A CLIMATIC INVESTIGATION OF THE RELATIONSHIP BETWEEN SYNOPTIC FACTORS AND HAIL OCCURRENCE IN NORTHERN GREECE DURING THE DOMINATION OF 500-HPA LOWS

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ABSTRACT

An objective detection and analysis of 500-hPa cyclones (lows) is performed during the warm period (15 April-15 October) of the year for the central and east Mediterranean region and especially for northern Greece. The NCEP/NCAR reanalysis gridded data of geopotential height and temperature are employed in the detection of lows and in the calculation of the various dimension, shape and instability parameters. The parameters are used in the identification of hail days during a period of 13 operational hail seasons in northern Greece where the National Hail Suppression Program is conducted. The estimated conditional probability (8%) for hail occurrence under low domination indicates that hailfalls are rather rare and lacking severity. When however, the PVA advection centers, which usually accompany the lows are considered, hailfalls are more frequent (20%) and severe. This is attributed to the increased low-level instability at the PVA centers in the absence of extended cloud covers. Hail-related lows are larger and bear a greater resemblance to circles than the ordinary lows. They are usually moderate or negligibly elongated in the northeast to southwest direction and originate at the east coast of Adriatic Sea.

1. INTRODUCTION

Since the first synoptic charts, synoptic conditions have been considered as a first approach to the investigation of meteorological phenomena (Yarnal, 1993), which take place in smaller scales. Hailfall or hail occurrence is a sub-synoptic scale (Orlanski, 1975) phenomenon with a typical dimension usually in the range 10-100 km. Compared to the typical dimension of a synoptic system (1000 km), it is smaller by one or two orders of magnitude. There are many difficulties (Fujita, 1986) in relating phenomena of different scales. A probabilistic approach is required to overcome the lack of theoretical knowledge about the exchange of physical quantities (energy, momentum) between different scales. An intermediate scale is sometimes required to fill the continuity gap.

The 500-hPa lows or 500-hPa cyclones (Parker, et al, 1989; Bell and Bosart, 1989) are synoptic features, which are easily identified and in the absence of organized surface systems characterize the prevailing weather. In the Mediterranean basin, this situation usually occurs during the warm-dry season of the year, when surface depressions are rare (Reiter, 1975; Radinović, 1987). Especially in northern Greece, 500-hPa lows are related to persisting cloudy weather (Maheras, 1982), rain and sometimes hailstorms (Riley, 1989; Hadji, 1993). These weather conditions are harmful to economic activities such as tourism and agriculture. Common harm in agriculture results from fungi infections. The infections are favored (WMO, 1988) on the wet plant surfaces, when clouds block the sun rays. The cracking of smooth skinned fruits (mainly cherries) because of the osmosis effect is another common harm. It usually occurs when mature fruit skin remains wet long enough. Damage from storms is the third common harm in agriculture. Hail damages are generally considered the most important because of the mature stage of the crops (Dalezios and Spanos, 1995) and the irreversible effect. In order to assess the importance of the harm, estimations of hail occurrence frequency during the domination of 500-hPa lows are required. A climatic investigation is therefore conducted and presented in order to estimate the hail occurrence frequency and to possibly identify the particular shape and dimension characteristics of these lows. The investigation is extended to synoptic and sub-synoptic factors, which influence hail occurrence such as static stability and geostrophic vorticity advection.

2. DATA AND METHODOLOGY

In the present study an objective 500-hPa cyclone detection is performed during the warm period (16 April to 15 October) of the year for central and east Mediterranean region and especially for northern Greece. The NCEP/NCAR reanalysis gridded data (Kalnay et al., 1996) of geopotential height and temperature at various levels are used for the detection of lows and the calculation of the parameters. The data have a spatial resolution of 2.5 degrees and a temporal resolution of 6 hours (00, 06, 12, 18 UTC).

Lows are determined as local minima in each 3X3 matrix (Figure 1(a)) of geopotential height values within the area of investigation. A gradient criterion (Spanos et al., 2003) is additionally applied to exclude weak lows, which probably originate from the assimilation procedure. Eight distances of the maximum closed isohypses from the center of the low are calculated along the eight primary directions (Figure 1(b)). The average distance, which is termed typical radius, represents the horizontal dimension of the low. The sum of two distances along the opposite directions is also calculated for the four pairs. The difference between maximum sum and the normal to the maximum measures the elongation of the low. This difference normalized by the maximum sum (also in the appendix) is a shape parameter termed eccentricity. Eccentricity describes the departure of the lows from circular shape and tends to zero in case of circular lows. The direction of the axis corresponding to the maximum sum, which is termed the direction of the major axis, is additionally determined as a third parameter (Figure 1(c)).

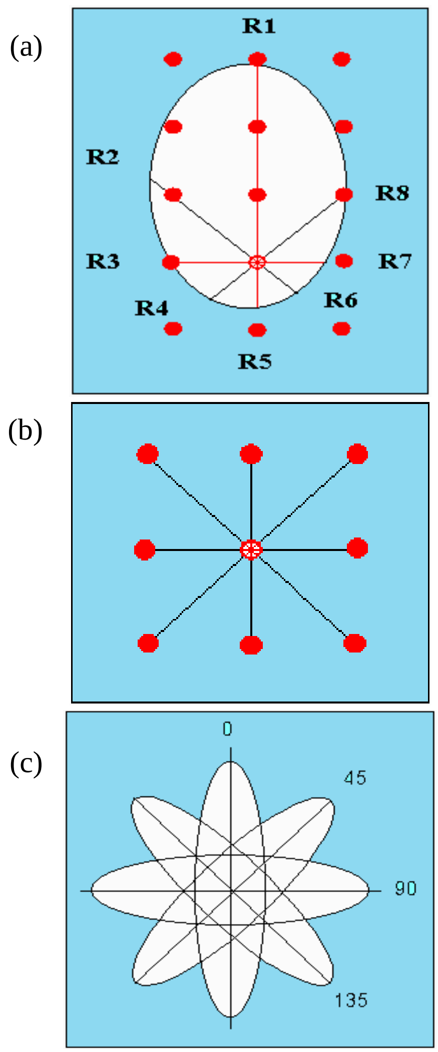

Fig. 1. Determination of synoptic parameters for the 500-hPa lows. Location is in (a), Typical Radius and Eccentricity in (b) and Direction of major axis in (c).

At the 500-hPa level, the geostrophic vorticity (ζ_g) is calculated from the horizontal Langrangian (i.e Holton, 1979) of geopotential height. Then the geostrophic vorticity advection is calculated through the Jacobian of geopotential height and the geostrophic vorticity (J(**Z**, ζ_g)). The formulae and the finite difference pattern (Fjortoft, 1952) used in the calculations are included in the appendix. Possitive vorticity advection (PVA) centers are determined as local maxima in each 3X3 matrix within the area of investigation. Centers with positive values are finally selected. A PVA center is assigned to each low according to the minimum distance from it. The detection of the lows and the calculation of the parameters carried out for a period of 13 hail seasons (between 1981 and 1998) in the area of Imathia-Pella (2340 km^2) where the National Hail Suppression Program (NHSP) is conducted. The calculation, which covers the entire number of low occurrences for the same period, is particularly focused on hail days. The verification of hail days is based on the hailpad network (Dalezios et al., 1991) and on radar-confirmed crop damage reports. In cases of lows persisting for more than one occurrence per day in northern Greece, the situation with the lower geopotential height is selected. Northern Greece (filled circles in Fig. 2) is used as an intermediate scale between the hail protected area (A1 in Fig. 2) and the entire central and east Mediterranean region.

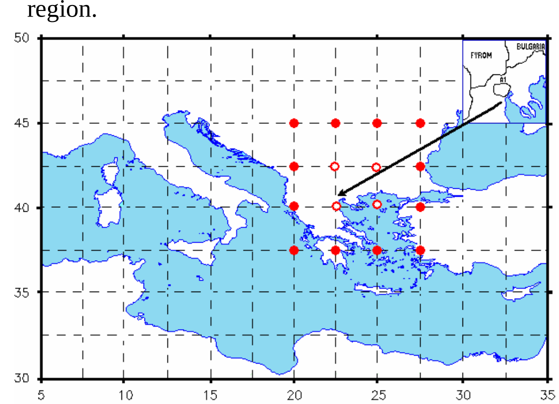

Fig. 2. Map of the investigation area, showing the grid-lines, the broader northern Greece (filled circles) and the grid-point boundary (outlined circles) of the project area (A1 at the right upper corner).

3. HAIL FREQUENCY, SYNOPTIC AND SUBSYNOPTIC CHARACTERISTICS OF LOWS

3.1. Hail frequency

Hail days occur under various synoptic regimes (Riley, 1989) such as northwest flow, cutoff low, southwest flow, zonal flow or even under ridge domination. There are numerous cases in which hail days are related to PVA centers accompanying a trough. These troughs are mostly short waves embedded in the northwest flow. During southwest flow hail is mainly attributed to frontal lifting and in case of ridge domination, air mass hailstorms are sometimes developed. The highest number of hail days occurs under the influence of northwest flow and the number of hail days during cutoff lows follows. The paper focuses in the last category, which is examined on a climatic basis.

The detection algorithm finally produced a number of 287 days with a low occupying the broader northern Greece. From NHSP archives, during the same period of years, 99 hail days are confirmed. Only 27% of these days are generally related either to the low presence or to the presence of a PVA center (accompanying the low) in northern Greece. Approximately half of these days (44%) are related only to low presence and the rest (56%) to a PVA center accompanying the low.

It seems that during the days, which are related only to low presence, the severity of hailfalls is considerably reduced. The various parameters that are used world wide to express hailfall severity are

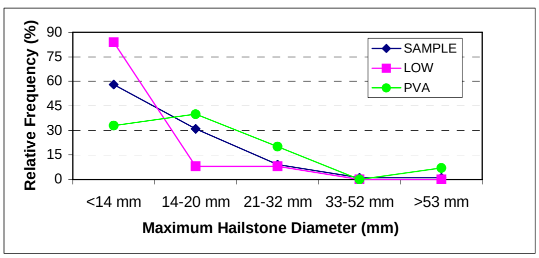

Fig. 3. Relative frequency distributions of maximum hailstone diameter for low situations, PVA centers accompanying lows and entire sample of hail days.

inter-correlated. In this paper severity is expressed in terms of maximum hailstone diameter deduced from the hailpad network. The categorization used in the paper was first introduced by Strong and Wilson (1981) and was adopted by NHSP. The first category is pea size, the second is grape size, the third is walnut size, the forth is golfball size and the fifth is greater than golfball size. The relative frequency distributions of these categories in the entire sample, in cases of low presence and in cases of PVA centers associated with lows, are shown in Fig. 3. The comparison depicts a reduction in severity when lows are present. This is consistent with what Hadji (1993) described as the main feature of a cutoff low situation. It is the increased frequency of embedded radar echoes and the small size of hail. On the other hand the severity is increased when PVA centers associated with lows are considered (Fig. 3). In this case pea size hail is less common while greater sizes occur more frequently.

The combination of the absolute frequency for all these categories provides the total hail occurrence frequency, which is then expressed relatively to the total number of lows or PVA centers affecting the area in the research period. The relative frequency (or probability) of hail occurrence is separately examined in cases of low and in cases of PVA presence in the area. Two areas are considered in this examination. The first is a broader area in northern Greece (Figures 2 and 4) and the second, which is included in the first, is the grid-point boundary (filled circles in Figure 4) of the protected area (A1). Relative frequency of hail occurrence for both areas is higher in the case of PVA centers (14% and 20% in the dotted line boxes in Fig. 4) than in the case of the low centers (7% and 8% in the continuous line boxes in Fig. 4). In the case of low centers, the percentage remains almost invariable (7% to 8%) in the two areas but when PVA centers are considered, there is a significant increase when moving from the first area to the second (14% to 20%). This behavior indicates that PVA centers determine the hail occurrence in space more accurately than the low centers.

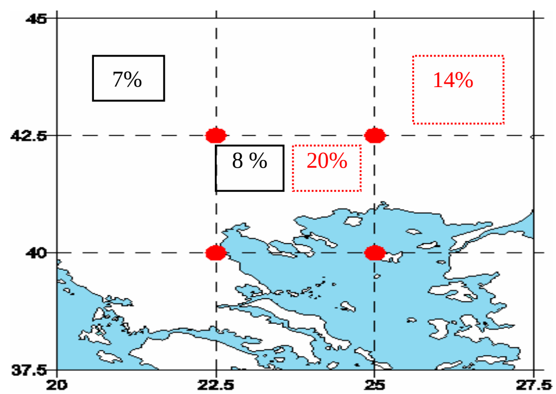

Fig. 4. Relative frequency of hail days when lows (continuous line boxes) and PVA centers (dotted line boxes) are present in broader northern Greece and in grid-point boundary A1 (filled circles).

3.2. Synoptic Characteristics

In an effort to identify the lows and the PVA centers, which are related to hail, some intensity and shape parameters are calculated. The average values are presented in Table 1, which also provides a comparison of these parameters among the three investigation areas. The second column of Table 1 indicates that the lows gradually become shallower as the area varies from the central and east Mediterranean region to the broader northern Greece and the grid-point boundary of A1 during hail days. A gradual increase in the representative dimension (typical radius) is observed in the third column. A gradual increase is also observed in the fourth column, which represents eccentricity. This variation indicates that the lows, which are related to hail, exhibit a more circular shape than the other lows in the area. It seems, however, that the behavior of the parameters is not a characteristic unique to hail occurrence. It probably constitutes a general characteristic of the 500-hPa lows in northern Greece, which is related to the origin and the evolutionary stage. No special pattern is deduced from column five which represents the variation of PVA values. The frequency distribution of the direction of the major axis of the lows is provided in the form of a circular diagram (Figure 5). The most frequent direction is NE to SW.

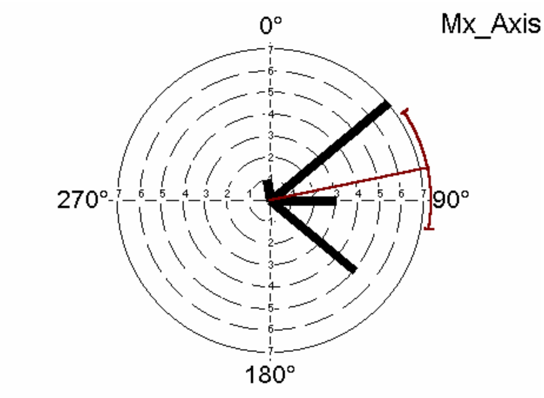

Fig. 5. Circular diagram of frequency distribution, for the orientation of major axis of the lows in broader northern Greece during hail days in A1. The thin line represents the circular mean and the brackets a 95% confidence interval.

3.3. Instability

To assess the role of synoptic factors in the modification of an instability environment necessary to the development of hailstorms, two static stability (instability) indices are calculated at the center of the low and at the PVA center. These parameters are the well-known vertical totals (Miller, 1967) and the Boyden index (Boyden, 1963). These indices are easy to calculate from the same data set but they do not incorporate the moisture factor. The temperature at 500 and 850 hPa levels is also provided for both low and PVA centers. Table 2 shows that on average, vertical totals is higher at the low centers than at the PVA centers. The Boyden index, which is a measure of instability at lower levels (1000-700 hPa), indicates the reverse. Moreover, 500-hPa temperatures at the center of the lows are generally lower than those at the PVA centers. The reverse is observed for the 850-hPa temperatures. It is evident that at the center of the low where a cold pool (Palmén and Newton, 1969) usually exists, instability increases because of the cold air masses aloft. On the other hand, at the PVA centers instability increases because of the warm air masses at the low levels. This is probably due to the warming by the sun in the absence of extensive cloud cover. The cloud cover, which accompanies a low, is observed either along the frontal surfaces when they exist, or around the center of the low when significant low-level convergence takes place. Sometimes, however, when conditions are favorable, extensive cloud masses are also formed at the PVA centers. These cloud masses are mesoscale features known as coma clouds (Browning, 1987; Barry and Carleton, 2001).

Table1. Average values of intensity and shape parameters for central and east Mediterranean region, broader northern Greece and grid-point boundary of A1.

Parameter /Area of Investigation	**Geopotential Height (gpm)**	**Typical Radius (km)**	**Eccentricity**	**PVA at Centers 10^{-9} sec^{-2}**
Central and East Mediterranean	5622	445	0.33	1.30
Northern Greece	5637	490	0.22	1.80
Grid-point Boundary of A1	5683	613	0.15	1.34

Table 2.Average values of instability parameters at low and PVA centers in grid-point boundary of A1 during hail days.

Average Values	**Vertical Totals**	**Temperature at 500 hPa**	**Temperature at 850 hPa**	**Boyden Index**
Values at Low Center	27.2	-17.2	10.0	96.2
Values at PVA Center	26.8	-15.7	11.1	96.7

4. SPATIAL DISTRIBUTION OF FREQUENCY AND ORIGIN OF THE LOWS

The spatial distribution of the frequency of lows, which are related to hail, is presented in Figure 6. The figure shows an absolute maximum to the northweast of A1 and a secondary maximum to the east or southeast. In the second case lows are found over the Aegean Sea while a ridge develops over west Greece. This combination places A1 under the influence of NW flow, which has been related to several cases of hailfall in the area (Riley, 1989; Hadji, 1993). On the other hand, the spatial distribution of PVA centers (Figure 7) shows a maximum to the northeast and an extension towards the southwest. The frequency maximum to the northeast of A1, indicates that hail in the area, occurs when PVA centers and the cloud cover which probably accompanies them moves east of the area. The area, however, is still under the influence of high PVA values. The circular diagram in Figure 8 also verifies the relative position of the PVA and low centers, which is seen in the comparison of the two figures (Fig. 6 and Fig. 7). Figure 8 shows the orientation distribution of PVA centers relative to the corresponding centers of the lows. The circular average lies in the range between 90º and 180º, which is at the SE of the lows.

The origin and simplified tracks of the 500-hPa lows, which are related to hail in Imathia-Pella, are presented in Figure 9. The majority of these lows come from the east coast of the Adriatic Sea. However, there are cases where the lows are generated at the northeast grid point of the grid-point boundary of A1. On the other hand, the origin of the lows with PVA centers related to hail is different (Figure 10). Most of these lows originate in the well-known (Radinović, 1989) cyclogenesis area of Genoa.

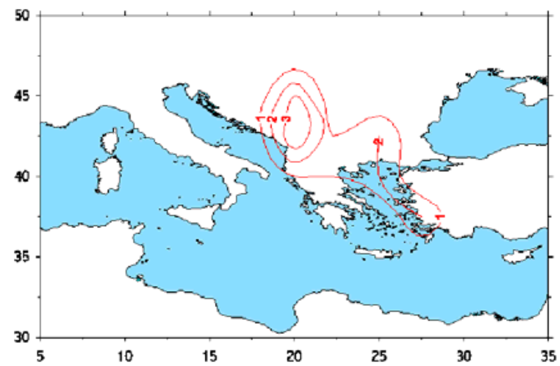

Fig. 6. Spatial distribution of low centers in broader northern Greece during hail days in A1 for 13 hail seasons.

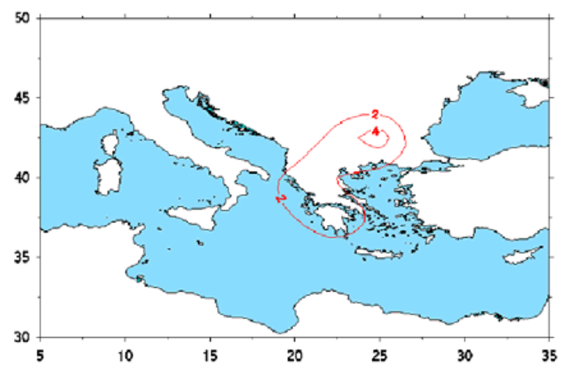

Fig. 7. Spatial distribution of PVA centers in broader northern Greece during hail days in A1 for 13 hail seasons.

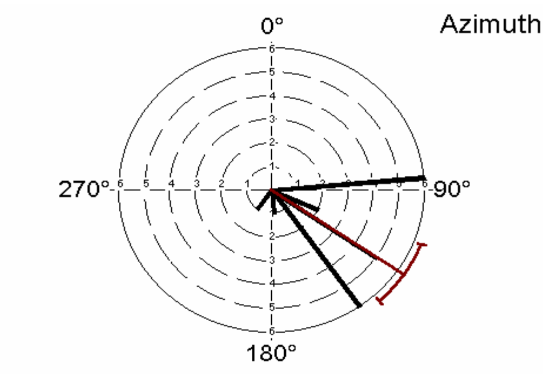

Fig. 8. Circular diagram of frequency distribution for the orientation of PVA centers relative to the lows in broader northern Greece during hail days in A1. The thin line and brackets as in Fig. 5.

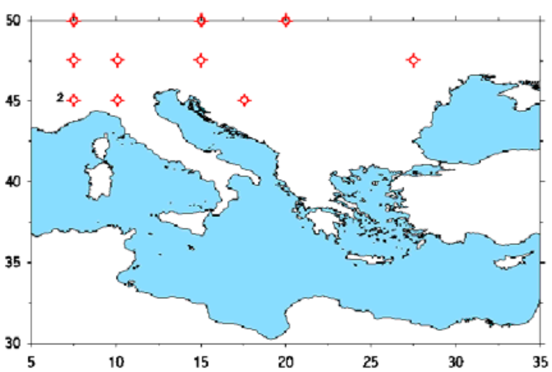

Fig. 9. Origin and simplified tracks of lows related to hail days in A1

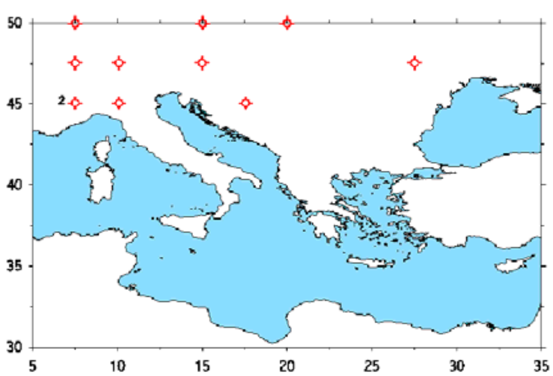

Fig. 10. Origin of lows with PVA centers related to hail days in A1.

SUMMARY AND CONCLUSIONS

The information presented in this paper suggests that the 500-hPa lows is the synoptic environment for one third of all hail days in Imathia-Pella (North Greece). In these situations, hail is almost equally attributed either to the increased instability due to the cold pool aloft, or to the action of PVA centers that usually accompany the lows. From the entire low population that affected northern Greece during 13 warm periods, only 7% is related to hail days. When the associated PVA centers are considered instead of the lows, this percentage is doubled (14%). The difference in these percentages indicates that hail is more common at the PVA centers than at the centers of the lows. The examination of the instability at the center of the two features showed that PVA centers are dominated by low-level instability and low centers by middle-level instability. It also showed that low-level instability is related to warm low levels and middle-level instability to cold middle levels (cold pool). A possible explanation for this combination is that it is the low-level warming (in the absence of significant cloud cover) that favors hailstorms. Low-level warming is usually blocked by cloud cover at the centers of the lows and the atmospheric environment is less favorable for hailstorm formation. In this situation convective clouds are weaker and embedded in stratiform clouds. This conclusion is further supported by the comparison of the two percentages for the grid-point boundary of the protected area (A1). For lows in this particular area the percentage remains the same (8%) but for the PVA centers in the same area it is considerably increased (20%). It is evident that the presence of a PVA center determines the hail occurrence in space more accurately than the presence of the low itself.

Specific characteristics of the lows, which are related to hail days, are further described for identification and forecasting purposes. The major axis of hail related lows mostly lies in the direction NE-SW. When compared to lows in the entire region, hail-related lows are shallower, larger in dimensions and bear a greater resemblance to circles. The PVA centers, which are related to hail, generally lie in the SE of the associated low centers. 500-hPa lows which are related to hail in Imathia-Pella, are usually generated on the east coast of the Adriatic while lows with PVA centers related to hail are generated in northern Italy and Europe.

APPENDIX

Figure 1(a) shows the pattern followed in the detection of 500-hPa lows with the low center at the middle of a 3X3 matrix of grid-point values. Figure 1(b) shows the determination of the eight distances ($R_1 \ldots R_8$) of the maximum closed isohypses from the center of the low. The distances are calculated by using the interpolation method between the successive grid-points. The typical radius (TR) is calculated by the formula:

$$TR = [\sum_{1}^{8} Ri\ ]/8 \qquad (1)$$

Eccentricity (E) at the same figure is calculated by the formula:

$$E=\{(R1+R5)-(R3+R7)\}/(R1+R5) \qquad (2)$$

The four directions of the major axis of the low are presented in Figure. 1(c)

Geostrophic vorticity is calculated from (3) :

$$\zeta_g = \frac{g}{fo}\left(\frac{\partial^2 Z}{\partial x^2} + \frac{\partial^2 Z}{\partial y^2}\right) \qquad (3)$$

The term in brackets is the Laplacian of geopotential height at plane x,y and can be approximated by using finite differences for the derivatives along the x and y axis :

$$\frac{\partial^2 Z}{\partial y^2} = \frac{\frac{Z_2 - Z_0}{d_1} - \frac{Z_0 - Z_4}{d_1}}{d_1} = \frac{Z_2 + Z_4 - 2Z_0}{d_1^{\ 2}} \qquad (4)$$

In the same manner:

$$\frac{\partial^2 Z}{\partial x^2} = \frac{Z_1 + Z_3 - 2Z_0}{d_2^{\ 2}} \qquad (5)$$

Subscripts 1,2,3,4 refer to the surrounding grid points of the low center (Figure 11).

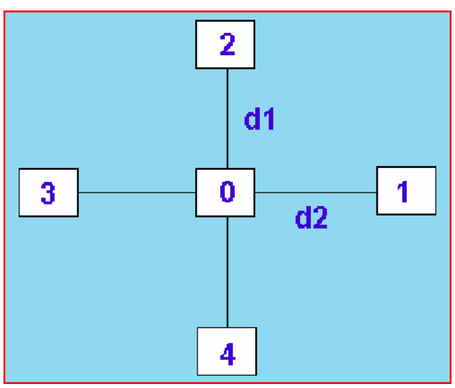

Fig. 11. Grid-point arrangement around the center (0) of a detected low for the calculation of vorticity advection in the finite difference pattern.

The geostrophic vorticity advection at point 0 is calculated from equation 6 where J represents the Jacobian of geopotential height and geostrophic vorticity :

$$-V_g \nabla \zeta_g = -\frac{g}{fo}\, J(Z, \zeta_g) \qquad (6)$$

The Jacobian $J(Z, \zeta_g)$ is analyticaly given by the following formula :

$$J(Z, \zeta_g) = \frac{\partial Z}{\partial x}\frac{\partial \zeta_g}{\partial y} - \frac{\partial Z}{\partial y}\frac{\partial \zeta_g}{\partial x} \qquad (7)$$

The application of finite differences approximation to equation 7 results in equation 8 which is the calculation equation for the geostrophic vorticity advection:

$$J(Z, \zeta_g) = \left(\frac{Z_1 - Z_3}{2d_2}\right)\left(\frac{\zeta_2 - \zeta_4}{2d_1}\right) - \left(\frac{Z_2 - Z_4}{2d_1}\right)\left(\frac{\zeta_1 - \zeta_3}{2d_2}\right) \qquad (8)$$

Equation 8 considers a standard grid distance d1 along the y-axis and a variable distance d2 along the x-axis depending on latitude.

REFERENCES

Barry, R.G. and A.M., Carleton, 2001: *Synoptic and Dynamic Climatology*. Routledge 11 New Fetter Lane London, 620 pp.

Bell, G.D. and L.F., Bosart, 1989: A 15-year Climatology of northern hemisphere 500 mb closed cyclone and anticyclone centers. *Mon. Wea. Rev.*, 117, 2142-2163

Boyden, C. J., 1963: A simple instability index for use as a synoptic parameter. *Meteor. Mag.*, 92, 198-210

Browning, K.A., 1987: Towards the more Effective Use of Radar and Satellite Imagery in Weather Forecasting. *Weather Radar and Flood Forecasting*. Edited by V.K. Collinge and C. Kirby. John Wiley & Sons Ltd, 239-263

Dalezios, N.R., M.V. Sioutas and T.S. Karacostas, 1991: A systematic Hailpad Calibration Procedure for Operational Hail Suppression in Greece. *Meteorol. Atmos. Phys.* 45, 101-111.

Dalezios, N.R. and S.I. Spanos, 1995: Operational Efficiency Assessment of Hail Suppression for Agriculture in Greece. *J. of Wea. Mod.,* 27 (1), 21-35.

Fjortoft, R., 1952: On a Numerical Method of Intergrating the Barotropic Vorticity Equation, *Tellus*, 4.

Fujita, T.T., 1986: *Mesoscale classifications: their history and their application to forecasting.*

Mesoscale Meteorology and Forecasting, ed. P.S. Ray, American Meteorological Society, Boston Massachusetts, 18-35.

Hadji, H., 1993: *Synoptic typing scheme.* Rudolph and Robitaille (editors), Greek National Hail Suppression Program, 1992 Annual Report Prepared by Joint Venture Company 3Δ-CIC-Avionic for National Agricultural Insurance Institute, Athens, 152 pp.

Holton, J.R., 1979: *An Introduction to Dynamic Meteorology*. Academic Press New York, 319 pp.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Irebell, S. Saha , G. White, J. Woollen, Y. Zhu, A. Leetma, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Huggins, J. Janowiak, K. Mo, C., Ropelewski, J. Wang, R. Jenne, D. Joseph 1996: The NCEP/NCAR 40-year Reanalysis Project. *Bul. Amer. Met. Soc.*, 77, 437-471

Maheras, P., 1982: *Climatologie de la mer Egée et de ses marges continentales*. Thèse d' Etat, Atelier de Reproduction de Thèses de Lille III, 784 pp.

Miller, R.C., 1967: *Notes on analysis and severe storm forecasting procedures of the Military Weather Center.* Tech. Rep. 200, AWS, USAF, 170 pp.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, 56, 527-530.

Palmén, E. and C.W. Newton, 1969: *Atmospheric circulation systems.* Academic Press, New York, 603 pp.

Parker S.S., J.T., Hawes, S.J., Colucci and B.P., Hayden, 1989: Climatology of 500 mb Cyclones and Anticyclones, 1950-1985. *Mon. Wea. Rev.*, 117, 558-570

Radinovic, D., 1987: *Mediterranean Cyclones and their Influence on the Weather and Climate*. Program on Short and Medium Range Weather Prediction Research (PSMP), WMO Sofia No 24, 132 pp.

Reiter, E.R., 1975: *Handbook for Forecasters in the Mediterranean*. Tech. Paper No 5-75, Environmental Prediction Research Facility, Naval Postgraduate School, Monterey, 344 pp**.**

Riley, G., 1989: *Synoptic scale aspects*. Rundolph et al. (editors), Greek National Hail Suppression Program, 1988 Annual Report. Prepared by INTERA Technologies Ltd. for National Agricultural Insurance Institute, Athens, 280 pp.

Spanos, S., P. Maheras, T. Karacostas and P. Pennas, 2003: Objective Climatology of 500-hPa Cyclones in Central and East Mediterranean Region during Warm-Dry Period of the Year. *Theor. Appl. Climatol.*, 75, 167-178.

Strong, G.S. and W.D. Wilson, 1981: The synoptic (instability) index: 1978-80 tests and new versions. Preprints, *15th Annual Congress, Canadian Meteor. and Oceanogr. Soc.*, Saskatoon, Saskatchewan 27-29 May 3p.

WMO, Technical note, 1988: *Agrometeorological Aspects of Operational Crop Protection*, Technical note No 192, Secretariat of the World Meteorological Organization, Geneva-Switzerland, 8-15.

Yarnal, B., 1993: *Synoptic Climatology in Environmental analysis*: A primer. Belhaven Press London and Florida, 195 pp.