APPLICATION OF SPATIAL INTERPOLATION OF METEOROLOGICAL DATA TO APPLE RIPENING MODEL

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Abstract

Aiming at an estimation of harvest time and an evaluation of fruit quality of a Golden Delicious apple cultivar, a spatial interpolation of temperature and solar radiation has been performed, searching for temporal and spatial relations among meteorological data and chemical−physical parameters, in **GRASS** frame. The study as been carried out using meteorological data obtained from 12 stations in an alpine valley for the period 1995−1998. The spatial interpolation method yielding the least mean error for daily temperatures (about 1°C) is the inverse−squared−distance, performed after a homogenization of values, all carried at a standard level of 0 m, making use of a second degree equation for modelling the vertical profile. The computation of mean errors was carried out by means of crossvalidation. Measured solar radiation was submitted to computation algorithms in **GRASS** in order to obtain the spatial distribution of radiation on an inclined plane with several aspects. The result of interpolation were used for a agricultural model: the prediction of harvest time and quality of apples.

1. The area of investigation

The study was carried out on the Non Valley, a 476 km^2 wide mountainous area in Trentino, Italy. The valley is the best known apple growing area in Italy. It is a wide valley, N − S oriented, run through by the Noce River, a right tributary of Adige. The valley itself displays a big span of elevations, going from the valley bottom of its lower part (about 250 m) to the summits of the mountains surrounding the upper part, with peaks reaching 2600 m. Nevertheless, the investigations concerned only the culticvated areas, to which agrometeorological applications are aimed. A geographical representation of the area is given in fig. 1. In the **GRASS** implementation the territory was represented by means of a digital elevation model (DEM) by a 10 m square regular grid.

2. The meteorological data set

All data came from the following networks of meteorological stations (see fig. 2):

1. temperature: both max and min daily values were taken into account from 12 stations scattered in the area, for a 4 year period (1995 − 1998);
2. solar radiation: one station (Cles, 650 m), located in the central part of the area: data have been calculated for every grid point only by geographical and topographical procedure.

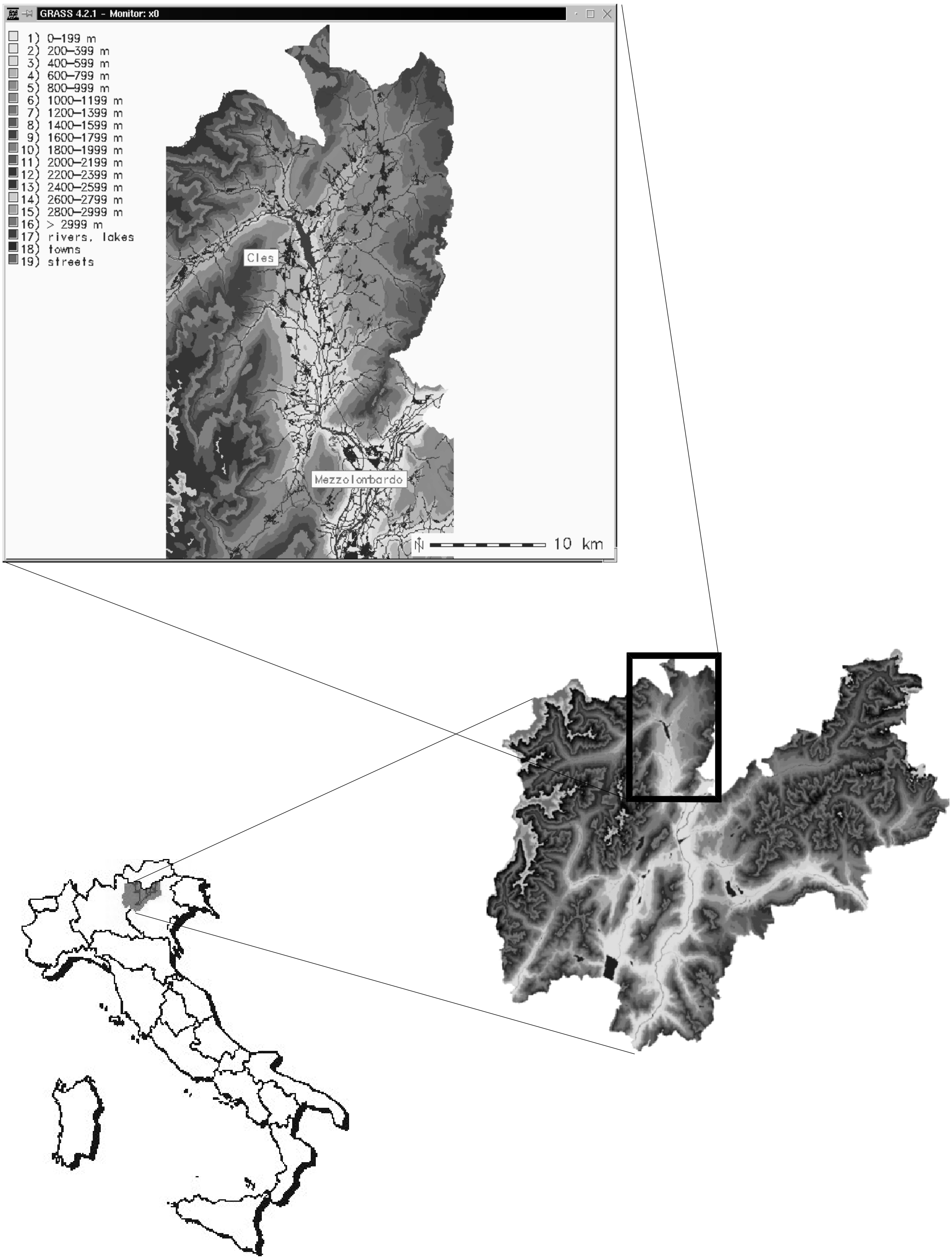

Figure 1: A geographical representation of the area.

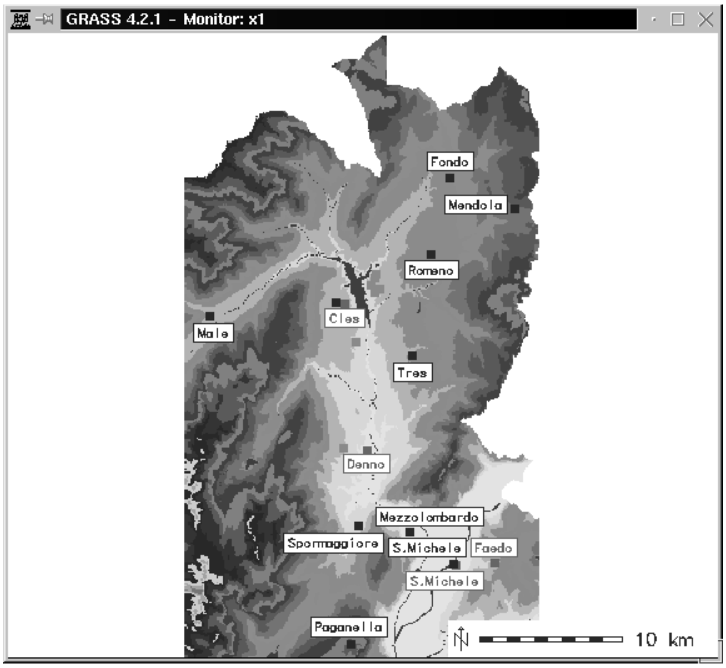

Figure 2: Locations of meteorological stations and farm raingauges.

3. Interpolation procedures

A spatial interpolation was applied to the following parameters:

1. maximum and minimum daily temperature;
2. mean daily temperature and daily temperature range;
3. daily global solar radiation (estimated only with geographical and topographical parameters).

3.1 Interpolation of temperatures

Among all the meteorological parameters taken into account here, temperature displays the highest variability with elevation, even if such a behaviour is not a constant in time and space. The need for dealing with comparable values requires a previous homogenization at a standard elevation, e.g. the sea level as suggested by Dodson, Marks, 1997. Such operation requires the definition of a function for modelling the vertical gradient of the 2 m temperature; the function has to represent a general trend for the vertical structure of 2 m temperature, valid for the whole area (Colombo, 2000).

The strict relationship between elevation and temperature is visible in fig. 3; no significant dependence of the latter from the horizontal displacement was detected (fig. 4).

A good approach has seemed the definition of a unique interpolating curve, expressing a hypothetical vertical trend. In order to model the ground thermal profile, a second degree equation was chosen to fit the measured values, applied to every daily max and min temperatures (Conrad, Pollak, 1950; Robenson, 1995; Pielke 1997). In general, temperature profiles tend to be inverted in winter, due to thermal inversion in the lower areas, located in the valley bottom; in those cases the second degree function performs appreciably better in comparison with a simple linear model; the latter is, on the contrary, very close to the first order function under different conditions, namely when no inversion takes place, and particularly for daily maximum values and in summertime.

For every day in the period and for both minimum and maximum temperatures, a fitting function was found and used for tracing values down to a fictitious standard level of 0 m. Having performed this homogenization of the measured values, the spatial interpolation of the values can be implemented in order to generate an array of fictitious values at the "standard" sea level on the area.

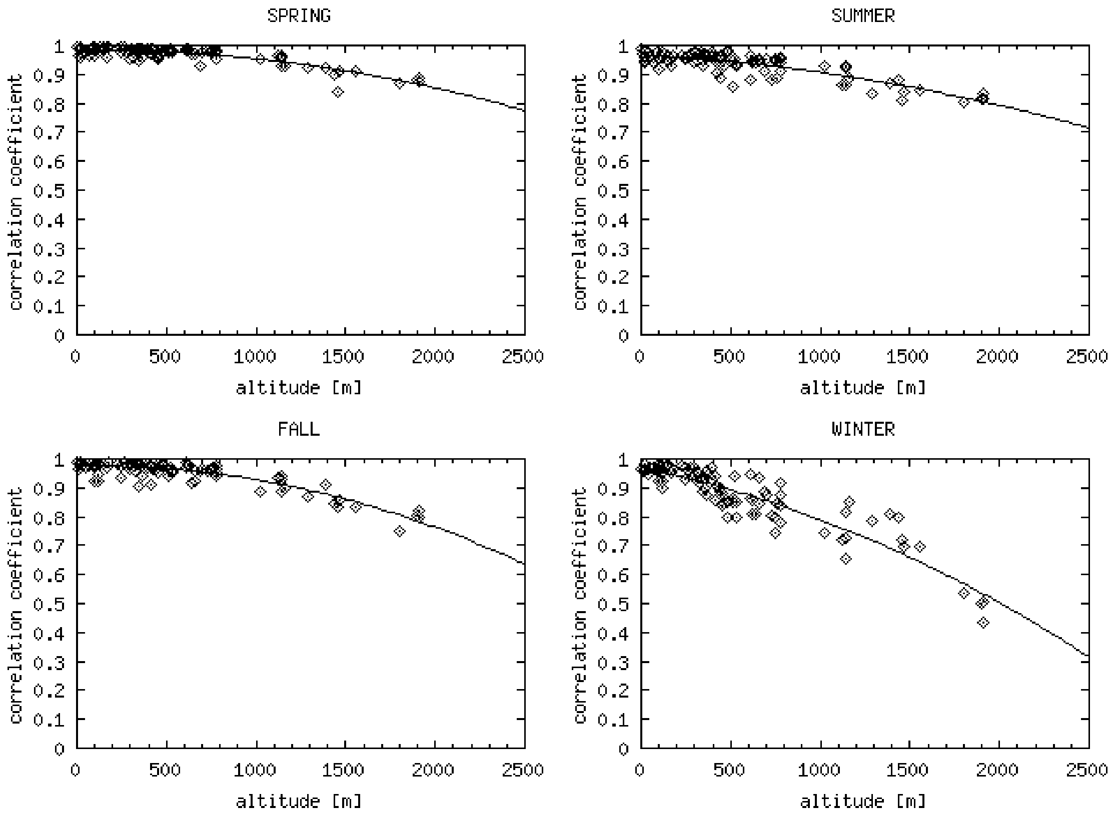

Figure 3: Correlation coefficients between daily temperature measured at different elevations vs. elevation gap.

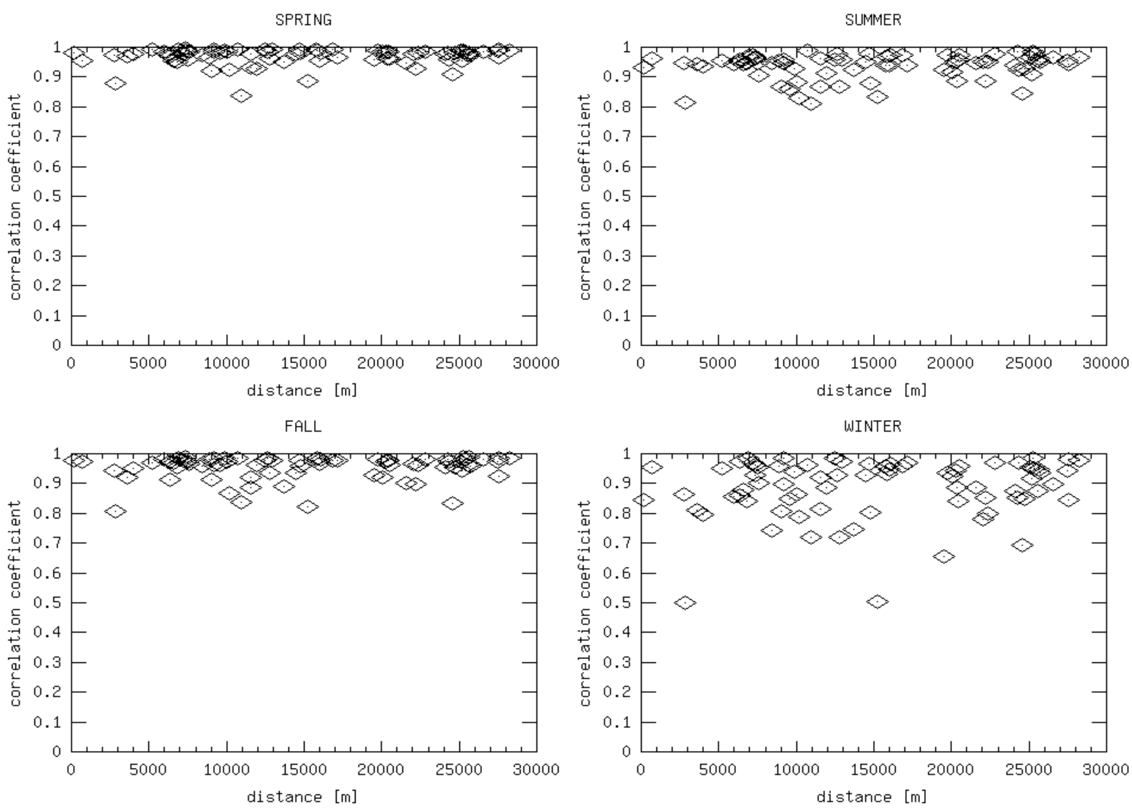

Figure 4: Correlation coefficients between daily temperature measured at different stations vs. distance between stations.

The best performing spatial interpolation methodology proved to be the inverse−squared−distance weighted average (IDW), suitable for its simplicity and low computation charge (Maracchi, Pieri, 1993; Colombo, 2000). A kriging tecnique approach was preliminarly attempted, with unsatisfactory results due to the low number of available stations associated to a strong anisotropy of the territory. Briefly, the spatial interpolation procedure for minimum and maximum daily temperatures can be resumed like this (fig. 5):

1. fitting of the interpolating second order function to the vertical displacement of values in a Temp. − Height graph;
2. estimation of fictitious temperatures for every measurement point at the "standard" level of 0 m, by applying the interpolating second order curve (item 1) for the lapse rate;
3. spatial interpolation of temperatures estimated at the sea level, by means of a inverse−squared IDW method;
4. inverse application of the experimental vertical profile function for estimating interpolated temperatures for every grid point at the true elevation, according to the DEM.

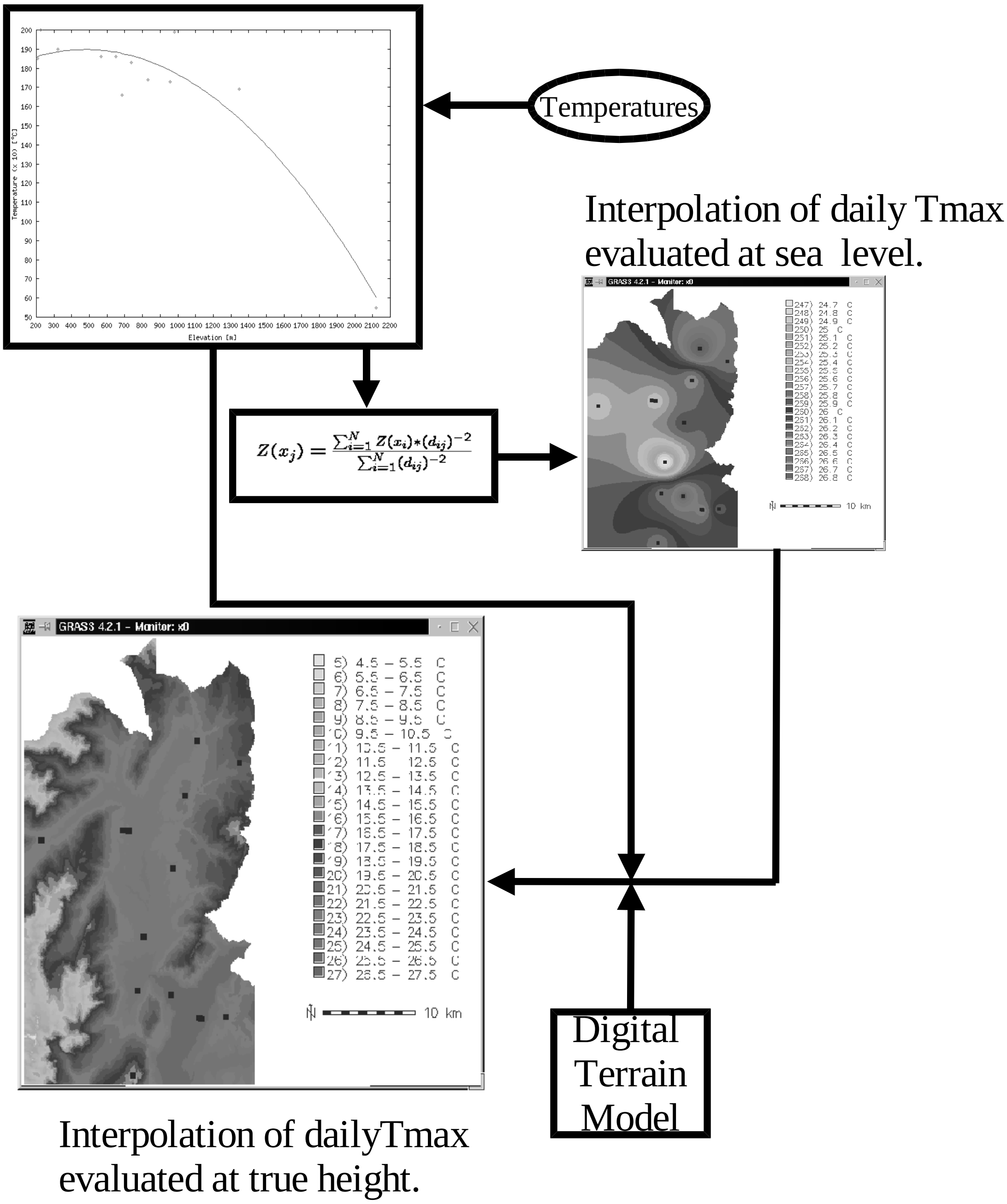

Figure 5: Spatial interpolation procedure for maximum and minimum daily temperatures.

After interpolation of minimum and maximum values, derived values for mean daily temperature and daily range can be easily calculated. The mean daily temperature was estimated by the arithmetic average of minimum and maximum values and daily range from subtraction of minimum value from the maximum one.

3.2 Global solar radiation

Extra−atmospheric radiation was evaluated for every day and every grid point with geographical, astronomical and topographical data (inclination and aspect) by a **GRASS** script (Liu, Jordan, 1964).

4. Evaluation of interpolation errors

Several methods are suitable for estimating interpolation errors. Among these, cross−validation (Tomczac, 1998) is perhaps the best known and employed. By this method the root−mean−square−errors (RMSE) have been evaluated for every interpolation operation, computing RMSE for the 365 days of the years 1995 and 1998.

4.1 Temperature

For minimum and maximum temperatures, the smallest RMSE span from 0.3 to 0.7 °C, the highest between 1.6 to 3.9 °C (T max) and between 1.3 and 2.5 °C (T min). These extremes express the RMSE produced by interpolating values at a station site, without taking into account the true measurement at that station; for every simulation a set of n RMSE is calculated, where n is the number of stations considered. On a monthly basis (tab. 6), the RMSE for both maximum and minimum values is about 1 °C (Colombo, 2000).

We must remark that in winter months the lack of some data has often lowered the performance of the interpolation (fig. 7C and fig. 7D). For mean daily values, average RMSE were about 0.6−0.7 °C, with the lowest values of 0.2−0.3 °C and the highest ones spanning from 1.0 to 2.0 °C (fig. 7A). For the daily temperature range, the minimum RMSE was between 0.2 and 1.0 °C, the maximum between 2.1 and 4.0 °C, with an average value of 1.5 °C (fig. 7B).

Month	Tmax[°C]		Tmin [°C]		Tmean [°C]		RangeT [°C]	
	Mean	DS	Mean	DS	Mean	DS	Mean	DS
1	1,3	0,6	1,0	0,4	0,7	0,3	1,9	0,7
2	1,2	0,3	1,3	0,4	0,6	0,2	2,2	0,7
3	0,9	0,4	1,1	0,3	0,7	0,2	1,7	0,5
4	1,0	0,4	0,8	0,3	0,7	0,2	1,5	0,6
5	1,0	0,2	0,9	0,3	0,7	0,2	1,4	0,5
6	1,0	0,3	0,9	0,2	0,7	0,2	1,4	0,4
7	1,0	0,3	0,9	0,3	0,7	0,2	1,4	0,4
8	1,2	0,2	0,9	0,3	0,7	0,2	1,6	0,3
9	1,2	0,6	0,8	0,2	0,7	0,3	1,5	0,6
10	1,2	0,8	0,9	0,3	0,7	0,3	1,6	0,9
11	1,0	0,2	1,0	0,3	0,6	0,2	1,6	0,5
12	1,1	0,3	1,3	0,3	0,7	0,2	1,9	0,5

Table 6: Monthly mean of daily RMSE for temperatures.

The linear correlation coefficient is a good indicator of the link between the value estimated by the interpolation and the true value at the measured points. For minimum and maximum daily temperature the linear correlation coefficient was 0.99, for daily range 0.91 (fig. 8). Tracing the scatterplots of the bias (predicted value minus observed value), we found the residual errors to be independent of the entity of the observed values, while for the daily range a tendency was detected towards an overestimation of the small ranges and an underestimation of the largest ones, fig. 9.

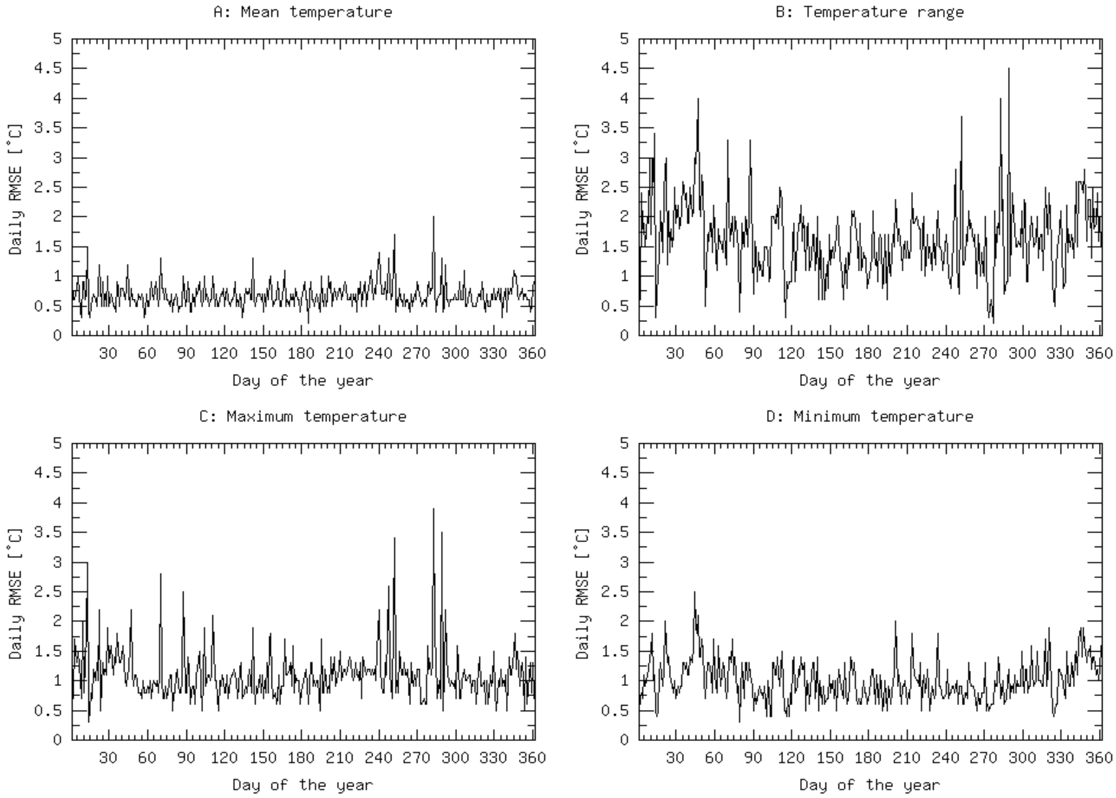

Figure 7: Annual trend of daily RMSE for temperatures.

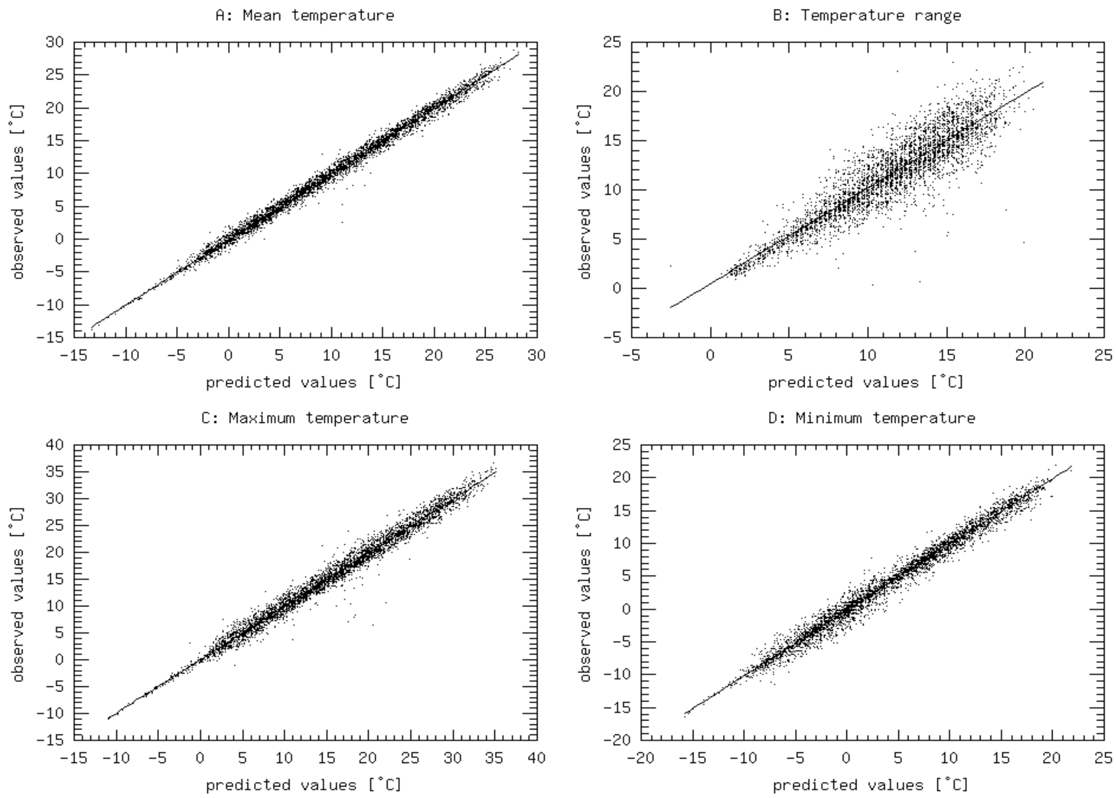

Figure 8: Scatterplots of observed values vs. predicted values.

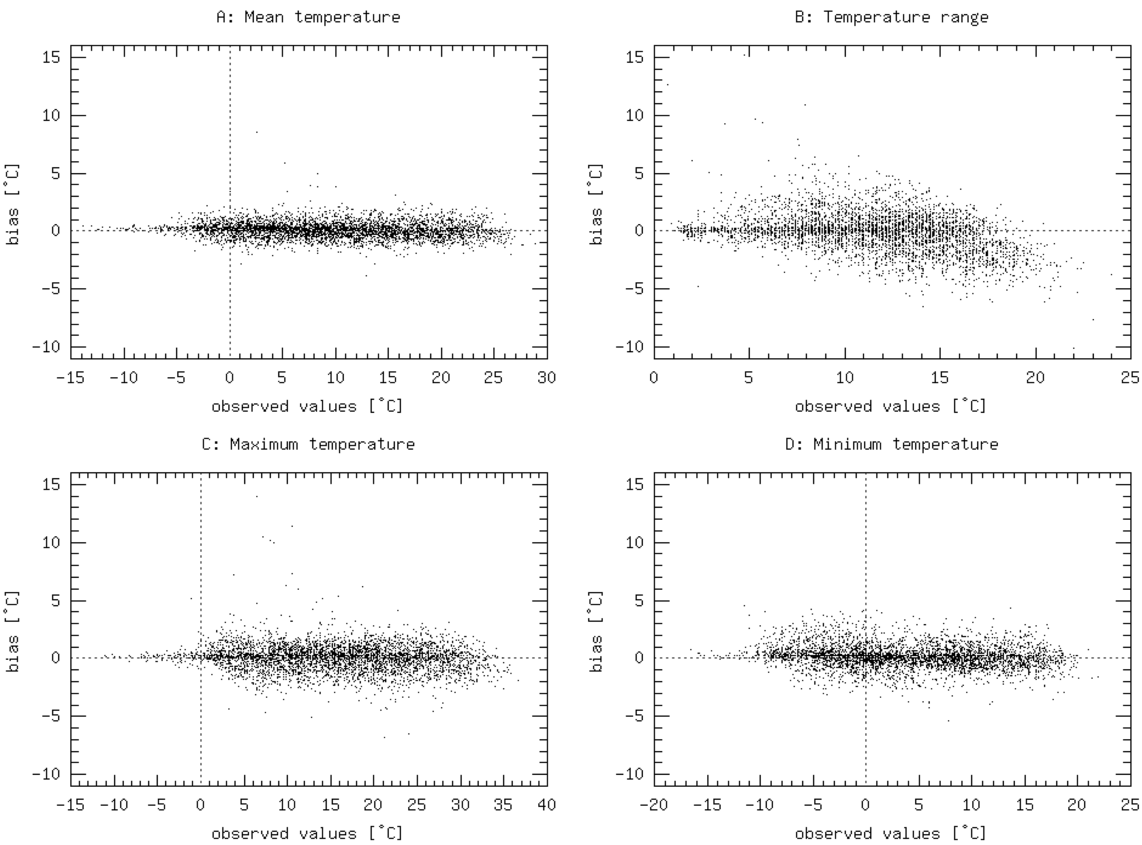

Figure 9: Scatterplots of the bias vs. observed values.

5. Agrometeorological application: apple tree phenology

Since ever, temperature and solar radiation have been taken as outstanding parameters in the ripening process (Smith and Barbieri, 1992). 400 geo−referenced chemical − physical measurements of ripeness (years 1995 − 1998) were available for this study, and correlation was established between meteorological parameters vs. harvest time and fruit quality. Chemical−physical data on apples of the years 1997 and 1998 were used to set up relationships with meteorological parameters; after the establishment of a regressive equation, analyses for the years 1995 and 1996 were used to test the model; in these two years analysis were too few for establishing reliable relationships with meteorologicals variables. All the available data were input to a relational database, for optimizing their storage and the effectiveness and rapidity of their use.

According to previous experiences (Colombo, 2000), the parameters exerting the strongest influence on the ripening process and on the quality of apples are those linked to topography (elevation, inclination and aspect), and to cumulate temperature and solar radiation. Due to a widespread use of irrigation in the area, the pluviometric variable was not taken into account, the water resource not being a limiting factor for growth and ripening of fruits. After choosing the parameters (fig. 10), a problem arose when dealing with phenological sampling (years 1997−1998), as an attribution of the proper physical information was required; as a matter of fact, the latter is generally not available at the exact locations of the sampling. Indeed, since only an occasional correspondence existed in our data between meteorological stations and sampling sites of chemical−phyisical properties of fruit, the need was clear for a spatial interpolation of maximum and minimum temperature and for global solar radiation. After performing this operation of spatial interpolation, the physical information (both topographic and meteorological) of the sites of phenological sampling were known for every period of surveys and got ready for establishing any comparison with such data. The **GRASS** implementation made easy the inference of information for any exact location in the area, corresponding to the phenological sampling sites.

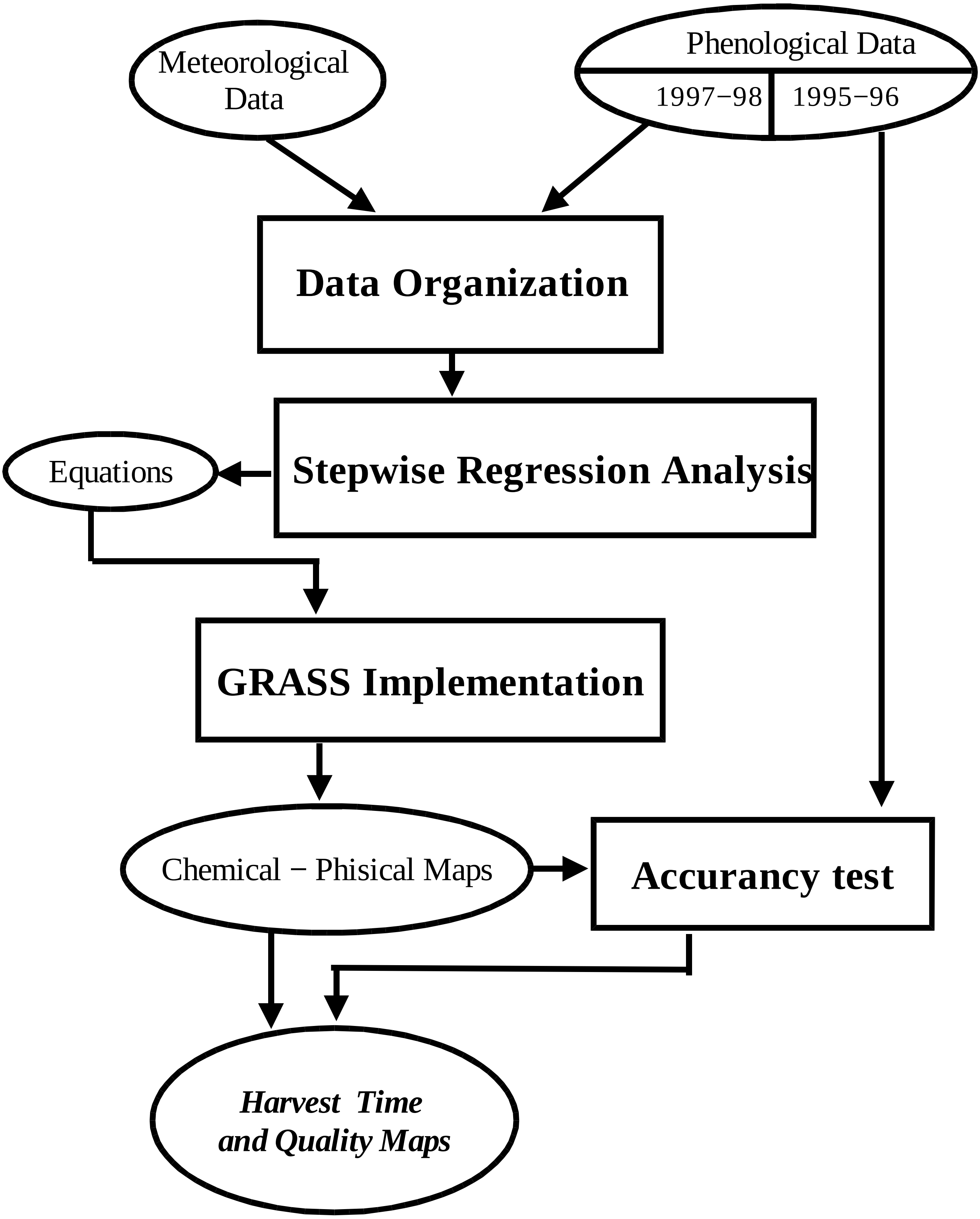

Figure 10 : A diagram for the implementation of the quality and ripeness model.

After making all data available in a **GRASS** frame, the specification of space−time relations for the prediction of the ripening state and quality of fruit was carried out by a stepwise regression procedure (Fabbris, 1983). Such analysis allowed a selection of the smallest subset of predictive variables which could satisfactorily explain the variability of the chemical−physical parameters, and the definition of the regressive coefficients. A simple multiple regression model was developed which can predict the phenological properties of the ripeness of apples with the simple knowledge of the meteo−climatic information on the territory. The implementation of this multiple regression equation ($R^2 = 0.79$) enabled us to plot ripening index maps (Streif index, Werth 1995; Lafer 1994, fig. 11).

The Streif index is calculated by chemical−physical measures on the apples: hardness, sugar content, and starch content (Werth 1995).

$$\text{STREIF Index} = H / (SU*ST)$$

1. H: penetrometer hardness (Kg cm^{-2});
2. SU: sugar content (degree Brix);
3. ST: starch content (international scale 1 to 10).

The three parameters have different roles in the definition of the ripening stage of apples. A short explanation is given.

1. Pulp hardness. The hardness of the fruit decreases as the ripening goes on. The optimal pulp hardness is different for every variety; this parameter is very important for the control of harvest time (and also for the fruit storage). The hardness test is performed by a penetrometer, measuring the resistance of the pulp to penetration.
2. Sugar content. As the ripening proceeds starch content and acidity decrease and contextually sugar content increases. Starch turns into sucrose (a complex sugar) and into glucose and fructose (simple sugars). Sugar content is the main parameter in the quantitative definition of the quality of an apple, having a direct link with taste. The scale for representing sugar content employed in Streif formula is the Brix degree, resulting from a refractometric measure.
3. Starch content. During the ripening process starch turns into sugar, by a hydrolysis process; then, a gradual decrease of starch takes place during the ripening period. This parameter is useful to determine the harvest time. Starch content can be evaluated by a colorimetric test with iodine & potassium iodide.

The accuracy of the prediction model, evaluated by the standard error of the stepwise regression, has been tested on samples gathered in the period 1995 − 1996, different from the one used for the set up of the model (tab. 12).

Index	Standard Error 1995−96	Standard Error 1997−98
Streif	0.038	0.015

Table 12: Comparison of errors: 1995−96 vs. 1997−98.

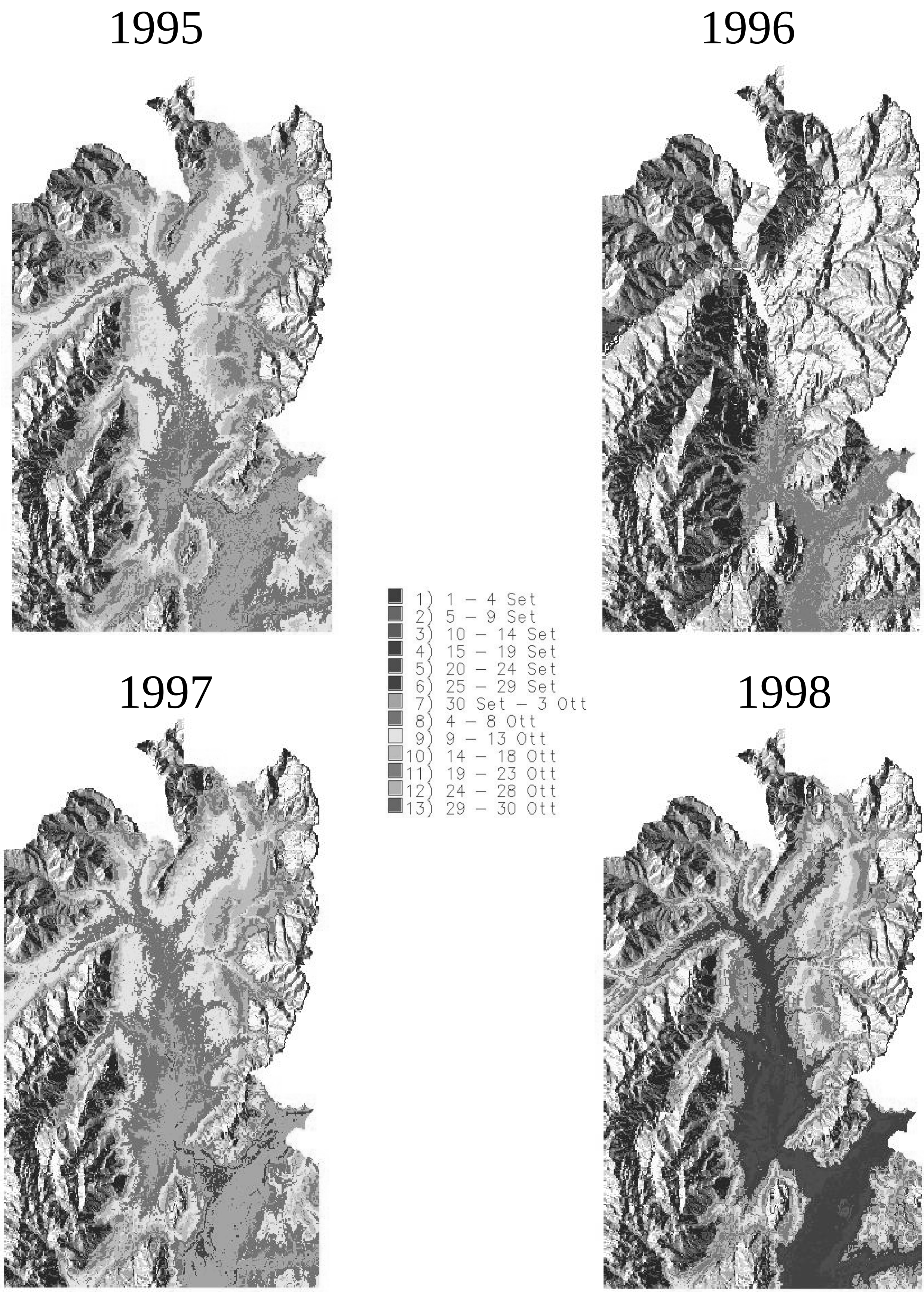

Figure 11: Streif's index maps.

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