

## WEATHER AND CLIMATE FORECASTS FOR AGRICULTURE

### 5.1 **NEED AND REQUIREMENTS FOR WEATHER FORECASTS FOR AGRICULTURE**

#### 5.1.1 **Climate-based strategic agronomic planning**

Weather plays an important role in agricultural production. It has a profound influence on crop growth, development and yields; on the incidence of pests and diseases; on water needs; and on fertilizer requirements. This is due to differences in nutrient mobilization as a result of water stresses, as well as the timeliness and effectiveness of preventive measures and cultural operations with crops. Weather aberrations may cause physical damage to crops and soil erosion. The quality of crop produce during movement from field to storage and transport to market depends on weather. Bad weather may affect the quality of produce during transport, and the viability and vigour of seeds and planting material during storage.

Thus, there is no aspect of crop culture that is immune to the impact of weather. Weather factors contribute to optimal crop growth, development and yield. They also play a role in the incidence and spread of pests and diseases. Susceptibility to weather-induced stresses and affliction by pests and diseases varies among crops, among different varieties within the same crop, and among different growth stages within the same crop variety. Even on a climatological basis, weather factors show spatial variations in an area at a given time, temporal variations at a given place, and year-to-year variations for a given place and time. For cropping purposes, weather over short periods and year-to-year fluctuations at a particular place over the selected time interval have to be considered. For any given time unit, the percentage departures of extreme values from a mean or median value, called the coefficient of variability, are a measure of variability of the parameter. The shorter the time unit, the greater the degree of variability of a given weather parameter. The intensity of the above three variations differs among the range of weather factors. Over short periods, rainfall is the most variable of all parameters, both in time and space. In fact, for rainfall the short-period interannual variability is large, which means that variability needs to be expressed in terms of the percentage probability of realizing a given amount of rain, or

that the minimum assured rainfall amounts at a given level of probability need to be specified.

For optimal productivity at a given location, crops and cropping practices must be such that while their cardinal phased weather requirements match the temporal march of the relevant weather element(s), endemic periods of pests, diseases and hazardous weather are avoided. In such strategic planning of crops and cropping practices, short-period climatic data, both routine and processed (such as initial and conditional probabilities), have a vital role to play.

#### 5.1.2 **Weather events**

Despite careful agronomic planning on a microscale to suit experience in local-climate crops, various types of weather events exist on a year-to-year basis. The effects of weather anomalies are not spectacular. Deviations from normal weather occur with higher frequencies in almost all years, areas and seasons. The most common ones are a delay in the start of the crop season due to rainfall vagaries in the case of rainfed crops (as observed in the semi-arid tropics) and temperature (as observed in the tropics, temperate zones and subtropics), or persistence of end-of-the-season rains in the case of irrigated crops. Other important phenomena are deviations from the normal features in the temporal march of various weather elements. The effects of weather events on crops build up slowly but are often widespread enough to destabilize national agricultural production.

#### 5.1.3 **Usefulness of weather forecasts**

Occurrences of erratic weather are beyond human control. It is possible, however, to adapt to or mitigate the effects of adverse weather if a forecast of the expected weather can be obtained in time. Rural proverbs abound in rules of thumb for anticipation of local weather and timing of agricultural operations in light of expected weather. Basu (1953) found no scientific basis for anticipation of weather in many of the popular proverbs and folklore. In a recent study, Banerjee et al. (2003) arrived at conclusions similar to that of Basu (1953). The proverbs and local lore show, however, that farmers have been keen to know in advance the likely weather situations for crop operations from time immemorial. Agronomic strategies to cope with changing weather are available. For example, delays in the start of crop

season can be countered by using short-duration varieties or crops and thicker sowings. Once the crop season starts, however, the resources and technology get committed and the only option left then is to adopt crop-cultural practices to minimize the effects of mid-seasonal hazardous weather phenomena, while relying on advance notice of their occurrence. For example, resorting to irrigation or lighting trash fires can prevent the effects of frosts. Thus, medium-range weather forecasts with a validity period that enables farmers to organize and carry out appropriate cultural operations to cope with or take advantage of the forecasted weather are clearly useful. The rapid advances in information technology and its spread to rural areas provide better opportunities to meet the rising demand among farmers for timely and accurate weather forecasts.

#### 5.1.4 **Weather forecasts for agriculture: essential requirements**

Forecasts calling for a late start to the crop season should result in departures from normal agronomic practices at the field level. High costs are associated with the organization and execution of such a strategy, and the relevant steps require a considerable amount of time. Therefore, pre-season forecasts must have a validity period of at least 10 days and not less than a week. Field measures to counter the effects of forecast hazardous weather, pests, diseases, and the like cannot be implemented instantaneously and hence mid-season forecasts should preferably be communicated five days in advance, and at the very least three days in advance. Dissemination of weather forecasts to agricultural users should be quick, with the minimum possible time lag following their formulation. Some of the measures, such as pre-season agronomic corrections, control operations against pests and diseases, supplementary irrigation, and the scheduling of early harvests, will be high-cost decisions. The weather forecasts must therefore be not only timely, but also very accurate. Weather forecasts should ideally be issued for small areas. In the case of well-organized weather systems, the desired areal delineation of forecasts can be realized. In other cases, the area(s) to which the weather forecasts will be applicable must be unambiguously stated.

#### 5.1.5 **Some unique aspects of agricultural weather forecasts**

Some aspects of weather forecasts for agriculture are quite distinct from synoptic weather forecasts. In synoptic meteorology, the onset and withdrawal of the monsoon is related to changes in wind circulation patterns in the upper atmosphere and associated changes in precipitable water content of air in the

lower layers. Preparation of fields for sowing and the sowing of a crop with adequate availability of seed-zone soil moisture requires copious rains. Rains that do not contribute to root-zone soil moisture of standing crops are ineffective. Agriculturally significant rains, or ASRs (Venkataraman, 2001), are those that enable commencement of the cropping season and that contribute to crop water needs. For agricultural purposes, it is the start and end of ASRs that are important. ASRs may be received early as thundershowers or may be delayed. Venkataraman and Krishnan (private communication) have drawn attention to the feasibility of commencement of the cropping season far in advance of the monsoon season in Karnataka, Kerala, West Bengal and Assam in India with the help of pre-monsoon thunderstorm rains. The climatological dates of withdrawal of the monsoon and the end of ASRs in a region can also differ significantly. Both the start and end of ASRs in a province may show intraregional variations.

The use of dependable precipitation (DP) at various probability percentage levels and potential evapotranspiration (PET) have been suggested for delineation of the start and end of a crop growth period on a climatological basis (WMO, 1967, 1973; Venkataraman, 2002) and have been used in many regions. The methods differ, however, in time units employed, the probability level chosen for DP and the fraction of PET used as a measure of adequacy of crop rainfall. Based on considerations of the level of evaporative power of air (EPA), the rainfall amount required to overcome the evaporative barrier, and phased moisture needs of crop demands, Venkataraman (2001) suggested that weekly or dekadal periods be used and that the commencement and end of ASRs be taken as the point at which DP at 50 per cent probability level begins to exceed PET and becomes less than 50 per cent of PET, respectively. Monthly values of PET can be interpolated to derive short-period values. So, when rainfall probability data for weeks or dekads and the monthly values of PET are available, the commencement and end of ASRs can easily be delineated.

While clear weather is required for sowing operations, it must be preceded by seed-zone soil moisture storage. Thus, forecasts of clear weather following a wet spell are crucial. Such forecasts of dry spells following a wet spell are also required for the initiation of disease control measures. There are areas where frequent thunderstorm activity precedes the arrival of rains associated with well-defined weather systems and once started, the rains persist without any let-up. In such cases, the agronomic strategy should be to utilize pre-season rains for land

preparation and resort to dry sowings in anticipation of rain to come in the next few days. Land preparation can be done with the expectation of impending thundershowers. Dry-sown seeds will get baked out in the absence of rains, however, so it is prudent to sow when there is a forecast calling for rain in the coming days. Thus, rainy season forecasts become crucial in such areas. In temperate regions, frost can pose a severe threat to agricultural productivity. Frosts normally occur when the screen temperatures reach 0°C. The depression of the radiation minimum temperature of crops below the screen minimum will vary with places and seasons. The radiative cooling will be maximal on cold nights with clear skies and minimal on warm nights with cloudy skies. Thus, owing to night-time radiative cooling of crop canopies, crop frosts can occur even when screen temperatures are above 0°C. Similarly, dew, which influences the crop water needs and the incidence of diseases, can get deposited over crops at lower relative humidities than what is deducible from a thermohygrograph. The frictional layer near the ground is ignored by the synoptic meteorologist, but low-level winds in this layer influence the long-distance dispersal of insects (such as desert locusts) and disease spores (wheat rusts).

It is thus clear that the types of forecasts for critical farming operations would have unique features that would require further processing of certain elements of synoptic weather forecasts.

## 5.2 CHARACTERISTICS OF WEATHER FORECASTS

A deterministic definition states that “weather forecast describes the anticipated meteorological conditions for a specified place (or area) and period of time”; an alternative and more probabilistic definition states that “weather forecast is an expression of probability of a particular future state of the atmospheric system in a given point or territory”. In view of the above, a weather forecast may be defined as a declaration in advance of the likelihood of occurrence of future weather event(s) or condition(s) in a specified area(s) at given period(s) on the basis of a rational study of synoptic, three-dimensional and time series data of sufficient spatial coverage of weather parameters, and analyses of correlated meteorological conditions. The positive effect of weather forecasts in agriculture is maximized if weather forecasters are aware of the farmers’ requirements and farmers know how to make the most use of the forecasts that are available. Response among varieties of a

crop to a weather phenomenon is one of degree rather than of type. The type and intensity of weather phenomena that cause setbacks to crops vary among crops and among growth stages within the same crop, however. Crop weather factors mean that crops and cropping practices vary across areas, even within the same season.

In the provision of weather forecasts for agriculture, the emphasis should be on the outlook for the incidence of abnormal weather and the prevalence of aberrant crop situations. Of course, one cannot determine abnormality unless one knows what the normal picture is, with reference to both crops and weather. Thus, the first step in familiarizing weather forecasters with the weather warning requirements of farmers is the preparation of crop guides for forecasters, which should give the times of occurrence and duration of developmental phases from sowing to harvest of major crops in the regions of their forecast interest, and specify the types of weather phenomena for which weather warnings and forecasts are to be issued in the different crop phases. Such guides can be used by forecasters to prepare calendars of agricultural weather warnings with a breakdown by periods and regions. In the crop guide for forecasters, normal values of important weather elements in the crop season should also be given for the short period adopted at the national level for agrometeorological work; this guide should also be made available to the farming community so that any farmer will know immediately what the normal features of weather will be for a given crop and season at his location.

The week is the accepted time unit for agrometeorological work in India. The crop weather calendars in use in India (shown in Figure 5.1), with the week as the basic time unit, are excellent examples of the type of compiled information that can assist forecasters in framing weather warnings and forecasts directed at farmers.

Weather forecasting now has a wide range of operational products that traditionally are classified under the following groups:

- (a) Nowcasting (NC);
- (b) Very short-range forecast (VSRF);
- (c) Short-range forecast (SRF);
- (d) Medium-range forecast (MRF);
- (e) Long-range forecast (LRF).

Each weather forecast can be defined on the basis of the following criteria:

- (a) Dominant technology;
- (b) Temporal range of validity after emission;
- (c) Characteristics of input and output time and space resolution;



- (d) Broadcasting needs;
  - (e) Accuracy;
  - (f) Usefulness.

Table 5.1 contains a general description of different types of weather forecasts based on criteria (a) through (e); Table 5.2 presents an almost qualitative description based on criteria (e) and (f).

  - (c) Maximum, minimum and dewpoint temperatures;
  - (d) Relative humidity;
  - (e) Wind speed and direction;
  - (f) Extreme events, such as heatwaves and cold waves, fog, frost, hail, thunderstorms, wind squalls and gales, low-pressure areas, different intensities of depressions, cyclones, and tornadoes.

### 5.3.1 Elements of agricultural weather forecasts

An agricultural weather forecast should refer to all weather elements that immediately affect farm planning or operations. The elements will vary from place to place and from season to season. Normally a weather forecast includes the following parameters.

- Amount and type of cloud cover;
  - Rainfall and snow;
- Microclimate inside crops in specific cases.

An agricultural weather forecast should also contain the following information:

- (a) Bright hours of sunshine;
- (b) Solar radiation;
- (c) Dew;
- (d) Leaf wetness;
- (e) Pan evaporation;
- (f) Soil moisture stress conditions and supplementary irrigation for rainfed crops;
- (g) Advice for irrigation timing and quantity in terms of pan evaporation;
- (h) Specific information about the evolution of meteorological variables into the canopy layer in some specific cases;
- (i) Microclimate inside crops in specific cases.



Table 5.1. Definition of weather forecasts

<i>Type of weather forecast</i>	<i>Acronym</i>	<i>Definition</i>	<i>Characteristics of output</i>	<i>Dominant technology</i>	<i>Other aspects</i>	<i>Time and space resolution of typical products</i>
Now-casting	NC	A description of current weather variables and description of forecast weather variables for 0–2 hours	A relatively complete set of variables can be produced (air temperature and relative humidity, wind speed and direction, solar radiation, precipitation amount and type, cloud amount and type, and the like).	Analysis techniques, extrapolation of trajectories, empirical models and methods derived from forecaster experience (rules of thumb). Basic information is represented by data from networks of automatic weather stations, maps from meteorological radar, images from meteorological satellites, local and regional observations, and so on.	A fundamental prerequisite for NC is operational continuity, and the availability of an efficient broadcasting system (e.g., very intense showers affecting a given territory) must be followed with continuity in provision of information for final users.	Typical time resolution is 1 hour; typical space resolution is in the gamma mesoscale range (20–2 km).
Very short-range forecast	VSRF	Description of weather variables for up to 12 hours	A relatively complete set of variables can be produced (see nowcasting).	Analysis techniques, extrapolation of trajectories, interpretation of forecast data and maps from NWP (LAM and GM), empirical models and methods derived from forecaster experience (rules of thumb). The basic information is represented by data from networks of automatic weather stations, maps from meteorological radar, images from meteorological satellites, NWP models, local and regional observations, and so on.	A fundamental prerequisite for VSRF is the availability of an efficient broadcasting system (e.g., frost information must be broadcast to farmers who can activate irrigation facilities or fires or other systems of protection).	Typical time resolution is 1–3 hours; typical space resolution is in the beta mesoscale range (200–20 km).
Short-range weather forecast <sup>a</sup>	SRF	Description of weather variables for more than 12 hours and up to 72 hours	A relatively complete set of variables can be produced (see nowcasting).	Interpretation of forecast data and maps from NWP (LAM and GM), empirical models, methods derived from forecaster experience (rules of thumb). The basic information is represented by data from networks of automatic weather stations, maps from meteorological radars, images from meteorological satellites, NWP models, local and regional observations, and so on).	In SRF the attention is centred on mesoscale features of different meteorological fields. SRF can be broadcast by a wide set of media (newspapers, radio, TV, Internet, and so forth) and can represent a fundamental piece of information for farmers.	Typical time resolution is 6 hours; typical space resolution is in the alpha or beta mesoscale range (2 000–20 km).

Type of weather forecast	Acronym	Definition	Characteristics of output	Dominant technology	Other aspects	Time and space resolution of typical products
Medium-range weather forecast <sup>a</sup>	MRF	A relatively complete set of variables can be produced (see nowcasting).		Interpretation of forecast data and maps from NWP (GM), empirical models derived from forecaster experience (rules of thumb). NWP models represent the basic information. Techniques of “ensemble forecasting” are adopted in order to overcome the problem of depletion of skill typical of forecasts based on NWP models. Instead of using just one model run, many runs with slightly different initial conditions are made. An average, or “ensemble mean”, of the different forecasts is created. This ensemble mean will likely have more skill because it averages over the many possible initial states and essentially smoothes the chaotic nature of climate. In addition, it is possible to forecast probabilities of different conditions.	In MRF the attention is centred on synoptic features of different meteorological fields. MRF can be broadcast by a wide set of media (newspapers, radio, TV, Internet, and so on) and can represent a fundamental piece of information for farmers.	Typical time resolution is 12–24 hours; typical space resolution is in the alpha mesoscale range (2 000–200 km).
Long-range forecast	LRF	From 12–30 days up to two years	Forecast is usually restricted to some fundamental variables (temperature and precipitation); other variables, such as wind, relative humidity and soil moisture, are sometimes presented. Information can be expressed in absolute values or in terms of anomaly.	Statistical (for example, teleconnections) and NWP methods. Coupling of atmospheric models with ocean general circulation models is sometimes adopted in order to enhance the quality of long-range predictions.	An extended-range weather forecast (ERF), beyond 10 days and up to 30 days, is sometimes considered.	Typical time resolution is 1 month; typical space resolution is in the beta macroscale range (10 000–2 000 km).

<sup>a</sup> It has been observed recently that SRF and MRF are converging towards a unique kind of forecast, because numerical weather prediction (NWP) models are the basis for both SRF and MRF. It might be more correct to distinguish between forecasts based on global models (GM) and limited area models (LAM), which range from now to  $h + 72$  h, and forecasts based only on GM, which range from  $h + 72$  h to  $h + 7–15$  days.

**Table 5.2. Accuracy, usefulness and main limitations of weather forecasts for agriculture**

<i>Type of weather forecast</i>	<i>Accuracy<sup>a</sup></i>	<i>Usefulness</i>		<i>Main limitations</i>
		<i>Real</i>	<i>Potential</i>	
Nowcasting	Very high	Very low	Low	Unsuitability of broadcasting system; insufficient flexibility of agricultural technology
Very short-range forecast	Very high	Low	Moderate	Unsuitability of broadcasting system; insufficient flexibility of agricultural technology; farmers do not know how to make the most use of available forecasts
Short-range weather forecast	High	Moderate	High	Further adaptation of forecasts to farmers' requirements is needed; farmers do not know how to make the most use of available forecasts
Medium-range weather forecast	High or moderate until 5 days; lower thereafter	High	Very high	Further adaptation of forecasts to farmers' requirements is needed; farmers do not know how to make the most use of available forecasts
Long-range forecast	Very low	High in warning of delays in arrival of weather systems. Very low otherwise	Poor	Reliability (The reliability of LRF is higher for the tropics than for mid-latitudes. This is because tropical areas have a moderate amount of predictable signal, whereas in the mid-latitudes random weather fluctuations are usually larger than the predictable component of the weather.)

<sup>a</sup> Subjective judgement of a weather forecaster working at mid-latitudes. The judgement refers to cloud coverage, air temperature and precipitation occurrence.

The weather requirements for each rice farming operation in the humid tropics are given in Table 5.3.

### 5.3.2 Format of forecasts

Formats of forecasts for agriculture vary widely in different agricultural contexts due to the high degree of variability among users, crops, agro-techniques, and so on. Specialized forecasts can be tailored for crops, animal husbandry, forestry, fisheries and horticulture. Forecasts by nature have a technical slant. Nonetheless, forecasts need to be couched in a language that is as simple as possible so that farmers are able to readily grasp their content. Therefore, "intermediaries" (employed by the National Meteorological Services and/or the extension wing of agricultural services) must be provided for, as a vital link between the forecasters (and their products) and the farmers, to explain

how forecasts are to be used as agrometeorological services for field operations.

A forecast produced for educational purposes and released weekly by the University of Milan, Italy, is presented in the Annex to this chapter. This product is composed of three main parts:

- A general evolution;
- A forecast for seven days (cloud coverage, precipitation, wind, air temperature and other phenomena, such as foehn, frost, and so forth);
- A forecast of water balance, net primary production and growing degree-days.

### 5.3.3 Forecasts for agricultural purposes

In order to arrive at forecasts geared toward agricultural users as detailed above, the forecasts that are initially framed need to be modified/processed. A

Table 5.3. Summary of weather requirements for each rice farming operation in the humid tropics

<i>Farming operation</i>	<i>Sky condition during farming operation</i>	<i>Soil (moisture) condition</i>	<i>Leaf wetness duration</i>	<i>Air temperature (°C)</i>	<i>Wind speed (km/h) during farming operation</i>
1. Land preparation (Hand hoeing/plowing/harrowing/rotavating of lowland farms)	Clear or cloudy day desirable	Moist or wet	Not applicable	≤40 desired	≤50
2. Seeding in seedbed or field, A <sub>1</sub> dry seeds A <sub>2</sub> pre-germinated	Clear or cloudy	A <sub>1</sub> moist, A <sub>2</sub> wet	Not applicable	<33 desired	<20 desired
3. Transplanting seedlings	Clear or cloudy day	Wet	Not critical	≤40 desired	0–30
4. Hand weeding/cultivating (upland farms)	Clear to partly cloudy day	Moist or dry	Not critical	≤40 desired	for comfort of workers ≤50 during operation
5. Irrigation	Clear or cloudy day	Moist or dry	Not critical	Not critical	Not critical
6. Spraying Pesticide or foliar fertilizer B <sub>1</sub> ground application B <sub>2</sub> aircraft application	Clear day desired; partly cloudy day and/or night acceptable. (Visibility should be adequate for low-level flight of aircraft)	B <sub>1</sub> Moist or dry desired for dry application in upland farms B <sub>2</sub> Not critical for lowland rice farms or aircraft application	Leaves should be dry at spraying time; no rain until at least 4 h after spraying	<33 desired	B <sub>1</sub> 0–18 (for ground application) B <sub>2</sub> 4–14 (for aircraft application)
7. Threshing/sun-drying/cleaning grain	Clear to partly cloudy for threshing and cleaning grains; clear for sun-drying	Dry surface for operation	Not applicable	No upper limit	≤25 during grain cleaning operation



more specific description of the processing of weather forecasts of single weather variables for agricultural purposes is presented below.

#### 5.3.3.1 Sky coverage

Forecast of sky coverage can be defined by adopting some standard classes, such as sky clear (0–2 octas), partly cloudy (3–5 octas), mostly cloudy (6–7 octas) and overcast (8/8). It is also important to give information about the character of prevailing clouds. For example, high clouds produce a depletion of global solar radiation quite different from that produced by mid- or low clouds. It is important to give an idea of the expected variability of sky coverage in space and time as well. A probabilistic approach may also be adopted in order to increase the usefulness of this kind of information.

#### 5.3.3.2 Bright sunshine

Sun shining though clouds will not affect crop performance, because in this case the reduction will be in diffuse radiation from the sunlit sky and the latter is only a fraction of total global solar radiation. So in cloud cover forecasts the fraction of cloud covering the sun should also be specified in addition to the total cloud cover.

#### 5.3.3.3 Solar radiation

The main parameters, extraterrestrial radiation ( $R_a$ ) and possible sunlight hours ( $N$ ), required to derive solar radiation ( $R_s$ ) from bright hours of sunshine ( $n$ ) are readily available on a weekly basis for any location and period (Venkataraman, 2002). The relationship between the ratio of  $R_s/R_a$  and  $n/N$  is a straight-line type. The value of the constants, however, varies with seasons and locations but can readily be determined.

#### 5.3.3.4 Precipitation

Snow and rainfall are probably two of the most difficult forecast variables. Quantitative forecasting of rainfall, especially of heavy downpours, is

extremely difficult and realizable only in rare instances and using highly sophisticated Doppler radars. For crop operations, however, the quantitative forecasting of rain is not half as important as the forecasting of non-occurrence of rains (dry spells) and the type of rain spell that can be expected.

Forecasts of rain can be defined by adopting some standard classes (Table 5.4) based on the climate and the agricultural context of the selected area. A probabilistic approach (Table 5.4) is quite important in order to maximize the usefulness of this forecast.

Adopting the scheme shown in Table 5.4, it is possible to produce daily information like this:

- (a) Mostly cloudy or overcast with rainfall (Class 3, high probability);
- (b) Partly cloudy with rainfall unlikely (Class 2, very low probability);
- (c) Sky clear with absence of precipitation.

Use of the same terms as in Table 5.4 to qualify the likelihood of occurrence of rainfall and rainfall amounts will confuse the public. It is better to use different terms for the two purposes. Thus, for forecasts on the chances of occurrence of rain, plain language such as “nil”, “very low”, “low”, “high” and “very high chance” should be used. If quantity can also be forecast, plain language terms such as scanty = <1 mm, moderate = 1–10 mm, heavy = 10–50 mm and very heavy = >50 mm should be used. The probability of occurrence of a given quantity of rainfall will vary with places and periods. So if probability is to be indicated for quantum of rain it should be based on climatological values of assured amounts of rainfall at various probability percentages in the area(s) and the period to which the forecast refers.

Fog can contribute significantly to crop water needs and can be measured by covering the funnel of a raingauge with a set of fine wires. Quantitative data on fog precipitation may not be available. Nomograms for predicting the occurrence of fog at airports are available with forecasters, however, and

**Table 5.4. Rainfall classes for a period of 24 hours**

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Quantity: Class 1: <1 mm (absent); Class 2: 1–10 mm (low); Class 3: 10–50 mm (abundant); Class 4: >50 mm (extreme)

Probability per the defined class of quantity: <1% = very low; 1–30% = low; 30–70% = moderate; >70% = high

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The classes presented cover a European area (the Po Plain, northern Italy) and can be quite different for other areas.

these can be adopted for use in agricultural weather forecasts.

Dew is an important parameter influencing leaf wetness duration and it therefore plays a role in facilitating entrance of disease spores into crop tissues. Dew is beneficial in contributing to water needs of crops in winter and in helping the survival of crops during periods of soil moisture stress, as the quantum of dew collected per unit area of crop surface is many times more than that recorded with dew gauges. Dew is also desirable for using pesticides and fungicides in form of dust. The meteorological conditions required for dew formation are the same as those for fog formation, except that there needs to be an absence of air turbulence in the air layers close to the ground and the crop canopy temperature must be lower than the screen temperatures. Thus, nomograms used by forecasters for predicting fog can be used to predict dew, in the absence of low-level air turbulence, by factoring into the temperature criteria the expected depression of crop minimum temperatures below the screen minimum.

#### 5.3.3.5 Temperature

Forecasting of air temperature is important for many agrometeorological applications. Forecasts of the temperature of soil, water, crop canopies or specific plant organs are also important in some specific cases. Crop species exhibit the phenomenon of thermoperiodicity, which is the differential response of crop species to daytime, nocturnal and mean air temperatures (for example, Solanaceae to night temperatures, Papilionaceae to daytime temperatures and Gramineae to mean air temperatures). It is possible to derive mean day and night-time temperatures from maximum and minimum temperature data.

Forecasts of temperature are generally expressed as a range of expected values (for example, 32°C–36°C for maximum and 22°C–24°C for minimum). If the forecast is directed at mountainous territories, temperature ranges could be defined for different altitudinal belts, taking into account also the effects of aspect. Special care could be reserved for temperature forecasts at particular times of the agricultural cycle, taking into account the values of cardinal and critical temperatures for reference crops.

Other thermal variables with a specific physiological meaning (for example, accumulation of thermal units or chill units) can be the subject of specific forecasts. The base temperature above which the accumulations will apply, however, varies with crop types (for example, wheat, maize and rice: 4.5°C,

10°C and 8°C, respectively). Therefore, for forecasting the dates of attainment of specific phenological stages of crops, time series data showing actually realized heat or chill accumulations by various crops up to the time that forecasts are issued have to be maintained. A probabilistic approach can then be adopted to forecast the probable dates that specific crops will reach particular phenological stages.

#### 5.3.3.6 Humidity

For the day as a whole, dewpoint temperature is a conservative parameter and is easier to forecast, as changes in dewpoint temperatures are associated with the onset of fresh weather systems. From maximum, minimum and dewpoint temperatures, minimum, maximum and average humidities can be derived. Users tend to understand the implications of the term “relative humidity” much better than other measures of air moisture content, such as vapour pressure and precipitable water. So the ultimate forecast has to be expressed in terms of relative humidity. Forecasting of relative humidity can be important in some specific cases. Probability of critical values (very high or very low) can also be important.

#### 5.3.3.7 Wind speed and direction

Forecasting of wind speed is important for many different agricultural activities. Wind direction can be defined as well. It is important to give an idea of the expected variability in speed and direction of wind. The monthly windrose at a station is a climatological presentation that indicates the frequency of occurrence of wind from each of the eight accepted points of the compass and frequencies of occurrence of defined wind speed ranges in each of the eight directions. Wherever possible, the windroses must be looked at before forecasts are issued.

For agricultural purposes, wind speed and direction are required at a height of 2 m. But weather forecasts of wind refer to heights greater than 2 m. Change in wind direction between 2 m and the forecast height will not occur. Wind speed at 2 m will be considerably lower than at the forecast height, however. Ready tables to convert wind speeds at any height to the speed at 2 m are available and may be used to forecast wind at a height of 2 m.

The term kilometres per hour, km/h, is much better understood by user interests than the terms Beaufort scale, metres per second, MpS or knots. So wind speeds must be forecast in km/h for a height of 2 m.

#### 5.3.3.8 Leaf wetness

Leaf wetness is produced by rainfall, dew or fog. Duration of this phenomenon can be important in order to plan different activities, such as the application of pesticides and harvesting of crops. Leaf wetness is a parameter that is scarcely recorded. A number of empirical methods cited by Matra et al. (2005) have been used to derive leaf wetness durations from meteorological parameters. It is possible to derive the hourly march of temperatures from maximum and minimum temperatures (Venkataraman, 2002). The temperatures during night hours have to be decreased by a value equal to the depression of the radiation minimum below the screen minimum. As mentioned earlier, dewpoint temperature is a conservative parameter. Thus, the number of hours during which dewpoint temperature is above the adjusted air temperature will give leaf wetness duration. The time taken for the moisture deposited on the crop leaves to evaporate also has to be included in the leaf wetness duration. The amount of moisture deposited on the crop may be many times more than that indicated by instruments. So the estimated moisture deposition has to be multiplied by a crop factor and the product divided by the evaporative power of the morning air. As a rule of thumb, two hours after sunrise may be added to the estimated duration of leaf wetness.

#### 5.3.3.9 Evapotranspiration

Forecast of evapotranspiration can be important to improve knowledge of the water status of crops. This kind of forecast is founded on the correct forecast of solar radiation, temperature, relative humidity and wind speed. For real-time use, forecast of evapotranspiration has to be founded on a forecast of pan evaporation, as discussed below.

The evaporative power of air (EPA) determines the peak water needs of vegetative crops and is the datum to which all measurements of evapotranspiration (ET) should relate. The Food and Agriculture Organization of the United Nations (FAO, 1998) has advocated the use of reference evapotranspiration  $ET_0$  as a standard measure of EPA. Computation of  $ET_0$  requires data on net radiation over a green crop canopy, low-level wind and saturation deficit of air. An empirical method to compute  $ET_0$  from routinely available meteorological data has been proposed.  $ET_0$  refers to turf grass. Agricultural crops have peak water needs greater than those of turf grass, while tall crops may have peak water needs that are higher than those of short crops. Data to compute  $ET_0$  on an operational basis are neither widely nor readily available.

Evaporation from pans filled with water (EP) is subject to weather action in a manner similar to that of EPA. EP is also easily measured. Venkataraman et al. (1984) have detailed methodologies to compute  $ET_0$  using measured values of solar and atmospheric radiation; they have also described using these values to derive ratios of  $ET_0$  to EP at a number of stations covering typical climate regimes. The use of pan coefficients to derive  $ET_0$  under varied surroundings and typical settings for the pans have been suggested in the literature (FAO, 1998). Data on EP and studies relating ET of crops to EP are available. The ratio of peak ET to EP, called relative evapotranspiration (RET), can vary in space and time, but is not difficult to determine.

#### 5.3.3.10 Water balance

A quantitative forecast of the probability of water excess or stress for rainfed crops, and of the timing and amount of irrigation for irrigated crops, is highly useful. This kind of forecast for rainfed crops is based on correct forecasting of precipitation and evapotranspiration. The water balance approach to arrive at soil moisture excess or deficiency would require daily forecasts of rain in the first month of crop growth and on a short-period basis thereafter. Influence of physiological control on crop water uptake during maturity (Hattendorf et al., 1988; Venkataraman, 1995) is also important. Since irrigation water is applied ahead of crop water consumption for forecasts of irrigation scheduling, forecasts of evapotranspiration and likely rainfall amounts on a short-period basis will do.

#### 5.3.3.11 Extreme events

The low level of predictability of extreme events acting at meso- or microscale (frost, thunderstorms, hail, tornadoes, and so forth) is an important limitation to the usefulness of forecasts for agriculture. Table 5.5, obtained from a subjective evaluation founded on state-of-the-art forecast technologies, illustrates the level of predictability of some extreme events with strong effects on agriculture. In order to give correct information to farmers, the adoption of a probabilistic approach could be important.

### 5.4 SPECIAL AGRICULTURAL WEATHER FORECASTS

Special agricultural weather forecasts provide the necessary meteorological information to aid farmers in making certain special “crop- and/or cost-saving”

**Table 5.5. Predictability of some extreme events relevant for agriculture (data are estimated for European area)**

<i>Extreme event</i>	<i>Predictability</i>			
	NC	VSRF	SRF	MRF
Frost	high	high	low	low
Thunderstorms	high	moderate	low	low
Showers	high	moderate	low	low
Hail	low	very low	un	un
Tornadoes	very low	un	un	un
Wind gales	high	high	moderate	low

very low: <1%; low: 1–30%; moderate: 30–70%; high: >70%; un = unpredictable (forecast cannot be produced with present technologies)

decisions regarding farm operations. For the same temporal distribution of weather parameters, different crops will react differently. Again, the effects of weather or weather-induced stresses and incidence of pests and diseases are critically dependent on the state and stage of crops during which these phenomena occur. The effects of anomalies of a weather element on a given crop are location-specific. Again, the crop fetches may range from large monocultural areas to small, dispersed areas of various crops. Thus, the requirement for these special forecasts will vary among and within the seasons, from place to place, from crop to crop, and with the kind of operation, namely, cultivation, post-harvest processing, and so on.

Special forecasts are normally issued once every day for a specific operation and generally cover the next 12–24 hours, with a further outlook if necessary. These special weather forecasts must be written by a trained agricultural meteorologist in consultation with farm management specialists for the current problems. They are normally issued for planting, irrigation, applying agricultural chemicals, cultivation, harvest and post-harvest processing, and they may also address other weather-related agricultural problems associated with the crop, its stage and location. Temperature bulletins for protection against freezing are also issued as special forecasts in areas where crops may suffer damage from freezing.

#### 5.4.1 Field preparation

Field preparation for rainfed crops is weather-dependent. In any dryland areas the amount of rainfall is very meagre and farmers should take

advantage of even minimum showers. Otherwise the moisture is lost. Minimal tillage is the current agronomic mantra for conserving moisture, retaining nutrients and keeping weeds out. An optimum soil moisture profile characterized by top dry soil, sub-surface moist soil and wet soil in the seeding zone is required to carry out field preparation for dryland farming. The prediction of the exact time of occurrence of rainfall in a particular location helps to initiate field preparation. An example of this is: “Pre-monsoon showers are expected in the 37th standard week of this year and farmers are requested to initiate field preparation activities before this week”.

#### 5.4.2 Sowing/planting

Seed germination is dependent upon proper light and moisture, as well as soil temperature. Even with no nutritional or soil moisture constraints, rot foraging capacities vary among crops in the same soil and within the same crop in different soils. Alternating temperatures assist the germination of many species of seeds and do not unfavourably affect the germination of those that do well under constant temperatures. The amplitude, which is the difference between maximum and minimum temperatures, decreases with depth and becomes negligible at a depth of 30 cm. Hence soil temperatures at 30 cm can be taken as constant. The temperature range at which soil temperatures will equal the air temperature will principally depend on the texture and structure of soil. Under a ground-shading crop, the depth of no diurnal change is pushed up compared to that seen under bare soil.

For germination and crop establishment, the soil temperature regime at a depth of 7.5 to 10.0 cm is of importance. At these depths the maximum and minimum soil temperatures tend to follow the maximum and minimum screen temperatures.

Thus, the diurnal variations in soil temperatures in the seed zone are beneficial and not harmful. Some species of seeds are light-sensitive, however, and for them the depth of sowing and adequacy of soil moisture at the desired depth are critical. In dryland agriculture, gap-filling to correct for poor germination is often not possible. Excess germination can be corrected by thinning and the dryland farmer would prefer very good germination followed by thinning, if necessary. The farmer must, therefore, know the existing soil temperature and what the changes in soil temperature and moisture will be. Of the above two parameters, soil moisture is more important. The rooting pattern also varies from crop to crop. Further, for many crop seeds, light is necessary to initiate germination. Knowledge of the likely values of these two parameters will help farmers avoid sowing under soil conditions that would lead to a poor initial crop stand, correction of which is often not possible and if possible may hinder germination and emergence, and which consequently would require the resowing of expensive seeds.

When direct planting is resorted to, the prevailing weather conditions dominate the crop stand and establishment. Agronomic measures to modify soil temperatures and conserve seed zone moisture to ensure proper germination in marginally adverse weather conditions are possible. From maximum and minimum values of surface soil temperature or air temperature it is possible to arrive at temperature amplitudes for a given depth of soil in a given type of soil. Thus, parameters that are of interest, namely temperature below and above soil surface, atmospheric humidity and soil moisture, need to be forecast.

Soil temperature forecasts are normally issued once daily prior to and during the normal planting season. They should give the present observed conditions throughout the area with a forecast of changes during the succeeding three days, since most of the crops need one life irrigation for the emerging plumule/radicle to protrude above the soil surface when seeds are sown. An example of this type of forecast is: "Bright sunshine during the next three days will cause soil temperatures to rise sharply. Soil temperatures at normal seeding depths are expected to reach and maintain levels favourable for cotton and groundnut seed germination by

early next week. Further, atmospheric temperature will be very high for the next few days, which may affect establishment of seedlings to be planted."

#### 5.4.3 **Application of agricultural chemicals**

Use of agricultural chemicals is inevitable in crop production. Overuse of agrochemicals such as fungicides and pesticides, however, especially the systemic types and inorganic nitrogenous fertilizers, leads to contamination of food produce and soil; pollution of air, aquifers and water reservoirs; and development of chemoresistant strains of pests, diseases and weeds. Weather forecasts as detailed in the ensuing sections on control of insects, diseases and weeds can not only help minimize the volume of agrochemicals applied, but also make the applications more effective. Agrochemicals constitute a sizeable fraction of a farmer's total cash outlay in any given production system. Minimization of the use of agrochemicals will reduce a farmer's cultivation costs and help increase the acreage of assured protection and nutrition of crops, without consuming additional resources.

The critical weather elements governing judicious application for efficient utilization are atmospheric temperature, precipitation, soil moisture content during the past and succeeding 24 hours, and the speed and direction of winds, with an emphasis on any changes in speed or direction during the forecast period. Precipitation can dilute or wash off the chemicals. Agricultural chemicals that require special attention with regard to meteorological factors are herbicides, growth regulators, hormones, insecticides, fungicides and nutrients, as well as those used for soil fumigation and rodent control. Only an agricultural meteorologist well versed in current farm operations can be aware of the different chemicals in current use and their varying requirements.

##### 5.4.3.1 **Foliar application**

Agrochemicals for application to soils have to be carefully chosen to avoid contamination of soil, leaching into groundwater aquifers, and runoff to water reservoirs. If the same effects can be achieved by aerial sprays, foliar application is to be preferred. Soil conditions often preclude application of chemicals to soils, and under these circumstances foliar application is the requisite technique. Temperatures at the time of application and immediately following are extremely important and can determine effectiveness of foliar application of nutrients and herbicides. For certain herbicides,



such as glyphosate, the effectiveness is enhanced if the atmospheric temperature is high at the time of application and the succeeding two to four hours. On the other hand, for foliar application of nutrients, atmospheric temperature should be lower in order to avoid phytotoxicity associated with soil moisture availability.

#### 5.4.3.2 Soil application

Precipitation is the most important factor that determines the efficacy of chemicals applied through soil. Precipitation in the succeeding 24 hours is the critical parameter. Limiting the amount of treatment through the effective use of weather information also leads to minimum pollution of groundwater and runoff.

Examples of forecasts for application of agricultural chemicals are:

*Wind speeds are expected to be mostly favourable for application of agricultural chemicals today and tomorrow. Wind direction will be variable and wind speed will range from 6 to 13 km/h in the forenoon and will become southerly with speeds of 13 to 24 km/h during the late afternoon. Temperatures are likely to exceed 27°C tomorrow. So caution should be exercised in applying oil-based sprays.*

*Heavy rain is expected in the next 24 hours, so foliar application of chemicals may be postponed.*

#### 5.4.4 Evaporation losses for irrigation

Irrigation water is costly to farmers in most agro-ecosystems today. Overuse can be both expensive and detrimental to the crop, while underuse can result in loss of crop quantity as well as quality. Estimates of daily consumptive use can be related to the free water loss from a Class A-type evaporation pan: the free water loss over the previous day for an area is obtained from the actual values recorded, while the loss for the succeeding 24 hours must be forecast based on the forecasts of rain, wind, relative humidity and bright hours of sunshine. For example, due to wetting of its surroundings by rain, the evaporation from a pan can be 20 to 30 per cent lower than with dry surroundings. Linear approximations have been derived for the estimation of solar radiation from bright hours of sunshine, potential evapotranspiration from either pan evaporation or from associated wind, and vapour pressure deficit terms. Consumptive use rate can be estimated not only from evaporation pan losses, but also from evaporation and shade temperature

measurements, or from formulae deduced from the energy balance equation. With these values, a farmer can be informed of the field water loss occurring after the last rain or irrigation and can also be advised on the timing and quantum of irrigation, taking into consideration the expected rainfall. In this connection, it is worth mentioning that Portugal was awarded the second prize in the International Society for Agricultural Meteorology (INSAM) contest of best examples of agrometeorological services (2004/2005) for assistance to farmers in arriving at a quantitative estimate of irrigation needs.

The following are examples of water-loss forecasts:

*Free water loss during the past 24 hours averaged 0.6 cm. Expected free water loss is 0.6 cm today and 0.8 cm tomorrow. Rainfall probability will remain low for the remainder of the week and crops will begin to suffer from moisture stress in four days' time. Supplementary irrigation of 7 cm in two days' time is recommended.*

*Rain is likely to occur in the next 24 hours in most of the areas in this region and so farmers may postpone their irrigation for this period.*

#### 5.4.5 Weeding

Weeds are one of the most serious afflictions for farming and successful farming includes weed management. Because of climatic influences, the distribution of weed flora across regions and their composition within a region vary greatly. There is no broad-spectrum weedicide that is effective against all weeds and is at same time non-toxic to crop plants, which means that herbicide prescription is a specialized job. The indication is that overuse of herbicides for an extended period will lead to chemoresistance in weeds. So herbicide applications must be minimal but effective. There are two methods of weed management, that is, hand/mechanical weeding and chemical weeding. For certain herbicides, prevailing weather decides the effectiveness of the application, as in the case of non-selective herbicides. Rain immediately after chemical weeding will neutralize the operation's effects and will result in a waste of money. Rains will help in the germination of dormant weed seeds or may promote better growth expression of weeds. Thus, clear weather following rain will assist hand or mechanical weeding.

Examples of weeding forecasts are:

*Rain is likely to occur in the next 24 hours in most of the areas in this region, so farmers may postpone application of chemical herbicides and hand/mechanical weeding operations.*

*Following the rain spell of the last three days, weather will remain dry for the rest of the week. Hand/mechanical weeding and chemical weeding in two to three days' time are recommended.*

#### 5.4.6 **Crop harvest and post-harvest operations (including crop curing and drying of meat and fish)**

The harvesting of agricultural produce and its immediate processing before storage assume vital importance, more so than any other field operations, because a few days of fickle weather at the end of the crop season can be ruinous. The forecast for such activities should be of high order to ensure that whatever yield can be saved on the field is saved and that what is gained on the field is not lost off it. While the general agricultural weather forecast should supply the meteorological information necessary for harvest operations, post-harvest operations such as curing and storage require special forecasts of certain elements. The primary weather factors for crop harvest are rainfall and atmospheric temperature, while for post-harvest operations, in addition to the above, sunshine, wind, relative humidity and dew are also important. Precipitation may increase the moisture content in the straw of rice crop, which may delay harvest operations. Low temperature may also cause a delay. Precipitation may leach the quality of forages. Basic post-harvest operations include simple drying, as in the case of medicinal plants. Light winds assist in the winnowing operations that separate grain from chaff. In the absence of wind, blowers have to be used. Low temperature in the atmosphere may delay drying of certain valuable medicinal compounds and result in their subsequent conversion into less desirable products. In crops like tobacco, this may entail complex processes involving enzymatic reactions that are influenced by humidity and temperature. It is worth mentioning here that in order to ensure high-quality end products either from crops or meat and fish, accurate weather forecasts for curing and related actions are essential.

The following is an example of a rice harvest forecast:

*Rain is expected in the ensuing week. Accordingly, harvesting may be done earlier.*

The following is an example of a tobacco curing forecast:

*Good tobacco curing weather prevailed during the past 24 hours. Extremely dry weather today*

*and tomorrow will tend to cause excessively rapid drying of tobacco. Shed should be partly closed to slow the drying.*

And finally, the following is an example of a meat drying forecast:

*Maximum temperature is expected to be around 30°C in the next three days. Farmers should take advantage of this period for meat and fish drying.*

#### 5.4.7 **Control of plant diseases**

Most plant diseases set in under conditions of wet vegetation and develop and spread when the wet weather clears. The rate of development of a disease depends on temperature. The cardinal and optimal temperatures for development vary with the disease organisms. Therefore, effective and economical control of most diseases primarily requires a vegetative wetting forecast. This forecast will include the number of hours during which vegetation was wet from rain, fog or dew during the preceding 24 hours; the temperatures during this period; and a prediction of the hours of wetting and of the temperature and sky conditions during the succeeding 24 hours. Armed with this information, a farmer should be able to obtain maximum control with a minimum number of chemical applications.

The computer has enabled pathologists and physiologists to generate biological models that describe the development of disease pathogens in plants. By introducing meteorological data, either daily or hourly, into these models, conditions favourable to disease development and the potential severity of outbreaks can be estimated for many diseases, such as leaf blight and stalk rot of corn.

The following is an example of a root disease forecast:

*Excess moisture prevailing in the root zone of vegetable crops in the past seven days may promote root diseases such as root rot and the like. Farmers are advised to carry out soil drenching with suitable fungicides to avoid heavy crop loss.*

#### 5.4.8 **Control of noxious insects**

Within broad limits, weather is one of the principal factors controlling insect occurrence and governing the general distribution and numbers of insects. Weather factors, acting in combination, can either foster or suppress insect life; for example, temperature and humidity control the time interval between successive generations of insects, as well as the

number produced in each generation. Feeding habits are also controlled by weather and climate. Large-scale, low-level wind patterns are an important factor in the migration of insect pests. With regard to insecticides used to control pests, weather controls not only the insects' susceptibility, but also the effectiveness of the pesticides.

Insect and plant biological computer modelling, using meteorological and insect light-trap data as input, is helping to determine the time and severity of economically damaging outbreaks of the corn borer and alfalfa weevil. Biometeorological models have been developed for the emergence of adult mosquitoes and the periodicities of their flight activities leading to displacement from breeding sources and infestation of urban and agricultural areas. These models demonstrate the importance and practical use of weather and climatological data to determine strategy, tactics and logistics in programmes to monitor and control pests and their vectors. The seasonal abundance and date of emergence of mosquitoes following first flooding of eggs are predicted from cumulative variation from normal of air temperature and solar radiation. Flight activity and dispersal of flies from breeding sites to infest agricultural and urban areas are predicted from 24-hour projections of temperature, humidity and wind conditions that provide optimum hygrothermal environments for energy metabolism. The projections for optimum flight periods from daily synoptic weather forecasts facilitate the detection of invasions of pest and disease vectors and also the timing of pesticide applications to intercept and eliminate pest infestations during displacement from breeding areas.

The following is an example of a mosquito control forecast:

*The incessant rains and floods may act as breeding grounds for mosquitoes. The municipal authorities are advised to spray suitable chemicals in the water bodies to avoid mosquito-borne diseases. Farmers are also advised to drain water from stagnant areas.*

The following is an example of a rice hopper forecast:

*The low temperature prevailing for the past 15 days and incessant rains may encourage development and infestation of rice hoppers. Farmers are advised to take suitable prophylactic spray measures.*

#### 5.4.9 **Transport of agricultural products**

Most agricultural products must be transported a fairly long distance from the place of production

to the marketplace. During transport, the temperatures of many varieties of produce must be held within very narrow limits to prevent deterioration and spoilage. Therefore, the heating and cooling of containers transporting them may be required. An accurate forecast of the maximum and minimum temperatures along the normal transport route is needed to plan the type of transport equipment and its utilization. Temperature forecasts may be given for areas for which they are not normally supplied, such as high, cold mountain passes, or hot, dry desert areas. A short weather synopsis for the period would also be valuable.

Transportation and commodity-handling agencies have expressed the need for climatological and meteorological information to improve decision-making in their logistics. For example, a series of snowstorms during the period of 28 January–4 February 1977 in southern Ontario severely disrupted the provincial milk collection system. The effects of these storms were manifold; not only was the schedule of the milk collection trucks disrupted, with serious losses resulting to the milk producers, but the trucking equipment sustained serious damage and the life of one driver was lost during a blinding snowstorm in a railway-crossing accident. The system handling a perishable commodity like milk depends on intricate scheduling geared to the farmers' storage capacity, in this case 2.5 days of milk production. Therefore, the collection trucks have to come every second day. In the case of Ontario, delays of three to four days resulted and the farmers, who often obtain 450 kg per milking and have no room to store the milk, were forced to pour it out, causing a considerable loss. The transportation system incurred a setback in the form of equipment loss and damage, overtime pay for extra hours worked and even injury and the death of one driver.

The following is an example of a forecast for the transport of onions:

*The low temperature prevailing in the past 7 days may lead to deterioration in the quality of harvested onion for transport through germination. Farmers are advised to make the necessary packaging arrangements to counteract the low temperature.*

#### 5.4.10 **Operation of agricultural aviation**

Aircraft are used for a wide variety of operations in agriculture and forestry. Because they operate at low altitudes, much below those of regular

transport aircraft, they require specific details not available in routine aviation forecasts, which usually include ceiling, visibilities and turbulence. For example, to achieve successful results, low-level (surface to 30 m) wind drift and stability factors are needed, while the strength of the surface inversion is extremely important if ultra-low volume sprays (where particle size may be as small as 10  $\mu\text{m}$ ) are to be used. Vertical motions of more than 0.5  $\text{cm s}^{-1}$  will cause such spray droplets to rise and disperse throughout the atmosphere rather than settle on the crop.

The following is an example of a dusting and sprinkler irrigation forecast:

*Heavy winds are expected at a speed of 60 km/h today. Farmers are advised to avoid dusting operations as well as operation of sprinkler irrigation systems.*

#### 5.4.11 **Prevention of damage due to chilling, frost and freezing**

The minimum temperature forecast is an integral part of farming in hilly and subtropical/humid regions. These regions need a special minimum forecast system particularly during the cropping season. This critical information will aid farmers in the judicious allocation of their resources, such as labour and other agricultural inputs, so as to avoid crop losses. The forecast should include the minimum temperature expected in the next 24 hours. This may be station-specific or for a particular region as a whole. As long a lead time as possible is extremely important for some crops, such as citrus and apple.

The following is an example of a frost damage forecast:

*Ground frosting is expected in the ensuing three days in certain parts of the northern localities and may damage grain crops. Suitable precautionary measures must be taken to avoid crop damage.*

An example of a special minimum temperature bulletin follows:

*A strong cold front moved through the agricultural districts late yesterday and very cold and dry air now covers the entire area. Temperatures are expected to drop sharply tonight from near 10°C at sunset to below 0°C by 0100. By sunrise minimum temperatures are expected to range from -7°C to -4°C in the coldest low-lying areas and from -4°C to 2°C in the higher locations. Minimum temperatures forecast for key stations tonight are as follows:*

*Key station*

*A: -4°C*

*B: -6°C*

*C: -7°C*

*D: -4°C*

*E: -3°C*

*F: -4°C*

*G: -5°C*

*Growers should relate their locations to the nearest key stations. Outlook for tomorrow night: continuing very cold with minimum temperatures generally -5°C to -2°C.*

#### 5.4.12 **Forestry operations**

From the selection of sites for afforestation to planning the harvesting of forest products, weather forecasts are of major importance to foresters. In many afforestation programmes, seeds of forest trees are sown from aircraft. Under these circumstances, precipitation plays a significant role in the germination and growth of the plant stands. When saplings are planted, precipitation plays a key role in their establishment. In addition to precipitation, the prevailing microclimate also helps to determine stand establishment. A forester can easily manipulate the microclimate through artificial mulching and other methods.

Fire is one of the greatest problems of forest management. The moisture content of inflammable parts of forest trees derived from measurements of physical atmospheric parameters is used to determine when fire danger alerts should be issued in some countries. Direct relationships exist between weather and potential fire danger and fire behaviour. Day-to-day reports and forecasts of temperature, relative humidity, wind, precipitation, thunderstorms and critical moisture content of inflammable parts are needed. Fire danger forecasts determine whether logging operations should continue and whether parks and forests should remain open for recreational purposes. The special forecasts should alert forestry personnel to the danger that fires will start (as a result of either human activity or lightning) and the potential rate of spreading, once started. Fire advisories are continuously issued on site to assist in controlling and stopping fires.

#### 5.4.13 **Fishery operations**

Weather and climate affect fisheries more than any other category of food production. Weather affects the safety and comfort of fishermen, as most of the fishing occurs when fish are sufficiently aggregated. Cyclonic storms affect the safety of the fishing vessel,



especially when the wavelength approaches the ship's length. Short-term weather forecasts can be crucial for planning fishery operations. Information on the intensity and tracks of cyclonic storms is immensely useful for the safety of fishermen operating in the oceans. Fog is another weather element affecting fishing and safety. Weather also affects fish behaviour, aggregation, dispersal and migrations. For their part, wind, currents, light and temperature, and also lunar periodicity, affect the behaviour of fish as well as other aquatic life (Cushing, 1982).

The growth of individual fish is closely linked to the temperature of the water. Temperature not only influences the distribution and movement of fish, but also subtly affects many important biological processes, such as the number of eggs laid, incubation time, survival of the young, growth rate, feeding rate, time it takes to reach maturity and a host of other physiological processes. Other climatic factors, such as the degree of insolation, are influenced by cloud cover, while climate-dependent environmental variables, such as changes in water quality and quantity, are associated with rainfall (Boyd and Tucker, 1998). These factors can act as physiological stimuli, particularly for the timing of the onset of reproduction (Lajus, 2005). For marine fisheries, slight changes in environmental variables such as temperature, salinity, wind speed and direction, ocean currents, strength of upwelling, and predators can sharply alter the abundance of the fish population (Glantz and Feingold, 1992).

Productive aquaculture sites need good water flow to remove solid and dissolved wastes and to maintain high oxygen levels in the cages. Any increase in the frequency or severity of storms as a result of climate change could be devastating for aquaculture operations (see also Chapter 13 of this Guide).

Most riverine fish populations depend on the flood plains associated with the river for feeding and breeding during the wet season. The catch of fish in the flood zones has been directly correlated with the intensity of floods in previous years: higher floods in one year result in better catches a year or two later. The response of fish to flood conditions is not only dependent on the quantity of the flood, but also on the form of the flood curve and its time.

Although some of its effects may be beneficial, El Niño may also have a strong detrimental influence on the fisheries and marine ecosystem. Increased frequency of El Niño events, which is likely in the warmer atmosphere, could lead to measurable declines in plankton biomass and fish larvae abundance in coastal waters of South and

South-East Asia. The area off western South America is one of the major upwelling regions of the world, producing 12 to 20 per cent of the world's total fish landings (IPCC, 2001). In such upwelling regions, nutrient-rich deep waters are brought to the illuminated surface layers (upwelled), where they are available to support photosynthesis and thus large fish populations (for example, Kapetsky, 2000).

With the advent of remote-sensing methods, fisheries can be studied using satellite and aircraft data. One of the important parameters that can be measured with sufficient accuracy is the sea surface temperature (SST), which has been related to the concentration of fish population. Anomalies in the water temperatures of major oceanic currents have resulted in low commercial fish catches in recent years. There have been declines, for example, in the sardine catch in the Sea of Japan associated with changing patterns of the Kuroshio Current in El Niño–Southern Oscillation (ENSO) years (Yoshino, 1998). Here it has been shown how sea surface temperature can be mapped on a regular basis and passed on to the fishermen, who could concentrate on high potential areas and improve the catch.

SST derived from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite serves as a very useful indicator of prevailing and changing environmental conditions and is one of the important parameters that determines suitable environmental conditions for fish aggregation. SST images obtained from satellite imagery over three or four days are combined and the minimum and maximum temperatures are noted. These values are processed to obtain maximum contrast of the thermal information. The process involves filming to prepare relative thermal gradient images. From these images, features such as thermal boundaries, relative temperature gradients to a level of 1°C, level contour zones, eddies and upwelling zones are identified. These features are transferred using optical instruments to corresponding sectors of the coastal maps prepared with the help of naval hydrograph charts. Later, the location of the potential fishing zone (PFZ) with reference to a particular fishing centre is drawn by identifying the nearest point of the thermal feature to that fishing centre. The information extracted consists of distance in kilometres, depth (for position fixing) in metres and bearing in degrees with reference to the north for a particular fishing centre. The PFZ maps thus prepared are sent to the fishermen for their use through facsimile transmission (fax) or by another mode of communication (WMO, 2004b).



#### 5.4.14 **Safeguarding animal husbandry**

It is well documented that the stress of adverse environments lowers productive and reproductive efficiency in farm animals. Hot or cold weather can adversely affect the performance of livestock by exceeding their coping capabilities. The impact of hot environments can be severe, particularly for animals with high levels of productivity. Specific responses of an individual animal are influenced by many factors, both internal and external. Growth, milk, eggs, wool, reproduction, feed conversion, energetics and mortality have traditionally served as integrative performance measures of response to environmental factors.

Temperature-dependent performance response functions have been developed for growing beef cattle, swine, broilers and turkeys; for conception rate and milk production of dairy cows; and for egg production of hens (Hahn, 1994).

##### 5.4.14.1 **Housing and production**

Behavioural responses to the environment may suggest alterations of management for animals subjected to specific conditions and may be useful in controlling the thermal environment. Other mitigating factors include physical characteristics of the surroundings (for example, flooring materials) and behaviours permitted by the production system (for example, animals huddling in clod conditions or moving to another microclimate, such as that provided by hovers).

Bruce (1981) estimated that the lower critical temperature for grouped nursery pigs on a solid concrete floor is 2°C higher than on a perforated metal floor and 5°C higher than on a straw-bedded floor. His evaluation also estimated that lower critical temperature for pigs penned singly is about 6°C higher than for grouped pigs, the difference being the huddling effect. A lower practical temperature limit of 3°C is suggested by the Comité International du Génie Rural (CIGR, 1984) for housed livestock to avoid freezing of waterlines and other management problems. Table 5.6 depicts the air temperature recommended for housing different kinds of livestock from various climate zones of the world to avoid adverse weather periods.

An instructive example is in South Africa, where du Preez and colleagues (du Preez et al., 1990a, 1990b, 1990c) have been mapping the monthly national temperature-humidity index (THI) values from 563 weather bureau stations covering the whole country as an aid to the optimum provision of livestock management. They found that the heat stress areas

expanded from August to January and contracted during the remainder of the year. There is a risk of moderate to advanced heat stress for dairy cattle during the period November to March. Their advice, based on THI values, is shown in Table 5.7. Given an adequate volume of meteorological data, the probabilities for different THI values can be calculated for the various seasons and thus their potential impact on production can be considered.

If the soil moisture deficit is being regularly monitored, it is possible to estimate pasture growth. Thus, using climatological and synoptic forecasts of probable conditions, and on the basis of weighting by dairy cow distribution, it is possible to predict milk production. The New Zealand Meteorological Service provides such a prediction to the New Zealand Dairy Board (WMO, 1988b). For many years L.P. Smith provided a nine-month forecast of winter milk production in the United Kingdom (Smith, 1968).

##### 5.4.14.2 **Assessment of pasture productivity and grazing**

The assessment of seasonal patterns of grass growth rates given by Brereton et al. (1987) in their model was used to calculate the number of days when the growth rate exceeded a value of 40 kg dry matter per hectare per day. This was used as a gross measure of the regional differences in the length of the grazing season. The model data were also used to estimate the date in spring when yield was sufficient for grazing to begin (1 500 kg dry matter ha<sup>-1</sup>). The analysis indicates that the regional and yearly variation in grass growth is sufficient to have a significant impact on the technical and economic performance of farms.

The pattern of seasonal production of pasture was studied for selected locations in mid-latitude Europe (WMO, 1996) and the pattern was found to be predictable in broad terms as a function of the changing weather from season to season within each year. Grazing systems are assembled accordingly, and the basic objective of the systems is to achieve high utilization efficiency by maintaining a balance between herbage availability and herbage demand. The balance is usually achieved by adjusting the size of the grazing area progressively during the year in line with the progressive changes in herbage growth rate. The scheme of adjustment of the proportion of land allocated to grazing or silage is based on a notional “normal” pattern of weather during the year. But even in “normal” years, when total herbage production is near the expected average, the supply of herbage can alternate between surplus and deficit several times during the year.

**Table 5.6. Recommended air temperature for housing various livestock**

<i>Species/classification</i>	<i>Weight (kg)</i>	<i>Ideal temperature (°C)</i>
<b>Poultry:</b>		
Hens	–	18 to 24
Broilers, young	–	27 to 28
Broilers, finishing	–	20 to 22
Turkeys, young	–	29
Turkeys, finishing	–	16 to 19
Swine, restricted-fed (2xM)	5	24 to 32
	20	21 to 31
	40	18 to 30
	80	14 to 28
	140	12 to 30
Veal calf	–	–5 to 20
<b>Rabbits<sup>a</sup></b>		
Fattening	0.5 to 2.5	16 (12 to 30 acceptable)
Adult	4 to 5	15 (10 to 30 acceptable)
Doe and litter	Avg.	18 (15 to 30 acceptable)

<sup>a</sup> Target relative humidity = 75%

**Table 5.7. Proposed practical and economical actions to protect dairy cattle in South Africa and Namibia in relation to THI values over 70 (from du Preez et al., 1990b)**

<i>THI values<sup>a</sup></i>	<i>LWSI category<sup>b</sup></i>	<i>Proposed precautions</i>
<70.0	Normal	Natural or artificial shade
70.0 – 71.9	Alert	Shade and/or well-ventilated barns, ad libitum water at shaded troughs
72.0 – 77.9	Critical	Former, plus overhead sprinklers and large fans in holding areas adjacent to the milking parlour; alter diet; consider heat-resistant breeds; limit stressful handling of stock to cooler hours of day or night
78.0 – 81.9	Danger	Former, plus shade over feed bunks and sprinklers with fans at feed bunks
≥82.0	Emergency	Occurs only on individual days. All former precautions applicable

<sup>a</sup> THI refers to the Temperature–Humidity Index. Various approaches to its formation are available (WHO, 1989). Du Preez used  $T \text{ dry bulb} + (0.36 \times T \text{ dewpoint}) + 41.2$ , with all temperatures in °C.

<sup>b</sup> LWSI refers to the Livestock Weather Safety Index.

The efficiency of a grass-based livestock production system depends on the maintenance of a critical balance between herbage demand and supply throughout the grazing season. If the supply is

allowed to exceed demand, herbage is under-utilized, herbage quality deteriorates and subsequent animal performance suffers. Where herbage supply falls short of demand, animal performance is

reduced and overgrazing can result in thinning of the sward and a reduction in herbage growth rate. A variety of options are available to the grassland farmer to make the adjustments to the system that are necessary to maintain an optimum sward/animal balance as the supply of herbage varies. For example, where herbage exceeds requirements, part of the grazing systems can be withdrawn temporarily and the herbage saved as silage. In paddock-grazing systems, in some circumstances, the grazing cycle can be extended, effectively storing grass in the field as a standing crop. In periods of herbage deficit an obvious option is to feed saved silage. The cycle can be shortened temporarily within limits.

#### 5.4.14.3 Forecasting diseases

A variety of livestock parasites, such as those that cause ostertagiasis and fascioliasis, and various tick and mosquito species, can now be reliably forecast using meteorological data. This was reviewed in WMO (1978) and updated in WMO (1989); the latter also reviewed metabolic and infectious diseases. See WMO (1988*b*) as well.

Tactical meteorological information is of obvious value in protecting livestock against the immediate dangers of (extreme) weather. It is also of value in disease control. For example, the incidence of sway-back, a congenital hypocalcaemia of sheep, can be forecast using the number of supplemental feedings and the probability of frozen ground. Timely forecasts of the need for feeding supplemental copper to pregnant ewes affect the incidence of the disease in newborn lambs if shepherds use the information. Similarly, after a period of cold spring weather there may be a sudden rise in temperature, which triggers the growth of young grass and a reduction in the absorption of magnesium; the consequent excess potassium acts as a magnesium antagonist. Clinical attacks of ovine hypomagnesaemia usually occur some five warm days after the temperature change (Smith, 1975; Hugh-Jones, 1994).

In order to benefit the livestock owners, epidemiologists have traditionally depended upon intervention programmes and preventive and control actions to confront an ongoing disease outbreak. In order to do this, a new concept of disease forecasting has emerged that seeks to forewarn farmers and forecast the devastating disease problems, with a view to the implementation of appropriate preventive measures so that the production system is not affected. Forecasting of animal diseases is a powerful tool of epidemiology that depends on reliable past information and data on the vital parameters associated with the occurrence

of diseases. Climatic conditions in an area are major parameters that facilitate induction of diseases in epidemic forms. A few examples of disease forecasting are described here (Burman et al., 2002).

- (a) Forecasting system for fascioliasis: this system was based on appraisal of rainfall recorded on each day. A day in which 1 mm or more rainfall was recorded was counted as a wet day and a positive correlation was found between the number of wet days during June and September and the incidence of fascioliasis. A minimum rainfall of 1 mm has been considered for wet days based on the lower evaporative demand on a cloudy day. The comparison of actually recorded and forecast rates in several areas of the globe confirmed the relationship between the prevalence and the number of wet days. The initial system did not take into consideration the environmental temperature during various months and hence the predicted values and the values that actually occurred were found to be at variance in certain areas. The forecasting system was modified by taking into account the mean weekly temperatures and days that were wet compared to the standard. The modified forecasting system gave an accurate forecast of incidence in all the geographic areas. A year having 12 or more wet days per month from June to September was taken as a standard year for comparison purposes;
- (b) Forecasting of foot-and-mouth diseases (FMD): the spread of FMD in various parts of the United Kingdom was predicted on the basis of the quantity of virus emission by infected animals, and meteorological conditions such as humidity, wind velocity, wind direction and rainfall. The outbreaks actually recorded at various places conformed to the predicted values. Similar predictions were also made for Newcastle disease in poultry in the United Kingdom;
- (c) Forecasting for vector-borne diseases: mosquitoes, midges, mites, flies, and the like are hot-weather insects that have fixed thresholds for survival and are prevalent mostly in tropical countries. Anopheline mosquitoes and *falciparum* malaria transmission are sustained only where the winter temperature remains above 16°C, while the variety of mosquitoes that transmit dengue, *Aedes aegypti*, is limited by the 10°C winter isotherms. Shifts in the geographic limits of equal temperature that accompany global warming may extend the areas that are capable of sustaining the transmission of these diseases.

#### 5.4.15 **Protecting plants used in horticulture and arboriculture (non-forest trees)**

The use of past observations can become an essential ingredient in predicting future conditions and modifying the zone forecast for a farm in a form of response farming. The information collected will also allow the grower to place protection equipment in those areas where it will most likely be needed. During a radiation frost, careful records of past occurrences can help make the critical decision of whether or not to begin protection measures. This is especially critical in areas where overhead irrigation is used. Microclimate information gathered before the establishment of a crop can help the grower select the site, type and amount of protection equipment.

According to Wurr (1997), the horticulturist's objective is to supply the product at the right time, of the right quality and with the right uniformity. All of these requirements are affected by the weather, and involve aspects of crop scheduling, crop prediction and crop management. In the area of crop management, more accurate weather prediction would offer opportunities to interactively modify crop scheduling as the season progresses; develop improved prediction systems for crop maturity; predict rates of crop deterioration or loss of marketability; delay transplanting to avoid deleterious field conditions; adjust transplant-raising conditions to provide more consistent transplants; develop improved irrigation scheduling; and optimize glasshouse crop environments. For example, if solar radiation can be predicted, even hours ahead, carbon dioxide levels for tomato production can be optimized. Similarly, if temperature can be predicted days ahead, the cost of heating can be optimized, good predictions of yield can be developed and predictions of pest activity and disease incidence can be improved.

For example, in India the nation's agricultural planning is primarily dependent on the reasonably accurate prediction of the total amount of rainfall from the beginning of June to the end of September. This kind of prediction comes under the category of long-range forecast (LRF). On the basis of LRFs, various precautionary measures can be planned and adopted. For example, if an LRF indicates below-normal rainfall, then necessary products can be purchased from the international market well in advance. Also, adequate arrangements can be made for the transport, storage and distribution of such products. The government authorities can work out various plans and schemes to counter the adverse

situation well in advance and strategies can be used at various administrative levels, such as states, districts and villages.

Prediction of rainfall, its intensity and duration well in advance (in the month of May for June and July) may, for example, help guava growers who cultivate the Mrig bahar variety to obtain a better yield. Prediction in August or September of rainfall for October to February may help grape growers adjust planning for pruning and mango growers to protect plants from mango hoppers and powdery mildew. Prediction of untimely rains, windstorms, and so forth will help banana, mango and grape growers to protect their plants from these hazards well in time. Prediction of a cold wave (night temperature below 6°C or 7°C) will help the banana, papaya and grape growers protect their crops well in advance so that they can take measures such as copious watering, smudging, and the like. Prediction of a heatwave (above 45°C) will help the banana, coconut and areca nut growers to take suitable measures. Timely prediction of frost may help the growers of vegetables such as peas, beans and okra to take suitable measures for protection of their crops.

In the United States, integrated pest management (IPM) in fruit orchards has been facilitated in the intermountain states through the products of the Sustainable Agriculture Research Education (SARE) project. Awareness about IPM has been increased in participating states, with many growers using weather data and prediction programmes to schedule cultivation operations in their orchards. Insect and disease control, pheromone release, irrigation, freeze prevention, maturity indices and fruit damage have benefited from weather database prediction programmes (Seeley, 2002). Table 5.8 shows some characteristics of frost/freeze protection for horticultural crops (Perry, 1994).

#### 5.5 **AGRICULTURAL ADVISORIES OR AGROMETEOROLOGICAL SERVICES**

"Agricultural advisories" or, in the language of this Guide, agrometeorological services (see Chapter 1 and, for example, Stigter, 2007) are an act of advice by internal experts of National Meteorological and Hydrological Services (NMHSs) to crop growers/livestock producers based on possible future weather and climate conditions, regarding "what to do" or "what not to do" to maximize advantages and minimize losses in production. Weather and climate forecasts have little importance unless they are

operationally used. This section will focus on weather forecasts. Good examples of climate forecasts as agrometeorological services, in combination with other information, can be found in Abdalla et al. (2002), Harrison (2005), and Meinke and Stone (2005), for example.

So that maximum advantage can be taken of weather forecasts, agrometeorological advisories are issued in consultation with experts of other concerned disciplines and take into consideration the past, present and predicted weather and its spatial-temporal behaviour. Any appropriate forecast on weather has tremendous benefits in terms of advance management of the negative impacts of vagaries of weather. This is because the cost of weather-related risk reduction before the fact is much smaller than the post-facto management of the losses (Rathore et al., 2006). These advisories recommend implementation of certain practices or the use of special materials to help effectively prevent or minimize possible weather-related crop damage or loss, for example, spraying advice based upon past and forecast weather conditions to combat crop diseases and insects; sowing advice for better germination and plant stand; and harvesting advice to obtain optimum crop maturity, quality, and the like. They also recommend initiation of cultural

practices that are weather-sensitive. A famous example in Africa is the service that was developed in Mali (for example, WMO, 1988a; Stigter, 2006). In the operation of agrometeorological services, it has been found that extension intermediaries between products of NMHSs and farmer-oriented organizations and farmers would be extremely helpful in getting agrometeorological services established and applied (see also Chapter 1 and, for example, WMO, 2004a).

An added advantage of such services is that wherever and whenever they are in operation, they help to reduce environmental pollution through the optimal use of agricultural chemicals. Some agrometeorological advisories are being issued by almost all the developed and developing countries on various spatial and temporal scales. In actual practice, a great deal remains to be done to achieve the expectations of a decade ago (Wieringa, 1996; WMO, 2004a). Increasing needs, commercialization and competition have improved this situation, however (for example, Stigter, 2006). Geographically large countries like China, India, the Russian Federation and the United States now have national bodies or organizations that issue advisories on a county/state/agroclimatic region basis (see an example from India later in this section), while small countries like Slovenia and the Netherlands

**Table 5.8. Characteristics of frost/freeze protection methods**

	<i>Advantages</i>	<i>Disadvantages</i>	<i>Comments</i>
Site selection	Preventive measure; location with good cold air drainage may be chosen		Best method of frost protection; visualize air flow and/or monitor minimum temperatures
Heaters	Radiant heat helpful in freeze; installation costs lower than irrigation; allows delay; no risk if rate not adequate	Fuel oil is expensive	Free-standing or pipeline; free-standing heaters need no power source
Irrigation	Operational cost lower than heaters; can be used for other cultural purposes, such as drought prevention	Installation costs relatively high; risk damage to crop if rate inadequate; ice build-up may cause limbs to break; overwatering can waterlog soils; does not provide protection in wind above 8 km/h	Plant part protected by heat of fusion; fixed-rate design delivers more protection than generally necessary; irrigation must continue until melting begins; backup power source essential
Wind machines	Can cover an area of 4 ha if flat and round; installation cost similar to heaters	Not effective in wind above 8 km/h or advective freeze	Mixes warm air near top of inversion down to crop height; may be used with heaters; may use helicopters
Fog	Blocks outgoing radiant heat and slows cooling	Has potential but is not currently practical	Uses greenhouse effect to trap heat in crop canopy and limit radiative cooling



issue advisories on a national basis (for example, Wieringa, 1996).

Some developed countries (European countries, Russian Federation, United States) that have advanced computing and communication systems may consider catering to the small temporal scale for agriculturally related advice and frequent updating of advisories (in terms of hours), while developing countries (like India, see 5.5.4) issue advisories covering a span of 3–10 days, which enable the farmers to take ameliorative measures. For the agricultural sector, location-specific weather forecasts in the medium range are, therefore, very important. These services may contain advice on all the farming operations or some specific operations, such as pest management (for example, Dacom, 2003), irrigation scheduling (for example, Maia et al., 2005), and livestock management (for example, Rivero Vega, 2005). An example of an agricultural advisory from India is provided in 5.5.4.

#### 5.5.1 **Preparation of agricultural advisories (agrometeorological services)**

The formation of agrometeorological services in forecasting requires close linking of various data providers and expertise from different fields. The basic requirement is that the forecast data must be for the desired period and for the specific location under consideration. For example, twice a week the National Centre for Medium Range Weather Forecasting (NCMRWF) in India, on the basis of a T-80 General Circulation Model, provides a location-specific weather forecast with a resolution of 150 km × 150 km for six parameters, namely, rainfall, cloud cover, wind direction and speed, and minimum and maximum temperature. These forecasts are further subjected to statistical and synoptic interpretation (Rathore et al., 2006).

A panel of experts then discusses the present, past and future status of weather and crop conditions and recommends the appropriate operations for better farm management based on such forecasts. Priority is given to predominant crops of the region and the most prevalent problems, keeping in view their relative economic importance. Management practices such as what, when and how to sow; when and how much to irrigate; which measures may be adopted for plant and animal protection from stresses caused by pest and disease, temperature, wind, rainfall, and so on, are suggested. Animal shelter, nutrition and health are affected by weather

to a large extent (see Chapter 12 of this Guide and 5.4.14) and hence must be considered in the services. On the basis of local agrometeorological and farming information and the weather forecasts, the specialists discuss the options and consequent effects and then decide on the advice to be given to farmers regarding the items that fall within the scope of their expertise. These elements together constitute the agricultural advisory (Singh et al., 1999).

#### 5.5.2 **Panel of experts**

Ideally, a panel of specialists in a topic of agricultural science and animal science is constituted for the preparation of agrometeorological services. The panel may include agrometeorologists, agronomists, soil scientists, plant pathologists, entomologists, horticulturists, nematologists, sericulturists, and specialists from agricultural extension, animal husbandry and plant breeding. Experts from all the various fields have to discuss the current crop situation, animal conditions and anticipated weather conditions in order to prepare services for the farmers and user interests of a region.

#### 5.5.3 **Information requirements**

Weather information required for services includes weather summaries of the recent past, such as the preceding week, for example, climatic normals for the advisory period and weather forecasts for the advisory period.

Required agrometeorological information includes some indices relating to agricultural production, such as the crop moisture index and drought severity index for the recent past.

Crop information for the preparation of advisories includes information on the present crop status detailing the type, state and phenological stage of crops; infestations of pests and diseases and their severity; and other crop stresses such as nutrient stress, water stress and thermal stress.

Soil information used in the preparation of advisories describes the spatial distribution of soils. Information on soil types, physicochemical properties, nutrient status, moisture status, elevation, and contour and slope of soils is also required for the compilation of advisories.

Other information on topography of the region, land cover and land use, irrigation facilities, irrigated and rainfed areas, availability of agricultural

inputs and market trends is also considered for the preparation of advisories.

#### 5.5.4 **Example of an agrometeorological advisory service of the NCMRWF in India: a preliminary impact assessment**

The impact assessment of this agrometeorological advisory service (AAS) was guided and monitored by a national committee of experts constituted for this purpose (Rathore et al., 2006). The AAS units selected four villages for the study. In general, units selected 40 AAS and 40 non-AAS farmers for their survey. The farmers in both categories (AAS and non-AAS) chosen by all units through random sampling were generally in the middle-aged group and had medium-to-large land holdings. The data revealed that the inputs used varied quantitatively and significantly between AAS and non-AAS farmers. Significant differences were observed in human labour, fertilizer and plant protection chemicals used. The timeliness of proper agro-advisories given for various farm operations, such as irrigation and application of fertilizer and plant protection chemicals, however, saved the crops from possible moisture stress, nutritional stress and pest attack, which contributed to better growth and development of crops, both qualitatively and quantitatively. The non-AAS farmers used the same quality of inputs, but their timing of applications was different from that of the AAS farmers. This timing did not lead to the control of nutritional and water stress and pest attack with the same efficiency, and ultimately led to differences in crop yields. The season-wise preliminary results are given below in a Table 5.9. Further details may be found in Rathore et al. (2006).

In conclusion, AAS farmers received agro-advisories based on medium-range weather forecasts, including optimum use of inputs for different farm operations. Due to a judicious and timely utilization of inputs, the cost of production for the AAS farmers was reduced by between 3 and 6 per cent, approximately. At the same time, the yield levels of the AAS farmers also rose by 8 to 21 per cent. The increased yield levels and reduced cost of production led to increased net returns of 10 to 29 per cent for the AAS farmers. These are preliminary results, because inputs differed among and between farmers. Care was taken to delineate impacts of weather-based farm advisories, but it was extremely difficult to segregate them from general agronomic advice, which was also included in the bulletin. Hence, the results also reflect impacts of activities that were not weather-based.

## 5.6 **PROBABILITY FORECASTS**

### 5.6.1 **The rationale for probability forecasts**

Agricultural predictions require forecasts of meteorological variables several days, weeks and even months ahead to enable informed management decisions. It is well known, however, that the climate system is chaotic and therefore accurate weather and climate forecasting is impossible because of the uncertainty in the initial conditions (Palmer, 2005) and structural inadequacies of prediction models (Palmer et al., 2005), given the uncertainty in the present knowledge and representation of the processes involved in generating weather and climate variability. There is

**Table 5.9. Economic impact of AAS of NCMRWF: preliminary results**

<i>Crop</i>	<i>Station name</i>	<i>% increase/decrease in cost of production (per acre)</i>	<i>% increase/decrease in crop yield (per acre)</i>	<i>% increase/decrease in profit (per acre)</i>
Cotton	Hisar	1	14	10
	Coimbatore	-4	16	16
Rice	Ludhiana	-6	9	18
	Kalyani	-3	21	29
Wheat	Ludhiana	-6	9	17
Mustard	Hisar	-3	8	13

**Agromet Advisory Services Bulletin**  
**Issued by India Meteorological Department**  
**State: Maharashtra**

Date of issue: 4/08/2005

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<i>Past weather summary (1/8/05 to 3/8/05)</i>	<i>Weather Forecast</i>
SW monsoon was vigorous over north Madhya Maharashtra and active over Konkan and Vidarbha.	Moderate rain is likely to occur at many places in Konkan, Vidarbha and Madhya Maharashtra, and at a few places in Marathwada.
Rain has occurred at most places in south and north Madhya Maharashtra and at many places in Marathwada.	
<u>Chief amounts of R/F in cm:</u>	
1/08/2005: Mahabaleshwar 31, Bhira 29, Santacruz 21, Gaganbawda 19, Colaba 16, Alibag 13, Ratnagiri and Harnai 10 each, Pune and Nagpur 6 each, Kolhapur and Akola 5 each.	Warning: Heavy rain is likely to occur at isolated places in Thane and Raigad districts and in Vidarbha during next 48 hours.
2/08/2005: Mahabaleshwar 39, Bhira 27, Santacruz and Ratnagiri 15 each, Harnai 10, Colaba 9, Dahanu 7, Pune 6, Patan and Mehekar 5 each.	
3/08/2005: Mahabaleshwar 18, Dahanu 17, Ratnagiri 9, Bhira 7, Pune (Pashan) 2, Aurangabad and Akola 1 each.	<u>Outlook:-</u> Decrease in rainfall activity.

*State and stage of the crops and the advisories*

81% sowing of Kharif crops was completed on 22 July. Paddy crop was damaged in the districts of Raigad, Ratnagiri, Thane, Sindhudurga and Kolhapur, and in the western talukas of Pune and Satara districts due to recent heavy rainfall; crops such as soya bean, groundnut and jowar are also likely to be damaged in Kolhapur, Sangli, Satara, Nanded and Parbhani districts. As heavy rain spell is decreasing slowly, re-transplanting of paddy in Konkan, South Madhya Maharashtra and Western Pune if nursery is available, or sprouting seed sowing, may be started after current rain spell. Sunflower or castor seed may be sown as contingency crop in Madhya Maharashtra, Marathwada and Vidarbha where crop has been damaged. Late sowing or re-sowing may be started after complete current rain cessation. Vegetable crops are likely to be affected by aphids and jassids due to warm high humidity, so farmers are advised to apply plant protection measures after current rain spell.

Details of crop information and the necessary advisories are given below

<i>Crop</i>	<i>Stage</i>	<i>State</i>	<i>Agromet/Agricultural Advisories</i>
Sugarcane preseasonal  (M. Mah., Marathwada, Vid.)	Active vegetative growth	Satisfactory, crop is under flood on the banks of Panchaganaga and Krishna rivers in south Madhya Maharashtra due to very heavy rain.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation. On the incidence of white woolly aphids, release 2 500 larvae of <i>Crysoperla carnea</i> or 1 000 eggs or pupa of <i>Konobathra aphidivora</i> per hectare on leaves early in the morning after current spell of rain on a non-rainy day.

<i>Crop</i>	<i>Stage</i>	<i>State</i>	<i>Agromet/Agricultural Advisories</i>
Kharif jowar (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory in Kolhapur, Sangli, Satara, western Pune, Nanded and Parbhani due to heavy rain; satisfactory in other districts.	Excess water may be drained out from the field.
Bajra (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory in Kolhapur, Sangli, Satara, western Pune, Nanded, Hingoli and Parbhani due to heavy rain; satisfactory in other districts.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation. A dose of 65 kg urea/ha may be applied after current spell of rain on a non-rainy day.
Rice (Konkan, M. Mah., Vid.)	Seedling  Transplanting (Early tillering in Konkan and South Madhya Maharashtra)	Crop is in poor state in all the districts of Konkan and in Kolhapur, Sangli and western parts of Pune and Satara. Satisfactory in other districts, mild incidence of stem borer in Thane and army worm and silver shoot in Sindhudurga district.	Postpone the transplanting of seedlings in Konkan and Madhya Maharashtra and Vidarbha.  For the control of stem borer use 10 G phorate 10 kg or 5 G quinalphos 15 kg/ha, or spray 850 ml endosulphan/ha in 500 litres water after current spell of rain on a non- rainy day.
Groundnut (M. Mah., Marathwada, Vid.)	Early vegetative growth	Satisfactory, crop is likely to be damaged in Kolhapur, Sangli, Nanded, Hingoli, Parbhani and western parts of Pune and Satara.	Excess water may be drained out from the field.
Soya bean (M. Mah., Marathwada, Vid.)	Early vegetative growth	Satisfactory, crop is likely to be damaged in Kolhapur, Sangli, Nanded, Parbhani and Satara. Mild incidence of leaf roller in Nagpur and Kolhapur and army worm and semi-lopper in Amraoti division.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation.
Irrigated cotton (Vidarbha)	Early vegetative growth / Active vegetative growth	Satisfactory, crop is likely to be damaged in Amraoti, Yeotmal	Excess water may be drained out from the field. A dose of 33 kg nitrogen/ha may be given by ring method after current spell of rain.
Kharif cotton (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory, crop is likely to be damaged in Nanded, Parbhani Amraoti, Yeotmal. Mild incidence of aphids and jassids in Nagpur and Nashik division.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation.

a need to address the uncertainty problem in such a way as to distinguish between those occasions on which forecasts deteriorate rather slowly with lead time (relatively skilful forecasts) and those occasions when they deteriorate rather rapidly with lead time (relatively unskilful forecasts). The answer to this question requires addressing the feasibility of quantifying the uncertainty in forecasts in a stochastic manner.

The rationale for probability forecasts has a scientific and an economic component (Murphy, 1998). First, weather and climate forecasts must be expressed in terms of probabilities (or equivalent modes of expression) to accommodate the uncertainty inherent in the forecasting processes. As the amount of uncertainty can be situation-dependent, the level of uncertainty associated with a given forecast can be properly conveyed in a stochastic sense through the use of probabilities. In general, forecasts expressed in a non-probabilistic format are unable to accurately reflect the true state of knowledge concerning future conditions of a forecast system. Weather forecasts must be expressed in probabilistic terms to enable the end-users to make the best possible decisions, as reflected by their levels of economic and/or social welfare.

Probability forecasting is not expected to be considered only in the formulation of weather and climate forecasts for agricultural purposes, but to be extended to the agricultural predictions themselves. Probability forecasts have already been demonstrated to have superior benefits in some agricultural applications that make use of meteorological and climatological information.

In particular, crop yield prediction has benefited from a collaborative effort within the seasonal climate forecast community. Challinor et al. (2005) and Cantelaube and Terres (2005) offer examples of probability forecasts of annual crop yield and compare the benefits versus non-probabilistic forecasts.

### 5.6.2 Formulation

Probability forecasts differ from non-probabilistic forecasts in that, depending on the expected likelihood of occurrence of an event, a probability value between 0 and 1 is assigned to possible future states. This probability is only a component of the probability distribution function (PDF) of the variable, which gives a probability forecast value for each possible event. Within the paradigm of deterministic prediction, a signal refers to the location of the mean of the PDF and its deviation

from the climatological mean, whereas the noise is represented by the spread of the PDF. For probability predictions, a signal is represented as the entire forecast PDF and its difference from the climatological PDF. This concept allows for an interesting definition of predictability: a variable  $x$  can be considered predictable if the forecast PDF of  $x$  differs sufficiently from the climatological PDF of the same variable to influence relevant decision-makers to make better decisions than they would without forecast information.

Forecast uncertainty can be quantified by a variety of methods, including subjective, statistical and dynamical ensemble methods. Similarly, probability forecasts can be generated through different methods. By considering a wide range of forecast information, forecasters can subjectively prepare probability forecasts. Alternatively, statistical/empirical techniques can be used either on their own, based on historical observational data (for example Mason and Mimmack, 2002), or in combination with dynamical models and past verification statistics (Kruizinga and Murphy, 1983; Coelho et al., 2006). It is certainly true that not all probability forecasts produced by these methods are precise. Nevertheless, it can be stated without equivocation that probability forecasts exhibit reasonable skill (and skill considerably in excess of that achieved by the corresponding non-probabilistic forecasts) and can be produced for most if not all weather conditions of interest.

Predictions using dynamical models of the climate system may require further explanation given their present ubiquity and continuous progress. Predictions with dynamical models require a good estimate of the initial conditions of the atmosphere and the ocean. Since the initial conditions can never be measured with infinite precision, the error propagation created due to prior abstractions in initialization fundamentally limits the ability to forecast precisely (Thompson, 1957). Small perturbations of the initial conditions grow fast, leading to a rapid loss of initial information and predictability. Lorenz (1963) confirmed this sensitivity in numerical simulations of a simplification of atmospheric convection based on three equations.

Forecast models are run many times from slightly different initial conditions, all of them consistent with the error introduced to estimate the best possible initial condition. This means that the forecaster has an ensemble of forecasts available at the same time and this technique is therefore otherwise known as ensemble forecasting (Molteni et al., 1996; Toth



and Kalnay, 1997). The ensemble can be used to produce probability forecasts without relying on statistical methods based on past events (Hagedorn et al., 2005). Assuming that the forecasts are independent realizations of the same underlying random process, an estimate of the forecast probability of an event is provided by the fraction of the forecasts predicting the event among all forecasts considered. Figure 5.2 shows an example of such probability forecasts produced with the monthly ensemble forecast system of the European Centre for Medium-Range Weather Forecasts (ECMWF).

Errors in the sampling of the set of initial conditions and in the dynamical model structure, however, mean that the dispersion of an ensemble forecast at best only approximates the forecast PDF (Hansen, 2002). This may lead to overconfidence in probability assessment based on ensemble relative frequencies. Some statistical methods have been considered to correct these errors and provide sound probability forecasts based on ensemble forecasts (Wilks, 2006).

The widespread interest in the development and application of ensemble prediction is a sign that the meteorological and climatological operational communities acknowledge explicitly the uncertainty inherent in the forecasting process. An opportunity now exists to provide the full spectrum of users with reliable probabilistic information concerning the likelihood of occurrence of future conditions through probability forecasting.

Dynamical predictions of weather and climate suffer from structural model uncertainty, in addition to uncertainties in initial conditions. Model uncertainty arises mainly because of the process of parameterization, that is, the way in which subgrid-scale motions are represented in weather and climate models (Palmer et al., 2005). At present, there is no underlying theoretical formalism from which a PDF of model uncertainty can be estimated. A pragmatic approach relies on the fact that dynamical forecast models have been developed somewhat independently at different climate institutes. An ensemble comprising such quasi-independent models is referred to as a multimodel ensemble (Palmer et al., 2004a, 2004b). This is an approach that can be easily extended to the user-model component to increase the skill of the end-user predictions.

### 5.6.3 Probability forecasts at different scales

The features described above are applicable to the whole range of probabilistic forecast systems, from

medium-range weather, through monthly and up to decadal and longer climate timescales, which are available with a varying updating frequency, as described in Rodwell and Doblas-Reyes (2005). Users may want to employ all these systems in an integrated forecasting system, updating decisions as new probability forecasts are available. For instance, managers might have access to probability seasonal forecasts once a month. This information can somehow be merged with that provided by monthly forecasts available once a week to improve the first few weeks of the seasonal forecast information.

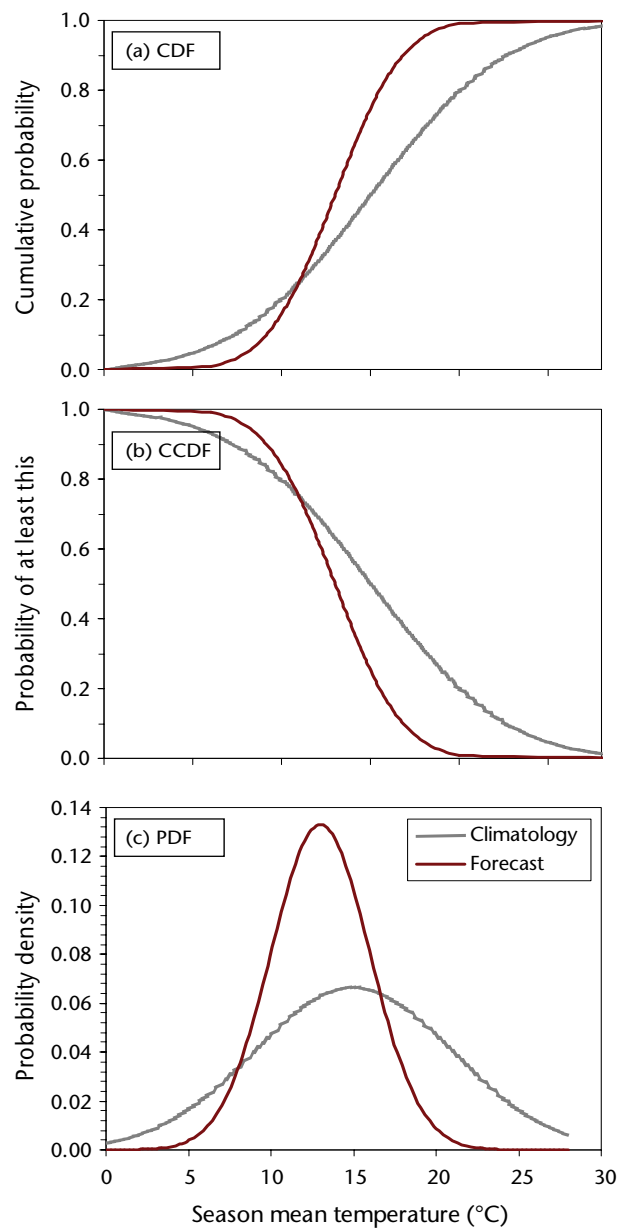


Figure 5.2. Hypothetical temperature forecast expressed as shifted cumulative distribution (a), probability of exceedence (b) and probability density (c)

Similarly, given that long-term decisions in agricultural systems are made at the interannual timescale, adaptation to ongoing climate change can be achieved by training the users to employ seasonal-to-interannual climate probability forecasts.

#### 5.6.4 Probabilistic forecast formats

Probabilistic forecast information can be conveyed in explicit, quantitative terms in the form of probability distributions or as categorical probabilities, implicitly in the form of time series, and qualitatively as narrative. Table 5.10 summarizes the strengths and limitations of each.

##### 5.6.4.1 Probability distributions

Forecasts of continuous quantities (such as precipitation and temperature) are appropriately interpreted, and expressed graphically as shifts from the climatological probability distribution. Probability distributions can be expressed in either cumulative or density forms (or in mass form in the

discrete case). A cumulative distribution function (CDF) expresses the probability that a random variable  $X$  takes on a value less than or equal to a given  $x$ , or  $F_x = \Pr \{X \leq x\}$  (Figure 5.2a). A CDF increases smoothly for continuous variables, and in discrete jumps for discrete variables.

The probability of exceedance (also known as the complementary cumulative distribution function, or CCDF) is simply one minus the cumulative distribution function:  $F_x^c(x) = \Pr \{X > x\} = 1 - F_x(x)$

(Figure 5.2b). The probability of exceeding a particular threshold (a CCDF), as in the case of rainfall, appears to be easier to understand than the probability of an outcome below a threshold (a CDF), as will be the situation with temperatures in winter.

For a continuous variable, the probability density function (PDF) is the first derivative, or slope, of the CDF. Graphically, it appears as the familiar “bell curve” for the normal distribution (Figure 5.2c), and shows the relative probability of

**Table 5.10. Alternative formats for probabilistic forecasts**

<i>Format</i>	<i>Use</i>	<i>Strengths</i>	<i>Weaknesses</i>
<i>Probability distribution</i>			
Histogram, Probability density (PDF)	Present entire forecast distribution of a measured quantity	Provides full distribution information Good at conveying relative probability of different outcomes, skewness, tails More likely exposed to PDF than CDF in school	Derivation of PDF difficult to explain Difficult to compare multiple distributions Interpretation might require training
Cumulative distribution (CDF)	Present forecast distribution of a measured quantity. Compare multiple distributions	Provides full distribution information Directly relates climatic thresholds and probability Straightforward to derive from, relate to, historical series Can compare multiple distributions	Interpretation usually requires some training
Probability of exceedance (CCDF)	Present forecast distribution of a measured quantity. Compare multiple distributions	Same as for CDF Belief that $\Pr \{X > x\}$ is easier to understand than $\Pr \{X \leq x\}$	Interpretation usually requires some training
Box plots	Present forecast distribution percentiles (0, 25, 50, 75, 100) of a measured quantity. Compare multiple distributions	Intermediate information between full distribution and simple range Percentiles (quartiles, median) and extremes explained as, for example, “ $k$ out of $n$ years” Can compare multiple distributions	Interpretation usually requires training

<i>Format</i>	<i>Use</i>	<i>Strengths</i>	<i>Weaknesses</i>
Error bars	Present a simple measure of uncertainty of a measured quantity on a deterministic (for example, time series) graph	Reduces distribution to expected value and a range	Potential ambiguity due to multiple error metrics  Ignores low-probability, high-impact events
<i>Categorical probabilities</i>			
Probability of occurrence	Present probability that a discrete event will occur	Appropriate format for extreme, high-impact events	Inappropriate for continuous quantities
Probability of exceeding median (or mean)	Probabilistic representation of spatial distribution of a forecast measured quantity	Simplest probabilistic representation Lends itself to mapping Useful when relative, not absolute, outcomes are relevant	Discards distribution information Imposes artificial thresholds Tendency to confuse shift in probability with shift in direction from “normal” Tendency to anchor on most probable category Local interpretation requires climatology information
Terciles	Probabilistic representation of spatial distribution of a forecast measured quantity	“Standard” for many operational forecasting institutions Lends itself to mapping Substantial existing experience and educational material	Same as probability of exceeding median Interpretation usually requires training Potential misunderstanding of category boundaries
<i>Time series</i>			
Analogue years	Possible supplement to aid explanation of formal probability formats	Provides an intuitive explanation of forecast in terms of past years with similar forecast	Resulting distributions inconsistent with more rigorous methods No clear evidence of relative ease of understanding
Predicted and observed series	Possible supplement to aid understanding and transparency of formal probability formats	Useful for explaining basis for probabilistic forecasts in terms of past performance Provides evidence that farmers desire as complementary information Allows users to intuitively validate probabilistic forecasts	Danger of contributing to deterministic interpretation Danger of anchoring if the current forecast is included
<i>Narrative</i>			
Narrative	Text-based media (for example, radio) Supplement to formal probability formats	Text-based media (for example, rural radio) sometimes have greatest reach at lowest cost	Qualitative descriptors of probability prone to inconsistent interpretation Difficult to explain basis for forecasts or their climatology context with text alone

every outcome. A histogram is used to represent the probability distribution of a discrete variable (known as a probability mass function, or PMF), and to approximate the distribution of a continuous variable based on the number of observations within each interval.

Both CDF and PDF are of value for farming decisions. Curves and histograms associated with probability density may be more familiar even to secondary school students. Use of CDF over PDF is preferable, however, as a CDF graph relates probabilities and climatic thresholds and it is relatively easy to relate a CDF to a time series.

#### 5.6.4.2 Categorical probabilities

Simple event probabilities are the appropriate way to express uncertainty about high-impact meteorological events when the primary concern is whether an event occurs, rather than its intensity. An example is the need to know the likely occurrence of rain, rather than its quantity, for control operations against pests and diseases. The climatological probability that a given event  $E$  will occur is estimated by its historical relative frequency, and it is defined as the limit as the number of observations  $N$  approaches infinity. A forecast provides additional information that modifies the climatological probability.

Categorical probability formats are also used routinely to express forecasts of continuous meteorological quantities of interest to agriculture. The climatological distribution is divided into categories, such as above and below median, terciles (for example, the wettest, middle and driest third of past years), or percentage probability of realization of a given value of a parameter and/or given situation. The forecast is expressed as a shift from the probabilities that define the categories. Categorical probability formats lend themselves to maps. Colour-coding represents the probability associated with a particular category (for example, above median), or the dominant category in the case of tercile forecasts. Probability shifts can be represented independently of the fine-scale spatial variability of climatological quantities.

The tercile format is being used for issuing operational forecasts and regional climate outlooks. The tercile and other categorical probability formats are not recommended as a primary means of presenting location-specific forecasts to user interests. Categorical probability formats discard potentially

useful distribution information, and impose thresholds that have no intrinsic relevance to decisions. Ambiguity about the definition of categories (O'Brien et al., 2000; Patt and Gwata, 2002), a tendency to confuse shift in probability with shift in direction from "normal" (Dalglish, personal communication) and a tendency to anchor on the most probable category make interpretation difficult in the absence of substantial training.

#### 5.6.4.3 Time series and analogues

A time series of observations and hindcasts based on an operational forecast model may be a useful complement to forecast distribution formats. It can reduce some of the non-clarity behind probabilistic forecasts by allowing users to evaluate the forecast system's uncertainty based on past performance. Showing hindcasts as expected values, however, carries the risk of miscommunicating a deterministic interpretation, particularly if the current forecast value appears in the graph.

Time series graphs can also be used to highlight analogous years (for example, El Niño or La Niña years) when predictors (such as SSTs and the Southern Oscillation Index, or SOI) were similar to the current year. This illustrates how the current state of predictors can shift the distribution of expected outcomes, and may be a useful way to present a probabilistic forecast that is based on such categorical predictors. Although forecasts that are based on continuous or multivariate predictors could also serve as a basis for selecting years when predictors were most similar to their current values, the probability distribution of the resulting analogue years will generally not be consistent with estimates from hindcast residuals (5.6.5.2) or global circulation model (GCM) ensemble distributions (5.6.5.3).

For time series data, bar graphs appear to be easier to interpret than points or line graphs. For a visual representation of relative depth of a column of accumulated precipitation, farmers can participate in drawing rainfall depths to scale, then filling in bars and adding axes.

#### 5.6.5 Deriving forecast distributions

This section briefly summarizes three objective methods to derive forecast probability distributions. For each method, probability distributions can be represented either empirically as illustrated, or by fitting the data to a theoretical distribution, which would typically be a gamma distribution for

precipitation amounts, and a normal one for mean temperatures. The simpler case of forecasting the probability of a discrete event is not addressed.

#### 5.6.5.1 From analogues

Statistical forecasting based on historical analogues involves classification of predictors into a few categories, such as El Niño, neutral and La Niña based on SSTs in the equatorial Pacific, then taking the set of past years falling within the category that corresponds to current conditions as a forecast distribution. Historical analogues provide a simple, intuitive approach to deriving and explaining probabilistic forecasts.

The marked year-to-year variations in the temporal distribution of a weather parameter on a short-period basis restrict the use of the concept of analogous years to specific situations, such as late or early setting in, early withdrawal or persistence of weather systems. Spurious predictors, artificial forecast skill and systematic underestimation of forecast uncertainty – risks inherent in statistical forecasting – are particular concerns for the analogue method when the number of categories and limited record length lead to small sample sizes within each category. Use of credible predictors and independent validation and hypothesis testing are essential to limit these biases.

#### 5.6.5.2 From hindcast residuals

Figure 5.3a shows a hypothetical time series of mean temperature observations ( $y$ ) and hindcasts ( $\hat{y}$ ), derived from sampling a multivariate normal distribution and calibrated to the observations by linear regression. The distribution around the current forecast  $\hat{y}_T$  is estimated by the distribution of hindcast residuals  $\epsilon_i = y_i - \hat{y}_i$ , centred on  $\hat{y}_T$ . Subtracting predictions from observations yields a time series of hindcast residuals ( $\epsilon$ ) (Figure 5.3b), which are then sorted to derive a residual CDF (Figure 5.3c). The forecast distribution for 2001 is obtained by adding its expected value,  $\hat{y}_{2001} = 12.^\circ\text{C}$ , to each  $\epsilon$  (Figure 5.3d). The method is applicable to statistical or dynamic forecast models, and accounts for the overall prediction error of the forecast system. Distributions derived from historical analogues (5.6.5.1) are a special case, which uses the subset of  $\epsilon$  from years within the given predictor class.

For strongly skewed variables, the magnitude of forecast residuals, and therefore the spread of a forecast distribution, tends to increase in the

direction of skewness. Because rainfall amounts tend to be positively skewed, forecast uncertainty tends to be greater in wet than in dry years. The residual distribution will not capture this bias unless the skewness is corrected using a transformation of the predictand and/or the predictor. Raising to a power  $<1$  (for example,  $y' = y^{1/2}$ ,  $y' = y^{1/3}$ ,  $y' = \ln(y)$ ,  $y' = 1/y$ ) can correct positive skewness. Box and Cox (1964) provide an objective procedure for selecting an optimal power transformation that can be automated in a spreadsheet. The forecast distribution is derived from the transformed series, and then the inverse transformation is applied to the entire forecast distribution.

#### 5.6.5.3 From ensemble forecasts

Several operational climate centres derive probabilistic long-range forecasts from ensembles of multiple GCM integrations. Initializing GCMs with different atmospheric conditions gives an indication of the uncertainty associated with initial conditions. Use of several different GCMs captures uncertainty associated with model structure and assumptions. The spread of resulting predictions can be interpreted as a measure of forecast uncertainty, but must be calibrated before forecasts can be expressed as probability distributions at a local scale. There is not yet a consensus about the best calibration method (Doblas-Reyes et al., 2005; Palmer et al., 2005).

#### 5.6.6 Interpretation and attributes of probability forecasts

Forecast probabilities can be interpreted as a relative frequency or as the forecaster's degree of belief. In the former interpretation, the uncertainty is a property of the system under consideration, whereas in the latter case the uncertainty is a property of the person issuing the forecast (Murphy, 1998). Measurement of the statistical consistency between the predicted probabilities and the actually realized frequencies is known as reliability. The ability of the probability forecast system to delineate situations in which an event occurs with lower or higher frequency than the climatological frequency is known as resolution. Measurement of the variability of the forecast PDF with reference to the climatological PDF is known as sharpness. Ideally a skilful probabilistic forecast should seek a trade-off between high reliability and resolution. In a perfectly reliable forecast system sharpness is identical to resolution. When reliability is not perfect, however, resolution and sharpness should not be confused. For a detailed discussion and



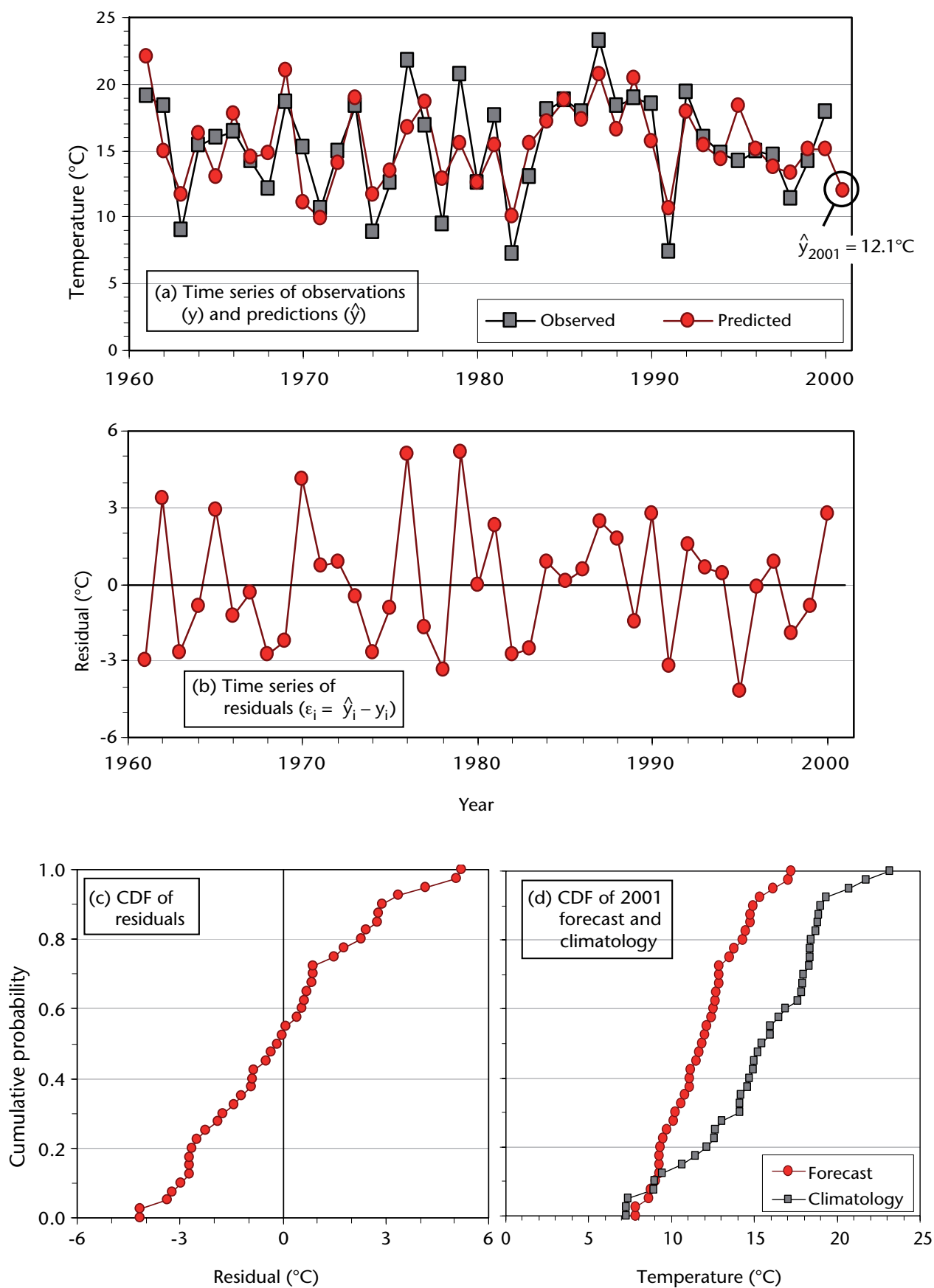


Figure 5.3. Steps in deriving the probabilistic forecast from hindcast residuals, illustrated with synthetic data

availability of tools relating to measures of reliability, sharpness and resolution, reference may be made to Jolliffe and Stephenson (2003).

### 5.6.7 **Communicating probabilistic forecasts to farmers**

#### 5.6.7.1 **Keys to understanding and applying probabilistic information**

There are fundamental difficulties in understanding and applying probabilistic information for decision-making (Nicholls, 1999; Tversky and Kahneman, 1981). Agricultural meteorologists can help farmers overcome some of these difficulties, however, particularly in settings that allow direct interaction.

As an example, presenting information in the form of natural frequencies (such as “Belle Glade gets more than 160 mm of rainfall in January to March in about 10 out of every 20 years”), rather than the equivalent but more abstract notion of probability of a future outcome (“the probability of getting more than 160 mm of rainfall next January to March at Belle Glade is 50 per cent”), tends to improve interpretation of probabilistic information (Gigerenzer and Hoffrage, 1995).

Another technique is to relate information to experience. The work of Hansen et al. (2004) suggests that probabilistic information acquired from personal experience is processed and applied more effectively than information acquired from statistical descriptions. Because farmers’ livelihoods are weather-dependent and inherently probabilistic, they can be expected to understand uncertainty from their own experience, although not necessarily in formal probability language or formats. Helping farmers map probabilistic forecast information into their own experience base can therefore enhance the utility of the information.

Trust and transparency are important as well. Building up trust in the credibility of information provided takes time and deliberate, planned efforts. Communicating probabilistic information in a transparent manner, and not as a “black box”, is essential in this effort, as it allows farmers to shift their trust from the information provider to the data and the process. Presenting past performance of the forecast system against observations, and explaining (in simplified terms) the process of deriving probabilistic forecasts, contribute to transparency and therefore help to boost confidence.

#### 5.6.7.2 **Teaching probabilities to farmers**

The logical progression of the following processes has proven to be a useful way to introduce farmers to probabilistic long-range forecasts and has been effective and well received in a workshop setting with smallholder farmers in Kenya, while a subset was used in a self-directed tutorial with farmers in Florida (United States).

Measured time series are related to farmers’ experience. For example, efforts are made to elicit farmers’ qualitative memory of climatic conditions for the past five years. Then observations from a nearby station are presented, and farmers are allowed to plot them as a time series bar graph and then validate the measured outcomes against their collective memory.

The time series are converted to relative frequency or probability. Starting with a blank graph indicating quantity (for example, seasonal rainfall) on the x-axis and frequency (for example, “years with at least this much rain”) on the y-axis, farmers are allowed to sort from lowest to highest (if using probability of exceedance) on the new graph. The points are connected, and the y-axis is changed from number of years to relative frequency or probability. The consistency between the two formats is emphasized.

Enough explanation and repetition are provided to ensure understanding. For example, rainfall associated with a given probability, probability associated with a given rainfall threshold, and the range of likely rainfall are discussed. It may be useful to draw hypothetical shifts and discuss their interpretation. One way to explain a shift in the climatological distribution to the right or left is to ask farmers to identify and discuss the climate in locations that are somewhat wetter or drier.

The procedure should be repeated, for example, for El Niño or La Niña years. Educating the rural communities about El Niño and La Niña will help convey the notion that a forecast is a shift of the climatological distribution, even if operational forecasts are more complicated or not based on the El Niño–Southern Oscillation phenomenon. By this point, farmers should be comfortable enough with the formats to allow use of prepared time series graphs with El Niño or La Niña years highlighted, and prepared shifted CDF or probability of exceedance graphs.

Forecast distributions are related to decisions. Organization of brainstorming sessions among

farmers about potential management responses to either hypothetical or actual forecasts will help to reinforce both their appropriate interpretation and their relevance for farming decisions.

Culturally relevant indigenous forecasts, gambling analogies or other analogies of decisions under uncertainty are used. This aspect of the process requires detailed understanding of local culture and language.

Accelerated experience through decision games is provided. Well-designed games that link real or imaginary payouts to decisions and sampled probabilistic outcomes allow farmers to experience, in a short time, a number of imaginary forecasts, decisions and sampled climatic outcomes, and imaginary or real payouts. Spinners and draws of colour-coded objects (for example, candies, buttons) have been used effectively to sample outcomes in proportion to prescribed forecast probabilities in educational decision games.

## 5.7 WEATHER FORECASTS FOR THE GENERAL PUBLIC

The provision of weather warnings and forecasts to the general public is one of the primary roles of all National Meteorological and Hydrological Services and is intended for relatively large areas where agricultural production may be diversified. These forecasts are limited to the meteorological elements and factors and should include forecasts of maximum and minimum temperatures; type, duration and amount of precipitation; cloudiness; and wind speed and direction. Agriculture, fisheries, forestry and water resource management, among many other sectors, benefit directly from the service. To be effective, forecasts and warnings obviously must reach users in a timely fashion. Moreover, they should be presented in a suitable manner and be readily understandable and usable. Since the forecasts are concerned with stating the weather probabilities of certain areas over certain time periods, the phraseology used should be in accordance with these probability aspects rather than precise, and flexible rather than rigid. The forecasts should be related to well-defined regional localities where configuration implies some degree of homogeneity of weather patterns (WMO, 2001).

The interpretation of the weather's influence on crops or agricultural operations is not mentioned in the general forecast. Only agricultural meteorologists with a thorough knowledge of current agricultural

techniques and operations must make such interpretations.

## 5.8 NOWCASTING AND VERY SHORT-RANGE FORECASTS

### 5.8.1 Definitions

Nowcasting (NC) and very short-range forecasting (VSRF) techniques were created for fields such as civil protection and transportation. Nevertheless, in the last few years their importance for agriculture has been rapidly growing due to the improvement of techniques for production and broadcasting of forecast information and the increasing flexibility of agro-techniques to cope with variability of weather conditions. A short definition and some general characteristics of NC and VSRF have been presented in Table 5.1.

NC is the extrapolation of current weather to some future time (up to 2 h), mainly based on the behaviour of existing phenomena as described by intensive observations; VSRF is the anticipation of events beyond the period during which extrapolation usually works (up to 12 h) (Schlatter, 1986). NC and VSRF focus on meso- and microscale weather events, with spatial scales below 1 000 km and timescales of several hours.

In the state-of-the-art services, NC is very close to VSRF from the point of view of applied forecast techniques and it is not easy to make a clear separation between the two techniques (Heijboer et al., 1989; Coiffier, 2004); for this reason they will be jointly discussed in this section. Some authors (for example Schlatter, 1986) say that NC could be based exclusively on extrapolation techniques and does not involve knowledge extensively applied for VSRF (physics, dynamics or the application of numerical and conceptual models).

### 5.8.2 Operational activities

Basic information about NC and VSRF is presented in Table 5.11. Agricultural and biological data, from ground truth or remote-sensing sources (such as local and regional observations of crop phenology, pests and diseases, agricultural practices), are important ancillary data for production of useful and reliable agrometeorological information (for example, nowcasting of precipitation or frost can be useful for a given crop only during particular phenological phases).

Usually the forecaster's work for NC and VSRF consists of producing a reference forecast based on available information and checking whether the actual behaviour of the selected phenomena agrees with the forecast one. This latter task needs real-time comparison of forecast values with real-time synoptic and/or remotely sensed data. When the actual evolution differs from the forecast one, the forecaster should be able to adjust the forecast and amend the products delivered to the end-users. This task becomes particularly critical when a severe weather event is taking place. For example, in the specific case of heavy precipitation (Horváth and Geresdi, 2003) the adjustment of the forecast over small areas with the help of the whole set of available tools, and the preparation of alarm bulletins, takes up all of the forecaster's time (Coiffier, 2004). The consequence is that it is crucial to have techniques at one's disposal to organize all the available data in a georeferenced framework, interpret the existing information, and display in real time the information for the forecaster. Automatic techniques useful for these aims are:

- (a) Geographical Information Systems (GISs);
- (b) Techniques for data assimilation and quality checks;
- (c) Techniques for analysis of spatial data;
- (d) Tools to detect differences between the forecast and the actual situation;
- (e) Numerical and conceptual models adapted to territory and operational activity.

All of the above techniques could be fault-tolerant and could also operate with reduced sets of data (Mouchart and Rombouts, 2005).

GIS is useful for the management of different kinds of basic data as georeferenced layers (Olaya, 2004).

Assimilation is the first phase of the operational chain of NC and VSRF and a fundamental aspect for the quality of numerical weather prediction (NWP) model products (Macpherson, 2001). Data quality checks are crucial to avoid the negative effect of wrong data that may not be detected by normal quality control procedures, which usually do not work in real time (for example: the effect of wrong hourly rainfall data on the quality of NC and VSRF). Real-time quality control procedures (checking of absolute and relative – spatial, temporal, intersensor and intersystem – consistency) are needed to eliminate outliers of faulty data and to highlight questionable data that need particular attention by the forecaster (Daley, 1993).

Analysis of spatial data is founded on geostatistical approaches in order to describe the spatial features of meteorological phenomena (Goovaerts, 1997) and to extrapolate their behaviour, field of motion and trajectory (Steinaker et al., 2000) from observations and remotely sensed imagery.

Automatic tools to detect differences between the forecast and the present situation are useful in order to minimize the subjective decisions of the forecaster and the possibility of error. The availability of a GIS technology is an important element for obtaining satisfying results in this case as well.

Numerical models are useful in NC and VSRF for prognostic and diagnostic purposes (Kaspar, 2003). Classical examples are given by energy balance models useful for analysis and forecasting of temperatures of vegetation (Bonan, 2002), or hydrological models useful for forecasting runoff and

**Table 5.11. Nowcasting and very short-range forecast: basic information for the forecaster**

	<i>Class</i>	<i>Data</i>
<i>Monitoring data</i>	Punctual atmospheric data	Local and regional observations of atmospheric phenomena (cloud coverage, present and past weather events) Data from networks of automatic weather stations
	Remotely sensed atmospheric data	Maps from systems for lightning detection Images from polar and geostationary meteorological satellites Maps from meteorological radar Sodar data
<i>Forecast data</i>	Data from numerical models	Products of NWP models (LAM and GM)
		Products from biological models (for example: phenological models)

floods due to strong rainfall (Jones, 1998; Gwangseob and Barros, 2001; Bowler and Pierce, 2004; Olaya, 2004; Grimbacher and Schmid, 2005). Availability of NWP models parameterized and validated for the reference territory and the weather phenomena for ready implementation in forecasting can be of great help. The usefulness of NWP prognoses can be evaluated on the basis of and taking into account the velocity of mesoscale development of weather phenomena. This means that time and spatial scales of NWP outputs must be defined in order to satisfy all the operational requirements for phenomena that show a very rapid mesoscale development (Heijboer et al., 1989), and that the assimilation procedure of NWP must be defined in order to receive local observational inputs with hourly or sub-hourly time steps.

Conceptual models are useful in order to provide: (i) a definition of phenomena in terms of features recognizable by observations, analyses or validated simulations; (ii) a description of the life cycle of phenomena (time of appearance, size, intensity and

accompanying weather); (iii) a statement of the controlling physical processes, which enables one to understand the factors that determine the mode and rate of evolution of the phenomena; (iv) specification of the key meteorological fields demonstrating the main processes; (v) guidance for predicting formation using the diagnostic and prognostic fields that best discriminate between development and non-development; and (vi) guidance for predicting movement, evolution, senescence and disappearance (Conway et al., 1999). Advantages offered by conceptual models to forecasters involved in NC and VSRF are summarized in Table 5.12. Some conceptual models with examples are mentioned in Table 5.13.

Further improvements in VSRF and NC could be obtained not only through the enhancement of operational and broadcast techniques, but also by means of an increase in the continuity of operations of agrometeorological services, which can also be obtained by expanding the automation of procedures.

**Table 5.12. Some reasons for the usefulness of conceptual models to forecasters (Conway et al., 1999)**

<i>Usefulness</i>	
1.	Help in understanding and diagnosing phenomena
2.	Synthesis of all available information
3.	Four-dimensional "mental picture" of atmosphere
4.	Basis for isolating weather processes
5.	Basis for extracting the main signals from complex patterns
6.	Tools for assisting diagnosis of numerical models
7.	Supplement to numerical models for the nowcasting scale
8.	Tools for identifying errors in the numerical forecast
9.	Fast forecast method
10.	Independent forecast method
11.	Forecast method particularly for hazardous weather
12.	Possibility of filling in data gaps

**Table 5.13. Some conceptual models with some examples**

<i>Conceptual model type</i>	<i>Examples</i>
Models of fronts and frontal substructures, including topographical influences	Frontal models, such as a model using conveyor belts (Browning and Mason, 1981)
Models of convective phenomena	Supercell thunderstorms (Ray, 1986) Radiation fog (Guedalia and Bergot, 1994)
Models of fog, frost and low cloudiness	Radiation or advective frost (Stull, 1997)
Models of topographically induced weather features Other models	Sea/land breezes (Atkinson, 1981) Forecasting of dust storms (Barnum et al., 2004)



**Table 5.14. Examples of the use of nowcasting and very short-range forecasts for agriculture**

<i>Objective</i>	<i>Principal forecast variables</i>
Manage works without producing soil compaction	Precipitation
Manage field activities during the growing period of crops	Temperature, wind and precipitation
Minimize the waste of biocides applied against weeds, pests and diseases	Temperature, wind and precipitation
Manage frost mitigation activities	Temperature of air and crop tissues
Manage harvest activities for different crops	Precipitation, relative humidity, wetness of crops
Prevent and mitigate the effects of flash floods or debris flow	Precipitation

### 5.8.3 Operational examples

Nowcasting and very short-range forecasting can be useful for many different agricultural activities (Table 5.14).

#### 5.8.3.1 Nowcasting and very short-range forecast of frost

Nowcasting and very short-range forecast of frost are extremely important for the management of agricultural practices against this event (such as low-volume irrigation, ground-based fans, trash fires). In Italy some agrometeorological services have used specific NC and VSRF outputs during the period crops were exposed to risk of late frost (from February to April) or early frost (October and November).

Friuli Venezia Giulia is a region located in north-eastern Italy with a significant presence of fruit trees (apple, pear, peach and actinide). Usually frost is very frequent during winter, but during spring and fall frosts pose a significant risk for fruit-growing. For this reason, several orchards are provided with low-volume irrigation devices that are used against spring frost and, in some situations, against fall frost (for example: risk for actinide fruits).

In order to switch on the irrigation, it is important to know when the frost will take place. The Regional Environmental Protection Agency for Friuli Venezia Giulia has produced a tool called ANGELA (*Algoritmo di Nowcasting per le GELate*, or algorithm for nowcasting of frost), which works routinely during periods potentially exposed to frost risk, giving the forecast temperature evolution from sunset to sunrise.

ANGELA is fed from dusk to dawn with the following data:

- Minimum temperature subjective forecast. This is the forecast of the minimum temperature for the coming night issued by the

forecaster. It is the synthesis of NWP outputs, meteorological data from all weather stations and the forecaster's skill.

- Hourly night-time temperature measurements gathered from automatic weather stations. These data are refreshed every hour so they give an up-to-date snapshot of the ground temperature field.

The physical model implemented in ANGELA for the night-time temperature drop is that of Reuter (Pelosi, 1986). In this model, the ground temperature is a function of sunset temperature and the time passed since sunset:

$$T_n = T_s - K \cdot n^{1/2}$$

In this equation  $T_n$  is the temperature at  $n$  hours from the sunset in °C,  $T_s$  is the temperature recorded at sunset in °C,  $K$  is the temperature drop coefficient and  $n$  is the number of hours since sunset. In spite of its simplicity, the model is quite realistic if the coefficient  $K$  is updated every hour during the night. The initialization of the model is done with the forecaster's minimum temperature, the sunset temperature and the length of the night in hours, assuming that the lower temperature is reached at the end of the night. In this step two values for  $K$  are computed: one concerning the pure minimum temperature issued by the forecaster and the other concerning the forecaster's minimum temperature minus 2°C. This is done to give two extreme values for  $K$ :  $K_{max}$  and  $K_{min}$ , which define the range for the  $K$  values computed in the further steps. The starting  $K$  is the simple average of the two extremes. Every hour after sunset, for each automatic weather station, the observed temperature is used to compute the new constants  $K$ . To give more robustness to the forecasts, that is to issue temperature forecasts without too much fluctuation throughout the entire night, the applied  $K$  is constrained in the defined range by means of a linear combination of  $K$ ,  $K_{max}$

and  $K_{min}$ . Furthermore, a quality check on observed temperatures is performed in order to avoid the use of local spikes.

Once the observed temperatures are available at the Agrometeorological Service Centre (CSA) and the ANGELA temperature forecasts are computed, an automatic connection with a local television broadcasting station updates the forecast, making the information available to everybody in real time. In recent years the ANGELA system was also adopted by the Veneto Regional Environmental Protection Agency.

In Trentino the frost warning service is run by the Agricultural Institute of San Michele (IASMA) and Meteotrentino. The service is aimed at providing minimum temperature forecasts to apple growers and crop practices assistants. Frost nowcasting is disseminated via the Web, while real-time temperatures (10° updating) are available via teletext and SMS on demand. For a selected number of stations, mechanistic models have been calibrated, which yield, site by site, the best estimates of minimum temperature when suitable meteorological conditions are predicted for the following night (clear sky, very stable atmosphere and calm or very light wind). If such conditions are assessed by the local meteorological service, models are implemented and issued on the Web. The Reuter algorithm (Pelosi, 1986) is also applied in an hourly update mode, correcting the hourly temperature decrease by recorded temperature data. Another approach consists of post-processing atmospheric model outputs by machine learning techniques: a “random forest” algorithm is applied to the fields predicted by ECMWF (temperature, wind, humidity, geopotential, sky cover) at the control time of 6 a.m. on the following day. The temperature forecast is improved with respect to the raw model output, and the forecast is available about 10 hours before sunset.

## 5.9 SHORT- AND MEDIUM-RANGE FORECASTS

### 5.9.1 Definition

Short- and medium-range forecasts describe the behaviour of weather variables (precipitation, air temperature, sky coverage and solar radiation, wind velocity and direction, and so on) and weather phenomena (frontal systems, anticyclones, tropical cyclones, squall lines, and the like). The typical range is beyond 12 hours and up to 72 hours for short-range forecasts (SRFs) and beyond 3 days and up to 10 days for medium-range forecasts (MRFs). A

short definition and some general characteristics of SRFs and MRFs are presented in Tables 5.1 and 5.2.

### 5.9.2 Usefulness for agriculture

SRFs and MRFs are important for farmers in the planning of work such as:

- (a) Preparatory activities, including land preparation and preparation of plant material;
- (b) Planting or seeding/sowing;
- (c) Management of crops, fruit trees and vines; application of fertilizer, irrigation; thinning, topping, weeding; pest and disease control;
- (d) Management of grazing systems;
- (e) Harvesting, on-farm post-harvest processing and transport of produce;
- (f) Livestock production activities (for dairy enterprises, beef systems, lamb and other livestock systems).

Furthermore, quantitative forecasts are an important source of data for simulation models that produce information useful for farmers (simulation of crop phenology; water and nutrient cycles; crop production; weed, disease and pest cycles).

### 5.9.3 State of technology

Forecast technology is constantly evolving due to the expansion of scientific knowledge of atmospheric systems and advances in technologies, such as monitoring tools that use satellites, networks of automatic weather stations, radars, lightning detection systems and so on. Other evolving technologies include forecasting tools, such as NWP techniques, statistical methods, empirical models, and methods derived from forecaster experience (rules of thumb).

The activities of the weather forecaster in nowcasting and very short-range forecasting are founded on analysis and extrapolation of trajectories that refer to a relatively wide set of products (radar maps, meteorological satellite images, NWP models, local and regional observations, and so on). In short- and medium-range forecasts, the evolution of atmospheric variables is mainly derived by numerical methods (NWP). The experience of the forecaster is important in order to evaluate the accuracy of outputs of one or more models for the particular area (topography, distance from sea, soil use, and so on).

The work of forecasters has evolved significantly over the years to take advantages of both scientific and technological improvements. The skill of numerical models has improved so much that some centres have implemented automating routine forecasts to allow forecasters to focus on high-impact

weather or areas where they can add significant value. It is not easy to determine a standard way to create weather forecasts since the methods used depend on several factors (Coiffier, 2004):

- (a) The forecast range;
- (b) The size of the domain to be covered (a large portion of the globe, a regional domain, a small country, a city);
- (c) The geographical context and related climatology (mid-latitudes, tropical or equatorial areas, isolated islands);
- (d) The potential risk associated with the expected weather at various ranges;
- (e) The organization of the forecast service (multi-purpose or specialized for agriculture);
- (f) The technical environment (available external and/or internal NWP products, in situ observations, satellite and radar images, lightning detection network, infrastructure catering to the needs of the forecaster, Web access);
- (g) The know-how of forecasters (professional experience and operational experience relevant to the selected area);
- (h) The reference end-user for forecasts (for example: general-purpose services or specialized ones for fields such as agriculture, civil defence, aviation, marine operations, hydrologic and water management service and road administration);
- (i) The reliability of the current state of weather variables.

#### 5.9.4 Forecasts and NWP

Numerical Weather Prediction provides useful information for up to approximately 6–12 days (120–240 hours) in the future. It is based on solving a complex set of hydrodynamic equations that describe the evolution of the atmosphere, subject to the initial atmospheric state and initial conditions at the Earth's surface. Since the initial state is not known perfectly, all forecasts begin with estimates. Unfortunately, the system is very sensitive to small changes in the initial conditions (it is a chaotic system) and this limits the ability to forecast the weather deterministically beyond 6–12 days.

MRFs are founded on the use of the output of one or more global NWP models. Moreover, SRF redaction is founded on local area models (LAMs). At present, the availability of LAMs until 2–3 days after their emission can be considered the limit between an SRF and an MRF.

It is important to define these forecasts and describe the principal inputs (such as NWP) and outputs, with some significant examples. Model output

statistics (MOS) are statistical methods applied to outputs of NWP in order to improve the forecast skill for local or microscale phenomena that are not correctly modelled in a mechanistic way (for example, frost, maximum temperature, rainfall quantity or probability).

#### 5.9.5 Probabilistic approach to SRF and MRF

An important evolution in SRF and MRF is represented by the introduction of a probabilistic approach to future states of weather. The same terminology adopted by forecasters is sometimes an expression of this uncertainty (see Table 5.15).

An example of a subjective probabilistic forecast for a viticultural area of Italy is represented in Table 5.16. Probability of precipitation was needed by farmers in order to apply pesticides during the vegetative period.

Ensemble forecasts are a mathematical method that can take into consideration the inherent uncertainty in MRF and SRF. Traditional weather forecasts are founded on the output of the best models available and used until they lose their skill due to the growth of small errors in the initial conditions. In medium-range forecasts, model skill is typically lost after six days or so, depending on the season. An alternate method that produces forecasts with skill up to 15 days after the initial forecast uses what is called the “ensemble forecasting” method, which was introduced to produce improved medium-range (3–15 days) weather forecasts. Instead of using just one model run, many runs with slightly different initial conditions are made. An average, or “ensemble mean”, of the different forecasts is created. This ensemble mean is likely to be better because it averages the many possible initial states and essentially smooths the chaotic nature of climate. In addition, it is now possible to forecast probabilities of different conditions because of the large ensemble of forecasts available.

#### 5.9.5.1 Operational services and SRF/MRF for agriculture

##### 5.9.5.1.1 Agrometeorological forecasting and advisory service

Agrometeorological forecasting services (or agrometeorological sections of general-purpose meteorological services) are organizations that produce information specialized for agriculture, forestry and fisheries. Agrometeorological (advisory)

**Table 5.15. Quantitative aspects and uncertainty of precipitation forecasts expressed by means of words used by the forecaster (from National Weather Service, n.d.)**

	<i>Probability of precipitation</i>	<i>Terms used</i>
	0%	None
	10%	Slight chance – Isolated
	20%	Slight chance
	30–50%	Chance – Scattered
	60–70%	Likely – Numerous
	80–100%	Categorical (“rain this afternoon”)
<i>General rules</i>	<p>The likelihood of occurrence of precipitation is stated as a percentage.</p> <p>A measurable amount is defined as 0.01” (one hundredth of an inch) or more (usually produces enough runoff for puddles to form).</p> <p>The measurement is of liquid precipitation or the water equivalent of frozen precipitation.</p> <p>The probability is for a specified time period.</p> <p>The probability forecast is for any given point in the forecast area.</p>	
<i>Examples</i>	<ol style="list-style-type: none"> <li>1) In a precipitation forecast, the following terms of duration imply a high probability (80–100%) of occurrence: brief, occasional, intermittent, frequent.</li> <li>2) If a forecast for a given county says that there is a 40% chance of rain this afternoon, then there is a 40% chance of rain at any point in the county from noon to 6 p.m. local time. This point probability of precipitation is determined by the forecaster by multiplying two factors: forecaster certainty that precipitation will form or move into the area x areal coverage of precipitation that is expected.</li> <li>3) If the forecaster is 80% certain that rain will develop but is expected to cover only 50% of the forecast area, then the forecast would read “a 40% chance of rain” for any given location.</li> <li>4) If the forecaster expects a widespread area of precipitation with 100% coverage to approach, but he/she is only 40% certain that it will reach the forecast area, this would, as well, result in a “40% chance of rain” at any given location in the forecast area.</li> </ol>	

**Table 5.16. Example of probabilistic approach to precipitation forecast. ERSAL (Lombardy Regional Agency for Agricultural Development) project for rationalization of pesticide distribution on vineyards. Forecast of rainfall for viticultural areas of Franciacorta, Cellatica, Botticino, Valtenesi and Lugana. Wednesday 2 July 1997**

<i>Day</i>	<i>Probability of rainfall</i>
Thursday	0
Friday	2
Saturday	1
Sunday	2

Classes of probability of rainfall: 0 = absent (0%); 1 = low probability (0–30%);  
2 = Medium probability (30–70%); 3 = High probability (>70%)

services are acts by such units for operational use. Some examples are discussed below.

#### 5.9.5.1.1.1 Forecasts of cold spells and paddy rice

Cold spells during differentiation of flower organs are a significant risk for rice crop in extreme areas of the boreal (for example, France, Italy, China) and austral hemispheres (for example, Australia).

A drop in temperatures below the critical threshold (10°C–15°C for most of the mid-latitude varieties) causes male sterility with a significant decline in production. Cold spells are frequently triggered by synoptic and mesoscale phenomena (outbreaks of Arctic air and related thunderstorms) that can be forecast relatively easily by means of SRF and MRF. Farmers who receive this information can act by raising the level of water in ponds.

#### 5.9.5.1.1.2 Output of NWP models and agro-meteorological simulation models

The Agrometeorological Research Station at Braunschweig of the German Weather Service (Deutscher Wetterdienst, 2004) has developed the agrometeorological advisory system AMBER. In AMBER, Kalman-filtered results of local (LM) and global (GME) LAM models at hourly intervals for locations of weather stations, as well as measured data at these locations, are used as boundary conditions for agrometeorological models. These are the AMBAV and AMBETI models, which calculate agrometeorological quantities for different crops and types of soil. These, in turn, are used to run a variety of models. Through the AMBAV model, the actual evapotranspiration for a variety of crops and types of soil is calculated considering soil moisture and crop development, which are derived from the phenological observations. In the AMBETI model, Braden (1995) calculates temperatures, water transport and moisture for several depths of different soils and for several canopies, including soil chill, as well as the development and melting of a snow cover. The interception of precipitation and radiation by crops and transmission of radiation into crop canopies, in addition to leaf wetness and leaf temperatures, are modelled.

With the help of these results from agrometeorological models for individual locations, the following information is derived by means of more specific agrometeorological models:

- (a) Occurrence of specific plant diseases and pests;
- (b) Advice about the need for spraying and other agricultural management/farming activities;
- (c) Soil tractability;
- (d) Optimal time for planting, irrigating and fertilizing for different crops;
- (e) Estimation of the extent of volatilization, runoff and infiltration of fertilizers, fungicides and pesticides;
- (f) Forecast of grain humidity, yield and harvest quality;
- (g) Estimation of the optimal harvest time for different crops and of each crop for different types of soil.

From the multitude of results obtained, those of interest for different groups of clients (for example, irrigating farmers, vegetable cultivators and animal producers) are selected and presented in different tables and figures. These results are sent automatically by e-mail and by fax to clients, such as individual progressive farmers, machinery groups

and agricultural organizations for given locations and their surroundings.

#### 5.9.5.1.1.3 Forecasts and distribution of waste or nutrients

In recent years, large animal-feeding operations in the United States have come under intense scrutiny. A rise in the number of these operations has occurred at a time of increased awareness of the effects of non-point source pollution. Regional initiatives, such as the Chesapeake Bay Program, have focused in part on the non-point pollution caused by animal-feeding operations. Environmental catastrophes, such as the North Carolina hog farm spillage in the wake of Hurricane *Floyd*, have served to focus the spotlight on large, concentrated animal-feeding operations.

National rules were defined in order to carry out operations like animal feeding or waste distribution without nutrient/pollution runoff. In particular, Natural Resources Conservation Service (NRCS) technical standards and guidelines state that wastes and/or wastewater may not be discharged on land when the soil is saturated, frozen or covered with ice or snow; during precipitation; or when significant precipitation is reasonably expected within the next 72 hours. As a result of these rules, discharge of wastes/wastewater over land is based on two forecast products of the National Weather Service (NWS):

- (a) A valid NWS forecast (Figure 5.4) as primary information;
- (b) A farmers' map (Figure 5.5) as a secondary tool that can be utilized to evaluate whether land application activities can be conducted when the forecast alone would not.

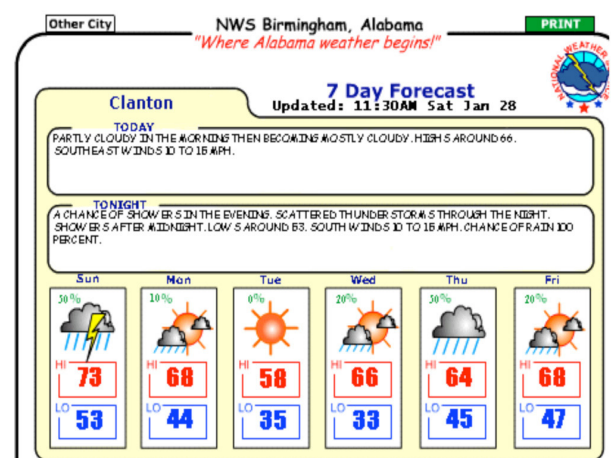
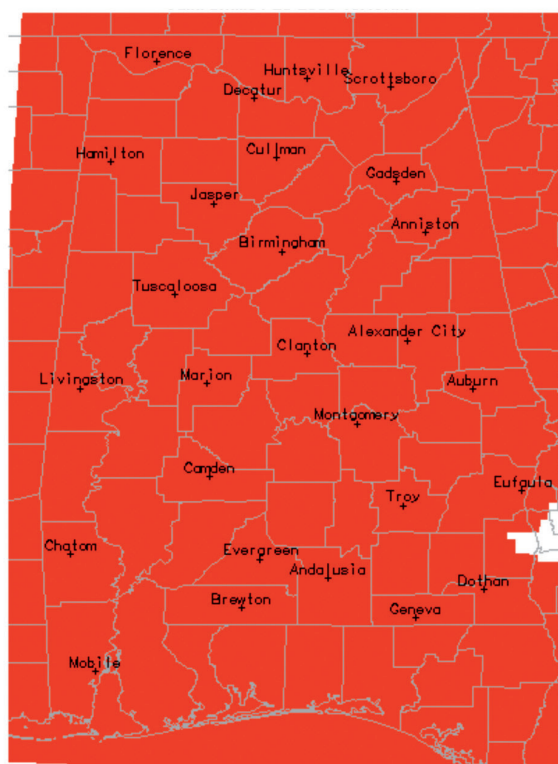


Figure 5.4. Example of NWS forecast available at [http://www.srh.noaa.gov/bmx/data/forecasts/Clanton\\_forecast.html](http://www.srh.noaa.gov/bmx/data/forecasts/Clanton_forecast.html)



Alabama Animal Waste/Nutrient Land Application Map  
Issued: Jan 27, 2006 10:19 PM Based on Current 72 Hour Forecast

Valid Until: 01-28-2006 10:19AM



Areas in red are unfavorable for spreading of waste/nutrients  
Areas in white are favorable for spreading of waste/nutrients

**Figure 5.5. Example of NWS forecast map**  
available at [http://www.srh.noaa.gov/bmx/data/FARMERS\\_MAP/farmers\\_map.html](http://www.srh.noaa.gov/bmx/data/FARMERS_MAP/farmers_map.html)

Farmers can dispose of animal waste/nutrient on land if the NWS forecast predicts less than 50 per cent rain chance for each of the next 72 hours. In this case, the farmers' map is not needed. On the contrary, if NWS predicts 50 per cent or greater rain chance for each of the next 72 hours, a farmer can use land for disposal only if the farmers' map shows that the area in which the application will take place is white (not red). In other words, the farmers' map is intended to provide farmers with an additional option when the likelihood of rain is elevated, but the amount of rain predicted is low (not expected to cause runoff from the field). If farmers need to use land for disposal when the rain prediction is 50 per cent chance or greater sometime during the next 72 hours, they can view the farmers' map (available on the Internet site of the NWS), verify that their area is white (not red), print a copy for their records, and then carry out the land disposal according to the nutrient management plan prepared as part of their facility's comprehensive waste management system plan.

Use of land application for disposal is not authorized up to 72 hours prior to a significant chance or amount of rain. Use of land application for disposal may commence or resume immediately following the rain, however, provided that the weather prediction for the next 72 hours is favourable, and field conditions meet NRCS technical standards and guidelines.

#### 5.9.5.1.1.4 Examples of operational agro-meteorological services in India

The India Meteorological Department (IMD) renders Agromet Advisory Services (AAS) to the country's farming community in the form of bulletins. These advisories are prepared jointly by the experts of IMD and agricultural specialists at respective state departments of agriculture and are tailored to the requirements of farmers in the given state. These bilingual (in the local/regional language and also in English) bulletins are disseminated on a real-time basis through All India Radio, the Doordarshan Kendra television network, newspapers and the IMD Website.

All the AAS centres of IMD actively monitor the state of crops, the occurrence of pests and diseases, and extreme weather events throughout the country. Accordingly, IMD issues warnings for pests and diseases and remedial measures against extreme weather events. These are communicated to users and to planners in time to safeguard crops, and they allow for updating of the status of agriculture at the policymaking level in the respective states. The AAS centre in the north-western part of the country also monitors the desert locust situation in north-west India and issues advisories to the state departments of agriculture concerned. Some examples of agrometeorological services in different regions of India are provided below.

##### *For north-west India:*

*Severe frost conditions prevail in Himachal Pradesh and Jammu and Kashmir during second week of January. Snowfall likely to occur at a few places over Himachal Pradesh and Jammu and Kashmir divisions for the next five days. Under these circumstances, farmers in the above states are advised to take the following precautionary measures:*

*Irrigation should be given to protect standing crops from ground frost, as adequate soil moisture keeps the soil comparatively warm and saves it from frost.*

*Owing to ground frost, smoking should be conducted to protect crops.*

*In the morning, two men holding a rope should move across the field so that the dew formed over the leaves will drop.*

*Protect the young saplings of orchard trees from cold injury by covering them with polythene or paddy straw.*

*As morning humidity will be of the order of 85 per cent in Punjab and Haryana, the incidence of rust diseases will be likely (above the economic threshold level) on wheat. It is advised to monitor the incidence of diseases and apply Mancozeb at the rate of 2 g/l of water. Use 200 litres of water for one acre.*

*For east India:*

*Blast disease may appear in the seedbed of rice during this period due to the prevailing weather conditions in West Bengal. If noticed, spray Ediphenphos 50% @ 1 ml or Triamiphos 48% @ 1 ml or Carbenidazole 50% @ 1 ml per litre of water. A total of 75 litres of water is required to spray 25 satak of seedbed land.*

*Downy mildew is reported in cucurbits in Orissa and the disease intensity is expected to increase further under the prevailing weather condition. To control downy mildew, spray Redomyl/Mancozeb @ 2 g per litre of water. Use 200 litres of water for one acre.*

*For north-east India:*

*There is a likelihood of incidence of pod borer on red gram during this period in Assam under prevailing weather condition. To control pod and apion borer, spray Melathion 50EC @ 1.5 ml per litre of water or Fenitrothion 50EC @ 2 ml per litre of water on a non-rainy day.*

*As there was no significant rainfall in most of the districts in Assam during last few weeks and dry weather will prevail for next five days, apply required irrigation wherever crops are at pod formation stage.*

*For south India:*

*There was no rainfall for the last five weeks in all the districts of Andhra Pradesh and no significant rainfall is expected for the next five days. Under the circumstances, apply irrigation to the standing crops to bring the soil moisture to its field capacity.*

*Release predators like *Dipha* sp, adopt wider spacing, inter-crop with soybean and pulses of short duration and ratoon sugarcane to control woolly aphids in Mysore, Mandya, Hassan, Bidar and Bangalore districts in Karnataka.*

*Attack of red palm weevil is reported in coconut in Kerala. Fill leaf axil with Sevidol 8 G @ 25 gm mixed with fine sand 200 gm per tree, and trunk hole filling and sealing with 10 ml DDVP in 1 litre of water.*

*For west India:*

*The lowest minimum temperature of  $-2^{\circ}\text{C}$  was recorded at Pilani on 09.01.06 in Rajasthan. Cold-wave conditions accompanied by ground frost likely to occur in extreme north of Jaipur and Bikaner divisions for the next five days. The following precautionary measures may be taken.*

*Irrigation should be given to protect standing crops from ground frost, as adequate soil moisture keeps the soil comparatively warm and saves it from frost.*

*Due to ground frost, smoking should be conducted to protect the crop.*

*In the morning two men holding rope should move across the field so that dew formed over the leaves will drop.*

*Protect the young saplings of orchard trees from cold injury by covering them with polythene or paddy straw.*

*As temperature is abruptly high, that is,  $3^{\circ}\text{C}$ – $9^{\circ}\text{C}$  above normal in Rajasthan, maturity of barley and wheat may be advanced by about 10–12 days, which may lead to shorter reproductive phase and lower yield of crops. Apply irrigation at frequent intervals to barley, wheat, gram, cumin, beans and vegetables to supplement the high rate of transpiration from the crop as temperature is  $3^{\circ}\text{C}$ – $9^{\circ}\text{C}$  above normal and there was no rain over the state for last few weeks and the dry weather will prevail for next five days.*

*For central India:*

*As there was no significant rain during last few weeks and dry weather is likely to prevail during next few days in Madhya Pradesh and Chattisgarh, apply irrigation to the standing crops to bring soil moisture to its field capacity.*

#### 5.9.5.1.2 General-purpose meteorological services

General-purpose services produce and broadcast forecasts for very wide categories of end-users. These services could survey the needs of farmers and provide information useful for this particular

category of users, especially when this information is crucial for quantity and quality of production.

### 5.10 LONG-RANGE FORECASTS

Long-range forecasts (LRFs) are forecasts for periods greater than one month. The contents of this section have been drawn mainly from the ECMWF Website ([http://www.ecmwf.int/products/forecasts/seasonal/documentation/ch1\\_2.html](http://www.ecmwf.int/products/forecasts/seasonal/documentation/ch1_2.html)).

#### 5.10.1 The basis for LRFs

Despite the chaotic nature of the atmosphere, long-term predictions are possible to some degree thanks to a number of components that are to a certain extent predictable, although they do show variations on long timescales (seasons and years) (ECMWF, 2005). The most important of these components is the ENSO cycle, which refers to the coherent, large-scale fluctuation of ocean temperatures, rainfall, atmospheric circulation, vertical motion and air pressure across the tropical Pacific. It is a coupled ocean-atmosphere phenomenon centred over the tropical Pacific, but the scale of the fluctuations is quite vast, with the changes in sea surface temperatures often affecting not just the whole width of the Pacific but the other ocean basins too, and the changes in tropical rainfall and winds spanning a distance of more than one-half the circumference of the earth. El Niño episodes (also called Pacific warm episodes) and La Niña episodes (also called Pacific cold episodes) represent opposite extremes of the ENSO cycle. The ENSO cycle is the largest known source of year-to-year climate variability (ECMWF, 2005).

Changes in Pacific SST are not the only cause of predictable changes in the weather patterns. There are other causes of seasonal climate variability. Unusually warm or cold sea surface temperatures in the tropical Atlantic or in the Indian Ocean can cause major shifts in seasonal climate in nearby continents. For example, the sea surface temperature in the western Indian Ocean has a strong effect on the precipitation in tropical eastern Africa, and ocean conditions in the tropical Atlantic affect rainfall in north-eastern Brazil. In addition to the tropical oceans, other factors that may influence seasonal climate are snow cover and soil wetness. When snow cover is above average for a given season and region, it has a greater cooling influence on the air than usual. Soil wetness, which comes into play most strongly during warm seasons, also has a cooling influence. All these

factors affecting the atmospheric circulation constitute the basis of long-term predictions (ECMWF, 2005).

To summarize, seasonal forecasts provide a range of possible changes that are likely to occur in the season ahead. It is important to bear in mind that because of the chaotic nature of the atmospheric circulation, it is not possible to predict the daily weather variations at a specific location months in advance. It is not even possible to predict exactly the average weather, such as the average temperature for a given month (ECMWF, 2005).

#### 5.10.2 Statistical and dynamical approaches to LRF

##### 5.10.2.1 Statistical approach to LRF and related limits

A possible starting point for seasonal forecasting is a good knowledge of climate, that is, the range of weather that can be expected at a particular place at a particular time of year. Beyond a simple knowledge of climatology, statistical analysis of past weather and climate can be a valid basis for long-term predictions. There are some regions of the world and some seasons in which statistical predictions are quite successful: an example is the connection between the rainfall in March–May in the North-east Region of Brazil and the sea surface temperatures in the tropical Atlantic in the months before and during the rainy season (ECMWF, 2005).

Another example can be seen in the experimental forecasts of El Niño based on the study of the correlation between this phenomenon and patterns of sea surface temperature, surface pressure and wind (Adams et al., 2003). In theory, a very long and accurate record of the Earth's climate could reveal the combined (and non-linear) influences of various factors on the weather, and analysis of many past events could average out the unpredictable parts. In practice, the 50–100 year records typically available represent an incomplete estimate of the Earth's climate. In addition, seasonal predictions based on past climate cannot take full account of anthropogenic or other long-term changes in the Earth's system (ECMWF, 2005).

##### 5.10.2.2 NWP approach to LRF and related limits

An alternative approach is to use the numerical weather prediction method by solving the complex set of hydrodynamic equations that describe the

evolution of the Earth's climate system. For an NWP-based seasonal forecast, it is important to consider both the atmospheric and oceanic components of the Earth's system. In fact, the air-sea interaction processes that describe the complicated interchange between the atmosphere and ocean are essential to represent the ENSO cycle. Just as for synoptic-range NWP forecasts, the calculation depends critically on the initial state of the climate system, particularly the tropical Pacific Ocean for ENSO. Because of the chaotic nature of the atmosphere, a large number of separate simulations are made. They will all give different answers in terms of the details of the weather, but they will allow something to be said about the range of possible outcomes and the probabilities of occurrence of different weather events (ECMWF, 2005).

If the numerical models were very realistic, and if very large ensembles of such calculations could be performed, the probability distribution of weather to be expected in the coming months would be accurately described. To the extent that predicted distribution differs from normal because of the initial conditions of the ocean, atmosphere and land surface, the ensemble calculations could predict the correct seasonal forecast "signal". Unfortunately, there are a number of problems that limit the seasonal forecast skill. Numerical models of the ocean and atmosphere are affected by errors, observations of the ocean are sparse, and techniques for estimating the extra uncertainty that this introduces are not yet well developed (ECMWF, 2005).

### 5.10.3 Reliability of LRF

The benefits of seasonal forecasting are likely to be most evident in forecasts for the tropics. This is because tropical areas have a moderate amount of predictable signal. This explains the use of LRF as a component of early warning systems (WMO, 2000) in order to extrapolate the potential occurrences of ENSO-related extreme weather/climate events. Models that transfer projected ENSO signals directly into agricultural stress indices have been developed for agricultural application (ECMWF, 2005). By contrast, in mid-latitudes random weather fluctuations are usually larger than the predictable component of the weather.

Much work will be needed to relate probabilities of large-scale weather patterns to detailed impacts and applications. It must be remembered, however, that there are tight limits on what is physically possible to achieve with a seasonal forecast system. It will be possible only to predict a range of likely outcomes. In many cases this range will be relatively large, and

there will always be a risk of an unexpected occurrence. In many parts of the world, most of the variability in the weather will remain unpredictable (ECMWF, 2005).

Some seasonal forecasts available today are issued with probabilities (or error bars) that have been properly calibrated against past cases. An example is the Canonical Correlation Analysis (CCA) prediction of El Niño variability, which is regularly shown in the NOAA Climate Diagnostics Bulletin. Such forecasts are probably fairly reliable, but they have very wide error bars: they may state that in six months there might be strong El Niño conditions, or fairly strong La Niña conditions, or anything in between (ECMWF, 2005).

## 5.10.4 Quality control of forecasts

### 5.10.4.1 Quality control data

The checking of forecast quality is an instrument that can be applied by services and end-users. In particular, end-users can choose better forecast products and services. Thornes and Stephenson (2001) present six attributes of a weather forecast that make up the total quality: reliability, accuracy, skill, resolution, sharpness and uncertainty.

The reliability of a forecast can be measured by calculating the bias. This will show if the forecasters are consistently over-forecasting the number of particular events (for example, frosts or snow). The percentage of correct forecasts is a very simple measure of forecast accuracy.

There are many different skill scores (for example, the Pierce Skill Score and the Odds Ratio Skill Score) that attempt to assess how much better the forecasts are than those that could be generated by climatology, persistence or chance.

Resolution is important in the forecasting of precipitation – being able to distinguish between snow, sleet, freezing rain, hail, drizzle and rain, for example. Sharpness is a measure of the spread of the forecasts away from climatology. For example, a forecast method that can predict frosts in spring as well as winter shows high sharpness, whereas a forecast method that can only predict frosts in winter has low sharpness. Uncertainty relates to the climate. For instance, some areas have comparatively fewer frosts than others.

A number of measures of forecast quality are therefore required, but in order to avoid confusion they must be easy to calculate and their



statistical significance should be testable (Thornes and Stephenson, 2001). The production and release of quality control data are important in order to guide the choice of the right weather prediction by farmers. If quality data are not available, agrometeorologists or farmers can use directly observed data (meteorological measurements of temperature, precipitation, sky coverage, weather phenomena, and so on) in order to evaluate the skill of forecasts. Statistical analysis can be carried out by means of non-parametric methods.

#### 5.10.4.2 Feedback to operational services

The feedback of end-users is important in order to improve the forecast performance of services and single forecasters.

### 5.11 DISSEMINATION OF WEATHER FORECASTS AND ADVISORIES

Irrespective of its nature and importance, any information is useless until and unless it is promptly delivered to the users (for example, Vogel and O'Brien, 2006). Reliability of forecasts, expected weather-induced risks or weather-induced losses, and farmers' attitudes towards risk will affect the use of weather forecasts. Meinke et al. (2006) introduce salience, credibility and legitimacy as essential factors. All these factors can be assessed through the participation of farmers (for example, Onyewotu et al., 2003; Roncoli, 2006). A farmer's risk-bearing ability (income and assets) and individual characteristics, such as vulnerability and preparedness, will determine his or her attitude and adaptation skills with regard to risk. This, combined with expected weather-induced losses, will decide whether a farmer will be willing to use weather forecasts. Based upon a farmer's experience with traditional weather forecasts and expected losses due to adverse weather at different stages of crop growth, the extent of his or her use of forecasts may vary at different seasons and crop-growth stages. Thus, particularly in developing countries, there could be a number of categories of farmers using forecasts and other information (Rathore et al., 2006). In China the conclusion was drawn from large surveys that farmers with different income levels and rural people working in different occupations related to agriculture clearly had varying information needs, information sources and uses of information depending on their educational level as well (Ying and Stigter, unpublished results). In this connection, there may be different target

groups of users for agricultural weather forecast services and other agricultural advisories.

Weather forecasts are generally used more by highly skilled professionals such as researchers, extension workers, policymakers and progressive farmers. On the other hand, agricultural advisories are used more by farmers with less formal education for farm management purposes. There are some similarities and dissimilarities between these two target groups. The first group of users may rely more on fast electronic systems for the transfer of information, such as the Internet, CD, Very Small Aperture Terminal (VSAT) networks and e-mail. Conventional methods of communication, such as bulletins, pamphlets, posters, postal letters, newspapers, radio, television, (mobile) phone, pagers, local announcements, village meetings, local time-bound markets and personal communication are better to reach the second group of users (for example Rijks and Baradas, 2000). With the advent of computers and the Internet, emphasis is often being placed on electronic communication systems. Television and radio services are still the best ways of communicating advisories among rural people, however, because these are not only rapid methods, but they make it possible to contact large and illiterate masses as well. Broadcasting of advisories in the local language provides an edge over other means of communication (WMO, 1992; Weiss et al., 2000). With television and radio there remains the drawback that information appears only for short periods, unless taped, while much Internet-based information can be accessed for a longer time.

#### 5.11.1 New dimensions in dissemination technology

Information technology is advancing very rapidly. There is good reason to claim that the present century will be the century of information technology. Easily available fast Internet facilities, supercomputers, high-capacity servers and efficient linking between information points have given a much-needed boost to information technology. While in the last century the communication systems were mostly one-way communications, in the present century interactive communication systems are being developed more extensively. There are some examples of interactive communication systems for the dissemination of agricultural advisories, and they are being adopted commercially by the most advanced providers and users in the United States, Japan and some European countries. The choice of technology must be made at the local level, however, and farmers have to be reached and exposed to information about the services. This



applies to developed and developing countries alike (see also Chapter 17 of this Guide).

### 5.11.2 **Internet-based communication systems**

The advantage of Internet-based interactive systems is that spatial variability in soil and management practices can be addressed. Farmers are advised on their farm-specific problems (for example Maia et al., 2005). Local weather conditions, type of soil, type of crop and phenological stage, as well as level and type of insect pest infestation, are considered in offering advisories for decision-making on sowing, harvesting, irrigation, nutrient management and chemical application (for example Dacom, 2003). In this system, users have the option of providing the observed field conditions or manipulating the input levels to analyse the different possible scenarios. An example from Denmark is described below to shed some light on this system. It should, however, also be realized that there is a serious risk that in many areas of the world it will not be possible to reach farmers through the Internet or other new technologies and therefore auto-referential services may end up being created.

### 5.11.3 **"PlanteInfo" and other Internet case studies**

The Danish Institute of Agricultural Sciences (DIAS) and the Danish Agricultural Advisory Centre (DAAC) jointly launched the Web-based online information system "PlanteInfo" (<http://www.PlanteInfo.dk>) in 1996 to provide decision support for crop production on an experimental basis. Over more than a decade, PlanteInfo has gone through many alterations and has now reached maturity in its effort to advise farmers on agricultural activities. More than 2 per cent of farmers and 50 per cent of crop advisers in Denmark are actively using the PlanteInfo system. Most of the PlanteInfo content is delivered as personalized Web pages requiring login; PlanteInfo stores information on users' geographical position and provides Web pages automatically on the basis of local weather observations and forecasts.

As an agrometeorological service, PlanteInfo provides information concerning arable crops (spring and winter wheat, spring and winter barley, oat, winter rye, triticale, spring and winter rape, peas, sugar beet and potato), fodder crops (grass and maize), vegetables (carrots, cauliflower, cabbage and onion) and fruits (strawberries and apples). A simple mechanistic simulation model runs in the background on input data generated

by PlanteInfo (Thysen and Jensen, 2004). Crop development and soil characteristics are considered for decision-making on irrigation and nutrient management. A separate module provides information on pests and diseases on the basis of weather parameters (such as aggregate temperature, aggregate soil temperature, rainy days, rainfall, humidity, and so forth) and the current state of the crop, as well as weeds, pests and diseases. Individual farmers are required to select the type of crop and cultivars and other input parameters, such as weather station and soil type, from a table on the Website. At the same time they are expected to furnish information on sowing, crop stage, amount of nitrogen applied, irrigation and previous crop (for residue management). The output is provided as a document that can be used after consideration of local conditions.

Other Web-based systems that provide agrometeorological services for crop management include SAgMIS in the Republic of Slovenia for irrigation management (Sušnik and Kurnik, 2004); IRRINET, BIDRICO and PLASMO in Italy for irrigation management (Rossi et al., 2004), irrigation and frost management (Gani et al., 2004), and grapevine downy mildew control (Orlandini et al., 2004), respectively; and ISIP (Information System for Integrated Plant Production) in Germany for plant protection (Röhrig and Sander, 2004). Paz and Batchelor (2003) developed another Web-based system for soybean crops in the United States, but forecast weather was not included and it does not deliver advice.

The Internet is also used in a non-interactive mode for the dissemination of agrometeorological services. The information is stored in text form on the Internet, and it is accessible to users from certain URLs, for example, <http://www.agmet.igau.edu.in> (Sastri et al., 2005). Advisories are also sent from the Internet to users by e-mail list servers, which require the e-mail addresses of the users.

The Advice concept (Thysen and Jensen, 2004) is aimed at bridging the information gaps and resolving the conflicting interests among information providers, information users (farmers) and intermediates (local advisers). It was observed over time that farmers are not enthusiastic to adopt the computer-based interactive advanced technology of advisory dissemination because of a reluctance to invest sufficient time in learning how to use the technology. But in recent years, agriculture has become an enterprise and a large number of professionals are engaged in the work of commercially advising farmers.

#### 5.11.4 **Communication systems based on mobile phones**

Systems for the dissemination of services based on mobile phone networks are used in both interactive and non-interactive mode. The most advantageous feature of mobile phone systems is that farmers are able to communicate with the Web-based systems while in the field and can request advice concerning a newly discovered problem. Farmers can also update the farm database immediately after observations or application of treatments. In PlanteInfo, the Irrigation Manager has been optimized to advise on irrigation scheduling for individual fields. The Irrigation Manager needs to be set up with information on soil type, crop and emergence date. Local weather data (observed and forecast) are provided by the PlanteInfo weather database. The request is sent from the mobile phone (smartphone) to the PlanteInfo server, which is directed to the PlanteInfo Mobile homepage. Users can access the PlanteInfo system on mobile phones and generate the desired output in an interactive mode.

Mobile-based communication systems can also be used to get services and information in non-interactive mode. This mode is generally used for receiving the weather forecast or warnings of weather hazards such as frost, flash flood and forest

fire. The PlanteInfo system provides services and information related to weather and agricultural warnings in both modes of mobile communication.

A frost warning system based on Short Message Service (SMS) technology was launched in the Friuli Venezia Giulia region of north-eastern Italy in 2003. This area is prone to frost, especially in the months of March, April, May and November. The ANGELA model forecasts the night temperatures with a time resolution of one hour. A frost warning is sent to farmers through SMS twice per night, so that they can take necessary actions to protect crops (Gani et al., 2004). The probable time and region for the occurrence of frost are mentioned in the SMS. The Norwegian Meteorological Institute has been using the Varsling Innen PlanteSkadegjørere (VIPS) Web-based warning system (Folkedal and Brevig, 2004) and the Governmental Extension Services in Germany have been using the Information System for Integrated Plant Production (ISIP) (Röhrig and Sander, 2004) to provide information and services for crop protection via SMS communication since 2003. An SMS system of information and services transmission is also being tested by the Environmental Agency of the Republic of Slovenia for irrigation management (Sušnik and Kurnik, 2004).

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# ANNEX

Università degli Studi di Milano  
Faculty of Agriculture – Department of Crop Science  
**CAMPUS WEATHER FORECAST**

**Thursday 16 June '05**

authors: Luigi Mariani and Domenico Ditto










(Students that want to co-operate to this forecast may contact prof. Luigi Mariani)

**Forecast produced for educational aims. The use for commercial or operational aims is explicitly denied. Servizio Meteorologico dell'Aeronautica and ARPA – Servizio Meteorologico regionale are the authorities for operational weather forecasting in Lombardia. Our data is not an alternative or substitute for the official weather forecasts.**

## GENERAL EVOLUTION

A ridge of the subtropical anticyclone gives conditions of stability and advects hot and humid air masses from North Africa towards Po plain. For the reference period weather will be sunny or almost sunny without significant probability of rainfall. Light winds or calm. Predictability of forecasted weather types: high until Monday, medium for Tuesday; low for the following days.

### FORECAST FOR MILAN EAST – FACULTY OF AGRICULTURE

cloudiness and significant phenomena							
Thu 17/6	Fri 18/6	Sat 19/6	Sun 20/6	Mon 21/6	Tue 22/6	Wed 23/6	Thu 24/6
							
							
Detailed forecast							
Thursday 17				Friday 18			
Sunny throughout the day with a few scattered clouds. No precipitation is expected. Light winds or calm. Low Temperature 20°C; High temperature 31°C.				Sunny throughout the day with a few scattered clouds. No precipitation is expected. Light winds or calm. Low Temperature 22°C; high temperature 30°C.			
Saturday 19				Sunday 20			
Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 23°C; high temperature 30°C.				Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 24°C; high temperature 30°C.			
1.6.1 Monday 21				Tuesday 22			
Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 24°C; high temperature 31°C.				Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 23°C; high temperature 29°C.			
Wednesday 23				Thursday 24			
Cloudy with low probability of rain (class 2; probability: very low). Light winds or calm. Low Temperature 23°C; high temperature 28°C.				Cloudy without rain. Light winds or calm. Low Temperature 24°C; high temperature 28°C.			

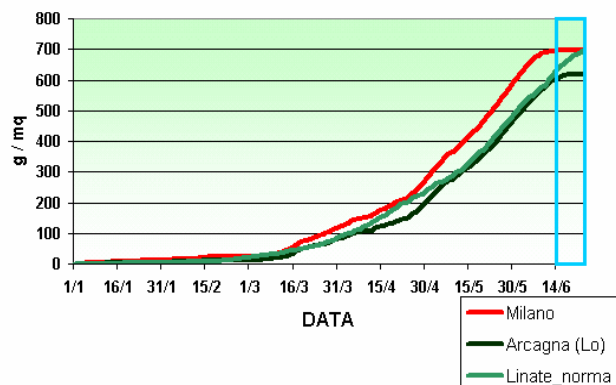
**Pluviometric classes in 24 hours: Quantity: class 1:** <1 mm (absent); **classe 2:** 1-10 mm (low); **classe 3:** 10-50 mm (abundant); **classe 4:** >50 mm (extreme) **probability for the reported class of quantity:** <1%=very low; 1-30%=low; 30-70%=moderate; >70%=high

NUVOLOSITA'					LEGENDA					
0/8	1-2/8	3-5/8	6-7/8	8/8	foschia	nebbia	pioggia	neve	foehn	temporale
										
										

## AGROMETEOROLOGICAL MODELS - 1 january / 23 june 2005

(cyan boxes are for simulations carried out on forecasted meteo data)

### 1. Net Primary Production (NPP)

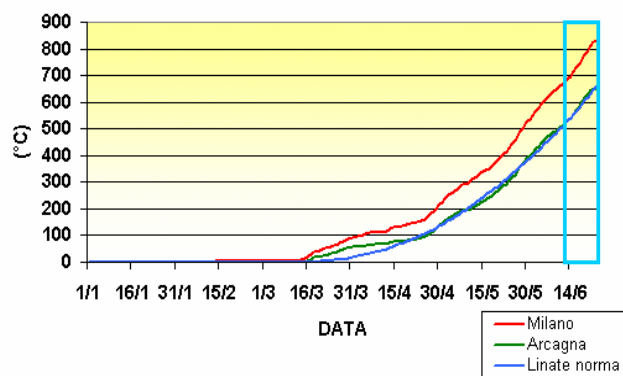


Net Primary Production (NPP) represents the organic carbon cumulated by plants. In this case NPP is referred to a meadow of C3 plants (*Arrhenatheretum*) and is estimated by SIM\_PP model (Mariani, Bocchi e Maugeri) [Carbon data =  $\text{g m}^{-2}$ ]

#### COMMENT TO DATA

The storage of carbon was stopped due to soil water shortage. In these conditions the total storage at Milano, that in the previous period was above the normal due to the UHI effect, is reached by normal production (Milano Linate).

### 2. HEAT UNITS - BASE 10°C



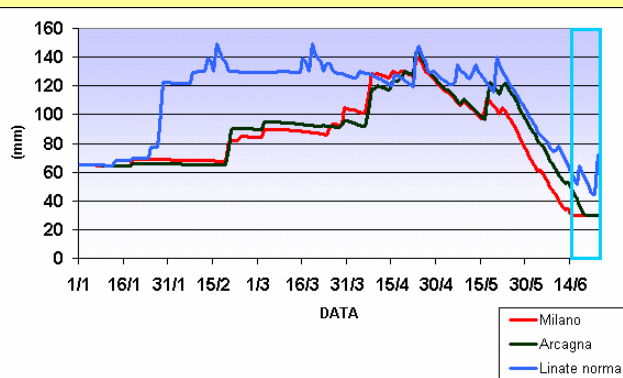
Thermal units (TU) are calculated subtracting 10°C from mean daily temperatures and cumulating only positive values.

They represent a measure of thermal resources for plants which present minimum cardinal of 10°C (summer crops, vine).

#### COMMENT TO DATA

Very close to normal TU calculated for Arcagna. Positive anomaly for TU cumulated at Milano, forecasted in increase also for the next week.

### 1.6 WATER



Soil water balance (WB) gives a quantitative evaluation of soil water useful for plants. This WB is carried out with the water balance unit of SIM\_PP model (Mariani, Bocchi e Maugeri). Reserve is composed by a single reservoir with field capacity of 130 mm and wilting point of 30 mm. Water content at the beginning of balance was 50% of the AWC.

#### COMMENT TO DATA

**The low levels of spring rainfall justify the anticipate emptying of soil water storage.**

*Sources of data: for the experimental farm of Arcagna we used data of meteorological station of Montanaso ([www.ucea.it](http://www.ucea.it)); for Milano Linate the reconstruction of daily data was carried out by means of a data generator to monthly climate data 1971-2000 of Servizio Meteorologico dell'Aeronautica ([www.meteoam.it](http://www.meteoam.it))*

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