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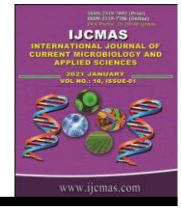

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Role and Importance of Weather Forecasts in Modern Agriculture

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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 timelines 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.

Introduction

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 climatologically 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 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 inter annual 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.

Weather events

Despite careful agronomic planning on a micro scale 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.

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.

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.

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 climatologically 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 decadal 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 decades 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 humidity than what is deducible from a thermo hygrograph. 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.

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 agro meteorological 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 agro meteorological work in India. The crop weather calendars in use in India 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) Now casting (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;

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

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.

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.

Solar radiation

The main parameters, extra terrestrial radiation (*Ra*) and possible sunlight hours (*N*), required to derive solar radiation (*Rs*) 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 *Rs*/*Ra* and *n*/*N t* is a straight-line type. The value of the constants, however, varies with seasons and locations but can readily be determined.

Precipitation

Snow and rainfall are probably two of the most difficult forecast variables. Quantitative forecasting of rainfall, especially of heavy down pours, 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 based on the climate and the agricultural context of the selected area. A probabilistic approach is quite important in order to maximize the usefulness of this forecast.

Adopting the scheme is possible to produce daily information like this-

(a) Mostly cloudy or overcast with rainfall (high probability)

(b) Partly cloudy with rainfall unlikely (very low probability)

(c) Sky clear with absence of precipitation

Use of the terms 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 rain gauge with a set of fine wires. Quantitative data on fog precipitation may not be available. Nomo grams for predicting the occurrence of fog at airports are available with forecasters, however, and 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, nomo grams 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.

Temperature

Forecasting of air temperature is important for many agro meteorological 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 thermo periodicity, 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 Graminaceae 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.

Humidity

For the day as a whole, dew point temperature is a conservative parameter and is easier to forecast, as changes in dew point temperatures are associated with the onset of fresh weather systems. From maximum, minimum and dew point temperatures, minimum, maximum and average humidity 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.

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 wind rose 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 wind roses 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.

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.

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 ET0 as a standard measure of EPA. Computation of ET0 requires data on net radiation over a green crop canopy, low-level wind and saturation deficit of air. An empirical method to compute ET0 from routinely available meteorological data has been proposed. ET0 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 ET0 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 ET0 using measured values of solar and atmospheric radiation; they have also described using these values to derive ratios of ET0 to EP at a number of stations covering typical climate regimes.

The use of pan coefficients to derive ET0 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.

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 to13 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.

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 agro meteorological 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.

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 chemo-resistance 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. Rains immediately after chemical weeding will neutralize the operation's effect 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.

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.

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. Bio-meteorological 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 hygro-thermal 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.

Transport of agricultural products

Most agricultural products must be transported a fairly long distance from the place of production to the market place. 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 snow storms 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 snow storm 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.

Agricultural advisories or agrometeorological services

"Agricultural advisories" or, in the language of this Guide, agro meteorological services 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 agro meteorological 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, agro meteorological 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.

Preparation of agricultural advisories (agro meteorological services)

The formation of agro meteorological 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 and hence must be considered in the services. On the basis of local agro meteorological 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).

Panel of experts

Ideally, a panel of specialists in a topic of agricultural science and animal science is constituted for the preparation of agro meteorological services. The panel may include agro meteorologists, 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.

Information requirements

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

Required agro-meteorological 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.

Example of an agro-meteorological advisory service of the NCMRWF in India: a preliminary impact assessment

The impact assessment of this agro-meteorological 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. 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.

Probability of forecasts

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 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.

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 live-stock systems).

In conclusion 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).

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