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THE SYSTEMATIC INTERPOLATIVE RADIAL SEARCH (SIRS)-- A METHOD TO COMPUTE GRIDPOINT VALUES FROM CONTOURS

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1. INTRODUCTION

Since 1985, the Techniques Development Laboratory (TDL) has been building and evaluating techniques which enable the forecaster to interactively prepare digital forecasts of weather elements. These techniques are being developed to test concepts and to gain experience in preparation for the Advanced Weather Interactive Processing System (AWIPS) scheduled for deployment by the National Weather Service (NWS) starting in 1996.

In the AWIPS era, it is envisioned that nearly all routinely-issued user products will be automatically composed and formatted from a common digital forecast database. The forecaster will prepare this database by graphically modifying fields initialized from digital forecast guidance. Therefore, the user interface in the interactive forecast entry and modification process will be critical to the success of the AWIPS-equipped Weather Forecast Office (WFO). Unless the interface is efficient and easy to use, proposed WFO staffing levels could prove inadequate.

For many years, NWS plans have identified contour drawing as the primary method by which forecasters will interactively define forecast fields in the modernized forecast office. It is envisioned that a forecaster will define forecast gridfields on a graphics screen by either drawing contours on a blank field, by modifying contours of gridfields initialized from guidance, or by modifying contours of gridfields representing a previous forecast. The underlying gridded field will then be computed from the forecaster-drawn contours.

The purpose of this office note is to document the Systematic Interpolative Radial Search (SIRS) algorithm to compute gridpoint values from contours. The historical context for the development of SIRS is discussed, and the technique is compared to other known contour-to-gridpoint approaches. A description of the SIRS algorithm is provided, and implementation details are considered.

2. THE DEVELOPMENT OF SIRS

Interactive techniques which enable the local forecaster to prepare digital weather forecasts began to be developed at TDL in 1985 on the Automation of Field Operations and Services (AFOS) system. These techniques, in combination with programs translated to AFOS from existing formatting software, comprised the earliest version of the Interactive Computer Worded Forecast (ICWF) system (Ruth and Peroutka 1993). The ICWF allows the forecaster to adjust matrices of basic forecast elements (e.g., temperature, cloud, wind, weather) displayed over a map of the local forecast area. These digital forecasts are then used to produce products in several formats.

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[1]General Sciences Corporation, under contract to the Techniques Development Laboratory, National Weather Service.

From June of 1986 until the present, evolving versions of the ICWF system have been used operationally at several Weather Service Forecast Offices (WSFO's). The most successful of these implementations has been conducted at WSFO Charleston, W. Va. As a result of ICWF technology, this WSFO now automatically generates routine public and fire weather products, and has increased its level of service by adding several agricultural, hydrologic, and public products to the existing product suite (Rezek and Parke 1990).

Although the ICWF supports the automated generation of numerous public and closely-related products, the long-term goal for entering and modifying digital weather forecasts in a common digital database is to support the generation of almost all routine NWS forecast products, including domestic and international aviation terminal forecasts (FT's and TAF's) and transcribed weather broadcasts (TWEB's). In order to accomplish this, the digital database must include forecast information with both higher spatial and temporal resolutions than are available in the ICWF. A database to support aviation product generation also must explicitly define multiple cloud decks. Recognizing these needs, TDL initiated the development of the more comprehensive Forecast Entry and Formatting System (FEFS) in July 1987 (Ruth and Vercelli 1989).

FEFS takes incoming station guidance in the form of probabilities and categories and converts it to hourly grids of sensible weather forecasts. FEFS provides the forecaster with a graphical interface to view, enter, and modify these forecast gridfields quickly and intelligently. Gridded information is then summarized into zone-based matrices for the generation of public, agricultural, and fire weather forecast products; into station matrices for the generation of domestic and international terminal forecasts; and into route-based matrices for the generation of transcribed weather broadcasts.

Preferred techniques for interactively entering and modifying forecasts of a common digital database are highly dependent upon the particular forecast elements being entered or modified. TDL's experience with the ICWF indicates that forecasters quickly develop methods of interacting with the database which "work best for them." Therefore, FEFS was designed to provide the forecaster with an interactive toolkit to manipulate gridfields of digital forecasts. This includes tools which directly manipulate digital values on the screen (e.g., increment or decrement points or areas, assign values to points or areas, and move forecast fields across the grid), perform time interpolation of quasi-continuous fields, interpolate discrete areas of clouds and weather in space, and adjust contours.

In the spring of 1989, several months before the first operational testing of FEFS was to begin, work was suspended in favor of porting the field-tested ICWF software to the Pre-AWIPS Demonstration System. The initial phase of this conversion was completed when TDL installed the ICWF on the Pre-AWIPS system in Norman, Okla., in January 1992.

The NWS has specified that AWIPS shall have upon initial deployment the capability to interactively modify gridpoint values through graphical techniques for hydrologic purposes. Since experience in such techniques was limited, TDL has recently continued work with graphical editing in order to more clearly specify what is needed in AWIPS. The results of this work will support, on the Pre-AWIPS system, the production of gridded quantitative precipitation forecasts (QPF) at Norman for use at the Arkansas-Red Basin

River Forecast Center, the production and use of QPF being a high priority NWS risk reduction activity. The techniques developed will also enable us to enhance the ICWF by providing a graphical forecast overview and tools to enable the forecaster to work with temperature, probability of precipitation, snow amount, and QPF graphically (Ruth 1993). Such enhancements should increase forecaster acceptance of this new method of producing forecasts.

3. THE SIRS ADVANTAGE

In addition to the SIRS approach, known techniques for computing gridfields from contours employ one of two basic methods: collecting a sample of points from each contour and then performing an objective analysis, or using functions to define a surface which can be evaluated at any point.

In a program developed to obtain gridpoint data from AFOS vector graphics (Fors 1982), an objective analysis is performed by sampling points from each contour. More recently, an objective analysis using the Barnes approach (Barnes 1973) has been employed at the Ohio River Forecast Center in Cincinnati, Ohio, to define grids from contours of precipitation amounts. A significant disadvantage to this approach is that gridpoint values computed from contours do not necessarily fall within the range of values of the contours which surround the gridpoint. For example, a gridpoint located in an area bounded by contours of 30 and 35 can take on a value of 36 or more if a 40 contour is also found nearby. When grids computed from contour values by this method are recontoured, the positions of original contours are not necessarily maintained.

In a forecast production system developed by the Canadian Atmospheric Environment Service (see Dickinson et al. 1989), B-splines are used to fit a surface onto a coarse grid from which values can be extracted onto a finer grid. Although this approach performs adequately for relatively smooth synoptic-scale fields, the interactive techniques to manipulate fields defined by these functions may not provide the forecaster with the necessary precision to define a local-scale gridfield which includes sharp discontinuities in the forecast for areas containing coastlines, mountains, or cities.

The primary advantage of SIRS is that it allows the forecaster to use contours to define a grid with considerable precision. A new contour entered to represent cooler temperatures along a lake shore does not affect the placement of a warmer temperature contour the forecaster had previously positioned around a nearby urban area. Contour intervals need not be uniform. For example, a contour interval of 5 degrees can be used to define temperatures over the plains of Colorado while a 10-degree interval can be used for the mountainous terrain beyond the Front Range. When redrawn from a grid computed by SIRS, contours appear virtually identical to ones the forecaster entered by hand.

4. SIRS ALGORITHM

SIRS computes gridpoint values from contours. Contours are identified by performing a multi-directional radial search for contours from each gridpoint to be computed. Gridpoints which are coincident with a contour simply take on the value of that contour. Values for all other gridpoints are computed in one of the following ways: averaging the values of the nearest contours, weighted inversely by the distance from the gridpoint to the contour; averaging values determined from directional gradients defined by contours; or averaging values of adjacent gridpoints and contours. The computation performed for any particular gridpoint depends upon the relative positions and values of its surrounding contours.

The following steps summarize the procedure used in SIRS to compute gridpoint values from contours.

STEP 1: Compute weighted average for gridpoints between contours of different values.

SIRS performs a multi-directional radial search for contours from each gridpoint to the edge of the grid. The nearest contour for each different contour value is selected from the contours closest to the gridpoint in each direction. Values for gridpoints are determined by averaging the values of the selected contours, weighted inversely by the distance from the gridpoint to the contour. If the set of contours is mathematically consistent[2], only two contour values are used in the weighted average for any gridpoint.

Fig. 1 shows gridpoint values computed by taking a weighted average according to Equation 1:

$$V_{x,y} = \frac{\sum_{i=1}^{n} \frac{C_i}{D_i}}{\sum_{i=1}^{n} \frac{1}{D_i}} \tag{1}$$

where $V_{x,y}$ = computed value of gridpoint x,y,
C_i = value of nearest contour to gridpoint x,y in direction i,
D_i = distance to nearest contour from gridpoint x,y in direction i, and
n = number of directions in which contours having different values are found.

For gridpoint (x=8, y=8), counting from upper left, in Fig. 1, a radial search is performed in eight directions. Directions are numbered clockwise 1 through 8 from northeast to north. The search yields the following values of C_i and D_i for the seven directions in which contours are found:

$C_1=50$, $C_2=50$, $C_3=50$, $C_4=50$, $C_5=50$, $C_7=40$, $C_8=40$,
$D_1=2.5\sqrt{2}$, $D_2=3$, $D_3=1.5\sqrt{2}$, $D_4=2.0$, $D_5=2.5\sqrt{2}$, $D_7=2.5\sqrt{2}$, and $D_8=5.75$.

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[2] A set of mathematically consistent contours unambiguously partitions a surface into areas which are greater than, and areas which are less than, the values of the contours bounding the area. When an area is bounded by contours having more than two unique values, these contours are mathematically inconsistent. Also, when an area is bounded by contours having one value, the contours bounding adjacent areas are inconsistent if they are not all greater than (or all less than) the value of that contour.

Directions having the closest differently-valued contours are selected. In this case, contour values and distances for directions 4 and 7 are used. According to Equation 1, $V_{8,8}$ is computed to be 46.39 where n=2.

STEP 2: Compute values for gridpoints between equally-valued contours using gradients.

When all contours nearest a gridpoint in each direction have the same value, gradients are used to compute the value of the gridpoint whenever possible. A gradient is calculated for each direction where at least one contour is crossed. If a second, more distant, contour with a different value is available in the same direction, the gradient is determined from the difference of the contour values and the distance between those contours. If only one contour is available in a direction, the value of the edge gridpoint in the appropriate direction is used to determine the gradient. If this edge gridpoint has been computed by a weighted average (STEP 1), the computed value is used to determine the gradient. If this edge gridpoint has not been computed, a gradient of zero is used for this direction.

Gradients for each direction are computed according to Equation 2a:

$$G_i = \frac{C'_i - C_i}{D'_i - D_i} \tag{2a}$$

where G_i = gradient in direction i,
C_i = value of nearest contour to gridpoint x,y in direction i,
D_i = distance to nearest contour from gridpoint x,y in direction i,
C'_i = value of second nearest contour to gridpoint x,y in direction i, (if second contour is not available for direction i, C'_i = value of edge gridpoint in direction i), and
D'_i = distance to second nearest contour from gridpoint x,y in direction i (if second contour is not available for direction i, D'_i = distance to edge gridpoint in direction i).

Gridpoint values are determined from directional gradients for every point having at least one non-zero gradient within areas enclosed by contours of equal value. Values are calculated according to Equation 2b:

$$V_i = C_i - G_i D_i \tag{2b}$$

where V_i = value of gridpoint x,y according to gradient in direction i,
C_i = value of nearest contour to gridpoint x,y in direction i,
G_i = gradient in direction i, and
D_i = distance to nearest contour from gridpoint x,y in direction i.

Values determined from directional gradients are constrained such that they stay within a permissible range of the nearest contour. The range limit is set according to the difference between the value of the nearest contour and the second, more distant, contour used in the computation of directional gradients. Range limits for gridpoints computed from directional gradients are determined according to Equation 2c:

$$R_i = C_i + (C_i - C'_i) \tag{2c}$$

where R_i = range limit of gridpoint x,y according to gradient in direction i,
C_i = value of nearest contour to gridpoint x,y in direction i, and
C'_i = value of second nearest contour to gridpoint x,y in direction i, (if second contour is not available for direction i, C'_i = value of edge gridpoint in direction i).

A constrained value in each direction is then determined for gridpoints according to Equation 2d:

$$V'_i = R_i \text{ when } |C_i - V_i| > |C_i - R_i| \text{ , otherwise } V'_i = V_i \tag{2d}$$

where V'_i = value of gridpoint x,y according to gradient in direction i constrained by range limit,
R_i = range limit of gridpoint x,y according to gradient in direction i,
C_i = value of nearest contour to gridpoint x,y in direction i, and
V_i = value of gridpoint x,y according to gradient in direction i.

When no contours are found in the direction opposite of a gradient, that gradient is weakened so that the range limit is not exceeded before reaching the edge of the grid. If that range limit was determined using an edge gridpoint instead of a contour in Equation 2c, the range limit is unreliable, and values for that direction are not used in any further computation. Adjusted directional values are computed according to Equation 2e:

$$V''_i = \frac{V'_i + C_i - \frac{D_i}{D_i + D_o}(C_i - R_i)}{2} \tag{2e}$$

where V''_i = value of gridpoint x,y using adjusted gradient in direction i,
V'_i = value of gridpoint x,y according to gradient in direction i constrained by range limit,
C_i = value of nearest contour to gridpoint x,y in direction i,
R_i = range limit of gridpoint x,y according to gradient in direction i,
D_i = distance to nearest contour from gridpoint x,y in direction i, and
D_o = distance to the edge of the grid in the direction opposite from direction i.

The value of the gridpoint computed from the adjusted gradient replaces the original value computed in Equation 2a when doing so minimizes its difference with the nearest contour according to Equation 2f:

$$V_i = V''_i \text{ when } |C_i - V''_i| < |C_i - V_i| \qquad (2f)$$

where V_i = value of gridpoint x,y according to gradient in direction i,
V''_i = value of gridpoint x,y using adjusted gradient in direction i, and
C_i = value of nearest contour to gridpoint x,y in direction i.

The values for gridpoints bounded by contours of equal value are then computed by averaging values computed from all available gradients, weighted inversely by the distance from the gridpoint to the nearest contour. This is done according to Equation 2g:

$$V_{x,y} = \frac{\sum_{i=1}^{n} \frac{V_i}{D_i}}{\sum_{i=1}^{n} \frac{1}{D_i}} \qquad (2g)$$

where $V_{x,y}$ = computed value of gridpoint x,y,
V_i = value of gridpoint x,y according to gradient in direction i,
D_i = distance to nearest contour from gridpoint x,y in direction i, and
n = number of directions in which contours are found.

The average value of the gridpoint is constrained so as not to exceed the least restrictive range limit in any direction computed in Equation 2c. Fig. 2 shows the gridpoint values computed in this step.

For gridpoint (x=3, y=6) in Fig. 2, a radial search in the eight directions yields the following values of C_i, D_i, C'_i, D'_i in the four directions which contours are found:

$C_2=40$, $C_3=40$, $C_4=40$, $C_5=40$, $D_2=1.5$, $D_3=0.75\sqrt{2}$, $D_4=1.5$, $D_5=4.75\sqrt{2}$
$C'_2=50$, $C'_3=50$, $C'_4=50$, $C'_5=41$, $D'_2=5.5$, $D'_3=5\sqrt{2}$, $D'_4=7.5$ and $D'_5=5\sqrt{2}$.

Directional gradients determined by Equation 2a are used to compute the following gridpoint values using Equation 2b:

$V_2=36.25$, $V_3=38.24$, $V_4=37.50$, and $V_5=21.00$.

A range limit of 30 is determined in three of the four directions by adding the difference between the nearest contour (40) and the second, more distant, contour used in the computation of the directional gradient (50), to the value of the nearest contour (40) according to Equation 2c. The range limit in the remaining direction is 39. This is determined by adding the difference between the nearest contour (40) and the edge gridpoint value of 41 computed in STEP 1 to the contour value of 40. Values computed using Equation 2b which are outside their range limit are assigned the value of the range limit according to Equation 2d. The constrained values are:

$V'_2=36.25$, $V'_3=38.24$, $V'_4=37.50$ and $V'_5=39.00$.

Because no contours are found in the opposite direction from any of the directional gradients used in this example, adjusted gradients are computed according to Equation 2e. One direction is dropped because its range limit was determined using an edge gridpoint instead of a contour. Values of gridpoints are computed using adjusted gradients according to Equation 2e. They are:

$V''_2=36.97$, $V''_3=37.75$, and $V''_4=36.61$.

Values of gridpoints computed using the adjusted gradient replace the values computed in Equation 2a as required by Equation 2f. The selected set of computed values is:

$V_2=36.97$, $V_3=38.24$, and $V_4=37.50$.

According to Equation 2g, the weighted average of these values for gridpoint $V_{3,6}$ is computed to be 37.65 where $n=3$. This value is within the range limit of 30 determined from the directional range limits computed in Equation 2c.

STEP 3: Compute values for gridpoints in shadow areas from adjacent gridpoints.

Gridpoints in "shadow areas" of the grid are computed by averaging values of adjacent gridpoints outside the shadow which were computed in the previous steps. Shadows arise when an area is blocked from direct view of different valued contours by equally-valued contours or because distant contours are not seen along a limited number of radial search paths. Fig. 3 shows gridpoint values computed for the two shadow areas of the grid.

Shadow areas are filled from the edge of the shadow to the center until all gridpoints have computed values. The average includes the adjacent gridpoint values from each of eight directions having a computed value. If an adjacent gridpoint with a computed value lies on the opposite side of one or more contours, the value of the nearest intervening contour is taken and nominally adjusted for use in the average. The adjustment preserves the position of forecaster-drawn contours on the grid in areas with weak or ill-defined gradients.

The sign of the adjustment to the value of the nearest intervening contour is determined by the relative values of that contour, any other intervening contour(s), and the adjacent gridpoint. The adjustment is negative if the value of the next contour or gridpoint in that direction is greater than the value of the nearest contour. The adjustment is positive if the value of the next contour or gridpoint in that direction is less that the value of the nearest contour. If the adjacent gridpoint lies on the opposite side of one or more pairs of equally-valued contours, the adjustment to the computed value of the gridpoint has the same sign as the difference between the value of the next contour or gridpoint in that direction, and the value of the pair of contours.

The values for gridpoints in shadow areas of the grid are computed according to Equation 3:

$$V_{x,y} = \frac{1}{n} \sum_{i=1}^{n} (AC_i + a_i) \tag{3}$$

where $V_{x,y}$ = computed value of gridpoint x,y,
AC_i = value of nearest contour or gridpoint to gridpoint x,y in direction i,
a_i = adjustment used to distinguish between the positive and sides of the contour in direction i, and
n = number of directions in which contours or adjacent gridpoint values are available.

For gridpoint (x=17, y=18) in Fig. 3, contours are used in two directions and adjacent gridpoints with computed values are used in three directions. The following values of AC_i are determined in five directions:

AC_1=69.0, AC_2=68.95, AC_3=68.25, AC_7=70, and AC_8=70.

The value of the adjustment a_i is zero in the three directions where no contours lie between the gridpoint being computed and the adjacent gridpoint. The adjustment takes on a negative value in the two directions where AC_i is determined from the 70 contour because the gridpoints on the opposite of this contour are greater than 70. For gridpoint (x=17, y=18), a_i has the following values:

a_1=0, a_2=0, a_3=0, a_7=-1, and a_8=-1.

According to Equation 3, $V_{17,18}$ is computed to be 68.84 where n=5.

STEP 4: Smooth selected gridpoint values.

It is often desirable to smooth areas of the grid computed by SIRS. This is done by computing an average for a gridpoint from the gridpoint value itself and the values of adjacent gridpoints in eight directions. In order to maintain mathematical consistency with forecaster-drawn contours, gridpoints adjacent to contours are not smoothed.

SIRS performs smoothing according to Equation 4:

$$V_{x,y} = \frac{V_{x,y} + b\frac{1}{n}\sum_{i=1}^{n} AC_i}{1+b} \tag{4}$$

where $V_{x,y}$ = computed value of gridpoint x,y,
b = smoothing parameter,
AC_i = value of gridpoint adjacent to gridpoint x,y in direction i, and
n = number of adjacent gridpoints used in smoothing.

In areas bounded by equally-valued contours, SIRS only replaces a gridpoint with its smoothed value when doing so enhances the gridpoint's difference with the contour value. Conditional smoothing in this manner preserves the strength of maximums and minimums which were determined using gradients. Values for gridpoints between contours of different value are smoothed unconditionally.

Fig. 4 shows gridpoint values smoothed with a smoothing parameter of b=8. For a grid evenly covered by contours as shown in this example, the benefit of smoothing is small. However, some improvement over the original gridpoint values shown in Fig. 3 can be seen in the top three rows of the rightmost five columns.

5. THE IMPLEMENTATION OF SIRS

A. Area of Influence

SIRS can be used to compute/recompute values for any or all points on a grid. When drawing, erasing, or modifying contours, it is desirable that only the gridpoints in an area bounded by the contours immediately adjacent to the modified contour be computed. This preserves detail beyond the resolution of contour intervals in areas of the grid which have been initialized from guidance or have previous forecaster-assigned values. If a forecaster were to draw, erase, or modify the position of the 60 contour on the grid shown in Fig. 4, only values for gridpoints in the area between the adjacent 50 and 70 contours would be replaced with computed values.

An exception occurs when modifications made to adjacent contours cause an area bounded by contours having a common value to change from a maximum to minimum (minimum to maximum) area on the grid. SIRS identifies these areas by comparing computed gridpoint values with the original values relative to the value of the nearest contour. If the computed and original values are inconsistent, the values for these gridpoints are also replaced with computed values. This case would occur in Fig. 4 if the value of the 60 contour were changed to 70 by the forecaster. This change switches those gridpoints within the existing closed 70 contour from a maximum to minimum area on the grid.

B. Contour Search Strategy

In order to facilitate rapid searching for contours, a finer mesh support grid is overlaid on the object grid for which gridpoint values are to be computed. The paths of automatically-generated contours, and contours interactively entered or modified on the display screen by the forecaster, are identified on the support grid as a series of forward and backward pointers in eight directions. Associated contour values are also maintained for points on the support grid. Contours are found in any direction by searching the appropriate points on the support grid for contour values. The support grid also serves to identify contours for interactive selection and repositioning by the forecaster.

Although SIRS is described above in terms of point-by-point processing for clarity, the algorithm can be optimized to search the entire grid for contours just once in each direction. The accuracy of the gridpoint values computed by SIRS can be marginally improved by increasing the number of search directions. TDL's current implementation of SIRS on Pre-AWIPS uses 16 directions. However, searching in eight directions provides quite reasonable results, as shown in the figures.

C. Support Grid Density

In addition to adjusting the number of search directions, the ratio of the number of points on the support grid to the number of data points on the object grid can be adjusted to match the processing speed of the host hardware. Fine support grids require more search time. However, because displayed contours cannot be smoothed beyond the resolution of the support grid, the support grid should not be coarse. The apparent smoothness of contours increases as the number of points on the subgrid approaches the pixel resolution of the display screen. TDL's current implementation of SIRS on Pre-AWIPS performs a radial search on a support grid four times finer (in each direction) than the 19 x 19 object grid.

When contour intervals are large and the number of support gridpoints between data points is small, the positions of contours can drift from areas of the grid with strong gradients into areas of the grid with weaker gradients if redrawn from the SIRS-computed gridded field. In order to lessen this effect, data values computed by SIRS are forced to be at least one integer value larger (or smaller) than the contour values used in their computation. This action also helps the forecaster to visually identify the positive and negative sides of contours on the screen.

6. PLANS FOR THE FUTURE

SIRS is currently a "laboratory technique" which still requires field-testing and tuning. It is only one of several tools which the forecaster could use to graphically manipulate digital forecasts in a modernized forecast office. Operational acceptance of SIRS not only depends on the technique itself, but on the strength of its integration with complementary tools to be used to visualize and manipulate digital forecast gridfields in the AWIPS-era.

ACKNOWLEDGEMENTS

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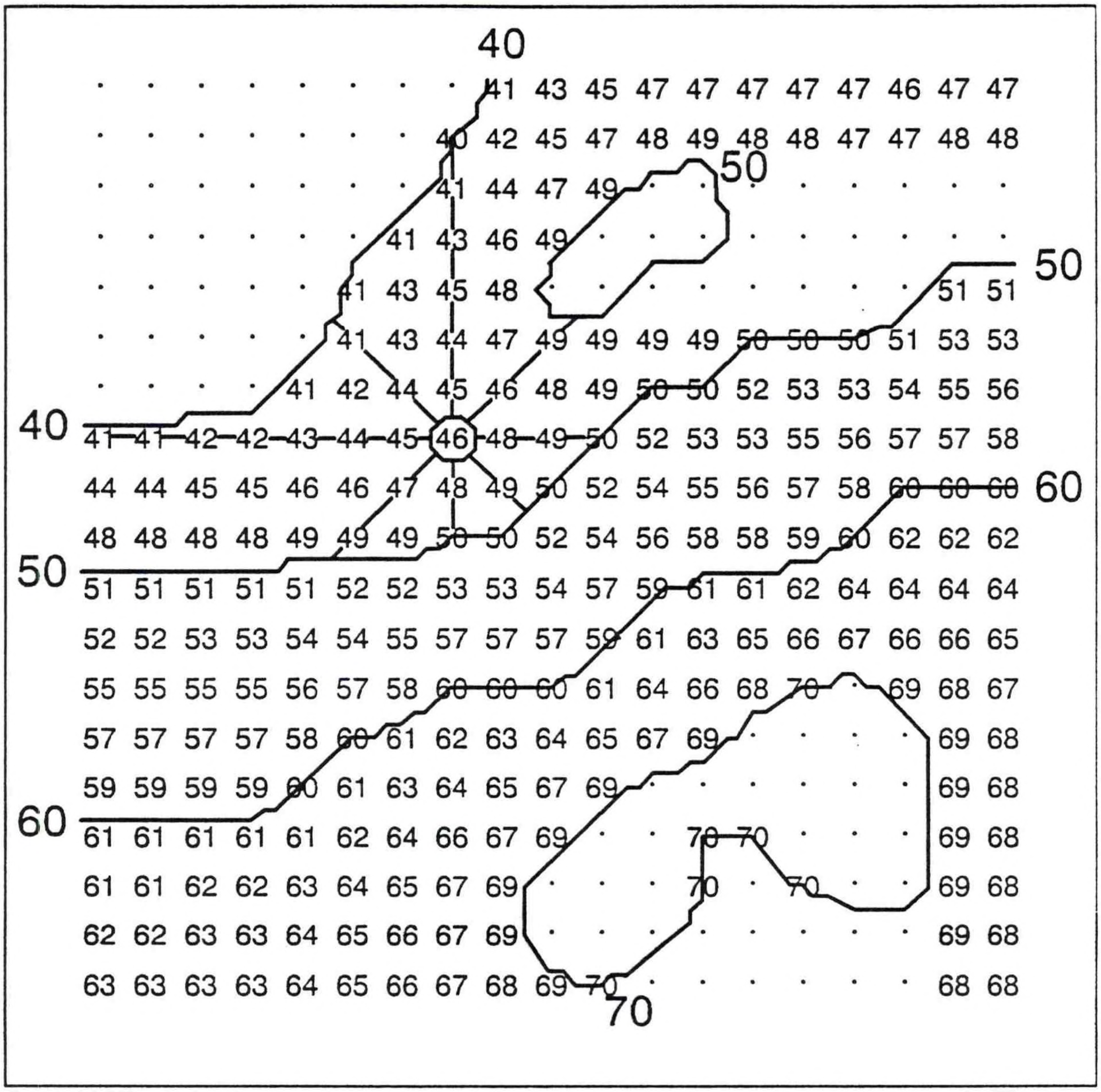

Figure 1. Gridpoint values computed by averaging contours in SIRS Step 1.

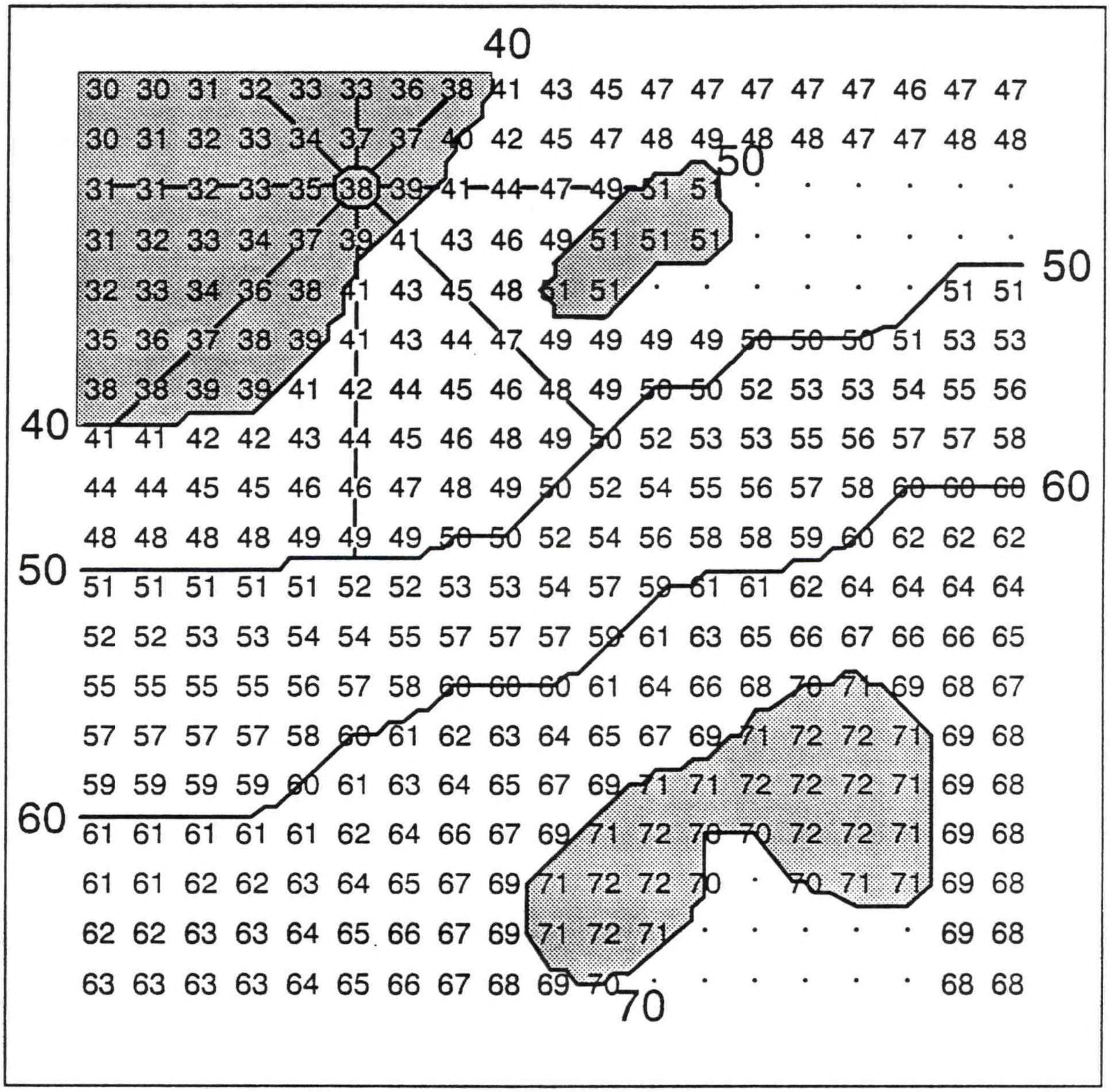

Figure 2. Gridpoint values (shaded area) computed from gradients in SIRS Step 2.

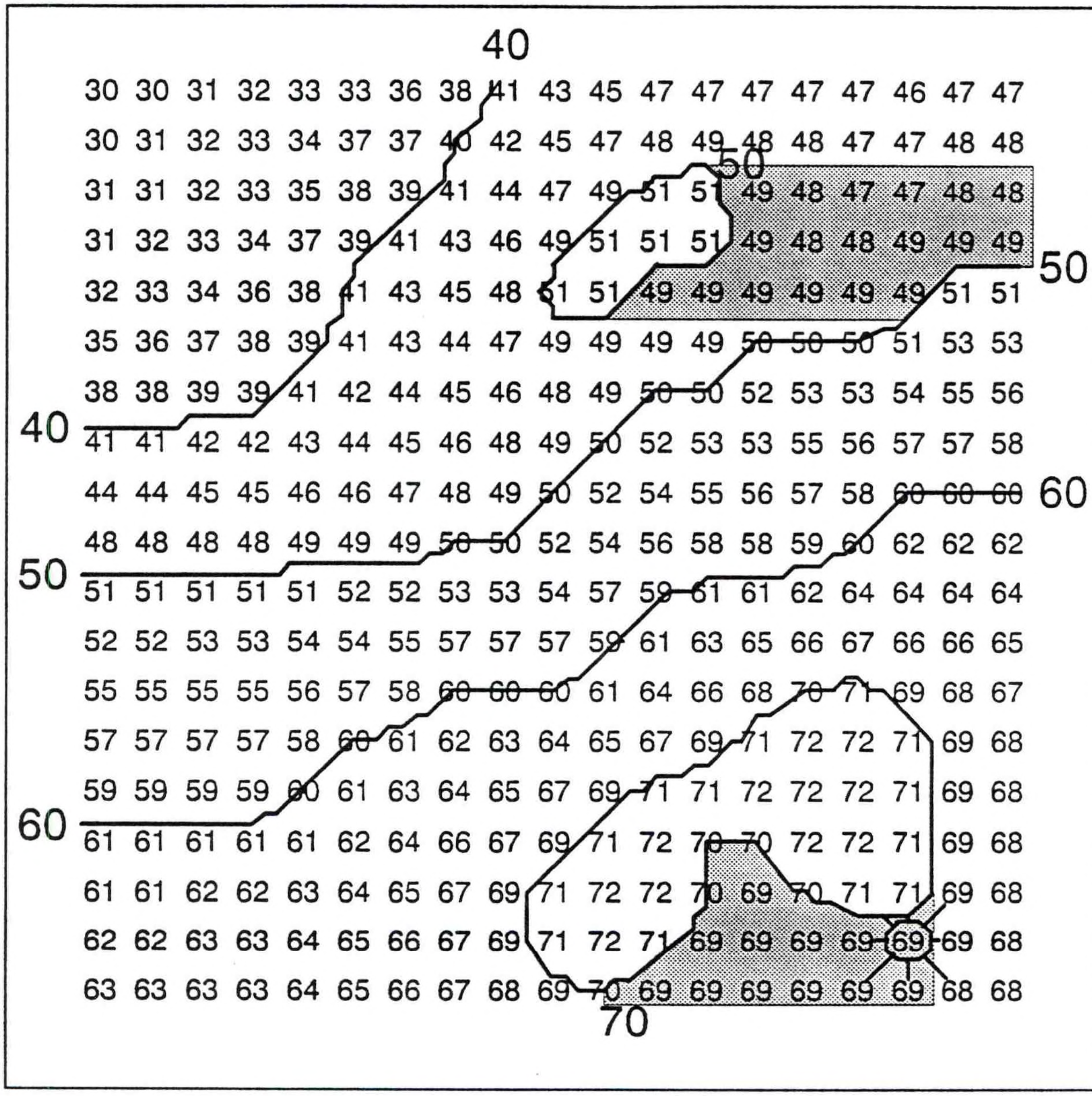

Figure 3. Gridpoint values (shaded areas) computed by averaging adjacent gridpoints in SIRS Step 3.

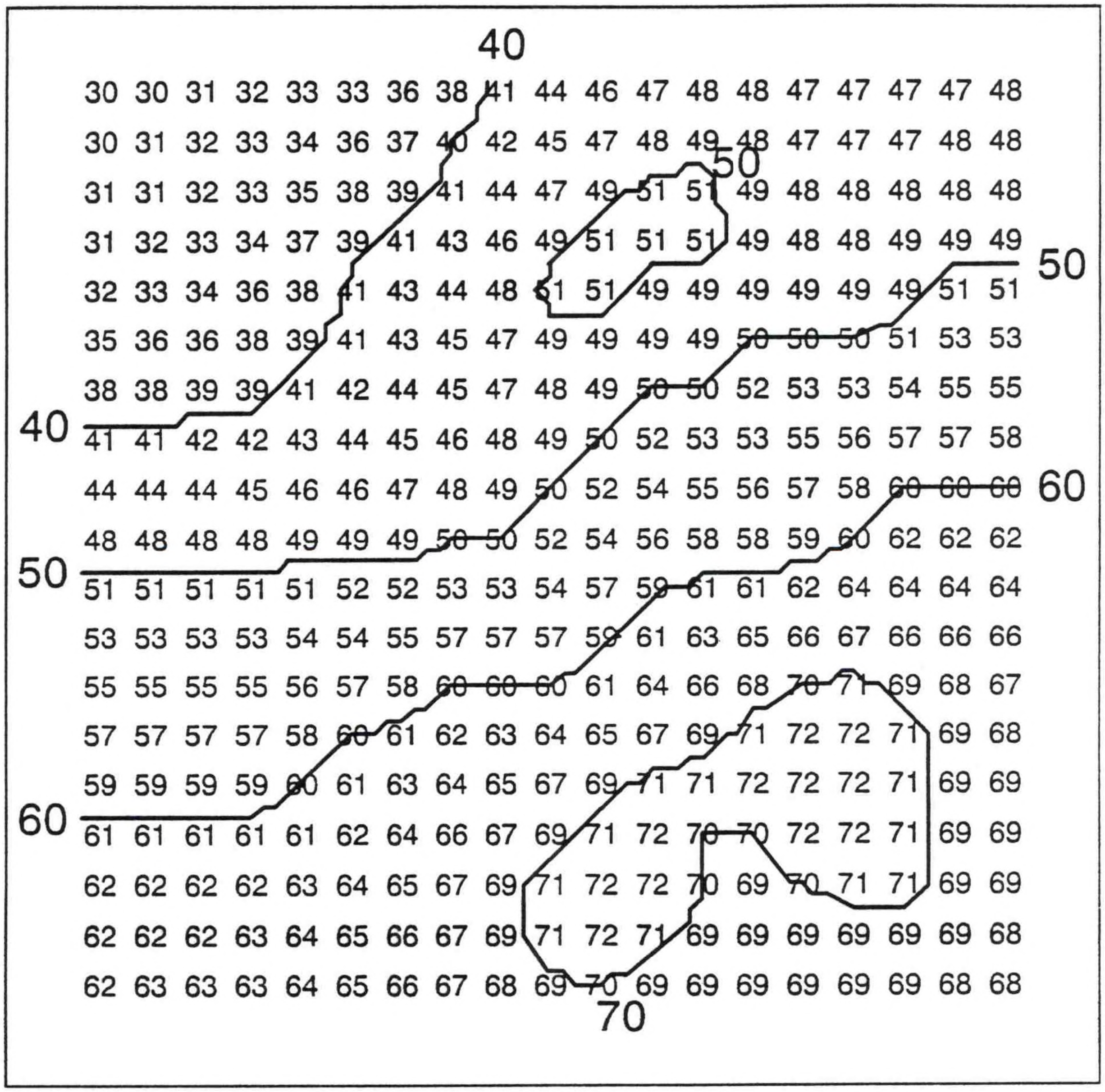

Figure 4. Gridpoint values smoothed in SIRS Step 4.