Spatial interpolation of daily meteorological data

Theoretical evaluation of available techniques

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ABSTRACT

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In agrometeorological crop yield models meteorological values at not observed points have to be obtained by means of interpolation techniques. In this study, interpolation onto a 50 × 50 km^2 grid of meteorological data for Europe was demanded. The choise of the appropriate interpolation technique depends on the spatial character of the variable. The spatial and temporal character of daily means of meteorological data in North-Western Europe is described. Europe is dominated by extensive and local circulation systems. On daily base most meteorological variables do not show great differences for distances between 50-100 km and simple interpolation techniques can be used. Rainfall, however, has a high variable spatial and temporal variable. Rainfall amounts, therefore, should be interpolated by means of stochastic interpolation techniques such as kriging.

Keywords: interpolation, meteorological variables, circulation systems, spatial and temporal characteristics, kriging.

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PREFACE

This theoretical evaluation of interpolation techniques of meteorological variables is part of the spatialisation study of the Yield Forecasting Models (Part II) project of the Joint Research Centre (JRC) in Ispra, Italy.

The Yield Forecasting Models project is being carried out by DLO The Winand Staring Centre, Wageningen, The Netherlands (SC-DLO). Its aim is to develop a yield forecasting model based on grid elements of 50×50 km^2. An important input in this model are meteorological data that have been measured at approximately 200 weather stations in the European Community.

This study was carried out for the fullfillment of an Ir-studies at the Department of Surveying and Remote Sensing of Wageningen Agricultural University, The Netherlands.

I wish to thank Ir L.L.F. Janssen and Prof. M. Molenaar of the Department of Surveying and Remote Sensing for their supervision and Ir C.A. van Diepen (SC-DLO) for the coordination of this study within the project.

Eric Beek.

SUMMARY

The aim of this study was to assess the most reliable method for interpolation of daily means of sunshine, temperature, relative humidity, windspeed and precipitation. The measured data originated from approximately 200 weather stations of the European Community. These data have to be interpolated onto a regular grid of 50×50 km^2 for use in a yield forecasting model. Therefore the spatial and temporal variability of the meteorological variables was described.

An inventarisation of possible interpolation techniques was made. Furthermore, literature was reviewed on the experience of interpolation techniques for meteorological variables.

The conclusion was that most variables can satisfyingly be interpolated using simple linear interpolation technique. The spatial variability of rainfall is more complex than the other variables. It is recommended to investigate the use of kriging for interpolation of daily precipitation means.

1 INTRODUCTION

Precise and up-to-date information on agricultural production is necessary for the implementation of the Common Agricultural Policy (CAP) of the European Community. During the past decades the CAP has led to a complex system of rules and subsidies all of which rely on a certain level of precision of agricultural statistics, including yield forecasts.

The Council of Ministers of the European Community has set up a Pilot Project for the Application of Remote Sensing in Agricultural Statistics, with the aim of improving the collection of statistical information and agricultural forecasts over Europe.

The project, commonly known as the Agricultural project for Monitoring Agriculture using Remote Sensing (MARS), is being carried out by the Institute of Remote Sensing Applications of the Joint Research Centre (JRC) at Ispra, Italy. The project commenced in 1988 is being supervised by the Agriculture Directorate General (DG VI) and the Statistical Office of the European Community (EUROSTAT). It is structured around several Actions, the most important being:
(1) Regional Inventories;
(2) Crop Monitoring and Yield Indicators;
(3) Yield Forecasting Models;
(4) Rapid Estimates of Areas and Potential Yields.

Most of the work is carried out under contract by national organizations. Within the framework of Action 3, DLO The Winand Staring Centre is conducting a study on the development of non-crop specific agrometeorological simulation models. The models will be installed in a Geographic Information System (GIS). The immediate aim of the study is to demonstrate a methodology and to test an operational system for obtaining sufficiently reliable estimates of yield and production of major crops. If successful, these models will be used for the semi-real time monitoring of agricultural seasonal conditions over the entire EC.

In the yield model, dynamic crop growth simulation techniques are applied to make quantitative estimates of biomass accumulation and yield formation. To apply the model to a single site for one year, data on crop, soil and weather are required. A full geographic coverage of the EC will be obtained by making simulations for all sites representing large areas in terms of soil and weather conditions. The definitive representative sites involves selection, interpretation, interpolation and aggregation procedures for crop, soil and weather data.

The present study is a contribution made by the Agricultural University of Wageningen on the subject of interpolation of meteorological data. It examines the prospect of applying interpolation techniques to daily weather data from observation stations for the projection of weather conditions on a rectangular grid (50×50 km^2).

The problem is described in Chapter 2 and then a comprehensive view of meteorological processes is given in Chapter 3. Several interpolation techniques are described in Chapter 4 and Chapter 5 shows that efforts have been made to find out if some of the methods had been used in the past. Future possibilities of using satellite imagery are dealt with in Chapter 6 and finally the conclusions are drawn in Chapter 7.

2 DESCRIPTION OF THE PROBLEM

The yield forecasting models being developed for the European Community (EC) use daily meteorological data obtained from the European weather observation stations. The meteorological data are needed for the calculation of daily growth rate of crops, their water use and water requirements, and phenologic development rate.

The models are applied on a regular grid of 50×50 km². For model development and validation, meteorological data for the past 30 years are available for about 250 meteorological stations in the EC. In the future, semi-real-time data will be obtainable from 450 stations in the EC, enabling a denser network.

Model results depend on accuracy or sensibility of the model and the reliability of the measured and interpolated input variables. For reliable and accurate model results both aspects are important. This study deals with reliability of the interpolated

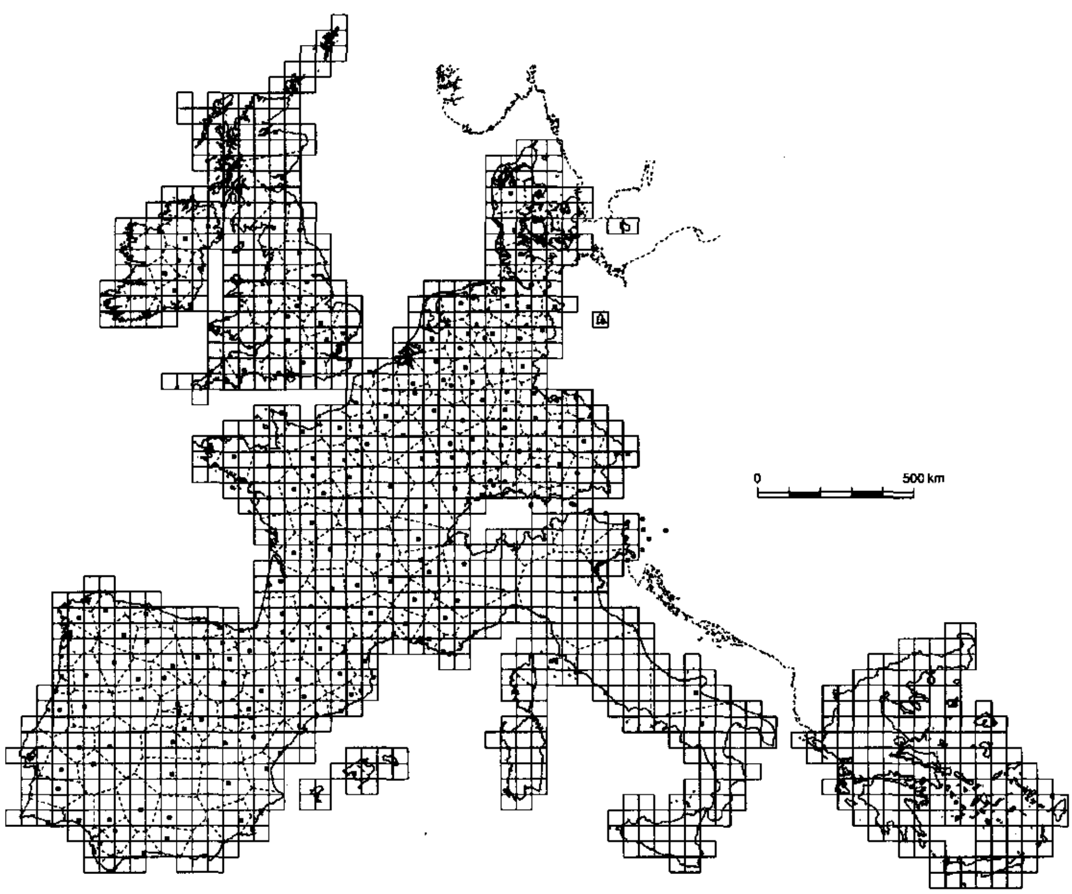

***Fig. 1** Map of the European Community with the weather observation stations and the grid of 50×50 km² forming the base for the model calculations*

meteorological data. The meteorological data required are the daily mean of sunshine radiation, temperature (minimum and maximum), humidity, windspeed and precipitation.

The data are measured at weather observation stations several times a day and then a daily weighted mean is calculated. Methods of measurement can differ from country to country, also the measurements themselves are erroneous and sometimes there are no measurements at all.

The observation stations in the EC are not equally distributed and the main problem is to find the most reliable technique for the interpolation of daily meteorological values onto a regular grid of 50×50 km^2.

In order to be able to choose a reliable interpolation technique, the variability of the different types of meteorological data in space and time related to the meteorological processes must be specified.

It is also important to know the existent interpolation procedures and to the extent to which they might be used for the interpolation of meteorological variables.
Another aim is to find out which experience is available on interpolation techniques in the meteorological fields.

At present, only data from the meteorological stations can be used for model input. In the future additional data such as remote sensing data, can also probably be used. It is therefore interesting to know the extent to which these additional data may improve the accuracy of the estimated data.

3 METEOROLOGICAL VARIABLES IN SPACE AND TIME IN EUROPE

This chapter deals with the scale of processes, the meteorological variables and the meteorological ground observations.

3.1 Scale of meteorological processes

The kinetic energy of air movements is divided into a broad scale of systems, varying from micro-scale turbulent flow to long planetary waves. A classification of scales is shown in Figure 2.

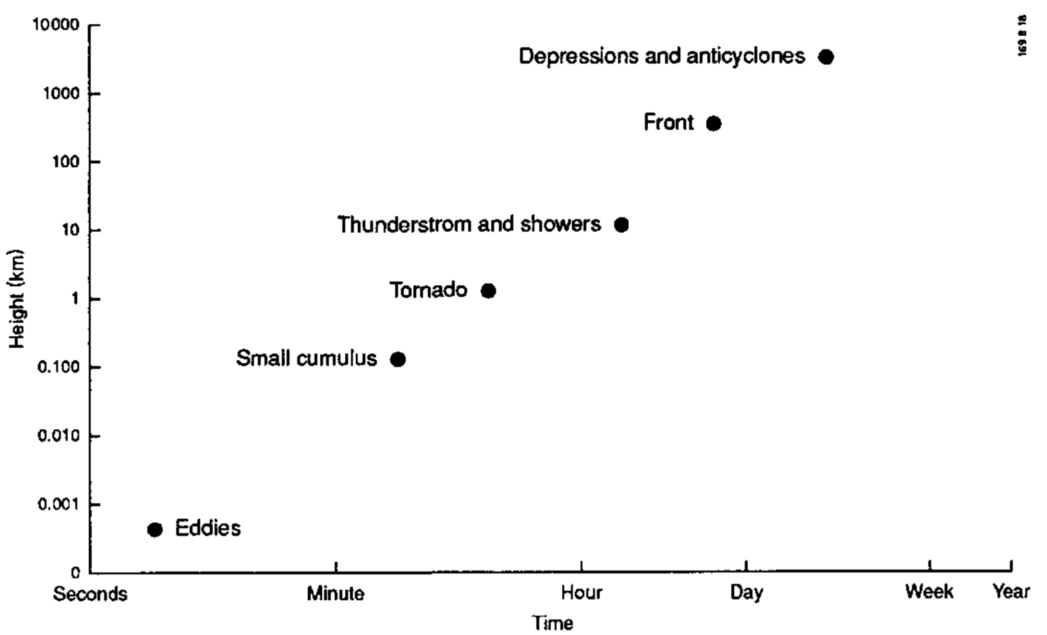

Fig. 2 Classification of weather circulation systems

The spectrum of circulation systems is not continuous, but shows some discrete transitions. The size of these circulation systems are within certain limits. Depressions, for example, range between 500 and 2500 kilometres and can last from a couple of days to a week; a thunderstorm of 10 kilometres will not last longer than a couple of hours and eddies have a typical time scale of seconds and a space scale of centimetres. If the daily mean of temperature, relative humidity, sunshine, windspeed, cloudiness and precipitation are given, the daily variation is eliminated. Comparing two weather observation stations *during* on a particular day can show a cloudy morning in one station and a cloudy afternoon in the other, but weighted over the whole day there would be no difference, because both stations had a half clouded day.

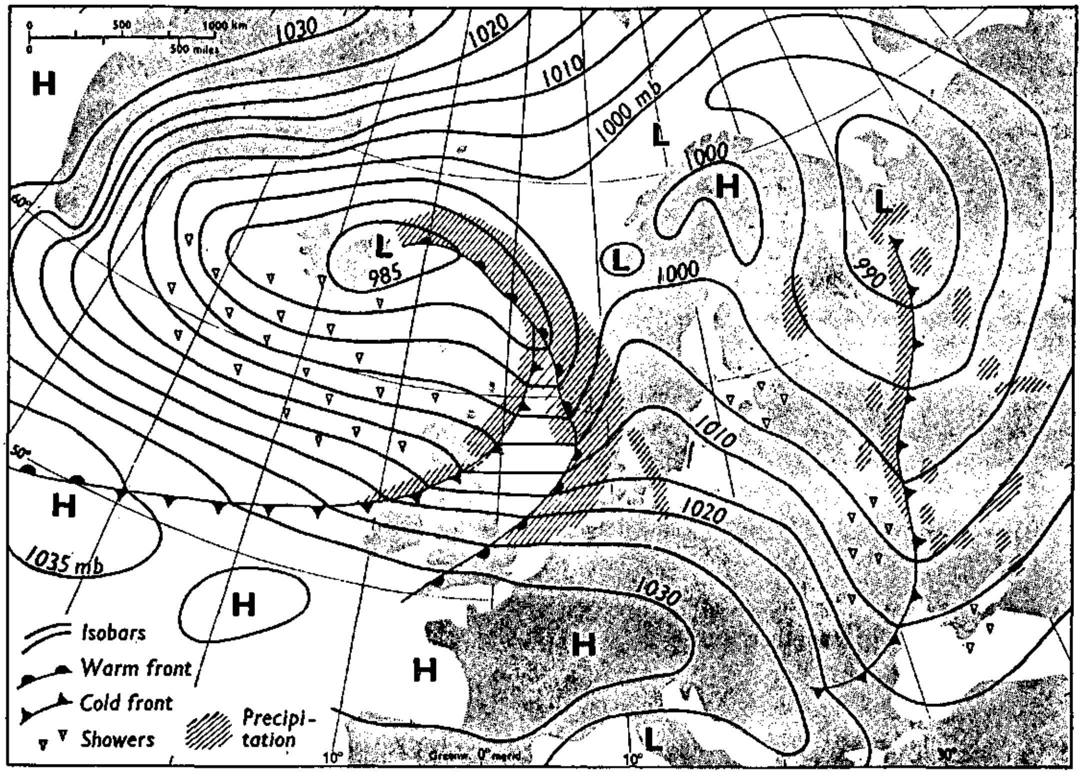

Fig. 3 Circulation of mild air to Western Europe

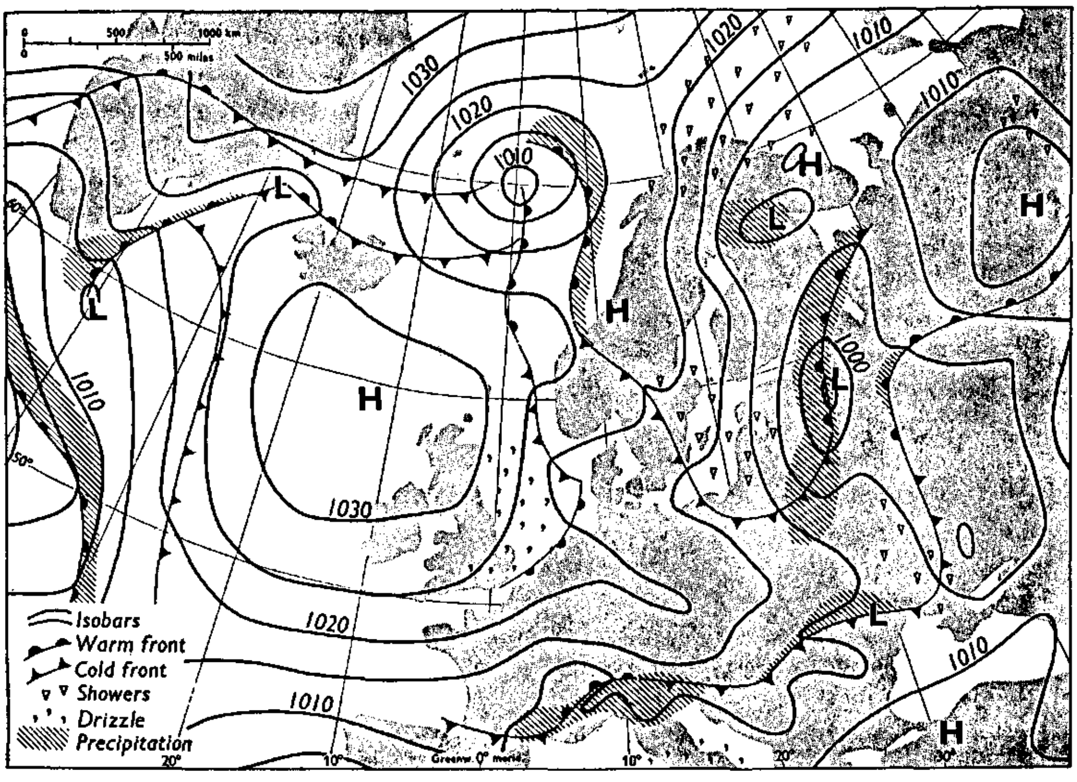

Fig. 4 Circulation of continental air to Western Europe

According to the World Survey of Climatology the EC has two climate types ; the Mediterranean and the Northern European or temperate climate. The basic phenomenon in the General Circulation air movements in the atmosphere in temperate regions situated between low, heated latitudes (subtropics) and high, cooled latitudes (polar region) is the meandering westerly "jet" stream of air, which has its maximum at 300 mb-level (more or less 9000 meters altitude). Although this westerly jet stream is persistent, the meandering pattern changes from day to day and the weather and climate of Western Europe is largely dependent on how this pattern around the jet stream shows up. The most frequent circulation pattern in winter, is a jet stream between an extended low pressure system in the North and an extended high pressure system in Southern Europe. At the surface the jet stream at the upper levels corresponds to the well-known "polar front" of the Bergen-school concept, at which the cyclonic activity on temperate latitudes take place. The cyclones, created at the polar front on the Atlantic Ocean and moving with the upper West-winds towards and across Western Europe, are the basic mechanisms by which the import of mild air from the Atlantic Ocean towards the continent takes place, shown in Figure 3. In this situation the weather of Western Europe becomes very mild and cloudy in winter and relatively cool in summer. Because of rather strong cyclonic activity, rainfall may be abundant in the Western parts of Northern Europe but decreasing towards the East.

In spring and autumn the most frequent circulation causes wet weather conditions in Northern Europe. In Southern Europe, however, the most frequent circulation causes steady weather in all seasons. A less frequent circulation pattern can exist if a high pressure cell blocking the oceanic cyclones transports cold or warm continental air towards Western Europe, as shown in Figure 4. Under such conditions cold winters or warm stable summers are experienced.

Meso-scale circulation patterns include showers (with their own internal circulation) which are the main sources of precipitation in Southern Europe during all the seasons and are also important in temperate parts of Europe in the summer. A more detailed description of these meso-scale circulation systems is given in the section on precipitation. If the weather is dominated by extensive pressure systems (low-and high pressure cells extending over 500-2500 kilometre), it may be assumed that most of the meteorological variables do not vary much over distances in the range of 50-150 kilometres (in contrast to the tropics where the weather depends on local features). This does not apply to abrupt changes in the landscape, eg a coast line, a large lake or a mountain range.

3.2 Variability of meteorological variables

3.2.1 Sunshine

Sunshine is related to latitude. The radiation of the sun is stronger at low latitudes than at high latitudes, and therefore regions in the neighbourhood of the equator receive more radiation than the polar regions. If clouds are present, sunshine will be reduced at the surface.

3.2.2 Temperature

Due to seasonal fluctuation of the radiation received by the earth's surface in Europe in the summer causes a *latitudinal trend* in temperature. In winter however there is a meridional trend caused by the influence of the warm ocean, which diminishes eastward where the continent gets colder. In Europe, the temperature varies a little over short distances. Extreme differences in a small region (eg 50×50 km^2) may occur sometimes, caused by the presence of a frontal system which forms the transition of two different air masses. The temperature diminishes with increasing altitude about 0.6 °C per 100 metres (Thompson et al. 1981).

3.2.3 Wind speed

In general, windspeed shows little variance over distances of 50-150 kilometres. The largest gradient is found in coastal areas, due to the coastal effect. Air movement over a large water surface is less influenced by friction than over land surface and therefore a higher windspeed occurs in coastal areas. In Figure 5 the monthly windspeed in The Netherlands illustrates the coastal effect. An interesting feature is that the Lake IJssel causes the same effect. Further inland the windspeed and the gradient decrease.

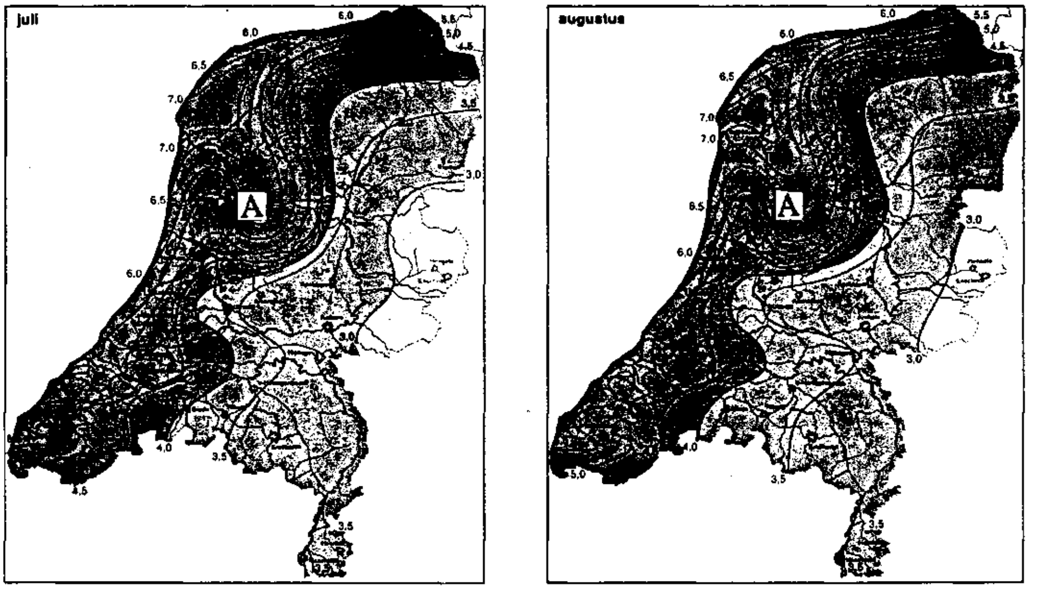

Fig. 5 Monthly windspeed (m/s) in July and August for The Netherlands (A: Lake IJssel)

3.2.4 Relative humidity

Little differences over distances of 50-150 kilometres occur. Again the coast has its special influence. The coastal humidity is usually higher (depending on wind-direction), while more inland the air gradually becomes drier.

3.2.5 Precipitation

Precipitation is a variable with a large spatial and temporal variety. The seasonal variability of precipitation is illustrated by mean monthly data from De Bilt, The Netherlands, indicating that both the amount and the duration of rainfall vary (Table). Apart from differences in intensity, there may be differences in the physical character of precipitation; rain, hail, sleet or snow.

Table Monthly precipitation amount, duration and intensity calculated from long term averages at De Bilt, The Netherlands (KNMI)

Month	Amount (mm)	Duration (hours)	Intensity (mm/hour)
Jan	67	67.4	0.99
Feb	50	49.8	1.00
Mar	51	53.0	0.96
Apr	52	46.8	1.11
May	54	37.3	1.44
Jun	70	37.0	1.89
Jul	77	42.1	1.59
Aug	88	43.2	2.04
Sep	65	40.5	1.60
Oct	69	49.3	1.40
Nov	75	65.4	1.15
Dec	79	69.0	1.14

The Table shows a notable variation of precipitation with respect to the total amount (50-88 mm/month) and intensity (0.96-2.04 mm/hour). Precipitation is caused by frontal zones (depressions) or convective systems (showers). Both surface- and upper air-observations show that the transition from one air mass to another tends to occur more or less discontinuously rather than gradually. Adjacent air masses separated by a frontal zone extending some 100 kilometre horizontally have been observed (McIntosh 1981). Precipitation on the passage of a front is distributed equally over an extended area with low intensities and a relatively long duration. Figure 6 shows a front passage, the vertical scale being exaggerated 100 times.

Rainfall from convective systems (showers) that can be influenced strongly by local circumstances, occurs in both the Mediterranean and temperate climate types: in summer in Northern Europe, and throughout the entire year in and around the Mediterranean. Showers have a considerable spatial and temporal character. Rainfall intensity from convective cells tends to be higher than in the case of frontal rainfall. The Table shows

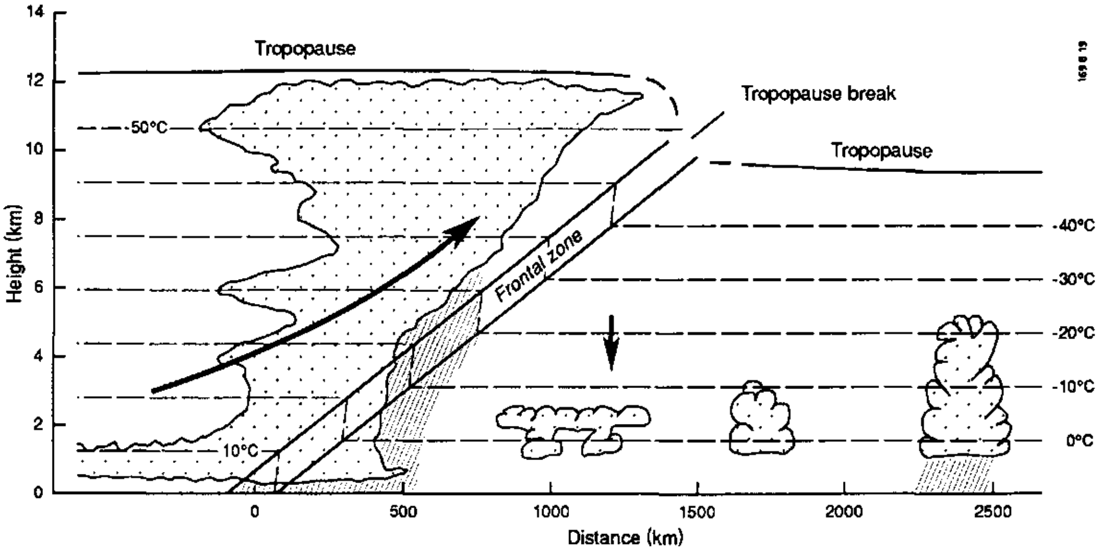

Fig. 6 The passage of a front

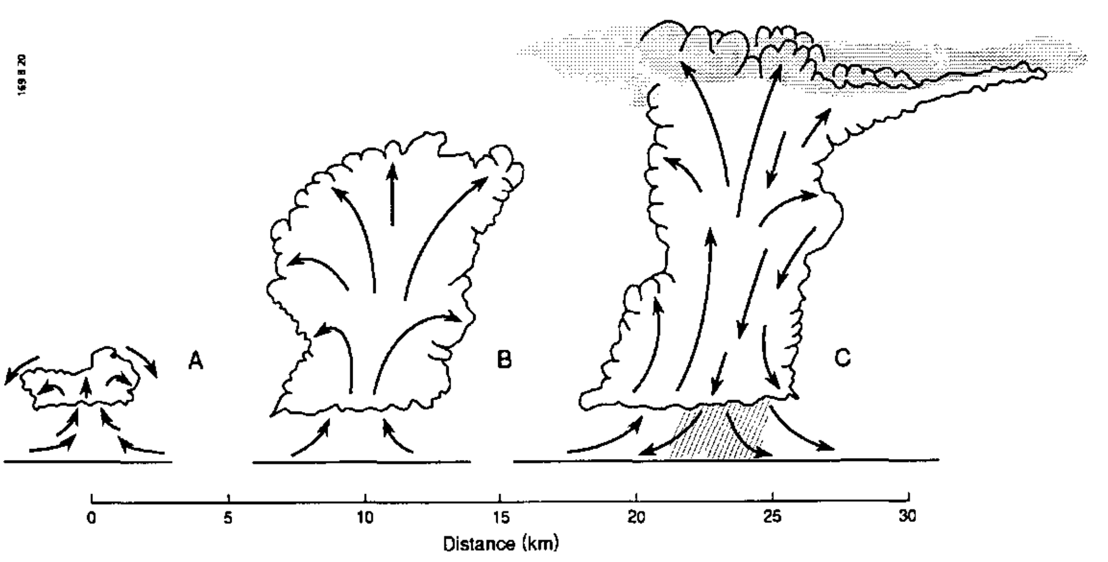

Fig. 7 Different types of cloud forming (A Fractal cumulus; B Altocumulus; C Cumulonimbus) with different spatial resolutions

for instance that the highest intensities are measured during the summer months (June-August). Showers are phenomena which normally have a spatial extent of 5-10 km. Showers are caused by the rising of thermals from a warm surface undergoing an adiabatic process and mixing with the air through which they pass. As cloud elements formed by successive thermals evaporate less readily into the moistened air there is a typical (unsteady) expansion of clouds, horizontally and vertically through different cloud forming stages (Fig. 7).

Clear signs of ice crystals near the cloud summit mark the cumulonimbus stage. Heavy showery precipitation always occur under the clouds simultaneously, sometimes with hail and thunder. Precipitation can start at an earlier (large cumulus) stage. A cumulonimbus is of the order of 5-10 kilometre in width and depth. When the horizontal extent is much greater than this, the cloud masses compromise the number of 'cells' that have merged.

Patterns of rainfall are greatly influenced by global geography, such as the size and surface configurations of land masses likewise the geometries and water circulation patterns of the oceans and seas. For example the mountain range in Scotland causes a considerable high precipitation on the West facing slopes and a low amount on the East facing slopes. Land and water bodies also have varying influences upon the precipitation dynamics of each other (Barrett & Martin 1981). *Rainfall is more susceptible than many atmospheric parameters to short- to medium-term fluctuations of spatial distribution*: climatic statements of rainfall compiled from various periods in the past may not be representative of current climatic conditions, whilst monthly and seasonal rainfall is in some regions highly variable, percentage variability levels up to 40-50% being by no means uncommon (Barrett & Martin 1981).

Cloud cross sections, based on aircraft observations show that the precipitation falls only from deeper clouds, implying that the area of precipitation was small in comparison with the area of clouds. The weighted daily meteorological averages shows that variation in most values on macro scale will be small.

3.3 Meteorological ground observations

The World Meteorological Organization (WMO) instructs on standardization of equipment and operational methods. However, it is not possible to achieve complete standardization because local conditions and requirements differ and it is necessary to take into account equipment and methods already in use in various countries. Every measurement has a margin of error, so every measurement has a range with the real value somewhere in it.

Errors in measurement are due to the location of the stations. For example the temperature is higher in a station located in a town or on the Southern slope of a mountain than outside towns or on Northern slopes. Therefore location of stations are not always representative for the total area. Some meteorological variables can be estimated very reliably, but some others are questionable. The Campbell Stokes recorder for example needs a minimum amount of radiation before it can record sunshine. As a result measured sunshine duration doesn't really say anything about solar input (McIntosh 1981). Cloudiness is estimated by a person and is therefore rather subjective. Rainfall is measured at 40 cm above the surface; and can have a deviation of 5% in windy conditions (but this is quite variable as different authors tend to give different deviations).

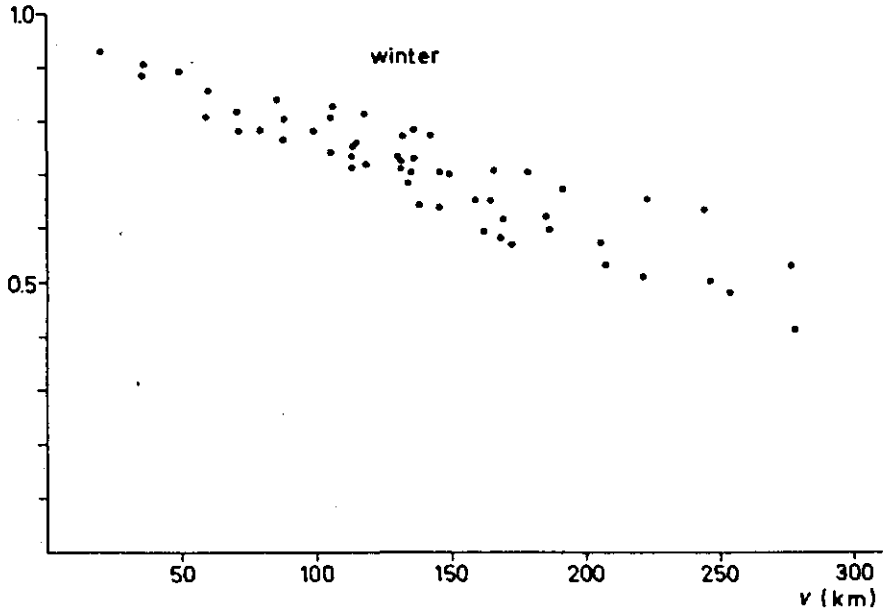

Fig. 8 Correlation coefficients of daily rainfall in winter over the period 1958-1971 from several Dutch observation stations (from Buishand 1977).

4 INTERPOLATION TECHNIQUES

There is a wide range of interpolation techniques, which can be divided into global and local techniques. The global techniques are described in section 4.1 and the local techniques in section 4.2. Apart from a subdivision in local and global interpolation techniques, a deterministic and stochastic subdivision can be made (Annex 1).

4.1 Global techniques

The global techniques interpolate values using all available data, for instance the total set of daily weather observations of the EC.

4.1.1 Trend Surface Analysis

By use of the "least-squares", a line or surface is fitted through the data points, assuming that the spatial coordinates are independent and the property of interest (Z) is the dependent variable. The long range variation of the property of interest (Z) is a combination of the geographic coordinates ($X_1..X_n$). The estimated Z^ is calculated by:

$$Z\hat{}(X_i) = b_o + b_1 X_i + b_2 X_i^2 + \ldots$$

X_i : coordinate of interest

b_o, b_1 and b_2 ...: polynomial coefficients

A regression line or surface (polynomial) is fitted in such way that the sum of deviations $\sum_{i=1}^{n}[Z(x_i) - Z\hat{}(x_i)]^2$ is minimized over n sample points. Z^ can be a linear function of X but often more complicated functions are used (Burrough 1986). Figure 9 gives an example of a linear and a quadratic surface through datapoints. A problem arises if the trend surface analysis contains clustered points; an uneven distribution of clusters can distort the fitted surface (Ripley 1981).

An undesirable feature of trend surfaces is the tendency to wave the edges to fit points in the centre. 'Polynomial regression is an ill-conditioned "least-squares" problem that need careful numerical analysis and this is equally true of polynomial trend surfaces. It is desirable to rescale the distances in the range -1 < 0 < 1 to avoid extremely large values of f{(X)}' (Ripley 1981).

The advantage of trend surface analysis is that it is easy to understand. In multiple regression the residuals from a regression line are assumed to be normally distributed, but the deviations from a trend surface are to some degree spatially dependent.

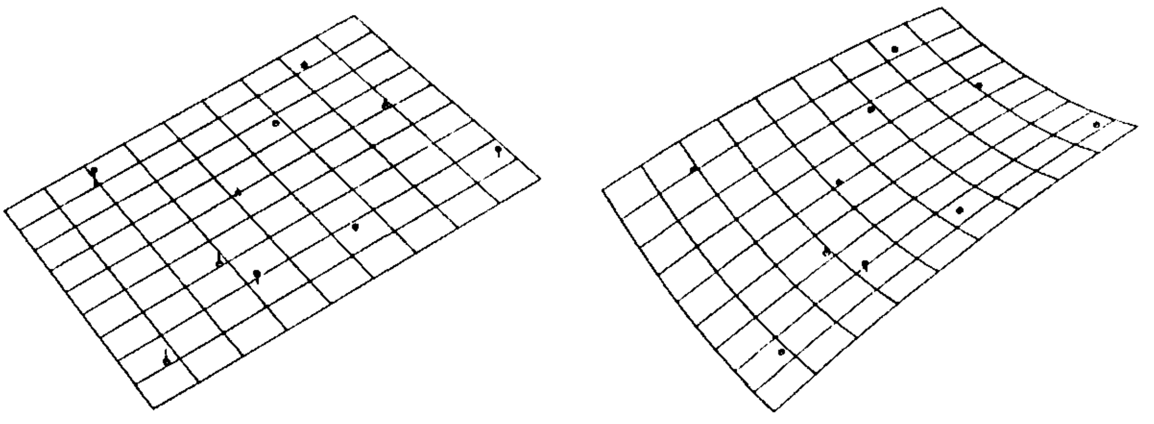

Fig. 9 Trend surfaces in linear and quadratic form

A positive correlation between the deviations of datapoints is likely to be present over short distances. In fact, trend surface analysis has been used to reveal parts of a study area that show the greatest deviation from a general trend prior to use some local interpolator (Burrough 1986).

4.1.2. Fourier series

Fourier series describe one or two dimensional variation by a linear combination of sine and cosine waves. This method is only suitable for periodic phenomena with a frequency within certain limits. In general, it appears that most surface features on earth, except for example ripples and sand dunes, are too complex to show strict periodic variations.

4.2 Local techniques

Local interpolation techniques estimate values from neighbouring points only.

4.2.1 Thiessen Polygons

Thiessen polygons is a local technique where the interpolated value equals the nearest observation value. The technique gives all the estimations the values at the point observations and no new values are added. Figure 10 shows a surface with a division in Thiessen polygons.

4.2.2 Moving Averages

An interpolation method which is applied very often is the moving averages. A window is used to achieve an interpolation of values within an area. Depending on the size of the window the short range variations will be emphasized or ruled out.

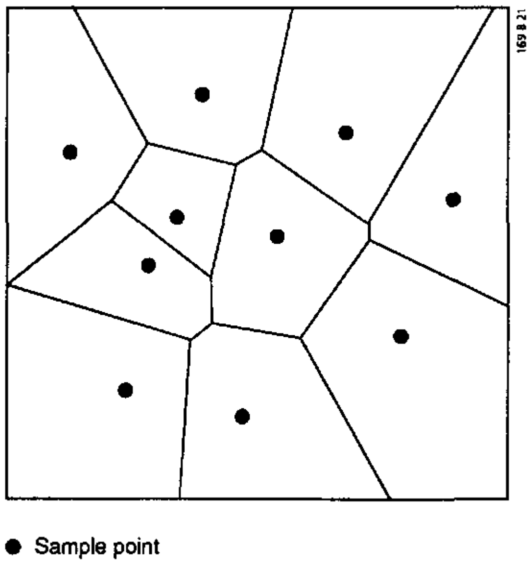

Fig. 10 Interpolation by means of Thiessen polygons

4.2.3 Weighted Moving Averages

The principle of weighted moving averages is the same as that of moving averages. Furthermore it allows some values more influence on the interpolated value than other values. The 'inverse distance' is the method usually applied, where the influence of sample points diminishes with the distance. It is possible to use the inverse squared distance weighting, where the significance decreases with the squared value of the distance:

$$Z^{*}(x_j)={}^{n}_{i=1}\Sigma Z(x_i)\cdot d^{-2}_{ij} / {}^{n}_{i=1}\Sigma d^{-2}_{ij}$$

Inverse distance is less appropiate if there are clusters of datapoints or when the datapoints are on an inclined plane (Fig. 11). To overcome this problem, a limited amount of points in each quadrant relative to x, should be used instead of all the points.

Because moving averages methods are by definition smoothing techniques, maxima and minima in the interpolated surface can occur only at data points. Some authors feel this to be undesirable and apply a correction by computation of the slope of the interpolated surface at each data point. This slope is used to project the form of the surface, rather in the manner used in B-splines (Burrough 1986).

4.2.4 Splines

Splines are piecewise functions that are exactly fitted to a small number of data points while at the same time ensuring that the joins between one part of the curve and another are continuous. The advantage of splines is that it is possible to use one part of the curve without recomputing the whole curve (Fig. 12).

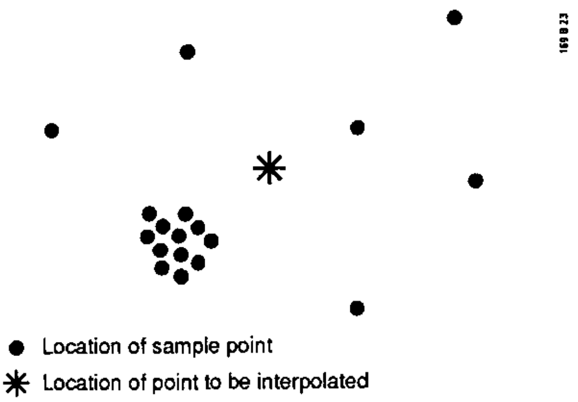

Fig. 11 If inversed distance is applied, problems occur when datapoints are clustered. The 10 clustered datapoints dominate the estimation at X (after: Burrough 1986).

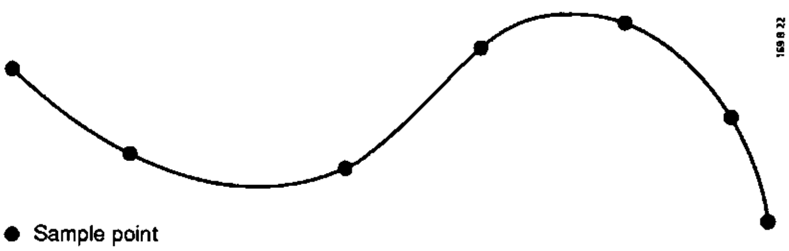

Fig. 12 A mathematical function is fitted through the points when splines are applied

The general definition of a piecewise polynomial function p(x) is:

$$p(x) = p_i(x) \qquad x_i < x < x_{i+1} \qquad i = 0,1,....,k-1$$

$$p_i^j(x_i) = p_{i+1}^j(x_i) \qquad j=0,1,.....,r-1; \qquad i=1,2,.....,k-1.$$

The points dividing x_o,x_k into k-subintervals are breakpoints; the points at these values are called 'nodes'. Because of the mathematical difficulty of calculating simple splines over a wide range, most applications use a special kind of spline, called the 'B-spline'. This kind of spline exists as sums of other splines that by definition have a zero value outside the interval of interest. B-splines allow local fitting from low order polynomials in a simple way.

In general, splines can be used for exact interpolation (the spline function passes through all data points) or for smoothing. The latter is sensible because experimental error is associated with values at data points. The advantage of splines is a quick calculation by the interpolation of a few points and it can give a clear overview of data. Estimation of errors is a difficult process which may be achieved with a process known as JACKKNIFE (Dubrule 1984).

4.2.5 Kriging

Kriging is based on the assumption that spatial variation of a regionalized variable is too irregular to be modelled by a mathematical function, but can be described more appropriately by a stochastic distribution. The interpolation proceeds exploring and then modelling stochastic aspects of the regionalized variable. The resulting information is then used to estimate the lambda weights for interpolation.

Kriging is based on the intrinsic hypothesis of the regionalized variable theory, which assumes that any variable has stationarity of difference and variance of differences. A variable $Z(x_i)$ is the sum of three components:

$Z(x_i) = m(x_i) + e'(x_i) + e''$
$m(x_i)$: structural component;
$e'(x_i)$: random spatial correlated component and
e'' : random noise or residual error term.

$m(x_i)$ is associated with a mean value or a constant trend, which can be described by a mathematical expression (Burrough 1986).

The random spatial correlated component can be found with the semivariogram, a complementary function that needs a brief explanation. Consider a transect along which observations have been made at regular intervals to give values z(i),i=1,2,....,n. Then, the relation between pairs of points h intervals apart, the lag, can be expressed as the variance of differences between all such pairs. The per-observation variance (gamma (h) between pairs is half this value:

$$\text{gamma}(h) = 1/2 \ \text{var}[z(i)-z(i+h)]$$

Gamma(h) is called the semi-variance, and is a measure of similarity, on the average, between points at a given distance, h, apart. If the mean of observations remains constant over distance d, then provided h is less than the semi-variance is half the expected squared difference between values at that lag:

$$\text{gamma}(h) = 1/2 \ E[\{z(i) - z(i+h)\}^2]$$

The graph of gamma(h) against h is the semivariogram, which has important characteristics:
a it reveals the nature of the geographic variation in the property of interest, and

b it provides the characteristics that are needed to calculate kriged estimates at previously unrecorded points.

In most cases it is found that gamma(h) increases by increasing h to a maximum, approximately the variance of data, at a moderate value of h, say D. The distance D is known as the *range*. If gamma(h) approaches the maximum asymptotically then D may be chosen were gamma(h) becomes sufficiently close to the total variance for practical purposes. Points closer together than the range are spatially dependent; points further apart bear no relation to each other, unless there is a periodic variation (Burgess & Webster 1980a).

In general, the plot obtained and known as the semivariogram can be fitted in a mathematical model. The spherical, linear and exponential model are often mentioned in literature. The exponential model eg describes a exponentially related semi-variance increasing with the distance.

By definition gamma(h)= 0 when h = 0 but any smooth curve that approximates the values of the semivariance is unlikely to pass through the origin. This intercept is the *nugget* variance and can be a consequence of the measurement itself. The value at which gamma(h) levels out is known as the *sill*. It consists of the nugget-variance plus a component c representing the range of variance due to spatial dependence in data. An example of a semivariogram is shown in Figure 13.

Kriging is an exact interpolator: interpolated values coincide with measured values at datapoints. Different methods of kriging are mentioned in literature (point or simple kriging, block kriging and universal kriging), but the main difference in these techniques is where the trend is known, i.e. simple kriging, and where trend is unknown described as ordinary kriging (Cressie 1990).

Point observations are used for point kriging, while block kriging takes place with values weighted to a block and universal kriging takes special local trends in the procedure. Burrough (1986), Burgess & Webster (1980a and 1980b) clearly describe these techniques.

4.2.6 Kriging and Splines

The objective of kriging is to obtain reliable data and not an aesthetic map; the shape of the interpolated variable is a consequence of the minimization criterion. It is the opposite of the spline interpolation, where the shape of the interpolation function determines the minimization criterion. The same analytical expression is used for the interpolator. This may prove useful, particularly when a quick visualization of the variable under study is needed, because spline interpolation will give a clear and fine

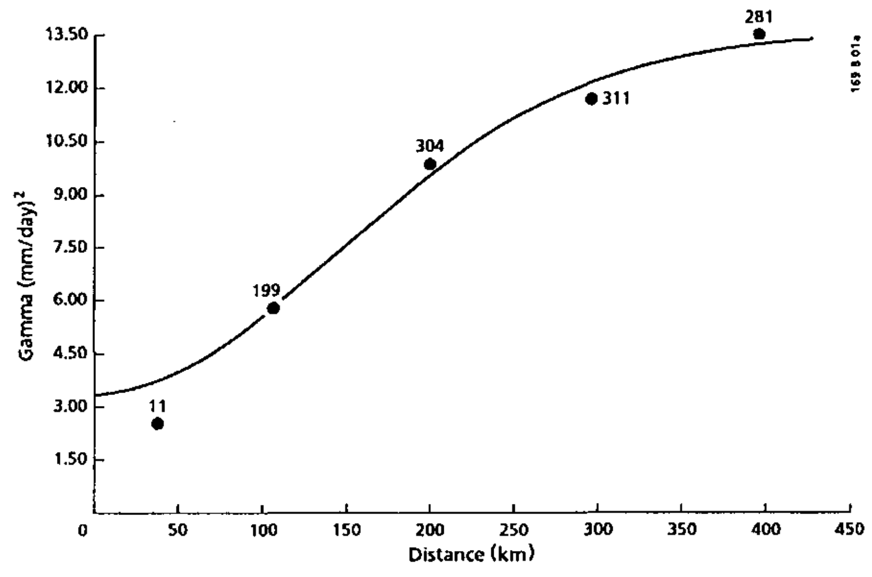

Fig. 13 Fitted model to semivariogram values of a specific day of daily means of rainfall data in the EC

map. Visualization has different aims than model calculations. Splined data should notbe used for calculations because the spline interpolator is not very reliable and the reliability of the estimation can not be assessed. With kriging it is possible to calculate the estimation variance at each point, which tells us how well each point is estimated compared to others and depends on the structure of the variable, through its order (k) and covariance K(h). The more irregular the covariance, the higher the variance. It also depends on the relative position of the datapoints and the relative position of the estimated point and the datapoints. The kriging variance is higher in poorly sampled zones.

Kriging first performs a structural analysis, so the estimation variance is meaningful, with splines this effect is obtained without any structural analysis (which might have a pure nugget-effect). Not knowing the structure of the variable, it is impossible to get an estimation variance. Kriged values can be interpolated on a regular grid. Also, the estimation error can be mapped (Dubrule 1984).

5 EXPERIENCES WITH INTERPOLATION TECHNIQUES

The literature was reviewed to ascertain which interpolation techniques had already been described for use in meteorological fields on the scale of Europe. Few articles deal with this, but probably one of the first approaches was taken by Cressman (1959), who proposed a method obtaining the estimated values by a mean value of the entire area. With the use of influence circles and the inverse distance interpolation technique the estimated grid point values were obtained by various correction steps. This technique, also called the technique of the successive corrections, is being used in the ECMWF at present for the daily weather forecast in Europe.

Gandin (1965) in the Soviet Union did some remarkable work in (statistical) meteorology. In his book "Objective analysis of meteorological fields" the variogram, simple kriging, ordinary kriging and simple co-kriging has been described with other terms than currently are used (Cressie 1990).

Based on research at the Royal Dutch Meteorological Institute (KNMI), De Bruin (1975) stated that because of the time- and space-related character of rainfall, statistical methods had to be used to interpolate the amount of precipitation. Therefore, it is necessary that observations will be reliable, otherwise the fluctuations in amount of precipitation wouldn't be different to the fluctuations caused by the observation errors. From comparative research on procedures for the interpolation of rainfall amounts Kruizinga & Yperlaan (1976) concluded, that linear interpolation was the best technique to obtain estimated values. Optimal interpolation (derived from Gandin), which in reality is kriging, did not show better results. However the database used may have been too small to produce good results with optimal interpolation and the kriging method was then still in an initial stage, only used in mining and soil science. It is quite conceivable that at that time the authors didn't have the possibility to work these things out.

A crop model using interpolation is MORECS :"Interpolation to obtain 40 × 40 km^2 is carried out. First the 9 nearest stations to the centre of each square are selected, up to a maximum of 100 km from the centre irrespective of whether or not they have data. However, if there is a station within 0.5 km of the centre then its observations are solely used. Otherwise, from the selected 9 stations 6 nearest to the data are chosen, with the proviso that there are no more than 2 stations in each octant. If less than 3 stations are found then an inverse distance squared method of interpolation is used, otherwise planefitting is carried out." ... " The interpolated temperature and vapour pressure are adjusted to the mean altitude of each square. Finally the wind speed values are converted to square estimates by applying a correction which takes into account the average roughness of the terrain.

Errors involved in using these interpolation procedures are unlikely to be large in the case of temperature and humidity which usually show only slow changes with distance after conversion to sea level. Acceptable estimates of wind speed can also usually be obtained. Greater difficulties are experienced with sunshine. The network of sunshine recorders is fairly sparse, even when both synoptic and climatological stations are considered, therefore it is difficult to establish a representative longterm daily average value of sunshine duration for the month in each square." ... "Rainfall shows large spatial variation, even over homogenous terrain, especially during summer. It is possible to establish fairly reliable long-term average annual rainfall for each square using data from the several thousand rainfall stations. This means that in very longterm estimates of MORECS square rainfall derived from the limited synoptic rainfall data will be satisfactory. *In the shorter term though, such estimates can be misleading*, and for this reason it is recommended that those who use MORECS outputs for irrigation scheduling should install there own raingauge" (Thompson et al. 1981 page 10-11).

At the Irish Meteorological Service surface fitting, successive corrections and the optimal interpolation (kriging) were compared. "The last two methods are better than surface fitting especially where there are large data sparse areas. However, with good data coverage simple surface fitting methods can be quiet satisfactorily and this paper discusses such a method.

The Cressman technique (Cressman 1959) is efficient and easy to implement. However, it has the disadvantage that it needs a first guess and a lot of fine tuning to give good results. The optimum interpolation method uses weighting parameters based on various spatial correlations. These parameters can be calculated objectively provided there is a large statistical data base. However, in the absence of such a database, we would have to choose these parameters by experiment and so optimum interpolation would be no better than the Cressman method in this regard" (Hamilton et al. 1988).

Hamilton et al. (1988) describe their "McLain's technique", how they implemented their dataset and the results. It is surprising that they compare and evaluate the results by using only the maps. They say: "Comparing Figure 9 and Figure 10 with the manual analysis of Figure 6 it can be seen that (a) a first guess is vital to obtain a reasonable analysis and (b) with our high data coverage optimal interpolation does not produce any improvement over McLain's method. Therefore, we have continued to use McLain's method for the operational production of rainfall maps."

They conclude with "The method has been in operational use since February 1985 and the results are of a quality comparable to the manual method which this computer has replaced."

In the paper nothing is mentioned about the accuracy in terms of standard deviation of input and output data. Returning to their observations on the maps it is interesting to note that the optimal interpolation maps do not show the great variety of estimated values in the South-Western part of Ireland; on the contrary it has been smoothened to give it a more realistic image. The authors mentioned at the beginning of this article that optimal interpolation requires a high amount of data input and say that in this case the McLain's technique will do a better job.

Cats (unpublished 1985) of the KNMI describes a simple linear interpolation method for meteorological fields, where the effect of coasts has been reduced to a minimum. He advised the use of the least complicated method for the interpolation of meteorological daily values, because the estimated values wouldn't differ too much.

6 ESTIMATION OF THE AMOUNT OF RAINFALL USING SATELLITE DATA

Rainfall is a complex variable and interpolation from a raingauge to the surrounding area is difficult (Sect. 3.2). Satellites made it possible to receive imagery with more detailed information on precipitation than the traditional ground observations. In the case of oceans or relatively small numbers of weather stations, the satellite observation techniques provided the possibility to further research on meteorological processes, which cause precipitation in these poor data covered areas. Furthermore, satellite data could provide a more rapid and comprehensive overview of the rainfall distribution in a given area to several ground stations (Shih 1990).

The basic assumption underlying all rainfall estimation techniques utilising visible and infrared satellite imagery, is that precipitating clouds can be distinguished from non-precipitating clouds: the former are usually thick (producing high visible response), and/or tall (with cold cloud top temperatures and therefore producing low infrared response).

More recently, several new techniques have been developed and the current range of satellite-based rainfall estimation techniques using visible and/or infrared data vary in both time and space scales depending on the application. For example, special interpolation techniques were designed for real-time precipitation estimation, seeking to make estimates at full temporal and spatial resolution of any available imagery.

The techniques can be classified in time and space scales (Annex 2), depending on the purpose for which they were designed. At present, a subdivision in whether the techniques are manual, interactive or automatic may be more appropriate.

When the first satellite data were received an expert was necessary to analyze the data. Whenever resources permit, manual techniques have now been superseded by interactive and/or objective techniques based on digital imagery, thus faster and more consistent computation of estimates can be obtained.

The Bristol/NOAA InterActive Scheme (BIAS) is an example of an interactive scheme developed in a partly-automated and improved version of a manual method (in this case the Bristol-method). BIAS is based on the interactive assessment of cloud type and cloud area by an analyst, and the translation of these assessments into 'cloud indices' by the computer according to an empirically derived menu. Initial estimates may be made for 6 12 and 24 hours periods, depending on the availability of the imagery, and these initial estimates may be adjusted by morphoclimatologic weights or, if available, synoptic weather reports. Verification tests over the USA for the AGRISTARS programme indicated that even when raingauge data were quite numerous and evenly distributed, improvement in rainfall estimation results from BIAS were equivalent to 5-25% when compared with isohyetal procedures alone (D'Souza et al. 1990). BIAS is one of the few satellite rainfall monitoring techniques which performs better in the midlatitudes than in the tropics, i.e. for layered stratiform rather than for convective cloud fields.

In general, interactive techniques have provided good ways of combining human skills with machines, the number of suitable-trained analysts however are scarce. Furthermore because interaction methods are time consuming, outputs from different analysts have been found to vary considerably.

Muller (1990) gives an extended bibliography on the use of image processing from Meteosat images. He stated that non-convective precipitation of the mid-latitudes is difficult to estimate. The automatic techniques are subdivided by D'Souza et al. (1990) in:

1 short-period infrared-based techniques;
2 short-period bispectral techniques;
3 short-period pattern-recognition techniques;
4 long period automatic estimation techniques.

In general, techniques suffer from the inability to distinguish, for instance, between cold tops of deep clouds (which precipitate heavily) and cold tops of shallow clouds (which may precipitate lightly or not at all). More sophisticated techniques use additional parameters such as cloud area and rate of cloud growth. Techniques have been developed for various purposes and applications. This makes it difficult to make a comparative evaluation of each technique (applied in different locations with few verifications).

More research is needed on the method of incorporating sparse "point" observations into homogeneous and extensive satellite estimate fields. Distance-weighted interpolation techniques have been shown to be somewhat inaccurate at great distances from reporting stations. The studies that applied the geostatistical interpolation techniques of kriging and co-kriging seem to be more promising (D'Souza et al. 1990).

For the temperate latitudes reasonable estimations of the amount of rainfall could be obtained by using satellite date in combination with ground radar measurements (De Bruin 1989).

Different methods of rainfall interpolation using satellite data were tested in a case study at DLO The Winand Staring Centre (Huygen 1989). This case study on rainfall estimations in Zambia where a sparse raingauge network was available was carried out for 10-day periods.

Linear regression, kriging and cokriging (using satellite data) were used to estimate rainfall. For the given dataset, linear regression proved to yield the best results. Little differences were found between the results of the kriged and cokriged rainfall amounts.

7 CONCLUSIONS

The aim of this study was to determine the most reliable interpolation technique for the estimation of daily means of meteorological variables (measured by European weather stations) onto a regular grid of 50 × 50 km^2.

Therefore the spatial and temporal distribution of the different meteorological variables were described. Furthermore, different interpolation techniques were described. Literature on experience in similar situations was reviewed.

The following conclusions can be drawn:
- If daily means are used, most meteorological variables do not differ too much over distances in the range of 50-150 km.
- In practice, there is little experience with interpolation of daily means of meteorological data onto a regular grid.
- For the variables sunshine, radiation, temperature, wind speed and relative humidity, a simple linear interpolation technique is expected to yield satisfactory results. Examples of a simple linear interpolation technique are a first degree inverse distance and a first order polynomial fitted through a trend surface.
- The most complicated variable is precipitation. Precipitation, is caused by different circulation patterns; it may occur in consequence of a local cumulonimbus or a front-passage. Precipitation has therefore a large spatial and temporal variability.

In choosing a suitable interpolation technique for precipitation it should be realized that due to its spatial and temporal variable character of rainfall a simple relation between distance and amount does not exist. Kriging is the interpolation technique that performs the most reliable estimation and also gives the estimation variance. Little experience has been obtained with kriging in meteorological fields.

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ANNEX

1 Subdivision of interpolation techniques by Burrough (1986)

2 Subdivision of rainfall estimation techniques according to space-time scale by D'Souza et al. (1990)

ANNEX 1

Subdivision of interpolation techniques by Burrough (1986)

Method	Deterministic/ stochastic	Local/ global	Transitions abrupt/ gradual	Exact interpolator	Limitations of the procedure	Best for	Output data structure	Computing load	Assumptions of interpolation model
'Eyeball'	Subjective/ deterministic	Global	Abrupt	No	Non-reproducible, subjective	Field data, aerial photo interpretation	Polygons	None	Intuitive understanding of spatial processes; homogeneity within boundaries
Edge-finding algorithm	Deterministic	Global	Abrupt	No	Often requires shapes to be defined and stored; better for man-made features than for natural landscapes	Raster images from remote sensors	Raster	Moderate	Homogeneity within boundaries
Proximal (Thiessen poly.)	Deterministic	Local	Abrupt	Yes	One data point per cell; no error estimates possible; tesselation pattern depends on data point distribution	Nominal data from point patterns	Polygons	Light/ moderate	'nearest neighbour' gives best information
Trend surface	Stochastic	Global	Gradual	No	Edge effects, outliers, complex polynomials do not necessarily have meaning; errors are rarely spatially independent.	Demonstrating broad features and removing them prior to other methods of interpolation	Points on a raster	Light/ moderate	Multiple regression—phenomenological explanation of trend surface; independent Gaussian errors
Fourier series	Stochastic	Global	Gradual	No	Not applicable to data; lacking periodicity	Periodic features such as sand dunes, ripple marks or gilgai, or man-made features	Points on a raster	Moderate	Strict periodicity in phenomenon of interest.
B-splines	Deterministic	Local	Gradual	Yes	No estimates of errors; masks all uncertainties in surface	Very smooth surfaces	Points on a raster	Light/ moderate	Absolute smoothness of variation
Moving average	Deterministic	Local	Gradual	No unless constrained	Results depend on configuration of data points and size of window; simple versions assume isotropy; no error estimates unless retrospectively calculated	Quick contour plots of moderately smooth data.	Points on a raster	Moderate	Continuous, differentiable surface is appropriate
Optimal interpolation (kriging)	Stochastic	Local	Gradual	Yes	Practical and theoretical problems of non-stationarity in data; large computing costs for mapping	Situations where the most detailed estimates and their errors are required	Points on a raster	Heavy (very heavy for universal kriging)	Intrinsic hypothesis (homogeneity of first differences); average local values can be represented by a continuous surface.

ANNEX 2

Subdivision of rainfall estimation techniques according to space-time scale by D'Souza et al. (1990)

Spatial Resolution					
25 km-2.5° squares					Global Precipitation Index FAO Kilonsky-Ramage Garcia
5-25 km	Kruger et al. Weiss-Smith	Bristol Fenner Whitney-Herman	Follansbee Stout et al. Martin-Howland	Creutin et al.	LeComte-Callis Motell-Weare
1-5 km	Scofield-Oliver Neil Lovejoy-Austin Robertson Tsonis-Isaac Wu et al. Lee et al. Griffith-Woodley Adler-Negri	BIAS	Heitkemper et al. Doneaud et al. Delbeato-Barrell Inoue	ADMIT PERMIT TAMSAT EARS-bv	
Temporal Resolution:	$\frac{1}{2}$-1 hour	1-6 hours	daily	1-10 days	10 days-1 month