tract of India. Biswas and Khambete (1979) and Biswas and Basarkar (1982) have further extended the study using micro-level stations over Maharashtra and Gujarat States and each State has been delineated into different rainfall pattern zones on the basis of probabilistic rainfall and also identifies drought prone areas. Similar studies have also been completed elsewhere in India.

3.2.2 Conditional Probability

A knowledge of distribution of wet and dry spells during monsoon season is of vital importance for successful planning as well as for various operations related to agriculture. When the probability of occurrence of dry spells of 2, 3, 4... weeks bounded by wet weeks is known, adequate steps may be taken for agricultural operations. Conditional probability can indicate whether the chance of getting certain amount of rainfall in succession is more or less. When two stations are getting more or less the same amount of annual or seasonal rainfall, the crop prospect is better at a station where rainfall is of continuous type than of interrupted. Fig. 11 gives the conditional probability of different threshold values of Anantpur situated in the dry farming tract of India where annual rainfall is 575 mm. It brings out the period where rainfall is more dependable. Markov chain model fitted to rainfall series can bring out spells bounded by wet period. Many workers, viz. Weiss (1964), Victor & Sastry (1979) used this model to identify dry period. Khambete & Biswas (1984) have developed an index using Markovian model and drought prone areas and intensity of drought have been demarcated with the help of this index.

3.2.3 Potential and Actual Evapotranspiration (ET) Under Different Climatic Conditions

Water is lost from fields as transpiration through plants and as evaporation from the soil and surfaces in between the plants. This combined loss is called evapotranspiration (ET). The amount of ET loss is called evapotranspiration. Climatic parameters such as radiation received, temperature, wind speed, vapour pressure deficits, type of soil and growth stage of the crop. Actual water loss from land surface is strongly influenced by the supply of moisture in the root zone (Denmead & Shaw, 1962).

Many equations (Thorntwaite 1948, Penman 1956, Papadakis, 1975; Doorenbos & Pruitt, 1977; Kanemasu, et al., 1976; Mukammal & Neumann, 1977) have been developed for calculation of this parameter and used for various purposes. These equations give the potential evapotranspiration rate. In natural environment, crops are subjected to some moisture stress during their growing season. Therefore, the potential evapotranspiration is not a good estimate of actual water loss from natural vegetation or of the water which is utilized by a crop. Actual amount of water used by field crops at their various growth stages can be known from direct measurements.

Many studies have been conducted to find out the ratios of actual water used by a crop to the potential evapotranspiration (AET/PET) and this ratio depends on many factors. In the early stages of dryland crops, the growth may not hamper at all even if the ratio is 0.3, but in the vegetative stage crop need water about 70% of potential evapotranspiration and in the ripening stage water requirement of many crops may be about one-third of the potential rate.
Jansen (1968) observed that the cumulative seasonal evapotranspiration for a dryland crop like sorghum, even under relatively favourable moisture conditions may be only 65% of PET. Replay (1966) found that in many farm crops, seasonal water used may range from 55% to 75% of PET.

**Figure 12** Water availability periods at different probability levels for two meteorological stations in India.
India Meteorological Department has installed about 35 Lysimeters in various soil and climatic zones of the country to find out water requirements of various crops. Vendataraman, et al. (1976) found that cumulative evapotranspiration of many crops is of the order of 70-75 of PET. Biswas and Khamete (1988) concluded from the analysis of lysimeter data for sorghum and millet that these crops used water from 61 and 66% of pan evaporation. Many years, water used at the vegetative stage is less than 80% of pan evaporation but the yield is above normal.

3.2.4 Growing period

Choice of suitable growing period is very much important to get optimum yield from a place. For this, adequacy of moisture and/or temperature needs to be examined. The best way to identify the growing period is to use various indices. In the tropical region where temperature is favourable moisture indices help find out growing periods. On the other hand temperature indices are used to find out growing period in the sub-tropics and temperate regions.

3.2.4.1 Moisture indices

Moisture index utilized is often a ratio of water use by a crop to potential evapotranspiration or pan evaporation. There are various indices which are used to find out crop growing period. Some of which are discussed below.

Troll (1965) proposed an index utilizing monthly rainfall and potential evapotranspiration calculated by penman's method. A month having mean rainfall more than mean potential evapotranspiration is defined as a humid month; otherwise it is a dry month. Troll divided the climate of the world into five groups based on duration of humid months and each was associated with some type of vegetation.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Duration of humid months</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Tropical rainy climate</td>
<td>12 - 9 1/2</td>
</tr>
<tr>
<td>(ii) Tropical humid climate</td>
<td>9 1/2 - 7</td>
</tr>
<tr>
<td>(iii) Wet dry tropical climate</td>
<td>7 - 4 1/2</td>
</tr>
<tr>
<td>(iv) Semi-arid climate</td>
<td>4 1/2 - 2</td>
</tr>
<tr>
<td>(v) Arid climate</td>
<td>&lt; 2</td>
</tr>
</tbody>
</table>

In this classification Troll considered the tropical and extra tropical regions separately. Under the relatively stable high temperature in the tropics, vegetation mostly depend on duration of wet month. According to Troll, this classification has been found to be useful for satisfactory explanation of vegetation zones of tropical Africa and South America. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) adopted this method for classifying semi-arid tropics. However, their recent study shows that the application of this system of climatic classification for delineation of semi-arid zones of India using mean monthly precipitation and potential evapotranspiration computed by Penman’s method is not satisfactory.
Moreover, in this classification dry months for crop growth have not been considered. There are many dryland crops that give optimum yield even though no month is humid during the growing period. From the manner of treatment, it is obvious that this method is quite good in delineating areas in very broad terms, but does not provide the kind of details and small scale information needed for agriculture.

Cochene and Franquin (1967) computed monthly water availability period with the help of modified rainfall and moisture lost over certain period. This modified rainfall \( P' \) is the sum of rainfall and ground storage (water available at the root zone) and this was compared with potential evapotranspiration (PET) calculated by Penman's method. They classified climate with the help of ratio \( P'/PET \). The following limits of water availability were chosen for classification:

<table>
<thead>
<tr>
<th>Range of ratios ( P'/PET )</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 or more</td>
<td>Humid (H)</td>
</tr>
<tr>
<td>1 - 1/2</td>
<td>Moist (M)</td>
</tr>
<tr>
<td>1/2 - 1/4</td>
<td>Moderately Dry (MD)</td>
</tr>
<tr>
<td>1/4 or less</td>
<td>Dry (D)</td>
</tr>
</tbody>
</table>

This approach was used to demarcate the climates of the regions south of Sahara in West Africa. The method suggested by them has some merits in that the length of growing seasons could be determined for particular location. It has also overcome many of the shortcomings mentioned earlier. The additional data needed to compute modified rainfall makes the approach difficult to adopt on regular basis. This method also does not take into account the risk involved in agriculture at a place. This approach has also been used by Brown and Cocheme (1969) for classifying climates of the high lands of Eastern Africa.

### 3.2.4.1.1 Growing Period Involving Risk Factor

Studies mentioned so far do not deal with the risk factor involved in any planning. It goes without saying that the planner, be a farmer or an agricultural scientist, must know the risk he is going to take in his endeavour. The study using average or normal rainfall cannot include this factor. In the dry farming tract or low rainfall areas, there is considerable year to year deviation of rainfall from the normal. In such a low rainfall area, the normal rainfall (monthly seasonal or annual) quite often is far too short of the water requirements of the crops. But experience shows that on a number of occasions crops are successfully raised. In such years the rainfall is more than the normal value and meet the water demand of the crops. So, for the purpose of any crop planning, one should know from long records the chance of meeting the water requirements of the crops. Accordingly, the planning has to be done on a probabilistic basis, which eventually takes into account the chance of successor failure. This aspect of the risk factor associated with any planning purpose was dealt with by Wallen and Perrin (1962) for the first time.
Wallen and Perrin (1962) classified the climate of mediterranean area (where annual rainfall varies from 300 to 500 mm) and tried to find out agricultural suitability. In this study they used the probability of receiving certain amount of annual rainfall, inter-annual variability and continentally. This is an important step. While planning for the cropping pattern, development of irrigation project, etc., the planner should have an idea of the risk he is taking in accepting a certain crop growing period. It is obvious that the action taken by the planner will depend heavily on the choice of the risk level. Based on this study, Wally and Perrin (1962) divided the mediterranean area into twelve climatic zones and suggested short duration crops for certain zones.

Hargreaves (1971) used, in his classification of identifying growing period, monthly probabilistic rainfall value at 75% probability instead of the normal rainfall. He used the incomplete gamma distribution to compute such values. He classified the agroclimate of an area on the basis of monthly moisture availability index (MAI) defined as:

\[ \text{MAI} = \frac{\text{DP}}{\text{PET}} \]

where DP (called dependable precipitation) is the precipitation at 75% probability level and PET is estimated potential evapotranspiration (Penman’s method). He computed crop growing periods on the basis of MAI. The period when MAI is less than 0.34 has been considered by him unsuitable for growing crops. The emphasis is on how continuous and long is the period during which MAI is equal to or greater than 0.34. He classified the climate into our groups viz. (i) very arid, (ii) arid, (iii) semi arid and (iv) wet arid and accordingly suggested crop potentials of different durations. In very arid climate MAI is less than 0.34 for all the months and the region is not suited for rainfed agriculture. MAI in an arid region is more than 0.34 for one to two months and so it is partially suitable for rainfed agriculture. In semi-arid region, MAI > 0.34 for three to four consecutive months and crops requiring 3 to 4 months growing period could be raised here. Wet arid is defined as areas where MAI is more than 0.34 for five or more months and long duration crop has been suggested for this region. In 1975, he brought out the relationship between MAI and degree of moisture deficit and combining the two he added two more groups for high rainfall zones in his early classification. This work has been done with special reference to NE Brazil.

Hargreaves classification provides answer to a number of important agricultural questions, such as the risk involved, the degree of moisture inadequacy and identification of the crop growing periods etc. But there are three major shortcomings in it viz. (i) month as the unit of time which is too long a period, (ii) consideration of only one probability level i.e. 75% and it is too high a limit for low rainfall areas, and (iii) assumption that fair growth can take in all stages of life of the crop when moisture supply (precipitation) is hardly one-third of potential evapotranspiration.

Sarker and Biswas (1980) improved Hargreaves classification by introducing three modifications, viz. (i) weekly MAI instead of monthly, (ii) different risk levels instead of one so that the planners can choose their own risk level and (iii) MAI > 0.3 and also >0.7 depending upon the crop growth phase. In this study, moisture availability index was defined as follows:
Moisture Availability = Weekly assured Rainfall
                      Index (MAI)                             Weekly Potential Evapotranspiration

Assured rainfall required to compute MAI has been obtained by fitting incomplete Gamma Distribution to historic weekly rainfall data.

On the basis of the weekly MAI at 50% level a broad classification was made which was sub-divided on the basis of the duration of water stress period. This MAI has however been computed for all decades (10...90% probability levels). Considering MAIs at all the levels a suitable level for crop growing can be selected for each zone depending upon the duration of adequacy of moisture.

There are many regions especially in the tropics where rainfall distribution is bi-modal. In this area MAI may be less than 0.3 during the mid season which affects crop very bitterly. As crop can bear at least one week water stress period, they indicated three types of water stress depending on the MAI less than 0.3 for 2 to 3 weeks, 4 to 5 weeks and more than 5 weeks. Further, the end of rainy season does not mean the end of growing season because crop can thrive on the stored moisture. It is, therefore, necessary to find out the amount of moisture stored in the soil at the end of the season when MAI is 0.3. The difference between seasonal assured rainfall and 2/3 of PET of corresponding period will go into stored soil moisture and plant can use it after the end of rainy season.

Biswas (1982) and Sarker and Biswas (1986) modified their classification to include mid-season water stress and duration during which crop can thrive on stored moisture at various risk levels. Fig. 12 depicts growing periods at different probability levels of two stations situated in the semi-arid tropics of India. Growing period significantly differ due to mid-season water stress period.

### 3.2.4.2 Temperature Indices

Temperature is perhaps the next most important weather factor that influences the growth, development and yield of most of the agricultural production. Temperature above a certain threshold value seems to be favourable for optimum growth although cultural practices and varietal factor may alter this value. Maximum and minimum temperatures together with light intensity and duration are normally used in assessing the impact of temperature on crop production. The concept of degree-days holds that the growth of a plant is dependent upon the total amount of heat to which it was subjected during the life time. On a certain day, if the temperature is above a datum value for \( n \) hours and the mean temperature during that period exceeds the datum point by \( m \) degrees, the accumulated temperature for the day is \( n \times m \) degree-hours or \( n \times m / 24 \) degree-day. By summing up the daily entries arrived in this way, the accumulated temperature above or below the datum value may be evaluated for a period such as a week, a month, a season or a year. This degree-day will differ from crop to crop and even for various phenophases of the same crop. For example this reference temperature found for sugarcane by Walter (1910) was 21°C. This concept of degree-day has ready application to agricultural activities. When using degree-days as an indicator, allowance must be made for other
events such as drought, because physiological response depends on a number of factors in addition to temperature.

3.2.5 Soil Temperature

Soil temperature influences the climate of the environment close to the ground surface and also atmosphere aloft. It is one of the important factors that control microbiological activities and processes involved in the production of plants. The rate of organic matter decomposition and the mineralization of organic forms of nitrogen increase with temperature. Consequently, the amount of organic matter that remains in soil is greater with lower than with higher temperature.

The rate of germination of seeds, and of root growth depends on the soil temperature. Seeds of different plants vary in their ability to germinate at low temperatures. Germination is slow process in a cold soil. As the temperature of soil rises, germination becomes more rapid up to a certain optimum temperature then falling off as the temperature rises further. The temperatures required for temperate crops are typically lower than for tropical crops is about 30° and then decreases. The best germination occurs at soil temperature ranging from 21 to 35° C depending on variety (Peacock and Heinrich, 1984).

Soil temperature affects root growth of plants and low temperatures hinder root elongation and show little branching, while high temperatures encourage finer and much more feely branching root system which subrises fairly rapidly.

Low soil temperatures at seedling time can be very harmful to crops, such as maize or sorghum, which need a high soil temperature for active seedling growth. At low temperatures seedling growth is very slow while the many parasitic fungi in the soil grow actively and rapidly and kills the seedling. On the other hand, seedling of the temperate zone cereals which are adopted to grow actively at these lower temperatures are relatively resistant to their attack. Water uptake from the soil is also influenced by the soil temperature. It increases at higher temperatures and reduces at lower temperatures.

3.2.6 Solar Radiation and Sunshine

Duration of sunshine and incidence of solar radiation have direct bearing on the photosynthetic activity of the plant. It has been observed that even under field conditions where mutual shading of leaves occurs, the photosynthetic rate increases, up to full natural intensity. The greater the incident radiation, higher the yield in many crops grown in the sub-tropical region. Duration of sunlight also plays a significant role in the development of tillers will be low due to considerable mutual shading. Many of the crops are adversely affected flowering due to lack of proper sunshine. Rice is a major crop of Asia, which is usually grown during the rainy season. When water becomes adequate, yield of rice in many areas depends on management of duration of sunshine period.
3.3 Climatic Hazards

The influence of climatic factors such as temperature, wind, moisture, sunlight, etc. on crops are closely inter-related and each is modified by the others. Daily, weekly or season variations in any or all of the climatic elements exceeding a certain limit alter the efficiency of plant growth and hence affect the agricultural production adversely. The effect of: (i) frost, (ii) hail, (iii) high wind, (iv) flood, (v) modified cyclonic storms, etc., on agricultural production, is described in the following paragraphs.

3.3.1 Frost/Extreme Temperature

The greatest agricultural risk associated with low temperatures is the threat of unseasonal frosts. Frost is the condensation that forms on cold objects when the dew point is below freezing. In the formation of frost, water vapour sublimates as a solid passing directly from a gaseous to a solid state.

Frost can form at any temperature below freezing. There are two kinds of frosts: (i) advection or air mass frost and (ii) radiation frost. There may be (i) air frost, which occurs when air temperature (usually in the standard stenvson screen) falls to 0°C or less, or (ii) ground frost, which occurs when temperature at or very near the surface falls to 0°C or less. In addition to advection and radiation frost, there is a special case of frost caused by loss of heat by evaporation. This occurs when cold rain showers which wet the leaves are followed by dry wind. This type of frost is considered to be of importance in Switzerland and other cold regions. Frost in these cases, occur while the air temperature is well above freezing.

The injury and death of plant caused by frost is due to the formation of ice crystals in and outside the plant cells. During dormancy, plants can withstand temperature lower than -10°C without injury, but once growth has commenced, temperatures a few degrees below freezing point may be fatal. Air mass frosts are common in winter in middle and high latitudes. They are problems primarily in relation to specific crops which are limited in their winter hardness. Actual plant damage may be the result of alternate freezing and frost heave in the soil. For production of most field crops, the only satisfactory solution to the problem of freezing and frost have in the soil. For production of most field crops, the only satisfactory solution to the problem of freezing is to avoid it. As far as possible planting should be undertaken after the potential danger is over. Selection of varieties which will mature before the beginning of the hazard, is yet another solution to this problem.

Damage due to radiation frost differs from freeze damage severity and in its occurrence. The radiation frost hazard is greatest during critical stages of growth. Germinating seeds are not often affected by surface frost, but young seedlings may be killed unless they are of frost-hardy varieties. Crops like potatoes, tomatoes and melons are vulnerable right up to maturity. The flowering stage is a critical period for most of field and orchard crops.

Avoidance of crop damage due to radiation frost is more important. Conditions of occurrence of frost are (i) prevailing stable air mass with cool surface temperature, (ii) clear sky
to allow loss of heat by radiation, (iii) little or no surface wind (iv), a relatively high dew point temperature and (v) topographic features which induce drainage of cold air into depressions. It is the latter factor which accounts for the spotty distribution of frost. Forming of frost crystals on plant depends on the dew point of the air. If cooling takes place till the dew point is reached at a temperature above freezing, the latent heat is released by formation of dew and retards further cooling. Below 0°C, frost will form. This process also releases latent heat, which explains why such frosts of short duration cause little or no damage. Evaporation of water from soil or plants especially after a previous rain, also serves to reduce the temperature at ground level and it is frequently a contributory cause of frost.

3.3.1.1 Frost Protection

Frost protection can be passive or active. Passive methods include agricultural practices such as clean cultivation, maintenance of proper soil moisture, wrapping of plants with insulating material and enclosing the basal part of the plant, proper selection of location, choice of growing season and breeding of cold resistant varieties. Most of these passive methods involve environmental modifications. These passive methods are also effective against advective frost. The active methods of frost protection are many. The most commonly used methods are heaters, wind machines, sprinkling and weather forecast.

Passive methods

(i) Site Selection:

Proper site selections for planting high value frost-sensitive fruits and vegetable crops are needed. Since cold air drains into low areas and pockets, planting sites should provide for natural air drainage into lower areas. Fence rows, wind breaks, or heavy vegetation may block air drainage and should thus be avoided in establishing planting in frost-hazard locations.

(ii) Plant management:

The following management procedures are useful for frost protection:

- Plant stand should be such so as to allow maximum air drainage.
- Planting should not be done before the recommended date.
- The beneficial influences of good soil fertility and adequate water supply should be exploited
- Pruning should be done to advantage.
- Chemical and plant hormones should be used to promote frost hardiness.
- Plant selection and breeding should be done to suite frost occurrence.

Varieties of certain fruits which blossom at the same time show quite marked
differences in susceptibility. Therefore, the breeding of resistant varieties, susceptible varieties offers good prospects.

**Active methods**

(i) **Radiation interception:**

Radiation frosts occur on clear nights because of the absence of clouds that would otherwise absorb some longwave radiation emitted by the surface. Artificial clouds of smoke or smoke screens are sometimes used to intercept thermal radiation from the surface. Smudge pots burning oil and smoke frequently been used for this purpose.

(ii) **Thermal Insulation:**

Nights of radiation frost are generally proceeded by clear days during which the soil receives heat from the sun. Where frost-threatened plants are small, it is possible to protect them by covers usually termed "hot caps" are quickly placed over small plants in the late afternoon and removed on the following morning.

(iii) **Air mixing:**

Frost can be disrupted by agitation and mixing of the warm air above with the colder air below. This is done with the help of engine driven propellers and fans.

(iv) **Direct air and plant heating:**

The existence of the temperature inversion during radiation frosts provides the physical basis for yet another means of frost protection. Air heated near the ground will become buoyant and rise to a level where ambient air is at the same temperature. If air temperatures are raised to a few degrees above freezing by controlled heating, the heated air will remain under a "roof" provided by the temperature inversion. Then the volume of air below that level will be warmed. The air temperature can be maintained above freezing only by a continued input of heat.

(v) **Application of water:**

Water can be used effectively to prevent frost injury. Fields may be flooded as a means of protecting crops from frost. Another, more effective use of irrigation water in frost protection is by sprinkling.

(v) **Soil Manipulation:**

Soil temperatures reach their peak in the fall. Thus, under conditions of radiation frost in falls, it may be possible to use the heat stored in the soil to mitigate the effects of frost. Irrigation prior to frost has sometimes been observed to result in reduction or avoidance of frost injury. This effect may be explained by the increased thermal conductivity that results when soil is wetted. When soils are warm, this increased conductivity may permit a significant increase in soil heat flux to the surface and to the air above.
3.3.2 Hailstorms, Thunderstorms and Duststorms

These are known as local severe storms. About 44,000 thunderstorms occur daily over the entire earth. They reach their greatest frequency in equatorial latitudes, where the occurrence is much larger over the warmer lands than over the oceans. From equatorial latitudes, there is a general decrease in thunderstorm frequency towards the poles. Thunderstorms are very rare beyond latitudes 60° or 70°. Thunderstorms caused by surface heating over land are most common in summer. They are always associated with unstable air and strong vertical motion that produce clouds of the cumulonimbus type. A great deal of energy for their development comes from the release of the latent heat of condensation in rising humid air.

There are points of similarity between thunderstorms, dust storms and hailstorms in their fundamental mechanism. In absence of sufficient moisture in the atmosphere, only duststorms occurs when enough moisture is present, a thunderstorm occurs.

A hailstorm is particularly a violent thunderstorm. Hail grows inside the cumulonimbus cloud in the zone of super-cooled water. The local distribution of hailstorms is rather peculiar. The conditions for strong vertical currents, which are a pre-requisite for hailstorms, would be best developed in tropical or sub-tropical areas, but the high temperatures in these areas forestall the formation of ice. The largest number of hailstorms take place in latitudes between 30° and 60°. In polar regions, where freezing temperatures are most frequent, intense vertical convection is absent. The best conditions for hailstorm formation are over inland mountains and plains where intensive heating leaders to instabilities in the air.

These local storms can cause severe damage to the standing crop by causing mechanical injury to the plans. In dust storms, the dust is raised by the wind and is carried several kms away. It causes damage to the plants, particularly small plants by covering them fully with dust. Hail causes direct damage to the plants. Local hailstorm may be a disaster, although over large areas it is a minor hazard compared to drought or the effects of low temperatures. The degree of damage depends on the stage of growth of the crop and upon the intensity of the hailstorm. Because hail is most common in the warm season, it frequently catches crops at a critical stage, pounding young plant into the ground, shredding leaves, or shattering flowers and seed heads.

3.3.2.1 Prevention

The present methods of hail suppression is to add freezing nuclei so as to produce smaller ice particles and thus promote the growth of hailstones of smaller size than nature would produce. Another method of hail suppression involves glowing coalescence and accretion process by introducing great numbers of condensation nuclei into the storm updraft, thus reducing the average drop size and narrowing the drop size spectrum (Wickmann, 1953, 1964; Ludham, 1958). The material used in hail suppression is mostly silver iodide. Russian investigators introduced the silver iodide particles by rocket into the cloud (Sulakvelidze, et al., 1967). The hail suppression research in the Caucasus and Transcaucasus area, on the basis of empirical evidence, has convinced that the technique is highly successful in hail suppression (Baltan, 1965). Results of hail modification activities appear to be mixed.
3.3.3 High Winds

Wind has its most important effects on crop production through the transport of moisture and heat. Movement of air increases evapotranspiration, but the effect decreases with increasing wind speed and varies among plant species. Moderate turbulence promotes the consumption of carbon-dioxide by photosynthesis. Wind may speed chilling of plants, or on occasions, prevent frost by disrupting a temperature inversion. Wind dispersal of pollen and seeds is natural and necessary for native vegetation and helpful for crops, but is detrimental when weed seeds are spread or when unwanted cross-fertilization of plant occurs. Continuous strong winds interfere with the pollination activities of crops. Direct mechanical effects are the breaking of plant structures, lodging of hay and cereals or shattering of seed heads. Fruit and nut crops may stripped off fan trees in high winds. The unfavourable consequences of soil depletion by some form of erosion. Low plants are sometimes completely covered by wind-blown sand or dust, abrasion of plant stems an leaves by sand particles is often associated with wind erosion. Along the shores of salt lakes and oceans, salts transported inland by the wind affect both plants and the soil.

3.3.3.1 Prevention of High Wind

Mechanical damage due to wind can be lessened somewhat by making use of natural or artificial shelter. Protected valleys and low slopes are suitable for some types of crops which are easily damaged by wind. Wind-breaks such as trees, shrubs, hedges of fences are widely used to protect crops. Some plants require only temporary protection which can be provided by screens or individual wind-breaks.

The reduction in wind speed caused by the presence of a wind barrier has real influence on the microclimate of the surrounding area. Modifying the microclimate can greatly influence the growth of plants in the protected area. The extent of protection is a function of height, density and width of the wind-break, the distance between wind breaks and their orientation to the prevailing wind. The permeability of the density of the shelter is probably the most decisive factor in determining wind speed reduction. Three main types of wind-barriers/shelter belts may be considered. Firstly, barriers of medium and uniform permeability from soil surface to the top of the barrier; secondly, dense or very dense barriers, and thirdly barrier of the "alley" type i.e. rows of tall trees without branches or shrubs. Dense barriers have the greatest wind-reduction zone immediately behind the barrier. Wind speed recovers sharply after the minimum is reached. Well designed wind-breaks are typically 50% porous and have a spacing of 10 times the height difference between wind-breaks and the protected crop (Brown, 1972).

3.3.4 Cyclonic Storms and Depressions

Cyclonic storms and depressions mostly develop over ocean/sea areas in the latitudes between 5° and 15° of both the hemispheres. Many of them enter into inland and cause widespread rainfall over the land. These storms and depressions are also accompanied with high winds and occasional tidal waves. High winds, heavy rainfall and tidal waves cause widespread destructions of crops, lives and properties. Their effects are severe in the coastal areas. Heavy
wide-spread rainfall causes flooding. High winds of the order of 100 km/hour can cause complete physical destruction of the crops, even large trees are uprooted or their trunks are broken.

Prominent areas from where cyclonic storms originate are the Pacific storms originated from the Pacific Ocean move in a westerly or north westerly direction, causing damage in the Philippines. Some of them curve again towards the north/north-east, affecting Taiwan and southern and eastern parts of China. Typhoons moving towards south adversely affect Fiji, Papua, New Guinea and eastern part of Australia. Almost every year, Caribbean region is affected by devastating hurricanes resulting in loss of crops and property. On an average about 18 storms/depressions form in The Bay of Bengal affecting adversely India and its neighboring countries. Cyclonic storms originated in the south-wester part of Indian ocean pass across Mauritius and some eastern parts of Africa.

3.3.5 Flood/Excess rainfall

Severe flooding caused by heavy rainfall is associated with cyclonic storms in areas where these storms cross the coast. Heavy rainfall with high intensity causes flooding and water logging, this damage standing crops. Lack of oxygen under water logged conditions quite often results in decrease of water absorption and transpiration. The effects of persistent water logging and consequent poor aeration vary widely depending on variety of crop as well as the duration of flooding, stage of crop and temperature conditions (Hendricks, 1972). Some crops like rice etc. thrive well in flooding condition.

Excessive amounts of water in the soil alter various chemical and biological processes, free movement of oxygen is blocked and compound toxic to the roots are formed. The prolongation of such a situation, or even its occurrence, may be due to poor drainage and can be overcome by correct drainage practices. A soil with high rate of percolation is unsuitable for cultivation as, when heavy rain occur, nutrients in soil can be removed rapidly. Heavy rain damages plants or interferes with flowering and pollination. Heavy rain tend to pack the top soil layers and delays or prevents the emergence of tender seedlings.

3.3.6 Other factors

There are many other factors that hamper the proper growth of crops and ultimately cause reduction in yield. Many of the dryland plants can give reasonably good yield if the air humidity remains at higher level as these plants have inbuilt capacity to extract moisture from air. High humidity during harvesting time can damage crop by delaying of drying of cereal crops and loss of seed and fibre of cotton plant. High humidity encourages the occurrence of crop pests and plant diseases. The formation of blight and recurrence of many of the pests are often due to higher humidity with some threshold temperature. Low humidity increases the desiccating power hence evapotranspiration will be more.
Prolonged absence of rain or scanty rain may create a condition unfavourable for crop production and plant growth. This upsets the normal water supply to the plants and reduces the crop production. This may lead to a condition of 'drought'. Wide-spread drought can create havoc on production systems. Agricultural drought may be defined in terms of the water need of crops growing under a specific combination of environmental conditions. It occurs when rainfall amounts and distribution, soil water at the root zone and evaporation losses combine to cause crop or livestock yields to diminish markedly. The results are heavy reduction in agricultural production and consequent insecurity of food supplies. It creates poor grazing conditions, low farm labour and low efficiency of investment.

Drought may be of three different forms viz. permanent, seasonal and unexpected. Under the permanent drought conditions of the arid or desert climates. It is appropriate that water must be applied at all time if a crop is to survive. For seasonal drought, allowance can be made by the proper application of regular irrigation. The most treacherous phenomenon is the unexpected drought, for, due to variations in rainfall pattern from the average, a long dry spell can catch the farmer/cultivator completely unprepared. In such a case almost total loss of a crop can occur. With present art of knowledge occurrence, continuation and cessation of drought can not be forecast reliably but its adverse impacts can be mitigated or avoided by taking timely suitable action by National Meteorological or Agricultural Departments.

3.3.7 Conclusion

Proper management of various weather parameters plays a major role in crop production at any place. For agricultural purposes, it is necessary to identify the main climatic factors of production. In the tropics moisture is the limiting factor of agricultural production and temperature in the medium and high latitudes. Proper emphasis should be placed on the prime factor of production depending on the region.

Agricultural planning should be drawn on the basis of probabilistic rainfall amount instead of normal rainfall especially in the low rainfall areas. This will help to know the chances of crop success and failure in a region where aberration is a rule rather than exception. Crop growing periods need to be computed with the help of probabilistic rainfall of appropriate time unit and atmospheric demands of a place to know moisture or temperature adequacy so that a suitable crop can be selected to get optimum yield.

Mid-season water stress period, stored soil moisture at the end of rainy season and additional water resources from run-off etc. are of enormous importance in assessing crop potential of low rainfall areas of the tropics.

Effects of hazardous weather can be minimized by the information on frequency of occurrences.
Better results in crop management can be achieved with the joint efforts or multi-disciplinary group comprising of those concerned with climate, soil and crop.

3.4 Practical Use of Agrometeorological Information in Agronomical Practices

3.4.1 Introduction

The farmers while making decision on day-to-day agricultural operations encounter many weather-sensitive problems. These problems may be handled more efficiently if he can be advised in light of short and medium range weather forecasts. The application of meteorology during agronomic practices demonstrate considerable economic value with very high

Agrometeorological application to the agronomic practices is diverse. Agrometeorological information may suggest better ways for selection of sowing time, preparation of field, application of fertilizers and pesticides, protection against adverse weather, irrigation scheduling, harvesting and post-harvesting operations because all these operations are weather-sensitive. The decisions regarding these farming activities must utilize weather forecasts and advisories to economic advantages. Practical use of agrometeorological information for some of agronomic practices is given below:

3.4.2 Tillage

The tillage practices are done to attain specific soil structure. In areas where water is scanty, loose layers of soil is created to conserve soil moisture. This type of dry mulching break the capillary connections and inhibit the upward movement of water, hence conserve it in the lower layers; contrary to this, compaction of top soil is desired in frost bound areas to increase its heat conductivity. This technique reduces frost liability of crops and is successfully practiced for the plantation crops. In the European climate, the loosening of the upper soil layer to a depth of 2 cm will lower the night minimum temperature by 2°C for moist soil and 3°C for dry soil (Geiger, 1965).

3.4.3 Irrigation Scheduling

The modern concept of irrigation shows that the water requirements of the crops is mainly determined by the climate. Evapotranspiration by a species is a physical process and involves conversion of water into vapour which requires energy. This energy is received from the sun and
wind. From the weather data, therefore, values of evapotranspiration by crop plants can be estimated. The knowledge about evapotranspiration losses of different crops helps answer two vital questions in irrigated farming, viz. when to irrigate and how much to irrigate.

3.4.4 Application of Fertilizers

The nutrients have to be supplied in balance with the expected moisture regime. As the later is generally unpredictable in dry regions and also extremely variable, determining the correct amounts of fertilizer application is one of the most difficult decisions which the farmer has to take. Also, the time and method of fertilizer application is to be correctly chosen depending upon prevailing atmospheric conditions. Hence, the question of fertilizer application cannot be dealt in isolation with that of weather.

Moisture is the prime requirement for dissolving the fertilizer to facilitate absorption of nutrients by the plant roots. However, excess precipitation invariably leads to leaching water in excess of what is required and will seep to lower levels taking soluble nutrients including those applied efficiency of fertilizer. In general, for a given soil type the efficiency of fertilizer application decreases with decreasing precipitation and with increase in evaporation. Therefore, agroclimatic analysis is required to ascertain effectiveness of fertilizer application and to know the minimum level of effectiveness consistent with a net gain in profitability over a number of years.

3.4.5 Protection Against Pests and Diseases

Sussenberger (1968) described a service established in 1967 by the Government to combat potato blight in Germany. Before 1967, the crop was formally sprayed on a regular basis for potato blight. Since 1967 producers have applied sprays only according to meteorological conditions. Curtailment of one spray application saved US $ 5 per hectare.

Giovanellit (1968) estimated that with meteorological information, Bordeaux vine growers in France eliminated 2-3 pest control treatments each year, saving FF 26 million annually. He also estimated that meteorological information in expand France eliminated one treatment a year in vineyards, saving FF 21 millions.

There exists a complicated interaction between pests and diseases and the weather which prohibits simple generalization. A knowledge of the life cycle of the pest or pathogen and its weather-sensitive phases is quite useful to investigate this intrinsic interrelationship and also to adopt suitable cultural practices for their prevention. The efficiency of application of insecticides and pesticides often depends upon a covering of moisture on the plant tissue. A thin film of water helps adhere the dust particle and spray droplets to be spread and diluted. The amount of water needed for adherence to the foliage is small and even the dew formed during nights may be sufficient. Hence application of dust in the morning is more useful. At the same time, too much of water would be detrimental.

Application of herbicides and their effectiveness are influenced by soil moisture and by temperature. Equally, the persistence of agricultural chemicals in the soil -possibly beyond
the desired period is effected by soil properties and conditions which, in turn, depend upon rainfall and evaporation, sunshine, temperature, humidity and wind.

From the foregoing discussion, it is obvious that meteorological expertise and advice could make a valuable contributions to decisions regarding the application and effectiveness of agricultural chemicals.

3.4.6 Crop Harvest

Before making a decision on harvesting, in general, the farmers allow to let the crop foliage dried which is considered as an apparent signature of the crop maturity. Hence, if crop is harvested at the right moment, i.e. just at the time when physiological maturity is obtained, one can save a lot of soil moisture to be utilized by a successive crop.

At the time of harvesting of corn in Germany, its water content should not be more than 17-20 per cent, otherwise special drying facilities are necessary. But due to rain and dew, the grain is often too moist during the harvest period. Knowledge of the weather conditions during the harvesting period enables the calculation of the period during which the moisture content of the grain will be less than 15 or 20 per cent as a result of meteorological conditions. This knowledge can be used for planning of harvesting so that artificial drying of the grain will not be necessary.

Fresh peas become worthless due to above normal temperature at the time of harvest. Anderson (1973) showed that extended-term forecasts of about one week can be useful to pea processors by giving them enough warning to let them harvest extra acres.

3.5 Crop-weather relationship

3.5.1 Crop Response to weather parameters

Crop weather relationship brings out the impact of weather parameter(s) on the growth, development of a particular phenophase or whole life span of a crop. It helps one to interpret the influence of meteorological parameters on crop growth and estimate the reaction of crop development to specific climatic factor or combined effects of different parameters. Thus it becomes a means to explain plant growth, development and final yield as a function of physical, chemical and physiological processes. It also provides an explanation as to why some factors are more important for growth and yield than others.

Temperature and rainfall or moisture are two main climatic factors on which growth and development of crops depend, although the combined impact of number of factors including those of weather is required to be taken into consideration to get ultimate product. It is not only the total amount of rainfall but its distribution during the growing period that determines the growth and yield. Impact of particular weather factor differs significantly at different growth stages of the same crop or for different crops. The relationships that exist between crop and weather can be evaluated using various techniques varying from simple correlation to dynamic modelling. Adequacy of a technique depends on the objectives. Resource virtually determines the type of techniques that can be applied. Resource is one on which one depends for help, aid and support.
A simple technique may be applicable for a particular case but it may not serve the purpose in other cases.

The importance of reliable estimate of yield for any area or a particular crop in advance of harvest needs little emphasis. It gives national government, planners and decision-makers enough time to make an early assessment of the overall food production in the country, so that policy decisions on price, import/export, storage and public distribution can be taken in time.

3.5.2 Effects of Weather on Crop Phenophases

Each crop has its critical stages and particular climatic factor becomes important at a certain stage as its effect can be felt easily either positively or adversely. These have been discussed briefly in this section in respect of some major crops.

3.5.2.1 Rice

Rice needs high temperature and is usually grown in tropical region where temperature is high. Some of the varieties can withstand even low temperatures. Nishiyama (1976) identified the favourable range of physiological processes of rice plant as approximately 17-32°C. McDonald, et al. (1974) found 30°C as the optimum temperature of net photosynthesis of ten cultivars found over different parts of the world. The tillering stage is sensitive to temperature and photoperiod (Robertson, 1973). Owen (1971) observed optimum air temperature ranges for rice as 20°C minimum to 30°C maximum. Optimum temperature for water was 25-30°C (Downey and Wells, 1974). Duration of bright hours of sunshine plays a significant role in rice cultivation. Sunshine must be always present for photosynthesis to occur. Many of the rice growing regions in Phillipines get limited hours of sunshine during the last 45 days before harvest that leads to decrease in yield significantly (Baradas, 1985).

Low land rice is usually cultivated in flooded conditions. Total Evapotranspiration (ET) which is evaporation from water and transpiration from plants may not differ very much during the life span of a particular variety at a given place. The total ET of rice can increase with increasing evaporative demand. It is reported that in low land rice cultivation, evapotranspiration can range from 538 to 821 mm (Brown, et al., 1872), while at upland conditions ET values of 409 mm have been reported. The water use increase with each successive growth stage, peaking during booting and decreasing thereafter. Matsuo (1959) reported that transpiration ratio ET/EP (water transpired/water evaporated) were 0.5, 1.0 and 1.3 at three growth stages. A few weeks after heading the transpiration ratio had dropped to 1.0 and continued to decrease. Lysimeter study in India (Rao, et al., 1976) indicated that ET/EP ratio remains almost 1.0 during the whole life period from swing to harvest at Canning. However, ET/EP ratio at Nellore shows a progressive increase to 1.4 until 50% flowering. From this peak value, the ratio declines sharply and remains at 1.0 until harvest.

Water stress has a serious impact at panicle initiation stage that may reduce yield by about 30% whereas Matsushima (1978) found that the effect of water stress had the most serious effect during the division stage. The second and third sensitive stages were flowering and spiklet differentiation respectively.
3.5.2.2 Wheat

Wheat can withstand wide range of temperature due to varietal differences. The main wheat growing regions of the world lie between about 30° to 55°N and 25 to 40°S (Kirkham and Kanematsu, 1982) where temperature, in many cases goes below freezing. For most satisfactory growth and development of grain, a cool, moist growing season followed by a bright, dry and warm ripening period of 5-8 weeks, with a mean temperature of 16-19°C is necessary. The minimum temperature for growth of wheat is 3-4°C and maximum is about 30°C. Asana and William (1965) found that day temperatures exceeding 25°C depressed grain production. There are some winter varieties that require low temperatures.

Water requirement of wheat is comparatively less than rice. From emergence to tillering, the young plants use very little of water. Irrigation or heavy rain during this period has adverse effects. Some degree of moisture stress during this period may even be beneficial (Lehane and Staple, 1967). Water requirements increase during the period of maximum vegetative growth. Moisture stress during flowering has very much adverse effect (Fig. 13) on grain yield reduction (Van Brakle, 1980).

3.5.2.3 Sugarcane

Although sugarcane is a tropical crop, it is adversely affected due to temperature fluctuations. Effect of temperature is pronounced, particularly during germination. Fig. 14 gives the effect of temperature on germination and it indicates that temperature between 28 and 32°C is reported to be optimum for germination. In India, Subba Rao and Prasad (1956) reported that for proper germination the temperature should be between 20 and 32°C. According to Humbert (1968), whenever the temperature falls below 20°C, the rate of germination is reduced and at 10°C, it is suppressed. Flowering is very sensitive to temperature. Low temperatures with high humidity are more favourable for early flowering than dry sunny weather (Stevenson, 1963). According to Coleman (1968) night temperatures below 18°C. can prevent flowering. However, with plenty of sunlight, temperatures above 18°C are found to encourage flowering. For ripening, the crop favours low temperature and less humidity. A gradual reduction of these factors during four to six weeks before harvest significantly helps ripening and more concentration of sucrose (Kakde, 1985).

Tood (1970) compared the water needs of many crops and found that those of sugarcane are quite high. The crop requires water continuously and most of the water absorbed is lost in transpiration. In Puerto Rico, Shih, (1985) found from lysimeter experiments that the crop transpires about 3.8 mm of water per day on the average over a period of about 418 days. Cowan and Innes (1956) obtained a similar amount for a fully developed crop in Jamaica. Campbell, et al. (1960) obtained values in Hawaii ranging from 5.7 to 8.6 mm and also reported that about 50 mm of water is required to produce one gram of dry matter, similar values were obtained earlier by Cowan and Innes (1956).

From an experiment conducted in Hawaii, it was found that the daily ET of a matured sugarcane crop was about 3-5 mm in winter and 7-9 mm in summer. The annual consumption varied from 1800-2400 mm. Biswas (1988) reported from lysimeter experiments that average ratio of ET/EP was found to be about 0.5 at the beginning and raised to 1.4 after 8-10 weeks.
In the maturity phase, consumption was only 50-60 percent of that of the active growth phase and at the harvesting season ET/EP was about 0.5

3.5.2.4 Sorghum and Millet

Sorghum and millet are basically tropical crops. These are also grown in temperate regions provided the temperatures are sufficiently high. In the temperate regions they are grown only in the summer season, whereas in tropical countries they can be grown throughout the year. They are better able than most grain crops to withstand high temperatures. For sorghum the minimum temperatures are 7-10°C for germination and 15°C for growth. Optimum temperatures for growth are 27-30°C (Quinby, et al., 1958). Karper, et al. (1981) observed that temperatures exceeding 26°C during the heading period adversely affect the flowering. Peacock (1982) observed that the best germination occurs at temperatures from 21 to 35°C. This wide range of temperatures indicated that genetic variations play a vital role for optimum germination. In case of millet, germination rate increases linearly with temperature from a base of 10 to 12°C to a sharp defined optimum at 33 to 34°C and sharply declines to zero at 45 to 47°C (García-Huidobro, et al., 1982). Fig. 15 gives the root elongation of millet (CV BK-560) as a function of temperature. It appears that optimum temperature for root elongation is 32°C.

The damaging effect of extremes of temperature on the number of grains per panicle is well documented. Ong (1983) found that the reaction between the number of grains produced by two millet cultivars as a function of mean air temperature and optimum range is 22 to 25°C, above and below of which grain number declines sharply. In sorghum, it was also reported that increasing temperatures increased the rate of grain fill. However, above 30°C the rate of will is no longer increased.

The ability of sorghum and millet to produce good yield under conditions of low soil moisture that are unsuitable for any other grain crop, make them the 'camel' of the plant world. Complete failure due to limited rainfall is much less frequent for sorghum and millet than any other crops. They can produce grain and give some yield using 200 mm of moisture during their growing period (Cocheme and Franquin, 1967). These crops show the lowest rate of decline in relative turbidity and least diurnal depression compared to other crops because they reduce the transpiration rate to a much greater extent than other crops (Slatyer, 1956) ET reduction resulted in some yield reduction (Dennis, et al., 1982). Ratio of ET/EP varies during different growth stages of the same crop. This ratio was found to be 0.3 by Doss, et al. (1964) at the germination stage. Jensen (1968) observed that cumulative seasonal evapotranspiration for sorghum was found to be only 65% of potential evapotranspiration. Similar result for millet was found by Dancette (1978). Biswas and Khambete (1988) concluded from analysing ET data collected from lysimeters that during the life span, water consumption by sorghum and millet was 61 and 66 per cent of pan evaporation respectively and germination will not affect if these crops get water 25-30 per cent of pan evaporation.

3.5.3 Methods to Evaluate Crop-Weather Relationship

There are various methods used to establish crop weather relationship varying from simple correlation technique to complex models in which impact of different parameters are taken into account. Out of these the following approaches are commonly used:
Figure 3. Effect of water stress at various growth stages on grain yield reduction in wheat (Van Bacle, 1980)

Figure 4. Effects of temperature on germination as measured by plant height (Humbert, 1968)
Figure 15. Germination rate of pearl millet (cv BK-560) as a function of temperature (Peacock, 1982)

Figure 16. Actual and forecast yield of wheat of Punjab
1) Correlation techniques
2) Crop weather analysis models, and
3) Crop growth simulation models

3.5.3.1 Correlation Techniques

Crop weather relationships have been extensively studied by using simple and partial correlation techniques. Multiple regression analysis has been used by many. These techniques are, however, not adequate to bring out fully the complete relationships that do exist between crop and weather. In the linear correlation and regression studies, there is an inherent assumption that the change in the dependent variable, accompanying unit change in each independent variable is exactly of the same amount, no matter how small or how large the independent variable is. Crop weather relationship being not so simple, cannot be expressed by linear relationship always. However, it gives us first-hand relationship that may exist between crop and weather.

3.5.3.2 Crop-weather Analysis Models

Crop weather analysis models are defined as the product of two or more weather factors each representing functional relationship between yield and weather. These models do not require hypothesis of the plant and environmental process. The input requirements are less stringent but the output information is more dependent on the input data. Thus crop weather analysis models are a practical tool for the analysis of crop response to weather and estimating the yield. In these studies two methods have generally been employed, viz. (i) Fisher’s response curve technique and (ii) Curvilinear analysis.

The response curve technique is essentially one of fitting a orthogonal polynomial to a parameter to obtain a set of distribution constants of the weather elements during the period of crop growth and then working out a multiple regression of these constants on the yield. Thus, this technique takes into account mainly the distribution of weather factors in time. This regression can be adopted to evaluate the slow and continuous response of the crop to changing weather elements.

Due to inherent complexity of the problem, crop weather relationship cannot be expressed always by linear relationship. Also there may be an optimum point of a particular crop characteristics with regard to one or more of the weather factors upon which the crop characteristics depend. Such information may be brought out by determining the curvilinear relation. The curvilinear analysis is capable of bringing out crop weather relationships which are not possible by regression technique. It provides a basis for estimating probable effect of new combination of weather factors on yield. It also enables one to predict the yield before harvesting.
3.5.3.3 Crop Growth Simulation Models

Simulation models are being widely used to simulate the growth of crops and to predict crop yield. These models take into account the physical, chemical and physiological mechanism underlying crop growth processes. If the basic plant processes viz. production and distribution of dry matter and weather relations are properly understood, the entire response of the plant to the meteorological conditions can be simulated. Simulation provides and insight into crop weather relationship, explains why some factors are more important for growth and yield than others. The field situation is simulated from basic data determined earlier from controlled experiments. The problem of continuous crop condition monitoring for handling practical problems such as early warning, etc., can be solved by dynamic growth simulation models. There will be many sub-models within the main model which can simulate photosynthesis, respiration, transpiration and stresses. Incorporating these components, growth and development can be assessed on daily basis. Large number of experimental observations on both meteorological and biological are required to run these models.

Of the Russian models, one of the most developed as regards biology and physics is the dynamic model of the agro-ecosystem productive process developed by Sirotenko and Abashina. It is a closed system of differential equations describing the dynamics of the crop phytomass, soil moisture and available nitrogen content in the soil.

\[ \delta M_p = G_p - D_p - g_p - P_p \]
\[ \delta W_i = g_{i-1} - g_i - T_i - \omega_i E \]
\[ \delta N_k = H_k - \alpha_k V_k - h_k V_k - V_k - A_k \]

where \( \delta \) is a symbol indicating a derivative, \( M_p \) is the mass of the \( P^{th} \) plant organ (leaves, stems, roots, hulls on the ear, and grain are distinguished), \( G_p, D_p, g_p \) and \( P_p \) are the rate of growth, respiration, disintegration and shedding of tissue, respectively; \( W_i \) is the moisture reserve of the \( i^{th} \) layer; \( g_{i-1} \) and \( g_i \) are the water flows through the upper and lower boundaries of the \( i^{th} \) soil layer; \( T_i \) is the water loss on transpiration from the \( i^{th} \) soil layer; \( E \) is evaporation from the soil; \( N_k \) is the available mineral nitrogen content in the \( K \) soil layer; \( H_k \) and \( h_k \) are the rates of nitrogen mineralization and denitrification; \( V_k-1 \) and \( V_k \) are the mineral nitrogen flows moving with the water through the upper and lower boundaries of the \( K \) soil layer; \( A_k \) is the nitrogen absorption by the plants from the \( k^{th} \) layer; and \( \omega_i \) and \( \alpha_k \) are logical variables.

In this model, growth is understood to be the formation of the structural mass from the stock of carbohydrates produced through photosyntheses and the disintegration of aging structures. The crop's daily photosynthesis is a function of the PAR intensity, stomatal resistance, temperature, photoperiod, and leaf index. The time step is twenty-four hours. The model has been adapted for many grain and vegetable crops. The meteorological data needed for and vegetable crops. The meteorological data needed for running the model are mean daily air temperature (\( T \)), number of hours of sunshine (\( S \)), mean daily air humidity deficit (\( d \)), and daily total precipitation (\( R \)).

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The model simulated plant growth and development for the whole vegetation period, from sowing to maturity. As can be seen from the above description, it is distinguished by its fairly detailed representation of the plants' water and nitrogen regime. This makes it possible to use the model for a wide range of soil conditions and farming techniques with a minimum input of local data to calibrate the parameters.

The model is specifically intended for spring and winter wheat, barley and some vegetable crops in the Soviet Confederation, it is also used in Bulgaria for maize and sunflowers. The following tasks can be carried out using the model:

- Assessment of current agrometeorological conditions;
- Management of the production process (primarily irrigation);
- Assessment of anticipated climate change impacts.

The model has also been applied within the scheme for assessing the agrometeorological conditions for spring wheat and barley yield formation in the European part of the Soviet Confederation. This complex scheme ensures automatic assimilation of real-time meteorological information, computation of meteorological fields, determination of the dynamics of biomass, soil moisture, available nitrogen content in the soil, and yield estimates for nodes on the regular 60 x 60 km grid. For each node on the grid, the following indices are computed daily:

- Productive moisture reserves;
- Total evaporation;
- Potential evaporation;
- Current nitrogen supply for the plants;
- Area of photosynthetic activity;
- Above-ground plant mass.

First of all, a computer programme was created with the wide range of possibilities described above.

Using moder statistical methods, regression models were developed for forecasting the areal mean grain crop yield in several areas of Kazakhstan.

The delineation of areas with fairly homogeneous environmental and climatic conditions was done using hierarchical clustering procedures. The object under study was grain crop time series. For each of fifteen districts, each further divided into five zones, an interpolating trend was created to determine the meteorological components of the crop time series. First of all, the principle of external completion was used, i.e. the introduction of additional information about the object under study: a trend is selected from the class of polynomials from which the yield’s deviation is fairly closely correlated to the complex index of the agrometeorological conditions of grain crop vegetation.
The standardized deviations of the yield from the trends were then grouped into five clusters following the "year-station" principle. The regression models' predictors were based on the 10-day index of agrometeorological conditions (IAC), including the areal means (somewhat modified) of total precipitation amounts ($R_{i \text{mod}}$), air temperature ($T_i$), and the index of the conditions:

$$IAC = \alpha_i R_{i \text{mod}} + \beta_i T_i$$

where the parameters $\alpha_i$ and $\beta_i$ are calculated for each 10-day period which makes it possible to consider the crops' dynamic environmental requirements. A scheme has been developed for assimilating precipitation, whereby precipitation $R_{i \text{mod}}$ includes the precipitation of the $i$th 10-day period and the amount of precipitation in the $i$th 10-day period, if it exceeds a given value, depending on air temperature.

Based on 10-day meteorological data and the index of agrometeorological conditions, the potential set of descriptive variables was formed by averaging over the various sections of the vegetation period. The most significant variables were selected from it using Furnival's "all-regression" method and Mallows' criterion $C_p$.

Some new type of regression models have been used for modelling the impacts of the main weather factors (precipitation and air temperature): crest regression for cases of strong correlation between predictors, and robust regression for cases of deviation of the predicted value from the normal distribution and the occurrence of overshooting.

The characteristic of the regression's shifted crest coefficients is their lower dispersion compared with coefficients obtained by conventional means when the predictors are correlated in the robust regression method, it is not the sum of the squares of errors which is minimized, but rather than general function, as proposed by Huber (1972).

Using the quasi-random number generator, an independent data sub-sample was taken from the main sets to verify competing models which on the dependent sub-sample was formed from 10-13 year-stations.

Example: Equations for forecasting the deviation of all grain yields from the trend in Central Kazakhstan.

1) *For the two-month forecast (calculated at the end of June)*

$$\Delta Y_2 = 0.736 \text{ (index of June conditions)} + 0.188 \text{ (total precipitation during the cold season)}$$

2) *For the one-month forecast (computed at the end of July)*

$$\Delta Y_1 = 0.60 \text{ (index for June conditions)} - 0.12 \text{ (air temperature during third 10 days in June)} + 0.105 \text{ (total precipitation during the cold season)}.$$
In running the above yield forecast model, the extrapolation of the yield trend is of great importance. For the short term (3-5 years), a linear trend is used which takes account of how old the information is and the greater resistance of the trend to sharp yield fluctuations in particular years. The calculation was done using the iterative method of weighted least squares with appropriately fixed weights.

This model has been successfully used for forecasting yields since the beginning of the 1980s. Programs have been written for greater speed and convenience.

### 3.5.4 Forecasting Phenological Phases of Crops

Weather parameters, nutrients and management practices have a combined impact on the growth and development of particular phenological phase of a crop. The present condition of a crop has a direct bearing on the successive phenophase. A knowledge in advance of any phenophase of a crop is required for many practical purposes such as agricultural management practices to be taken at a future time and forecasting of ultimate crop yield. All the phenophases of a crop are not equally sensitive to weather parameters, in one stage direct impact can be felt easily and in other case it is not much prominent. Whatever may be the case, forecasting of crop phenophases need knowledge of earlier stage of a crop, meteorological conditions and other inputs given to the crop.

Numerous research workers have used various techniques to forecast the dates of crop phenophases. Weinberger (1968) used temperature in forecasting the ripening date of vegetable crops. Lomas, et al. (1970) and Lomas and Burd (1983) attempted using climatic and phenological data in forecasting ripening date and commencement and duration of the flowering period of citrus respectively.

Potato is a crop which requires low temperature and its growth in different phenological phases is dependent on congenial temperature. Flowering and tuber-initiation are directly associated with temperature. It is possible to forecast these stages from temperature alone (Moorby and Milthorpe, 1975, Midmore 1984). Germination of groundnut crop increases from 12°C to 31° and then decreases to zero at 48°C. A study on dry matter production of groundnut shows that the duration from sowing to the end of pod filling increases from 45 days at 31°C to 22 days to 19°C. Israeli, et al. (1988) developed a methodology using regression equation to forecast the distribution of flowering of banana in the Jordan valley in which they used the earlier flowering dates and agrometeorological data.

An example of a model to forecast phenological phases of crops is that developed for the tropical fruit guava (*Psidium guajava L.*) in central Mexico by Ruiz (1991). The regression equation developed for this model is as follows:

\[ TR = \frac{193}{T_1 - 9.29} + \frac{244}{T_2 - 13.8} + \frac{428}{T_3 - 10} + \frac{2076}{T_4 - 8.4} \]

where:
TR = Thermal requirement in days from first irrigation until the commencement of harvest
T₁ = Mean daily temperature for the period of first irrigation to plant sprouting
T₂ = Mean daily temperature for the period of sprouting to flowering bud appearance
T₃ = Mean daily temperature for the period of flowering bud appearance to flowering
T₄ = Mean daily temperature for the period of flowering to fruit maturity

The numbers in the numerator are the thermal constants determined for each phenological period of guava, that is the growing degree-days (GDD) required from one phase to another.

The way of use of the model at the practical operation level consists in replacing the mean daily temperature in order to know the approximate number of days required to reach a given phenological phase. Suppose we have to estimate the duration (in days) from flowering to fruit maturity, having a mean daily temperature of 25°C during this period.

Computation is as follows:

\[
TR = \frac{2076}{(T₄ - 8.4)} = \frac{2076}{(25 - 8.4)} = \frac{2076}{(16.6)}
\]

\[
TR = 125 \text{ days}
\]

3.5.5 Crop Yield Forecasting

Crop yield forecasting helps to estimate crop production much before harvest and thereby provides more lead time for planning and decision-making purposes at the national and international level. At the national level, pre-harvest estimates of crop yield/production would be useful to the policy-makers and planners for making advance planning of food imports or exports. It also helps in early recognition of areas of developing food crisis and in modification of national food policy in light of surplus or shortfall. It becomes an aid to the national Governments to decide the types of the relief measures to be undertaken on priority basis and provide alternate employment in the drought affected areas. At the international level, the agencies responsible could use such information in connection with the management of World Food Security Programme and in determination of donor and receptor in case of surplus and shortfall of food production, early recognition and continuous monitoring of potential areas of crop failure and the planning of food relief programme, etc.

Crop yield forecasting can be made using different techniques. Adequacy of a technique depends on the accuracy required. In some cases forecasting is done using one or two required. In some cases forecasting is done using one or two parameters, whereas in other cases number of parameters are taken into consideration which need sophisticated modelling. Type of the technique/model that can be used is dependent on resources. Resource is the one on which one can depend for help, aid and support. In many places, one has to satisfy oneself with a simple technique due to lack of resources.
3.5.5.1 Methods of Crop Yield Forecasting

There are three principal methods to forecast crop yields:

(1) Forecast based on eye observations on the growing crop;

(2) Forecast based on observations on biometrical characters made on the growing crop; and

(3) Forecast using meteorological and other inputs.

3.5.5.1.1 Forecast Based on Visual Observations on the Growing Crop

Crop yield estimation based on the crop condition reports made by agricultural officials seems to be the oldest and most widely used approach in the world, even though it is realised that it is capable of giving dubious results. In this method no weather factor is involved.

In many countries, there is more objective assessment of average yield on the basis of actual harvest of randomly selected plots. This technique is no doubt scientific than the earlier methods of crop estimations. However, for getting the estimates, one has to wait till nearly the crop harvesting periods.

In USA also the use of crop condition reports and a forecast of prospective yield in terms of weight per unit area is still in vogue. The reports from individual reporters are passed on the regional offices who in turn pass on the reports duly scrutinised to the central office. In the central office, these indicators are weighted by the area of the crop in the respective localities and a consolidated estimate for each geographical region derived.

3.5.5.1.2 Forecast Based on Observations on Biometrical Characters

To develop a suitable method for forecasting crop yields, it is necessary to discover specific plant characters which are useful predictors of yield. The advantage of selecting those specific plant characters is that these characters are the integrated effects of weather and other factors up to the time, when observations are recorded. Once these plant characters are identified, a suitable prediction model has to be developed, which could be used to relate yield with biometrical characters. The forecasts of crop yield based on biometrical observations in comparison to farmers’ or officials’ appraisals have at least two major advantages: (1) greater objectivity and (2) use of by-product information readily available or obtainable by making minor modifications. In regard to objectivity, farmers’ or officials’ reports may not reflect accurately the impact of recent changes in varieties and cultural practices. Relevant information which can be conveniently collected, include changes in components of yield over time and comparisons of yield characteristics among varieties or cultural practices. Further these also enable one to determine the accuracy of the predicted yield for a given set of values of biometrical characters.
3.5.5.1.3 Forecast Based on Weather Parameters

Weather exerts a pronounced influence on agricultural production. It may influence production directly by affecting the growth and structural characteristics of the crops such as plant population, number of tillers and leaf area or indirectly through its effect on the incidence of pests and diseases. The meteorological variables which may influence the plant growth are precipitation, soil moisture, soil temperature, maximum and minimum temperatures, sunshine hours, relative humidity, etc. Several studies have been carried out in different countries of the world on production of yield based on suitable prediction models. These models may be based on indices related to main climatic factor of production and on indices related to main climatic factor of production and yield and in other cases a complex model of many parameters. Two simple models using rainfall alone are discussed below.

a) Generalised Monsoon Index

The Generalised Monsoon Index (GMI) is a simple tool to monitor rainfall conditions during the monsoon season as well as overall crop conditions and expected yield in a qualitative way. The Generalised Monsoon Index can also be used in the crop yield forecast models to assess the yield in quantitative terms.

The Generalised Monsoon Index (GMI) is defined as follows:

\[ GMI = \sum_{i=1}^{n} W_i P_i \]

where \( W \) is the weight and \( P \) the actual monthly rainfall in the \( i \)th month \( i \), \( n \) is the number of months during which crop was in the field.

The GMI weight are given as:

\[ W_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \]

where \( R_i \) is the monthly normal rainfall in the \( i \)th month and \( \sum R_i \) in the normal seasonal rainfall.

b) Yield Moisture Index (YMI)

The Yield Moisture Index (YMI) is based on weighted monthly cumulative rainfall. The weights are functions of the crop water requirements and vary from stage to stage of a crop. The YMI is a simple index that helps the user to assess agroclimatic crop conditions during the crop season. It can be used as one of the parameters in the crop yield in a quantitative way.

The Yield Moisture Index (YMI) for any particular crop is defined as follows:
\[ YMI = \sum_{i=1}^{n} Pi Kc_{ij} \]

where YMI is the yield moisture index for the jth crop (rice, maize, etc.).

\(Pi = \) The rainfall during the ith crop stage
\(i = \) The crop stage. It assumes the following values:

1 = Planting or transplanting
2 = Vegetative
3 = Flowering/reproductive
4 = Maturity, etc.
\(n = \) Total number of crop stages
\(Kc_{ij} = \) The appropriate crop coefficient for the ith crop stage and jth crop.

The agroclimatic indices mentioned above are used for the assessment of crop yield in a qualitative way and also in statistical models as parameters for estimation of crop yield in quantitative terms.

c) Empirical-Statistical Models for Yield Forecasting

In this approach, one or several variables (such as weather factors, soil characteristics, biometric observations for a time trend representing technological advancement) are related to crop yield. The weighing coefficients in these models are obtained in an empirical manner using standard statistical techniques such as multivariate regression analysis. This methodology is a practical approach for forecasting of crop yield, thought it does not easily explain cause and effect relationship.

Many countries in the world are presently using these models for forecasting crop yields. In Canada, Williams, et al., (1975) developed an empirical relationship for predicting wheat yield using precipitation, potential evapotranspiration, soil texture, topography and trend terms. Baier and Robertson (1968) and Baier and Williams (1974) used soil moisture, rainfall, etc., for predicting cereal yields. In USA the work by Thomson (1969, 1975) is a typical example of the use of multiple regression analysis in crop forecasting. Such techniques are also available from Brazil, Mexico, Iran, Turkey, Israel, USSR etc. (Lomas, 1973; Villalpando 1983; Hashemi, 1973; Coffing 1973; Da Mota and Wendt 1975; Ulanova 1975 etc).

A few examples of such forecasting using this model are given below.

A model for estimating potato yield in Germany using the following function has been developed (WMO, 1955).

\[ X = 232 x_1 + 95 x_2 + 915 x_3 + 399 x_4 + 886 x_5 \]

where:
\[ X_1 = \text{Difference in mean value of air temperature for the second and first halves of the period between planting and sprouting} \]
\[ X_2 = \text{Average daily precipitation during the period between planting and sprouting.} \]
\[ X_3 = \text{Mean air temperature during the period between sprouting and flowering.} \]
\[ X_4 = \text{Average daily precipitation during the period between sprouting and flowering.} \]

A value of \( X \) between 4300 and 5300 corresponds to the standard yield. If \( X < 3500 \), the yield will be at least 25% higher than the standard value; if \( X > 6100 \), at least 25% lower; if \( 3500 < X < 4300 \), 10-25% higher; and \( 5300 < X < 6100 \), 10-25% lower.

India Meteorological Department has developed empirical-statistical regression models for forecasting paddy and wheat yield on meteorological sub-division wise basis where these crops are grown. Based on these models forecasts are issued during the crop growing season for these crops (Das, et al., 1971, Chowdhury and Sarwade, 1985). Besides weather and crop data a dummy variable called 'Technological Trend' is issued in the models. The use of hybrid varieties large scale use of fertilizers and insecticides, better irrigation and management, etc., have contributed for the sharp rise in yield. The increase due to all these factors has been combined and termed as 'Technological Trend' due to non-availability of separate yield figures for each of these components. In the models a factor has been introduced to account for the technological trend.

For the example the following equation has been developed to forecast wheat yield for Punjab:

\[ Y = 2355.4 - 53.16 X_1 + 91.1 X_2 - 33.62 X_3 + 97.91 X_4 + 2.08 X_5 \]

where:

\[ Y = \text{Yield in Kg/ha.} \]
\[ X_1 = \text{Mean minimum temperature (°C) during 2-11 January} \]
\[ X_2 = \text{Total number of rainy days between 8-15 February.} \]
\[ X_3 = \text{Mean max. temperature (°C) during 24 February to 2nd March.} \]
\[ X_4 = \text{Technological Trend} \]
\[ X_5 = \text{Difference between rainfall land PET (mm) during December and January.} \]

Following this equation, yield has been estimated. Fig. 16 gives the actual and forecast yield of wheat for Punjab.

It is important to note that in spite of its limitations, the statistical method may be a practical way to address a problem when resources are limited.

3.5.6 Conclusions

Crop weather relationship helps one to understand the impact of weather parameters on the growth, development of a crop and also brings out crop growth as a function of physical, chemical and physiological process. It has a great scope for practical application for
diversification of agriculture, viz., selection of suitable crop or varietys so as to enable to avail beneficial aspects of weather and ultimately increase yield. The relationship that exists between crop and weather can be evaluated using various techniques such as correlation techniques, simulation modeling, etc. Simulation process explains why some factors are more important for growth and yield than others and provides an insight regarding distribution of dry matter production.

Another practical application emerged out from crop weather relationship is quantitative yield forecast much before harvest. This becomes an efficient tool for national planners/policy-makers for advance planning for import, export and public distribution and at the international level in management of world food security programme and selection of donor and receptor in case of surplus and shortfall of food production.

### 3.6 Crop Protection - Agrometeorological Aspects of Pests and Diseases

#### 3.6.1 Crop Pests

Crop losses from pests are significant in both developed and developing countries. For example, losses from insect pests alone have been documented to be as high as 87% in sorghum and 57% in maize in Kenya (Walker, 1984). Overall pre-harvest crop loss due to insects in the USA, has been reported as 13% (Pimental, 1978). Losses may be due to either pre-harvest or post-harvest damage or both.

Agrometeorology is used in predicting the emergence or particular developmental stage of a certain insect pest. Until the environmental conditions exist, or have been "accumulated" as in the use of heat units, to allow a pest to reach the stage where action must be taken, it is not cost-effective to scout for the pest or apply treatments that are not yet needed. However, it must be noted that using agrometeorological information in carrying out better management of treatments is not appropriate for all pest problems. To limit or avoid damage from some pests, preventive measures must be taken before it is known the problem will develop.

Through research, the environmental requirements, usually heat and moisture regimes, have been documented for specific resident pests. With this knowledge and accurate agrometeorological data the presence of a particular pest may be predicted, i. e., managers can determine if the environmental pre-requisited conditions have been met to allow the insect to develop and exist as a threat to a given crop. Once predicted, actual field observations are used to confirm the presence of the pest and then regular monitoring can begin until the economic threshold has been reached which requires action (treatment).

Specific examples of insects for which the environmental requirements have been determined are described in proceedings of several WMO seminars, workshops and reports and other journals (EPPO Bulletin 1983; Krishnamurthy and Mathys 1989; Rijks and Mathys 1987, 1988; Thompson, 1986; WMO, 1988). These publications include numerous references to other publications on this subject.
3.6.1.1 Locusts and Other Migratory Pests

Agrometeorological information can also help predict the arrival of immigrant pests from source locations. Forecast trajectories provide guidance for the movement of airborne pests and thus provide some warning of pending arrival in an as yet uninfected location. The Desert Locust (Schistocerca gregaria) has received the most study. Presently, control methods use monitoring of seasonal breeding areas and movements of pest populations to form swarms. This strategy has proven successful and thus little damage has occurred since the Desert Locust plague in Africa began in 1949 and ended in 1962. Details of the methods employed are documented in Pedgley (1981).

Wind occasionally carry small numbers of insect pests very large distances. Sometimes these insects do not arrive in numbers large enough to cause damage but provide a breeding stock, which can multiply quickly and reach economically damaging levels. Examples of such cases for aphids, black cutworm (Agrotis ipsilon Hufnagel), green cloverworm (Plutella xylostella (L.)) and the Oriental Armyworm (Pseudaletia separata (Wlk.) are described in Thompson (1986).

3.6.1.2 Other Pests

Rodents, birds and other non-insects can be important pests in agricultural systems. Work in this area is limited compared to the activity ongoing in insect management, but some exists. Thompson (1986) cites work where sequences of rainfall are used to predict rat damage to sugarcane. Myllymäki (EPPO Bulletin, 1983) concluded that climate models are a useful tool in planning rodent control strategies.

3.6.2 Crop Diseases

Losses from diseases are considerable worldwide, on a large variety of agricultural crops. Climate and weather are the main factors in many diseases particularly temperature and humidity. For many years experiments have been carried out to find relations between specific agroclimatic expressions and the timing of appearance and spread of the disease. This was done for potato blight, wheat rust, apple scab and many more diseases. There are different techniques and methods, most are of empirical nature. Most use historical climatic data, some others use predicted climatic data.

WMO (1988) contains a number of tables presenting the agrometeorological parameters that are in use for various diseases and crops in the different countries. Mostly, observed data are used more frequently than forecast data. In most cases temperature and humidity have the widest use compared to all other climatic parameters. In many countries methods and formulas have been developed to predict diseases appearance - many of these are operational. The disease that has been most investigated having a very long history global wide is the potato blight. The history of disease forecasting by using agrometeorological data is the longest in potato blight. Later on similar approaches have been applied to many other diseases.
3.6.3 Applications

The main uses of crop protection schemes are: reduction of expenses by using reduced chemicals and spray applications, savings of fuel, as well as saving in depreciation and labour, accompanied by increase in crop yield and/or quality. The main goal is to reduce risk and spread of pests and diseases by minimum cost.

Agrometeorology has various uses in this field. It may prevent mistiming of a spray application and then avoid the washing of the material by rain before acting or the unnecessary use of a pesticide, when the weather is unfavourable to the pests development. Also prevention of damage to off-target crops by allowing period when spraying should be avoided because of the likelihood of dangerous spray drifting. In the long run, good agroclimatic advice, based on weather reports of a long series of years can indicate preferred locations for new plantings of crops according to their sensitivity to pests and diseases development.

Forecast of meteorological conditions, encouraging disease and pests development, may be either general or in the form of numerical values of specific weather element. These can be used to predict the time or progress and severity of the attack, in order that control measures can be started.

Another way is providing operation advice on timing of chemical applications. This is extremely important from the economical aspect (Thompson, 1981). There are also examples for short, medium and long range warnings.

3.6.3.1 Methods of Forecasting

During the last 5 years typical trends in development of forecasting methods in crop protection have taken place. The main trend is introduction of new technologies in order to improve the forecasting. Use of automatic meteorological stations, improvement of field measurements, improved telecommunications, etc. The main goal is to improve the basic data and using models in order to improve the forecast. On the other hand, efforts are done to fasten transfer of data to the experts' assessment as well as fasten warning dissemination to the users.

In France, efforts were made to characterize an automatic station which could be used for various purposes including phytosanitary risks. The station was initially designed for three sensors (temperature, humidity and rainfall) and include up to 7 other agrometeorological parameters, can memorize also biological observations, like growth stages, number of insects trapped and so on. Access was available by phone (Minitel) or to specific procedures. They provide the Research Institute and Plant Protection Services with real time information for the evaluation of phytosanitary risks (Jubel 1990).

Huber et al., (1990) reported a micrometeorological study of grape wetness duration which was conducted during the summer of 1988 over a vineyard in the Bordeaux area, France. Experimental results are shown for artificial wetness of grapes during humid and cloudy weather conditions. Modeling of the microclimate surrounding the grapes is initiated in an effort to
predict environmental factors which are potentially favourable to the infection of grape berries by fungal diseases.

Lomas, reviewed the microclimate of a sprinkler irrigated crop and the effect of sprinkler irrigation on disease outbreaks (Firenze proceedings 1990). Microclimatic modifications due to overhead irrigations may be decisive where macroclimatic factors create marginal conditions for disease development. The situation when macroclimatic conditions favour plant disease or under extreme arid conditions is different.

Jacquard-Romon and Paulin (1990), found that one of the predominant characteristics of fireblight on Pomoideae, caused by Erwinia amylovora, is the great variability of outbreaks through successive years, for the same plant and the same site. This irregularity is determined by two types of factors: firstly, the quality and quantity of the inoculum present in the orchard and its surroundings, secondly, the value of certain climatic parameters leading to infection. For such a sporadic and destructive disease, it is highly desirable to set up a decision-making tool in order to assure adequate control. The fireblight software system used incorporates, in addition to the factors specifying the level of inoculum and the climatic situation, phenological data for the cultivars concerned as well as specific weather forecast data. This software can be used on a microcomputer and questioned every day from the 1 March to the 30 June. It includes epidemiological and phenological data recorded in the orchard and can eventually specify the treatment adapted to the situation of the plot. The basis of this software is described, the results of the first applications are given and the conditions of practical use are specified.

Pessi, et al., (1990), noted that for the effective management of some pests and many pathogens the monitoring of local weather conditions in the vicinity of the fields and orchards is important. When these conditions are immediately considered together with the stages of various biotic and site factors, it is possible to predict levels of risks of pests and disease activity. Obtaining this information rapidly is essential timed interventions by farmers and growers. Microprocessor-based equipment designed to monitor the weather or farms, "drive" pest and disease models, and provide crop risk levels, weather summaries and allied information such as day-degree accumulations.

Baker (1990), reported a computer simulation models that can be used to examine the probable life cycles of a pest if it were to be introduced into a new area. The technique is based on obtaining and adequate simulation of the timing of the life cycle in an area where the pest is endemic and then running the simulation programme with the same biological data but with meteorological data from site in the new area. Validation can be obtained by using the same simulation technique to estimate the timing of events, such as flight periods, the life cycles of indigenous pests where the estimation can be compared with observations.

Several examples are given for using weather data for forecasting of pests:

The Rothamsted Insect Survey co-ordinates a network of suction traps throughout the UK aphid research (Harrington, et al., 1990). Some of the traps have been operating continuously for 25 years and it is now possible to use the data in relation to meteorological data for forecasting purposes. Aphids cause particular problems if they occur early in the crop growing season. At this time crops are more prone to direct damage caused by removal of phloem and they are especially vulnerable to virus diseases transmitted by aphids. An indication of the likely
severity of aphid levels in spring and early summer forewarns growers of potential problems and insecticide manufacturers of likely demand for their products.

Another example is that apple worm reported by Kamali (1990). Khorasan is the second largest apple producing province in Iran and apple worm (*Laspersia Pometella*) is one of the important key pests in that province. This pest has three generations and causes a serious damage to apple orchard.

Forecasting and supervising pest control network in this province for apple worm began in 1984. It was based on heat unit requirements for different stages of pest development. Data of flying peak was determined by the use of pheremon traps and the exact date of chemical application was recommended. Flying date of first generation was calculated on the basis of 130 degree days from the start of a threshold temperature of 10°C. Probability of the date of passage from this threshold temperature (25% - risk) was calculated from the long term weather data.

In France, the flowering period corresponds to the maximal susceptibility of fireblight host plants (Jacquart-Romon, 1990). *Erwinia amylovora* can only contaminate flowers under certain conditions of temperature and rainfall (Billing, 1978). A method for the determination of the flowering period is still necessary to assess the potential risk of the disease in a particular zone, on a particular host-plant. The period of full flowering in pear can be specified with sufficient accuracy by use of an exponential approximation of the effect of heat, together with statistically based assessment of the constant need for heat and cold for breaking of dormancy and initiation of flowering, based on the method of Bidage (1967) for apple. The epidemiological risks can also be assessed for a theoretical flowering period centered on this stage. This study was implemented by using a series of climatic and phenological data recorded in the Pays de Loire (France), for two pear cultivars: Passe Crassane and Williams. Moreover, this approach was taken when estimating the potential risk of fireblight on pear, at four localities in Greece. Efforts are done to fasten transfer of data to the experts assessment as well as fasten warning dissemination to the users.

### 3.6.3.2 Treatments (pesticides, etc.)

Agrometeorological information is essential for proper treatment techniques. Forecasts of rainfall, wind speeds and maximum temperatures are required to attain optimum pesticide application results. Some treatment materials require moisture for activation, some must have ten to twelve hours of drying after application, and some materials have volatility levels and so must be applied during temperatures safely below this level. A detailed report on the relationship between weather and applying pesticides has been published by Elliott and Wilson (1983).

### 3.6.4 Conclusions

Agrometeorology has a well defined part to play in the protection of crops from pests. Although many of these pests are now relatively easily controlled with pesticides there is great incentive to more efficiently use pesticides, in an environmentally sound scheme. Agrometeorology has much to offer in this area. Present knowledge can be used to guide grower
in their management practices. Continued research and improvement of the meteorologically based models for predicting pest development will enhance this ability further. The combination of the most accurate models possible to predict pest development and an increased accuracy of the meteorological parameters used as input to these models will make a significant contribution in stabilizing crop production worldwide.
Chapter 4

Preparation of Agrometeorological Information and Dissemination

4.1 Introduction

Agrometeorological information and advice can help significantly to increase quantity and quality of agricultural production. Better application of agrometeorological resources cannot only lead to increased production, but also appreciably reduce loss and damage. Other things remaining unchanged, weather information properly applied, can help increase agricultural production, and appreciably reduce loss and damage and improve planning and decision making in the entire agricultural business community.

Meteorological information may be in the form of reports of current weather conditions, forecasts of future weather events or analyses of past weather can be useful in agricultural production.

4.2 Preparation of Agrometeorological Information

4.2.1 Bulletins and Advisories

In the preparation of agrometeorological information special care must be taken in selecting the type of data to be divulged. Likewise, quality of meteorological data should be verified before these data are analyzed and disseminated to users, using adequate methods now available (Abbott, 1986; CLICOM System, 1986; INSTAT, 1989).

In addition to daily weather forecasts for the agriculture, routine agrometeorological advisory bulletins are desirable to be issued at least once a week. These bulletins are to be prepared jointly in consultation with agricultural scientists.

These advisories may recommend implementation of certain practices or the use of special materials to help effectively prevent or minimise possible weather-related crop damage or loss, for example (i) spraying advice based upon past and forecast weather conditions to combat crop diseases and insects, (ii) harvesting advice to obtain optimum crop maturity and quality and (iii) to initiate cultural practices which are weather-sensitive. Agrometeorological advisory services help the agriculturists to make the most complete and rational use of climate and weather data to operate economically, to produce high and consistent yields and to economise productivity of crops and animal husbandry.

General agricultural weather forecasts provide information to farmers, so that they may make their own operational decisions. But they do not advise them as how to minimise damage from unfavourable weather, or to take advantage of favourable weather. What is required is a well interpreted and appropriately worded bulletin, giving the expected effects
of weather on the individual crop and incorporating the advice to farmers on field operations. The Agrometeorological Advisory Bulletins issued by agricultural meteorologists in co-operation with agricultural scientists and extension specialists fulfil the above objectives.

4.2.1.1 Information Requirements

Information required to prepare agrometeorological bulletins includes meteorological and agricultural data. Meteorological data are collected on a daily or hourly basis depending on the type (conventional or automatic) of agrometeorological stations. Agricultural data, on the other hand, are collected in the crop fields usually by agriculturists who, along with agrometeorologists, prepare agrometeorological bulletins and advisories. Agricultural data include phenological information of the main crops; crop conditions, including eventual crop damage caused by pests, diseases and adverse weather conditions; and soil moisture conditions. Guidelines to collect agricultural and agrometeorological data are presented in Todorov, 1982; and Villalpando and Ruiz, 1993).

The information required for planning and management decisions depends on the nature of those decisions. For example, present weather and short-period forecasts are useful in making operational decisions, while analysis of past climatic data are especially useful for planning decisions. Planning decisions could be based on medium- and long-range forecasts and climatological data. Predictions concerning yield, diseases and pests are usually based on current and past weather and agricultural data, rather than on weather forecasts.

In the Russian Federation, agrometeorologists receive and generalize the many observations made at agro- and hydro-meteorological stations located on collective and State farms, and meet the farmers' various requirements for data.

These stations make continuous observations of the state of crops, development phases, height and as well as a number of meteorological elements (precipitation, temperature, wind, air humidity, etc.). Every ten days, a large number of stations make observations of the reserves of available moisture in 10 cm layers up to a depth of 1 metre. In winter, they observe soil temperature at the depth of the tillering node of winter crops. Where winter crops are grown, samples are taken several times during the winter to determine the overwintering capacity. In the spring, the state of the winter crops in the fields is monitored approximately every ten days after the beginning of the vegetation period. In addition, the reserves of available soil moisture, the percentage of plants which have died during overwintering, the state of the surviving plants, the number of surviving plants per square metre, the number of stems per square metre, and the height of the plants are observed, while the general state is also assessed.

To ensure a better assessment of the crop conditions, hydrometeorological observations record the most important meteorological elements (air temperature, precipitation, etc.).

Aircrafts have been frequently used in recent years for crop surveys to estimate the state of crops over large areas using aerial photometry.

The numerous above-mentioned observations which are very important for agriculture are transmitted by the observing stations to operational centre where they are processed,
analysed and generalized by agrometeorologists for dissemination to users.

4.2.1.1 Meteorological Forecasts

Meteorological forecasts are given to the general public usually once or twice a day. These general forecasts can also be disseminated to agricultural users. The agricultural-oriented forecasts may include rainfall probability and possible amount, maximum and minimum expected temperatures, wind speed and direction, and sky conditions, among other parameters. These forecasts should include an explanation on the possible impact of weather elements on specific agricultural practices (irrigation, spraying pesticides, applying fertilizers, planting, harvesting, etc.). In this way farmers and agricultural organisms may understand and start applying the weather information.

Application of meteorological forecasts to protect animals against adverse weather is a common practice in some countries. An example of that is the National Meteorological Service of Uruguay which has been providing this service to sheep producers since almost a decade ago.

4.2.1.1.2 Agrometeorological Forecasts

The weather elements which influence the agricultural operations and crop production can be forecast up to different spans of time. However, with increase in time span, the accuracy of the forecast decreases.

An agricultural weather forecast should refer to all weather elements which immediately affect farm planning and operations. These include: (i) cloud cover and duration of sunshine, (ii) weather and rainfall probability, (iii) temperatures, (iv) winds, (v) humidity, (vi) dew, (vii) drying conditions and (viii) soil water status, etc. Further, special agricultural weather forecasts to aid the farmers in making certain "high cost" decisions are planting dates (soil moisture and temperature), application of agricultural chemicals (temperature, precipitation and wind speed), irrigation scheduling (evaporation loss, rainfall), crop curing (drying condition), control of plant diseases (temperature, humidity, cloudiness and precipitation), transportation of agricultural products (climatological and current weather information) and agricultural aviation (wind, fog, snow).

Farming involves calculated risks of which one of the most important is weather. Categorical forecasts do not indicate the degree of meteorological risk involved. For example, the knowledge of the probabilities of continuous dry or wet spells are useful to the farmer in his operational decisions. Hence agrometeorological bulletins can be made more useful if they include probability of occurrence of certain events.

Monthly and seasonal outlooks, if included in the bulletins, may help in taking the decision whether or not to grow marginal crops, in management of limited water resources, in choosing the most economical variety of crops, in planning pests and diseases control measures and in determining crop yields.

In addition to the information on meteorological factors and weather conditions, an
agrometeorological bulletin should contain the information on the ongoing operations in the field, stage and state of the crops and pests and diseases. The crop calendars can also serve a useful purpose. These information help the agricultural meteorologists and the specialists to formulate precise and effective forecasts and advisories needed for a particular region for the particular period.

4.2.1.1.3 Feedback Information from Users

Assessment of the utility of the agrometeorological bulletins, their impact and improvement can be made only by an effective system of collecting feedback from the user level. For this purpose, the efficient extention system - as detailed earlier maintained by the National Agricultural Agency is made use of. The assessment after a crop season or during the pest and disease epidemic or at any stage can be directly obtained from the extension official in each district. Further, periodical meetings of the agrometeorologists, agricultural specialists and the farmers, agricultural scientists help in effective utilization of this service. Standing machinery for the evaluation of the effectiveness of these bulletins should be created at each forecasting office, and periodical visits to the village community centres should be made.

4.2.1.2 Practical Applications of Bulletins, Forecasts and Advisories

Agrometeorological information is valuable in many types of agricultural production and it also has application at each stage in the planning and management of farming. The general fields of application are:

(i) **Long-term planning:** Long-term planning for an agricultural region or for a particular enterprise is very necessary. This includes, for example, consideration as to whether the capital investment necessary to produce food crop is justified or whether the area should be exploited for forage products and livestock. Such decisions are based largely on the agroclimatic information.

(ii) **Medium-term options:** Medium-term options cover a period of several months. This includes consideration of water balance and energy balance. Assessment of suitable crops and varieties may be based on the probabilities of the different seasonal weather.

(iii) **Short-term operational decisions:** These relate to a period ranging from a few hours to a week or ten days. These often involve decisions based on the state of the crop and current or forecast weather, for farm operations such as cultivating, irrigating, spraying and harvesting. Meteorological Services issue most of the agrometeorological bulletins for agricultural production. Efficient crop management depends on useful, timely information presented in an easy understandable form. Meteorological information helps the farmers (planners) to take decisions that will prove most profitable under actual circumstances, for example, by choosing the best time for certain operations or selecting the best plant varieties and livestock breeds for the anticipated conditions. It is therefore
of great economic value only through its effective use in the decision process. For this, it is necessary that the users receive the information in suitable form and time to translate it into profitable action. Effective application depends also on management, knowledge of meteorological/agricultural interrelationships.

4.2.1.3 Interdisciplinary Group

Agrometeorology is an interdisciplinary activity in which agronomists, soil scientists, veterinarians, plant pathologists and others have their roles. In such a multi-disciplinary scheme, little progress can be achieved unless interdisciplinary co-operation and liaison is well established and mutual study projects are undertaken with an aim to integrate all the theoretical and practical knowledge.

The important task of issuing "Agrometeorological bulletins" calls for co-operation. This is not a field in which the meteorologists can successfully go alone.

The relationship between the weather and crop are varied and complex, hence no single discipline or research organization can solve them without liaison with the others. It is, therefore, vital that there should be a "team approach" in building up an agrometeorological service.

The objectives of an agrometeorological service can be fully achieved only if there is close collaboration between agricultural and meteorological interests. Meteorologists and agricultural scientists should co-operate towards making meteorological and climatological information, an "operational tool" in every farmer’s day-to-day activities and in his weekly, seasonal and long-range planning. The services can be jointly developed and furnished by the meteorologists and agricultural scientists.

4.2.1.4 Recommended Format and Language

The format of an agrometeorological advisory bulletin may include: (i) a synopsis of the weather conditions during the past week; (ii) weather forecast for the next 48 hours with emphasis on those meteorological elements of importance to current ongoing operations in the fields as well as with reference to the existing nature and variety of the crops and their stage and state; (iii) an outlook of the forecast weather conditions for a further period of at least two days. Probability forecasts may also be included under this; (iv) information about the crop, their stage and state, ongoing agricultural operations, infestation of pests and diseases, and; (v) adequacy of agrometeorological advice for taking suitable measures by the agriculturists keeping in view the interpretation of how the weather conditions prevailed up to the present and expected weather in future which will affect crops, livestock and farm operations.

The second and third parts are essentially a short-range operational forecast issued for general farm activities. The forecast period covers two days with an outlook for the third and fourth (continuous attempt are being made to increase the duration of the short range forecasts). These forecasts are prepared to acquaint the farmers with the expected weather conditions and to carry out their farm operations with the minimum risk involved of their costly inputs and
crop losses.

The information derived from guidance charts and forecasts issued from the national meteorological centres and prognostic charts for surface and upper air are utilized for this purpose. Another useful guidance is the "Crop-weather Calendar" prepared by the National Agrometeorological Services.

The fourth part contains the factual information on the species and varieties of crops, their stage and state, ongoing agricultural operations and insects, pests and diseases. This information is gathered by the National Agricultural Departments through their extension service.

The final part consists of the agrometeorological advices which are jointly framed by the agricultural meteorologists and the agricultural specialists. These are based on the studies conducted and the knowledge available on "Crop Weather" relationships, probability analysis of rainfall, weather and insects and pests and their interrelationship and a knowledge of available agricultural resources.

Interpretation of weather for crops takes into account the impact of weather on germination, growth rates, crop protection and irrigation demands. The cumulative effect of weather encountered and anticipated is used to determine the necessity of chemical sprays, dates of harvest, duration of harvest, quality and storage capabilities of grains, fruits and vegetables.

Interpretation of weather on farm operations takes into account the drying rate of soil, evaporation losses, the effect of heat, cold and wind on application of chemicals and fertilizers; the drying rate of curing and wetting and the rewetting of grains and hay.

The interpretation of weather for livestock is generally based on an index based on temperature, humidity effect on livestock. This index provides an indication regarding heat stress, cold stress and shelter requirements; and the effects of weather on the productivity of milk, meat and eggs.

The incidence of plant diseases can be forecasted in the light of accumulated and anticipated weather as there exists a very close relationship between many plant diseases and the weather. Both synoptic and statistical approaches are used for these forecasts, which are concerned with probable development, extent and time of spread or suppression of the diseases. Advice on control measures to be taken are also included.

4.3 Dissemination

4.3.1 Methods and Time of Dissemination

4.3.1.1 Dissemination of Agrometeorological Bulletins

The Agrometeorological bulletins are meant to be utilized by the farmer in the field in his day-to-day operations. As such, the primary objective in the dissemination of these
bulletins could be that: (i) the format should be fixed which will enable the farmer to become accustomed to a given flow of information; (ii) these should be made available to the farmer at a time of his convenience; (iii) the broadcast or telecast should be done at the leisure time of the tiller in the field; (iii) the bulletins should be worded in a simple language - preferably in the local language of the farmer; (v) there should be separate bulletins covering subdivisions of the country or state so that only the relevant information is available to the farmer in each district.

In India, these bulletins are broadcast by a network of National Radio Stations covering small villages. Generally, the broadcast is done in the early morning (when the farmer is getting ready to go to his field), in the afternoon (when the farmer can find some leisure in his lunch time) and again in the evening (when the farmer is back home after the day’s work). These are broadcast in the local language. The National Television Network also telecasts in the regional languages. The National Ministry of Agriculture has developed a very good infrastructure, both at the state and at the district levels, for efficient rapport with the farmers in the fields.

To make the efficient implementation of advisories there must be improved communication system to take them to block/village, level/community. Development Centres should explain the benefits of the advisories to the farmers in their language which will help them to: (i) accept new agricultural technology for obtaining higher yields, (ii) assess his resources and take rational decisions for the best use of the agrometeorological advisory bulletins, and; (iii) find out the necessary technical know-how as well as inputs to apply the technology to his own situation.

4.3.1.2 Dissemination of Agrometeorological Information

The way in which meteorological information is provided, its contents, and its form are important factors that determine its effective utilization. Not less depends the quality of information on the way in which it is made available to the user. Verbal contact between the user and meteorologist, either directly or by telephone, or by the users’s listening to the radio at a set time, dialling recorded information or subscribing to a postal information service, have been for many years the principal methods used. Today, the variability of dissemination methods is high, from simple traditional methods like the above-mentioned to much more sophisticated methods - electronic computers etc.

WMO (1988) gives detailed information on the subject concerning crop protection. The Telcel French system is described by Roques (1990) in the book "Using Meteorological information and products". Here will be given short summaries that can be applied to all aspects of agriculture including farming systems.

4.3.1.2.1 Conventional Methods

**Personal Communications**

Personal communications between farmers and advisors is an accepted method for agrometeorological information. This is more effective in regions and countries
where other and more sophisticated methods are not available. This method is an useful complementary method to other methods. This method in general cannot be given to the farmer on a mass basis.

Post

This method is still a basic method of dissemination in many countries. The great advantage of postal products is the large amount of data that can be included in each bulletin or message. A 10-day summary, forecast data, instructions for protection and explanations can be summarized in a report. However, one must expect a delay of at least a few days for the information to reach the farmers, which makes this methods helpful in planning rather than providing an operational service. This method is important also for economical considerations. There are ways to improve postal services by Press.

Press

This method is useful quick and relatively cheap. It seems that the volume of the data will be here much more limited than by bulletins.

Telephone/Fascimile

Telephone and fascimile are quick and direct means from the advisor to the farmer. Both are limited by telecommunicational problems. It is often difficult to contact the advisor. The taped message may be sufficient for the progressive farmer, and needs to be updated only when necessary. In many countries, the telephone is used as a method for issuing the warning. For example, there are recorded weather forecasts available from some meteorological and agricultural offices by telephone responder or 'code-a-phone': (the code-a-phone service in Canada, updated several times daily, has proved to be very accepted).

In several countries, separate channels are available from the meteorological and extension services. In general, the telephone has proved to be a swift and relatively inexpensive means of disseminating products in many countries.

In Israel, a new method now operational -Telemesser. This is a recorded message operated by a vocal telephone and free for each farmer that has a telephone (30 parallel channels). In the same time, a message is disseminated by computer to a certain list of subscribers based on regional, professional or any other basis. This is especially useful in disseminating specific warnings like frost forecast, wind storm and hot spells and so on or urgent crop protection instructions.

Radio

Radio receivers are everywhere. They are also cheap and portable. Actual information can be transferred to the farmer including data instructions explanations and educational programmes.
Television

Television is obviously an effective medium to issue weather and agricultural advisory products and is used as a disseminating medium in many countries of the world including a general forecast given once or twice a day. Educational programmes can be given successfully on TV as well as special warnings and explanations.

4.3.1.2.2 New Technologies

The quality of information depends on the level of the national telecommunications. Less-developed countries which have not sufficient equipment for high speed communications are not, in general, able to disseminate the information that contains very short-range forecasts quickly enough. Developed countries are now able to disseminate these forecasts and the methods of nowcasting are widely used.

For disseminating agrometeorological information not many countries are capable of using new technologies.

The 1980’s have brought significant changes in the way weather and climate information is communicated, and the development of videotex systems in many countries introduced new technologies for provision of the weather and climate information. Indeed it is evident that, as we move into the late 1990’s, communication of information will be involved in many climate-dependent decision-making activities. It will be easier as the various videotex systems become more common.

Videotex systems are specially designed to provide information to specific groups such as wheat growers, grain storage companies, fruit growers, etc. The type of information that can be provided to these specialized customers include the whole range of weather and climate data available in national meteorological services.

It seems that weather and climate information will finally break through the communication barrier.

Videotex and Teletext

The first videotex system was British Telecom’s PRESTEL, introduced in 1979. This is a computer-based information service which may be accessed via public telephone lines to provide frames of information that are then displayed on a modified television receiver. The computer holds more than 100,000 frames of data. PRESTEL contains a considerable amount of information of interest to farmers, (including some disease and pest control advice.).

The advantages are:

1. Information retrieval is instantaneous, giving up-to-date products to the user.
2. Information retrieval is concise, obviating the need to sift through numerous
reports, studies and manufacturer’s literature.

3. The system is interactive, allowing users to have a direct line to the specific information sources. For example, one can request literature from a particular information provider or request details from particular source in addition to those contained in the PRESTEL data-bank. No special skills are required to interact with the system, which is designed to achieve simplicity by using advanced technology. More details in the WMO (1988) are provided.

The Teletel system is a new means of communicating information to the public at large. Any telephone subscriber can have a small terminal with a screen, the Minitel, on which he can call up pages of information put out by the ‘data communication distributors’, computers which transmit information using the ‘videotex’ transmission standard (Roques 1990). The system makes it possible to offer very cheaply, to a very large number of users, benefits which had until then been more costly and restricted to a few subscribers. These benefits are:

- Real-time availability of information
- Information storage (printer, microcomputer)
- Interactive capability in some magazines

The Meteorological Office in France has six regional data communication distributors, each of which houses one or more magazines aimed at various categories of user. Under these headings are offered forecast bulletins and recently observed data. For forecast bulletins, the Teletel systems has a number of advantages:

For the user:

- The information, in written form, is therefore easier to digest and can also be stored,
- There are several bulletins in the same magazine which cover different areas, which make it possible, simply by changing the page, to obtain meteorological forecasts for areas which are quite extensive or remote; the updating rate is the same as for telephone recorded information services (two or three times a day) and the information is immediately available.

In some magazines the benefits of the transmission system make themselves felt, in the speed at which processed data, such as potential evaportranspiration, water balances or temperature totals relative to various thresholds are made available.

Some of the sophisticated magazines have interactive applications which make it possible for farmers to use the meteorological databank for calculations concerning their own crops, and example of this is the IRRITEL application discussed in the paper by S. Dervaux which is also in this volume).
Telex and methods using computer-to-computer links

These methods refer in particular to the transfer of meteorological service or regional weather centre to organizations that interpret the information before using advisory information to the farmer. It is important to note that almost direct computer-to-computer linkage can be made by telex managers connected to each computer and then automatically passing or receiving telex messages. A number of countries use telex to pass agrometerologically-based information between various organizations. In some cases telex is employed to pass warnings to individual farmers on a repayment basis: More detail are found in the WMO (1988).
Chapter 5

Training and Education

5.1 Training

5.1.1 Introduction

Most countries offer various agrometeorological services to the public and carry out research, field-measurements and surveys. The agrometeorological staff has to improve permanently its knowledge by training programmes, professional visits to other linked institutions, agricultural institutions and university faculties.

5.1.2 Organized Training

Agricultural instructors, planners and researchers have to be trained on new applied methods and techniques of agrometeorology to agriculture, as well as to be permanently involved on the list of agrometeorological services offered to the agricultural community. Specific relevant material has to be given to different groups. For example, evaporation, evapotranspiration to extension service people, chilling units, heat units, topoclimatology to fruit tree growers, use of climatic data in the field to crop protection people and so on. These professional groups have to be trained once a year or more. Such training programmes have to include basic material and climatic data of the present season and possible applications. The training could be organized in co-operation between meteorological services and linked associations, various growers packing and marketing organizations and university faculties. Curriculum has to be planned carefully to each trained group. Professionally university lecturers can support in planning and teaching, organizations and institutions can help administratively and financially by supplying audio-visual training material, posters and pamphlets. Policy makers can benefit from workshops by discussing actual problems linked to agrometeorology. For example, reduce of water allocations to farmers as a result of a continuous drought, or replanning of fruit trees planting as a result of economy and marketing problems. Problems like these have to be discussed with agrometeorologists. The workshop should include short lectures, presentations and demonstrations. The discussions and decisions will be used as a basis for decision and policy making.

An example of organized agrometeorological training is what is followed in the Russian Federation. In the Russian Federation, agrometeorological training at the highest level (engineer) is carried out at the Odessa Hydrometerological Institute’s Meteorological Faculty through both internal or external (i.e. correspondence) courses. There is an annual selection of 50 agrometeorologists as internal students, and 25 as external students. The course lasts five years for the internal students, and six for the external students. During the first two years, all students at the Meteorological Faculty have the same curriculum covering the basic subjects of physics, mathematics and humanities. This gives them a grasp of modern physico-
mathematical methods which they can apply in their subsequent specialized studies, homework, laboratory work and
the annual and final diploma projects.

All specialization, including in agrometeorology, begins in the third year. Since agrometeorology is a cross between geophysics and biology, the agrometeorological curriculum contains a significant number of subjects given on the biology course.

Agrometeorological students thus attend lectures on humanities, physics/mathematics, meteorology, agrometeorology and plant growing. Their knowledge of the subject is tested orally at colloquia and through their 3-4 written papers per semester.

The study plan contains seven annual papers and projects which the students have to produce during the given year on the subjects: general meteorology, computer techniques and programming, soil science, plant growing, agrometeorology, agroclimatology and agrometeorological forecasts.

The Agrometeorology and Agrometeorological Forecasting sub-faculty is the main place where the agrometeorological engineers are trained. Here, students are trained in the following subjects:

1. Agricultural meteorology;
2. Environmental protection;
3. Agrometeorological forecasts;
4. Agroclimatology;
5. Statistical methods and agrometeorology;
6. Mathematical models in agrometeorology;
7. Microclimatology;
8. Agrometeorological basis of land improvement;
9. Aerospace methods of study in agrometeorology;
10. Economics of hydrometeorological services to the economy.
11. Botany;
12. Soil science;
13. Plant physiology and ecology;
14. General agriculture and plant growing;
15. Agrometeorological measurement and data-processing methods.

Students in the Agrometeorology and Agrometeorological Forecasting sub-faculty write annual course papers and projects. For example, during the third year the course paper covers plant growing under the general title "Biological characteristics of the crop".

During the second semester of the third year, a project has to be written on the subject "Agrometeorological conditions for .... crop growth in the .... region". The project is to be written during the fourth year (in respect on or several crops)".

The fifth-year project is on "The impact of agrometeorological conditions on the ... crop yield". The results described in the course papers and projects have to be defended by the
students before the corresponding sub-faculty commission.

The students' theoretical knowledge is strengthened and expanded not only by the course projects but also by laboratory work, i.e. research on each of the subjects under study. Methodological instructions for the laboratory work are drafted and printed within the sub-faculty.

The study plan for agrometeorological engineers includes seven practices (carried out at the agrometeorological training station and at the industrial-science training unit) on botany, soil science, meteorology, actinometry, environmental sounding methods, agrometeorology and agrometeorological forecasts.

Practices are also provided on meteorology, agrometeorology and agrometeorological services to agriculture, but these take place in various institutions belonging to the Russian Federation State Committee for Hydrometeorology and in the Hydrometeorological Centre of the Russian Federation.

At the end of the course, a diploma project has to be written, which must show familiarity with the literature, and application of the knowledge acquired in solving specific scientific and operational problems, hence the students' preparedness to work in agrometeorology.

The diploma projects are on very varied subjects and are supervised not only by the sub-faculty's instructors, but also by the country's leading agrometeorologists. They are virtually partial research projects on the main aspects of agrometeorology, agroclimatology and agrometeorological forecasting. The results obtained have to be defended by the students before the State Examination Commission.

Lectures on agricultural meteorology and agrometeorological forecasting have started to be given over the last few years at the Russian federation state universities.

Medium-level agrometeorologists, mainly technicians and observers are trained at the hydrometeorological technical colleges.

5.1.3 Exhibitions and Field Demonstrations

It is recommended that meteorological services will offer the public once in a year or two years an 'open day' during which the agricultural community can visit exhibitions of instruments maps and operating systems. Short lectures should be given to the farmers on relevant subjects and update information on services. Field demonstrations can help the farmers and instructors in understanding the subject of agrometeorology. For example, demonstration of frost prevention methods, windbreaks and shelterbelts and so on. Field experiments might be an interesting destination for visits. Permanent exhibitions should be demonstrated in the national meteorological service, as well as in other institutions. Those could be located in regional institutions or agricultural schools.
5.2 **Education**

5.2.1 **Introduction**

The book (Price-Budgen, 1990) "Using meteorological information and Products", includes a chapter 'means and methods of education of users'. In this chapter two articles are the most relevant to our subject:

1. The roles of universities and meteorological training institutions in the education of users and the general public.

2. The introduction of agrometeorology into the curriculum of agricultural technical and secondary schools.

5.2.2 **Audiovisual**

No doubt that today a serious attention should be given to education in agrometeorology. Very good audiovisual material and literature are available. Recommended are educational programmes in the radio and television that should be given during convenient times for the farmers. For actual important subjects, specific video cassettes should be prepared, like irrigation methods (based on evapotranspiration) forest fires (Australia) frost prevention (Israel), crop protection (Australia) and so on. Slides should be demonstrated on various subjects. In Spain an album including photos, explanations and slides on the battle against bacteria of the Rosacea ('El Fuego Bacteriano de las Rosaceas') is used for training. Abstracts of seminars and symposia should be published to the agricultural community.

5.2.3 **Brochures, Pamphlets and Posters**

Brochures, pamphlets and posters are highly recommended. In preparing such material professional support can be given from the ministry of agriculture and agricultural institutions and organizations. The disseminating of the material should be made by them. In professional agricultural journals a permanent contribution on agrometeorology can be published. This should include climatic data of the next month, summary of last month's weather, articles, recommendations, advice, popular scientific papers, reports on field experiments and its preliminary results.

5.2.4 **National and Regional Pedagogic Centres**

These could be linked to libraries or remain independent. In such centres everyone should be able material according to his need.

Material according to this should include literature on all aspects of agrometeorology, slides, films, video cassettes, brochures, pamphlets and posters, various types of Atlases bulletins and so on. This could encourage high school and university students and lecturers to visit, to read, to look and to undertake research work in agrometeorology.
Chapter 6

Conclusions and Recommendations

Conclusions

1. Quality of agrometeorological data collected in an appropriate network design is essential for meaningful planning and operational applications.

2. Agrometeorological observations should include documentation of the physical and biological environment. Therefore, a list of meteorological, biological and phenological observations is suggested. WMO Guides Nos. 8, 100 and 134 should be followed to record all these parameters.

3. Agrometeorological information needed for planning and operational activities (including accuracy and period of analysis) is discussed, for land use and management, for selecting varieties of plants and breeds of animals, and for crop management and production practices such as irrigation, pests and diseases and crop-weather relationships.

4. The sources or failure of a new or modified agricultural undertaking depend largely on the impact of climate conditions. Therefore, the assessment of agroclimatic resources is an indispensable component in order to make an adequate use and management of land.

5. Agricultural planning should be based on the use of rainfall amount probabilities instead of normal rainfall, especially in low-rainfall areas. This will help to know the changes of crop success and failure in a region where aberration is a rule rather than an exception.

6. The selection of varieties of plants at local or regional levels should be based on agroclimatic studies carried out to determine the climatic requirements of the different crop varieties. Agroclimatic requirements of crops should include solar radiation, water, temperature, humidity and photoperiod, among the most important climatological factors.

7. Phenological characterization of crop varieties is a useful tool for crop planning and management. Hence, the collection and analysis of phenological observations in perennial as well as in annual crops should be a permanent activity of all agrometeorological stations.
8. Mid-season water stress period, stored soil moisture at the end of the rainy season and additional water resources from run-off, etc. are of enormous importance in assessing crop potential of low-rainfall areas of the tropics.

9. Better results in crop management can be achieved with the joint efforts of multidisciplinary groups comprised of those concerned with climate, soils and plants.

10. Crop-weather relationship is a useful tool to understand the impact of weather parameters on the growth, development and yield of crops. Practical applications of crop-weather relationships include agriculture diversification, selection of suitable crop varieties, and crop yield forecasting, among others. The latter is specially important for planners/policy-makers for advance planning, for import, export and public distribution of food crops.

11. Agrometeorology has a well-defined participation to play in the protection of crops from pests. The combination of the most accurate models possible to predict pest development and an increased accuracy of the meteorological parameters used as input to these models, will make a significant contribution in stabilizing crop production world-wide.

12. Timely agrometeorological information and advice can help significantly to increase quantity and quality of agricultural production. Other things remaining unchanged, weather information properly applied can help increase agricultural production and appreciably reduce loss and damage and improve planning and decision-making in the entire agricultural business community.

13. Dissemination of agrometeorological information can be done using either conventional methods such as bulletins, radio, T.V., press, post, etc. or new technologies such as teletex, videotex, computer-to-computer links, etc. Quality of information will depend on the level of national telecommunications. Less developed countries are not, in general, able to disseminate the information that contains very short-range forecasts quickly enough, while developed countries are now able to disseminate these forecasts and the methods of nowcasting are widely used.

14. Training on the use of agrometeorological information should deserve more attention by all institutions concerned with the applications of meteorology to agriculture. Agricultural instructors, planners and researchers have to be trained on new applied methods and techniques of agrometeorology to agriculture.

15. Finally, emphasis should be put on the importance of education in agrometeorology to users, including farmers, technicians, professionals and the general public, on which universities and meteorological institutions should play an important role.
Recommendations

1. Given the practical use in agriculture of the information contained in this report, it should be used to publish a handbook or manual. Such a manual should be translated into other working languages for the benefit of more country Members. Updating of this manual should be kept in view during publication.

2. WMO should appoint a consultant to update periodically the technical material contained in this report.

3. It is recommended that parts or the whole material contained in the report be used in roving seminars and short-term training courses on practical applications of agrometeorological data in agricultural planning and management.

4. Agrometeorological data needs for agricultural crops as described and discussed in this report, did not include specific agrometeorological data required for selected crops. Therefore, it is recommended that, as a further step to this report, technical documents be prepared by CAgM on the agrometeorological information required for selected crops including food and industrial crops, as well as vegetables, fruits and pastures. (This recommendation was considered, approved and implemented at the tenth session of CAgM).
Chapter 7

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