MESOCYCLONE DETECTION AND CLASSIFICATION ALGORITHM

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**Abstract:**
A proposed four-dimensional algorithm for automated detection of mesocyclones employs resolution-dependent thresholds of rotational velocity and shear. This algorithm incorporates complementary features of earlier techniques suggested by Hennington and Burgess and by Forsyth, Bjerkaas and Petrocchi. Classification of mesocyclones by calculation of total rotational kinetic energy is proposed as a possible means for early assessment of the destructive energy of the resultant tornado.
MESOCYCLONE DETECTION AND CLASSIFICATION ALGORITHM

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1.0 INTRODUCTION

Mesocyclones are circulating regions, averaging 5 km in diameter, located within some intense and well-organized thunderstorms. Although infrequent, they are an important aid in providing a storm warning signature detectable by Doppler radar. Nearly all mesocyclones are associated with some form of severe weather, and about half of them spawn tornadoes. The typical mesocyclone starts at mid-levels (about 5 km) in a storm and rather slowly extends upward and downward. Convergence and other severe weather manifestations generally do not occur until the mesocyclone base reaches the ground, a process that averages 31 minutes in duration (Burgess et al., 1982). Consequently, detection of a mesocyclone early in its development cycle will yield a greater lead time for forecasters than is presently available.

Mesocyclones have been successfully detected for many years through visual inspection of the velocity field provided by a single Doppler radar. Accomplishment of this task in real time, however, demands the constant and alert attention of a meteorologist. Economical and reliable employment of human resources in an operational scenario requires the aid of an automated mesocyclone detection scheme. Automation is especially needed during tornado outbreaks, when two or more mesocyclones may occur simultaneously within range of a radar.

It is proposed that this automatic processing be performed by a four-dimensional detection algorithm that identifies mesocyclonic shear with a resolution-dependent shear threshold applied over a minimum velocity difference. These criteria are intended to enable the algorithm to detect small mesocyclones, and large ones at great ranges (where impaired azimuthal resolution may reduce measured shear) without triggering false alarms due to natural small-scale variability in velocity. This proposed algorithm will vertically correlate mesocyclonic shear features and tabulate their temporal persistence.

The development of this four-dimensional mesocyclone detection algorithm is a natural extension of less comprehensive algorithms proposed by Hennington and Burgess (1981) and by Forsyth et al. (1981). These earlier algorithms have some complementary features. The former detects mesocyclonic shear based on a combination of shear and momentum thresholds, and computes the horizontal extent of the circulation in radial as well as azimuthal direction. The latter scheme is based only on shear between velocity peaks and correlates this shear vertically and temporally. Momentum thresholding was not incorporated in our mesocyclone detection algorithm because of its tendency for rejection of small but intense vortices, such as tornado vortex signatures, and for acceptance of certain large-scale patterns with less than the requisite shear. We suggest, however, that mesocyclones be classified by trends of their rotational kinetic energy, and angular momentum. This may be a means for early assessment of the destructive energy of the resultant tornado. For vortices of equal size, rotational kinetic energy is proportional to the square of maximum rotational velocity, so this parameter may be especially sensitive as an indicator of the probability of a tornadic circulation penetrating to the ground and inflicting severe damage.

2.0 PROPOSED ALGORITHM

The algorithm is capable of detecting cyclonic and anticyclonic circulations over a wide range of scales. It computes the horizontal and vertical extent, average shear, momentum, rotational kinetic energy and temporal persistence of these circulations.

Criteria for the detection of mesocyclones have been set forth by Donaldson (1970), and later by Burgess (1976). Three basic requirements are: 1) significant azimuthal shear must exist between closed velocity contours of opposite sign (provided storm motion has been removed). 2) Shear pattern and closed isodops must extend vertically for a height interval comparable to the horizontal diameter. 3) The shear pattern must persist for a time interval greater than one half of the revolution period of the feature. Burgess et al. (1982) defined the evolutionary stages of mesocyclones: 1) The organization stage is characterized by growth of the circulation area upward and downward, from mid-levels. Convergence as well as rotation may be revealed in the low-level signatures. The organizing stage ends when the mesocyclone's base extends to the lowest elevation scan. 2) The mature stage is characterized by a period of maximum velocities. During this stage tornado potential is greatest. The mesocyclones may show some convergence at lower levels, pure core rotation at middle levels, and some divergence at the top. Generally the top of the circulation is slightly lower than the peak during the organization stage. 3) The dissipating stage begins when the mesocyclone summit drops rapidly, and the maximum velocities decrease. At the end of this stage the circulation exists in a shallow layer and is very weak.
2.1 Scale Considerations

Although a great majority of mesocyclones and tornadoes are cyclonic, a few anticyclonic tornadoes have been observed. Therefore, we have ensured that the algorithm can detect anticyclonic circulations. Since mesocyclones have long been recognized as the vorticity-producing units for tornadoes we have included the detection of tornado vortex signatures (TVS’s) in our algorithm. The algorithm is capable of detecting many scales of meso-circulations. For all practical purposes we shall confine our analysis to only those scales between a small TVS and a large mesocyclone, that is, from several hundred meters to 20 km in horizontal extent.

2.2 Algorithm Processing

This algorithm has evolved from a two-dimensional mesocyclonic shear algorithm proposed by Hennington and Burgess (1981) (further developed by Zrnic et al. (1982)) and a three-dimensional mesocyclone-TVS algorithm developed by Forsyth et al. (1981). We have modified and merged these algorithms so that they process data in close to real time and automatically archive mesocyclone attributes for later analysis.

The algorithm processing can be broken into five steps. These are:

1. The algorithm searches for gradients in the Doppler velocity field. This is accomplished by identifying either increasing or decreasing velocities in the azimuthal direction.
2. When a run of constantly increasing or decreasing velocities ends, the shear along the run is tested. If the shear exceeds a resolution dependent threshold a pattern vector is formed by joining peaks in the velocity field at constant range. The following six attributes of pattern vectors are saved: beginning and ending azimuths, beginning and ending velocities V, range to the pattern vector, and time of the beginning azimuth.
3. After each azimuth scan is completed the pattern vectors are grouped together into two-dimensional features. The tests for association of two pattern vectors are close radial proximity (less than 1 km), and azimuthal overlap. The two-dimensional features that have a radial extent of 0.6 km (4 range gates) or more are saved for consideration in elevation scan. The attributes saved for each two-dimensional feature are: the number of pattern vectors in the feature, minimum and maximum azimuth, beginning and ending range, and the minimum and maximum peak velocities and their orientation with respect to the radar beam.
4. The vertical correlation consists of comparison of the locations of features observed at successive elevations. If the distance between the centroids of the two-dimensional features is less than the sum of their diameters they are assumed to be correlated and their attributes are averaged for comparison with features from the next lower azimuth scan. This process continues until the end of a volume scan at which time the attributes of the three-dimensional features are analyzed.
5. As recommended by Donaldson (1970) and Burgess (1976) the shear pattern for a mesocyclone should persist for one half the period of the vortex rotation. The algorithm computes the persistence of a feature and sets a flag when this criterion has been met.

The first test on a three-dimensional feature is a check for cyclonic and anticyclonic circulation. Next the azimuthal and radial diameters are checked, and if they are not within 50 percent of one another the feature is labeled a shear area. Otherwise, the diameter is compared to the vertical depth of the feature. If they are within 50 percent of one another the feature is called a mesocyclocne. When the shear for a mesocyclone exceeds the resolution-dependent threshold for TVS it is labeled as a tornado.

Two-dimensional features that are only observed at one elevation are called single-height features.

The results from this analysis can immediately be written to a screen for operator interpretation, and to a hard copy device. The mesocyclone’s average shear, momentum, rotational energy, and identification number are stored for future analysis.

2.3 Resolution-Dependent Shear Thresholds

In order to compensate for the cross-beam degradation of resolution with range we have applied resolution-dependent thresholds for shear and peak velocity difference as criteria for retaining pattern vectors.

Hennington and Burgess (1981) and Zrnic et al. (1982) used a combination of momentum and shear thresholds to determine if a pattern vector is saved for further processing. In order to detect smaller circulations (e.g., TVS) we have eliminated the momentum thresholding because it implies a minimum length for a pattern vector. The momentum of a pattern vector is estimated from the product of the measured velocity difference (V-V) and the azimuthal distance R(0-0); shear is the quotient of these two quantities.

The velocity pattern around a non-divergent mesocyclone is generally modeled by a Rankine combined vortex (RCV). This means that the core of the mesocyclone, defined as the region between velocity peaks of opposite sign, is assumed to rotate as a solid body. As the mesocyclone is moved out in range the peak velocities decrease significantly as more and more of the mesocyclone is encompassed by the radar pulse volume. At the same time the diameter of the feature appears to increase.

We have derived our shear dependence by considering the effect of increasing range of the resolution of a RCV. Brown and Lemon (1976) present some enlightening results of a RCV model developed by Zrnic and Doviak (1976). This paper addresses the problem of identifying a TVS describing a RCV as it is moved out in range.

In this analysis we have assumed data are collected at increments equal to the antenna beamwidth. The basic indicator of the resolution dependence of a feature is the ratio of the radar beamwidth (BW) to core radius (CR). If this ratio is much less than 1 the radar can resolve the mesocycle fairly well, whereas it increases there is a degradation in the observed feature. At beamwidth to core ratio greater than 2 the true attributes of the feature are difficult if not impossible to resolve.

A minimum azimuthal shear criterion for mesocyclone detection was first used by Donaldson (1970) and later corroborated by Burgess (1976) from a study of several years of...
mesocyclone data. If we assume that an azimuthal shear of $5 \times 10^{-3} / \text{s}$ is a practical cut-off between mesocyclonic and non-mesocyclonic storms, and that the minimum allowable velocity difference is $15 \text{ m/s}$, we can see that the smallest, lowest shear mesocyclone we will permit is $3 \text{ km}$ in diameter. With a beamwidth ($a$) of 0.9 degrees we can easily resolve this feature out to a range of $110 \text{ km}$ ($RW = 1.5 \text{ km}$), after which the beamwidth to core radius would be greater than 1. At 220 km our beamwidth is approximately 3 km or twice the core radius of the RCV. Brown and Lemon's data show that a beamwidth twice the core radius would smooth the peak velocities to approximately 62 percent of their original magnitude, and the core radius would appear to be slightly larger than its true size. Consequently the shear reported for the feature would be somewhat less than 62 percent of the "true" shear. If the ratio of the beamwidth to the core radius of a tornadic feature is large, the apparent core radius can be much larger than the actual size. For example, when the beamwidth is 3 times the core radius the peak velocities detected by the radar may be 1.5 core radii from the center of the rotation.

An illustration of the momentum and shear thresholds used by Zrnic et al. (1982) can be seen in Fig. 1.

The shaded region of this figure represents the mesocyclone detection region. These thresholds do not permit the detection of TVS's, as the low momentum threshold precludes small but intense vorticies. Since no objective criteria for the detection of TVS's have been established we shall use the guidelines adopted during the Joint Doppler Operational Project (Burgess et al., 1979). These are the presence of shear greater $5 \times 10^{-2}$ and a rotational velocity greater than $30 \text{ m/s}$. This feature could have a diameter of less than $1.5 \text{ km}$ and would be in region I of Fig. 1, and precluded from further processing with the original momentum thresholding.

Fig. 2 is a representation of our resolution-dependent shear threshold.

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Fig. 1. Mesocyclone detection thresholds suggested by Hennington and Burgess (1981) portrayed in terms of velocity difference and azimuthal distance across a shear pattern. $H_m$ and $L_m$ are lines of constant shear, and $H$ and $L$ are lines of constant angular momentum. A shear pattern falling into the shaded area is accepted as a mesocyclone. In region I, which includes many high-velocity tornado vortex signatures, all shear patterns would be rejected.

Fig. 2. Mesocyclone detection threshold (including TVS's) suggested in the present paper, portrayed in terms of velocity difference and azimuthal distance across a shear pattern. A shear pattern observed with perfect azimuthal resolution (Beamwidth/Core Radius = 0) would be accepted as a mesocyclone if it fell into region I. With decreasing resolution both the shear and velocity difference thresholds would be relaxed in the direction of the dashed arrows. For a Beamwidth/Core Radius = 2, the mesocyclone acceptability space is expanded to include region I and all of region II.

The hatched region (II) of this figure represents the sliding mesocyclone detection region, and the shaded region (I) represents the perfect resolution thresholds. Using the resolution-dependent shear threshold one can see that the TVS discussed above would be included in processing. The shear threshold decreases and the minimum velocity difference decreases as the RW/CP ratio increases. The constant shear and velocity
difference lines in Figure 2 represent the ex-
treme of the thresholds used in the algorithm.
Assuming perfect resolution of a feature we ap-
ply a $5 \times 10^{-3}$ shear threshold and a velocity dif-
ference threshold of 15 m/s. As the RW/CR ratio
increases we gradually decrease the shear and
velocity difference thresholds to $2 \times 10^{-3}$ and
$0.1$ m/s at RW/CR = 2.

3.3 MESOCYCLONE CLASSIFICATION

Burgess (1976) provided the earliest de-
tailed classification of mesocyclones. In the
first four years of single-Doppler data ac-
quired by NSSL, the average difference in rota-
tional velocity between tornadic and non-tor-
nadic mesocyclones was less than 3 m/s. How-
ever, the few mesocyclones which produced maxi-
tornadoes had rotational velocities averaging
more than 10 m/s greater than the non-tornadic
one. These early statistics showed very little,
if any, predictive value for tornado occurrence
among mesocyclones. They do, however, suggest
that the heavily-damaging maxi-tornadoes, which
injure and kill a disproportionately large num-
ber of people, may be preceded by mesocyclones
having unusually large rotational velocities.

Carrying this thought a step further, it
seems to us that classification of mesocyclones
according to their rotational kinetic energy
would be even more useful than rotational veloc-
ity or angular momentum. Rotational kinetic en-
ergy is proportional to the square of velocity,
so the mesocyclones with higher velocities
would be emphasized more than those of larger
size. Integration of rotational kinetic energy
with height would provide an energy index for
each volume scan, and could be an aid in
rating the solution of a mesocyclone. The
strength of total rotational kinetic energy in a
mesocyclone may enhance the ability of a fore-
caster to predict the touchdown of a maxi-tor-
ando.

4.0 PRELIMINARY RESULTS

As a test of the algorithm we have pro-
essed a number of volume scans of data collected
prior to 1979 (Burgess et al, 1970). Our test
data are from April 16, 1979 starting at 1810
CST, just prior to the predawn tornado touch-
down. In the first volume scan the algorithm
identifies a well-developed mesocyclone. Out-
puts from the second volume scan reveal that
the mesocyclone is moving to the east and that
there is a two-dimensional TVS shear at eleva-
tion angles of 4.0 and 4.9 degrees, the peak
velocities at these levels being 33 and -36 m/s.

As the antenna dropped down for the next volume
scan (1900 CST) we have a two-dimensional TVS
shear with peak velocities of 15 and -36 m/s at
1000 meter level. On the completion of
the integration between the algorithm identifies
a four-dimensional TVS shear. The maxi-
tornado touched down at 1820
CST, at which time the radar was scanning at
high elevation angles. The development of this
mesocyclone at low levels, the tornado
skimming the ground by the time the antenna drops
to lower elevation. This feature is identified
as a mesocyclone in two volume scans and
appears to weaken slightly although maintaining
very strong shear.

5.0 CONCLUSIONS

A resolution-dependent pattern recognition
algorithm for detecting mesocyclones and tornado
vortex signatures has been developed.
The algorithm identifies three-dimensional
cyclonic and anticyclonic eddies by
computing their average shear, angular momentum,
and rotational kinetic energy. The time continuity
of the detected features is confirmed by a persist-
ence criterion, and the peak velocities at every
elevation angle are recorded.

Initial tests of the algorithm appear to be
promising. More studies must be done in this
area to improve our understanding of mesocyclones
and the mechanisms involved as they spawn torn-
adoes. The interactions between a mesocyclone's
momentum, shear, and kinetic energy as it follows
its life cycle should yield some valuable statistics
regarding the potential destructive power of the
circulation.

Further refinement of the algorithm is like-
ly to take place as more data is processed. In
particular the minimum feature size, the velocity
difference and shear thresholds, and the beam-
width to core radius ratio cut-offs can only be
evaluated after extensive testing. Probability of
detection and false alarm statistics need to
be compiled over a wide range of cases in order
to give us better understanding of the algorithm's
performance.

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